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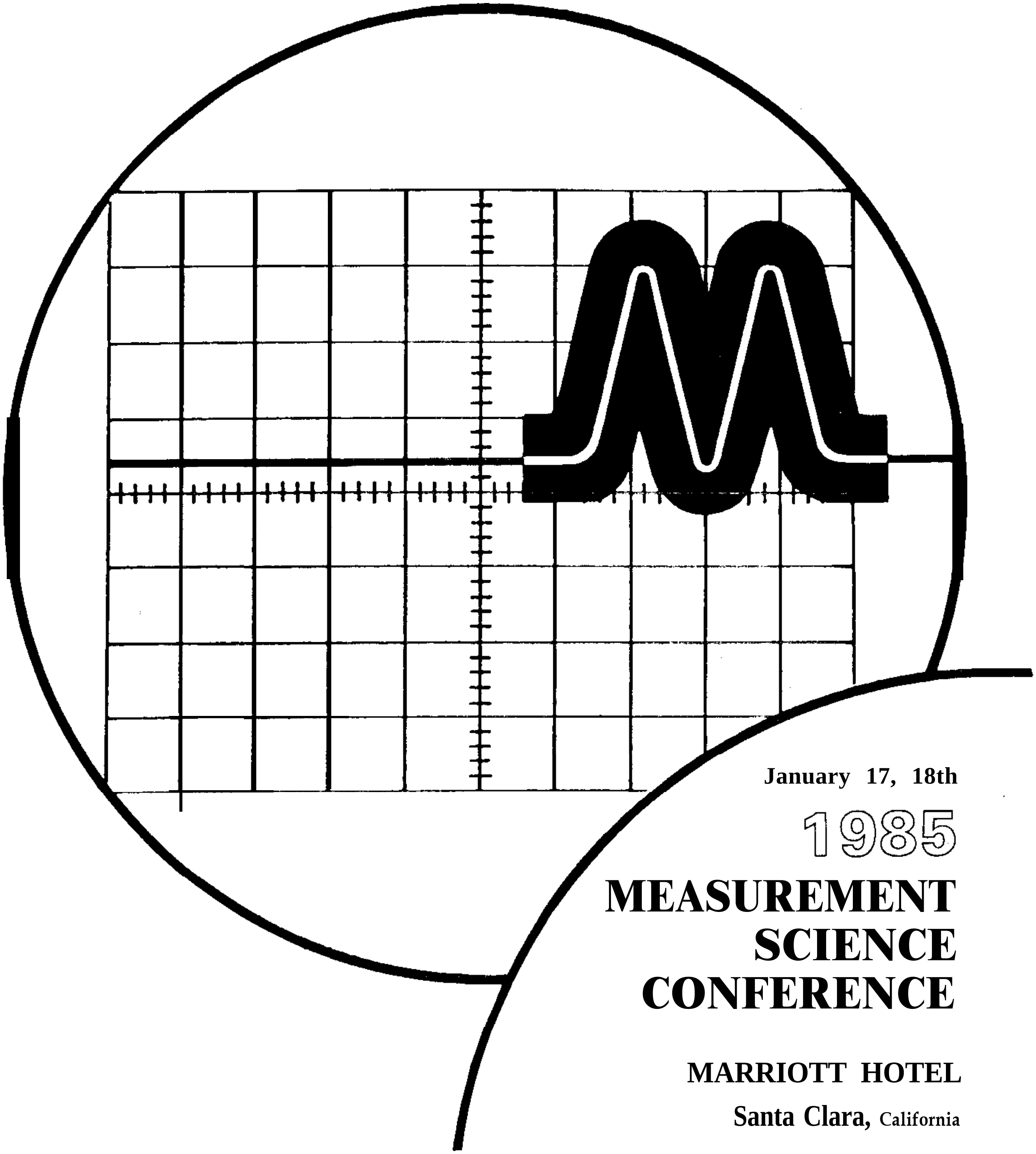

January 17, 18th

1985 MEASUREMENT SCIENCE CONFERENCE

MARRIOTT HOTEL
Santa Clara, California

"CHANGE AND CHALLENGE"

1985
MSC SUPPORTING ORGANIZATIONS

American Society for Quality Control
California State Polytechnic University Pomona
Government Industry Data Exchange Program
National Conference of Standards Laboratories
Precision Measurements Association
IEEE/Instrumentation and Measurement Society
ISA/Aerospace Industries Division
ISA/Test Measurement Division

MESSAGE FROM THE CONFERENCE CHAIRMAN

BOB WEBER

On behalf of the 1985 Measurement Science Conference Committee I wish to thank all participants (attendees, exhibitors, session developers, speakers and numerous helpers) for their assistance in providing a highly successful conference. The evaluation forms submitted by attendees indicated that the overall quality of the Conference was generally perceived as excellent. This is a tribute to the many people who freely donate their time and talents to the planning, administration and many other facets involved in staging the Measurement Science Conference.

The Santa. Clara Marriott Hotel proved to be a "top-notch" conference site. The facilities, food, and courteous/ responsive hotel staff were significant contributors to the quality and success of the conference.

This year's program was outstanding, providing a variety of technical and management papers relating to the activities of the metrology community. William A. Messina's (IBM-GPD) paper, "Use of Trimmed Means for Manufacturing Production" was the recipient of the "Best Paper award. Dr. Robert Soulen, NBS, and Robert M. Silva, VTI, Inc., received honorable mention recognition and checks for their papers. Norm Belecki, NBS, and Woody Eicke, consultant (NBS retired) were selected as co-recipients of the Andrew J. Woodington Award. This award is given as recognition of professionalism in Metrology.

The Conference was privileged to have outstanding keynote and luncheon speakers. Tom McDermott, Rockwell International, was the conference keynote speaker and Richard Anderson, Hewlett Packard, and Barry Shillito, Chairman of Teledyne International, (Retired), were the luncheon speakers.

This year's exhibits were excellent. The number and quality of exhibits grows with each conference.

Hopefully all attendees to the 1985 Measurement Science Conference found it to be stimulating and rewarding. We welcome your comments to assist in the continuing effort to improve the conference each year. We look forward to seeing you at next year's conference to be held in the Irvine Marriott Hotel, Irvine, California, January 23 and 24, 1986.

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Weinschel Engineering
Wiltron Company
Yellow Springs Instruments Co.

1985 MSC KEYNOTE ADDRESS

The following is the Keynote Address presented by Mr. Thomas C. McDermott at the Measurement Science Conference held at the Marriott Hotel in Santa Clara, California on January 17, 1985.

Mr. McDermott is Corporate Vice President, Quality and Reliability Assurance, Rockwell International Corporation, Pittsburgh, PA.

QUALITY PERSPECTIVES

It's a pleasure to be here today and to participate with you in the 1985 Measurement Science Conference. Rockwell International has been a strong supporter of this conference since its inception. We recognize the importance of sharing new concepts and ideas on a subject that is vital to our nation as well as to the individual organizations that we represent.

The Measurement Sciences are important because they are the basic foundation on which the rest of our technology is built. Our current level of technology could not exist without our measurement standardization and control activities, and our future technology will be based on our ability to further expand and refine that capability. Your conference program shows that you are working hard in that direction.

This morning I would like to share some thoughts with you about the changing competitive environment which this nation faces in the international marketplace and the implication of these changes to those of you involved in the Measurement Sciences.

For many years the United States was the unquestioned leader in the international marketplace. We had the highest technology, the best quality and an efficient mass-production-oriented manufacturing system. We had a very favorable balance of trade and our only real competition was from labor intensive products which were produced in nations that had extremely low labor rates. In the last decade this position has changed significantly. We find strong technology emerging from both Europe and the Far East in a number of areas that in the past had been dominated by this country. We have seen a dramatic change in the quality of products produced overseas as compared with those in the United States. We have seen new innovative production concepts in the form of automation, robotics and "just in time" inventory. We have also seen a dramatic reversal in this nation's balance of payments. While some of the balance of payments problem stems from the strength of the U.S. dollar, a good deal comes from high technology, high quality products that are invading traditional American markets. In short, we are facing a strong level of foreign competition today and that competition will continue to grow.

There are probably many reasons for this change in the level of international competition. Certainly, government investment and consortiums in aircraft development and manufacture have helped the European Aircraft Industry. Investment in new plant and equipment has helped a number of our neighbors in the Far East, particularly in the basic industries. Some believe that the basic difference is in government industrial policies or from cultural differences or a host of other factors. Let me suggest some, which I believe have had a major influence.

The first of these is attitude. We had been leader for many years. Perhaps we became a little complacent. As Avis says in its famous slogan, "When you are number two, you try harder." Perhaps, we developed a mind set to accept certain truths which are no longer valid. Or perhaps, we locked ourselves into a standard of performance where things were good enough. Whatever the reason, we did not, in many cases, provide the right attitude to stimulate innovation, and others that "tried harder" found a better way. I think a good example of this is in the area of economic build quantities. The general approach used in this country was to determine the size of production lots considering the set up time for equipment and safety margins to provide insurance that there was always sufficient stock at each step in the production process to take care of unanticipated changes. These changes involved such things as fallout from rejected products, change in the mix of products required by changes in demand, etc. The result of this activity was additional space by each machine to handle the queue of material and the increased investment in work-in-process. We had established a "mind set" in this country that accepted set up time as a "given" as well as the expected quality level of the process.

The Japanese, on the other hand, devoted their efforts to the reduction of set up time and to improved quality of the process. Set up times were reduced to a point they no longer had a major impact on the economic build quality formula and improvement in quality eliminated the need for safety stock.

The final result was the virtual elimination of work-in-process inventory and complete flexibility in adjusting the manufacturing process to sales demand. The success of this concept, which is commonly referred to as "just in time' was the refusal of the Japanese to accept the "status quo" or the "givens" in the manufacturing process.

A second factor, which has improved the competitive position of our foreign competition, and Japan in particular, has been the emphasis placed on product quality. This is first an attitude that perfection is possible and second, a dogged determination to achieve this goal. Perhaps a good example of this was the case of a Japanese plant of the Hewlett Packard Company. This particular plant had been experiencing a defect rate of 0.4% from their wave solder process. In the first year of effort they reduced the defect rate of 40 ppm. In the second year, the defect rate was reduced to 3 ppm and they are currently working to reduce this even further. This is not an isolated example but reflects the type of activity going on throughout their industrial organizations. Another example involves a study made by the Ford Motor Company on transaxles that are produced to Ford drawings in a plant in the United States and one in Japan. Ford disassembled 10 transaxles from each plant and remeasured all components. The results of this teardown inspection indicated that all parts from both plants met the requirements of the Engineering drawings. The parts from the Japanese plant, however, showed much less variability about the nominal dimension than those made in the United States plant. In addition, the transaxles from the Japanese plant had a much better record of field performance and much lower warranty costs. These are several examples of using process quality to enhance the competitive position. Not only is the product performance better, but manufacturing costs are reduced because of less scrap, rework and warranty costs and perhaps even more important is the improvement in customer satisfaction.

The third major area which has improved the competitive position of foreign competition involves the extensive use of automation with emphasis on robotics to achieve a high degree of flexibility in that automation. Automation is effective for several reasons. First, it results in consistency of operation since it eliminates the human variable. Robots can work around the clock without tiring and the only fringe benefit they require is a little preventive maintenance. Foreign competition has made more extensive use of robotics and are considerably ahead in implementing the factory of the future concept.

The final area that I would like to address involves education and training. A number of recent studies have indicated that the United States is falling behind the international competition in this very important area. The report by the National Commission on Excellence in Education indicates that the quality of education in this country had deteriorated significantly in recent years. Some of the disturbing findings of this study are the following:

- Some 28 million Americans are functionally illiterate by the simplest tests of everyday reading, writing and comprehension.
- the College Boards Scholastic Aptitude Tests demonstrate a virtually unbroken decline from 1963 to 1960. Average verbal scores fell over 50 points and average mathematics scores dropped nearly 40 points.
- International comparisons of student achievement completed a decade ago reveal that on 19 academic tests, American students never were first or second, and in comparison with other industrialized nations, were last seven times.

A more recent study by the University of Illinois, which tested a large sample of Japanese and American students in mathematical skills, concluded:

- The average Japanese high school student is better in mathematics than 93 out of 100 typical American high school students.
- When only the top American students tested were compared with the top Japanese, the Americans fared even worse. Only one in 1,000 American students scored as high as the top 10% of the Japanese on the same math test.

Another indication of how serious the Japanese are in the education of their people is the fact that Japanese students go to school 240 days per year versus about 190 days per year for American students. In addition, the focus of their higher education process appears to be directed at technology and manufddturing process improvement. For every 10,000 people in Japan, 400 are engineers and scientists vs 70 in this country.

The obvious implication of this emphasis on education and distribution of skills is that we can expect increasing competition in the future in many areas that have been traditional areas of strength for the United States. The major competitor we face in the international marketplace is obviously Japan. It might be well, for a moment, to consider the reason for their motivation and approach. Japan is made up of four major islands and a large number of small islands, comprising 148 thousand square miles, which is approximately equal to the size of Montana. Slightly more than 70 percent of the land in Japan is mountainous, about 67 percent is forested and 15 percent is devoted to agriculture. Japan has only 18 percent of the land usable to support a population of 119 million people. Because of 'limited natural resources, the country's main avenue for survival has been to convert others' raw material to finished product for sale in the world market. Their key strategies, therefore, have been the factors that make those products saleable; namely, product quality and the efficiency of the manufacturing system. That these strategies have been successful is obvious. What they portend for the future is a level of competition that may threaten the survival of some of our basic industries in the United States. It is important, therefore, that all of us recognize the need for quality and productivity improvement if we are to survive in the international marketplace.

Now let me relate some of the above observations to the field of the measurement sciences and suggest some things that may be appropriate for you to consider.

What is your attitude about your role in the competitive environment? Do you feel comfortable or complacent about your activities? Do you have a "mind set" on what can and can not be accomplished to make your operations more effective and more efficient. Do you have a burning desire for orders of magnitude improvement?

Let's look at the reliability of test equipment. How often do you have to recall equipment because of lack of long-term stability? Are we spending more time on improving the efficiency of our recall programs than in developing more reliable equipment. A number of highly accurate products today are achieving performance levels measured in millions of hours mean-time-to-failure and I'm not talking about parts but reasonably complex systems. Why shouldn t we expect the same level of performance from our test equipment? Have we set our design reliability goals high enough? Are we applying proven reliability and maintainability techniques to improve these products? These are fundamental issues that need to be addressed not only by test equipment designers but by the user community. With test equipment becoming a larger portion of the production process, it is imperative that we find more efficient and effective means of performing the test function and in maintaining that equipment used in the test process. We need to rethink these issues and be certain that we -have the proper attitude.

What about the quality of our measurement effort? In general, I have found metrology and calibration people to be very meticulous in their work but several questions come to mind. Are you taking full advantage of the statistical tools available to improve the effectiveness and efficiency of our work? Are you continuing past patterns of calibrating individual instruments and then replacing them in a test console without a full understanding of the interrelationship that exists in the total system? Or, are you developing a systems approach to calibration that takes the total factors into consideration? Last year when the NBS budget was under consideration and funds for the measurement assurance program were being reassessed, I was surprised at how few companies were involved in these programs.

When I mentioned reliability earlier, I was considering not only qualitative improvements but improvements in the efficiency of the calibration process. There is a lot of money involved in the equipment calibration effort. It's not only the calibration effort itself but its equipment downtime, and the need for larger quantities of equipment to support the production process, transportation costs moving equipment to and from the laboratory, as well as potential damage to the equipment in the transportation process. All of these factors suggest-a need for much greater effort on the development of effective methods of performing on-site calibration. There has been some very good work done in this area but the possibilities of improvement seem limitless. Consider the Utopian, for example, where all references are provided remotely to each test station with a computer-controlled self check prior to use. I'll let your imagination wonder on that one for awhile.

The last area I want to address is education, since it has a strong influence on each of the other areas. We need to improve and expand our educational resource base in the measurement sciences as well as other areas of technology. We need to consider not only the physical phenomenon in which we deal but the design and operation of the entire measurement process. We must encourage young people entering the educational process to pursue a career in science and engineering, and we must provide the resources and encouragement to those on the job to pursue a program of continuing education. Conferences of this type present an excellent method of maintaining such currency.

I have discussed some of the competitive factors at work in the international marketplace. I hope that I have convinced you that we are facing some very worthy adversaries. Our ability to succeed in this marketplace depends on changing some of our fundamental beliefs and concepts and a level of effort far surpassing our activity in the past. Our success will depend on everyone doing their job better. This includes those of you in the measurement sciences. as well as those in the technology production and supporting fields. I hope that I have stimulated your thinking in this matter and know that we can achieve impressive results if we put our minds to it.

T. C. McDermott is Corporate Vice President, Quality and Reliability Assurance, Rockwell International Corporation. In this capacity, he is responsible for all Quality and Reliability Assurance activities of the Corporation; acts as the Corporation's senior advisor on Quality, Reliability and Safety; chairs the Corporation's Product Integrity Committee and the Quality and Reliability Assurance Councils; represents the Corporation on Quality and Reliability Assurance matters with professional and trade **associations,** customers and government agencies.

He is a graduate of Pennsylvania State University where he received a B.S. degree in Industrial Engineering in 1951. His graduate studies were made at Carnegie Institute of Technology where he received his M.S. degree in Industrial Administration. He also completed the Program for Executives at the University of Southern California.

Mr. McDermott in his 24 years with Rockwell has held a number of management positions in the Aerospace, Electronics, and Automotive Operations of the Corporation. These positions have included Vice President of Quality and Reliability Assurance at the Space Division during the **Apollo** and Saturn programs; Vice President **of** Operations for the Autonetics Group, and Vice President of Production Operations for the Corporation's Electronics Operations.

He served with the U.S. Air Force for ten years. During this time his duties included being Chief of the Plans Branch, Quality Control Office in AMC Headquarters, as well as Chief of Plans and Engineering in the Quality Assurance office at the Ballistic Missile Center.

Mr. McDermott is a Fellow of the American Society for Quality Control **(ASQC)** and presently holds offices of: Chairman, Staff Compensation and Benefits Committee; **Chairman,** Financial Advisory Committee; and Deputy Treasurer. For ASQC, he participated in a variety of activities, such as, Program Chairman for the Annual Technical Conference in 1965-66, Vice President 1966-68. President 1968-69, and Chairman of the Board of Directors 1969-70.

Mr. McDermott has been active in the Electronic Industries Association where he previously held the position of Chairman of the Quality Assurance Committee, Government Equipment Panel. He served as the Corporate representative to both Quality Assurance and Product Support Committees of the Aerospace Industries Association. He is a member of Sigma Tau and Alpha Pi Mu honor fraternities and belongs to the National Management Association, American -Institute of **Industrial** Engineers, and the Society of Automotive Engineers.

T. C. McDermott has served on various local (California) civic organizations, such as, Chairman, Manufacturing Group, Orange County, CA, United Way; Member of the Advisory Board for the Orange County National Alliance of Businessmen (JOBS); and Member of the Dean's Advisory Council for the Pepperdine College Law School.

1985 WOODINGTON AWARD WINNER
— FOR PROFESSIONALISM IN METROLOGY —

MR. NORMAN B. (NORM) BELECKI   MR. WOODWARD G. (WOODY) EICKE

RICHARD W. ANDERSON
General Manager
Microwave & Communications Instrument Group
Hewlett-Packard Company

Richard W. (Dick) Anderson is general manager of Hewlett-Packard Company's Microwave and Communications Instrument Group. He is responsible for six entities in the United States and two overseas. They are: Stanford Park Division, Palo Alto, California; Network Measurements Division, Signal Analysis Division, and Microwave Technology Division, all in Santa Rosa, California; Spokane, Washington; Colorado Telecommunications Division, Colorado Springs, Colorado; Queensferry Telecommunications Division, and Queensferry Microwave Operation both in South Queensferry, Scotland.

Anderson joined Hewlett-Packard in 1959 as an engineer in the Microwave Division and in 1965 was promoted to engineering section manager for that division. In 1968 he moved to HP's Santa Clara Division as engineering manager. He became general manager of the former Automatic Measurement Division in Sunnyvale in 197 1 and 1974 was named general manager of HP's Data Systems Division in Cupertino. He was named general manager of the newly-formed Computer Systems Division, headquarted in Cupertino, California, in 1980.

Born in Brigham City, Utah in 1937, Anderson graduated with a bachelor's degree in electrical engineering from the Utah State University in 1959. He received his master's in electrical engineering from Stanford University in 1963. Anderson is currently on the board ofdirectors for the Cupertino Chamber of Commerce and is a director of Gerber Systems Technology. He has served as past treasurer and cochairman of the San Francisco section of the IEEE.

BARRY J. SHILLITO
Chairman, Teledyne-International (Ret.)

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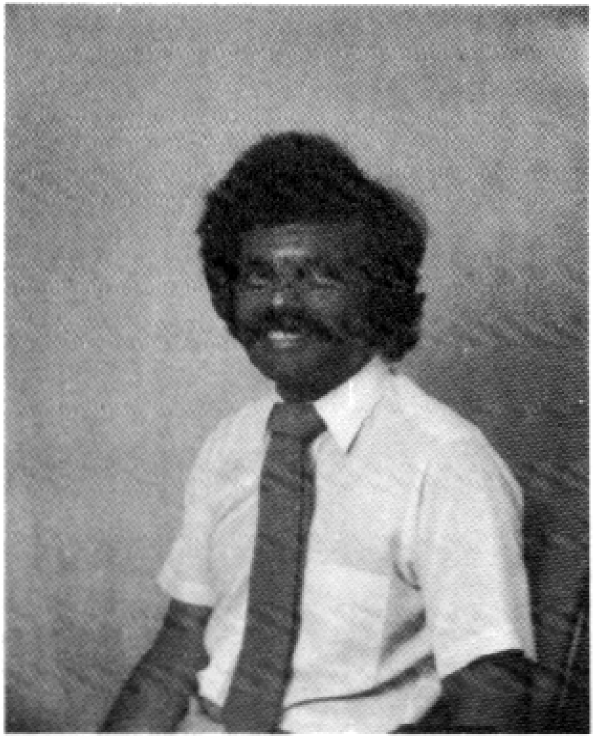
Secretary of Defense Distinguished Public Service Medal, presented **February 1, 1973:** Cited as one of the architects of revised policies and procedures for acquisition of major defense weapons systems and single individual most responsible for success of President's Vietnamization program in area of logistics.
Secretary of the Navy Distinguished Public Service Award
Republic of China Cloud and Banner Medal
Republic of Vietnam National Order of Vietnam
Founders Medal, Society of Logistics Engineers, 1975
National Security Industrial Association Edward M. Greer Award, 1978
1978 Distinguished Alumnus Award, University of Dayton, Ohio

1985 BEST TECHNICAL PAPER AWARD

"USE OF TRIMMED MEANS FOR MANUFACTURING PRODUCTION"

William A. Messina
IBM-GPD
Tuscon, Arizona

Mr. Messina has been employed for the past three years at IBM's General Product Division in Tuscon, Arizona. His current assignment is as a Consulting Statistion. Prior to joining IBM, he worked as a Reliability Engineer for eight years at Lockheed Missile & Space Company in Sunnyvale California. He holds a Master of Science Degree in Statistics from the University of Arizona. He is a member of ASQC and ASA. He has presented papers at the 37th Manual Quality Congress in Boston and the 40th Rochester Quality Control Conference.



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National Bureau of Standards

"Calibration Test Program Sets"
Dick Calhoun
Navy Metrology Engineering Center

SESSION V-B LASER AND OPTICAL FIBER METROLOGY

Aaron Sanders
National Bureau of Standards

SESSION V-C TIME AND FREQUENCY MEASUREMENTS-APPLICATIONS

Frank Koide
Rockwell International

"Phase Noise Measurements - Methods, Solutions, and Trends"
Karen R. Bonner
Catharine M. Merigold
Hewlett Packard Company

"Time And Frequency Domain Measurements For GPS Rubidium Frequency Standards"
F. K. Koide and E. A. Rheingans
Rockwell International Corporation

SESSION V-C Time and Frequency Measurements-Applications (con't)

"How and When To Perform Allan Variance Calculation or Phase Noise Measurements"
David Allan
National Bureau of Standards

"Precision Frequency Sources - A Status Report"
Dr. Sam Stein
Ball Corporation

"NBS Time And Frequency MAP Program"
David Allan
National Bureau of Standards

"Time Transfer And Clock Analysis Via The Global Position System (GPS)"
James A. Buisson
Naval Research Laboratory

"Clock Characterization Turtorial"
David W. Allan
National Bureau of Standards

"New Time And Frequency Services At The National Bureau Of Standards"
S. R. Stein, G. Kamas, and D. W. Allan
National Bureau of Standard

SESSION V-D SURFACE METROLOGY

John R. Van de Houten
TRW Operations & Support Group

"The Interaction Between The Dependent Measurements Of Surface Finish And Size"
William E. Drews
Rank Precision Industries, Inc.

"Automated Nondestructive PBS™ Measurements Of Surface And Subsurface Defect Distribution In Silicon And Gallium Arsenide Wafers"
Robert M. Silva, Fred D. Orazio, Jr., Robert B. Sledge, Jr.
VTI, Inc.

SESSION VI-A TECHNICAL EDUCATION AND TRAINING

John Martin
Westinghouse

SESSION VI-B BAR CODING AND VOICE TECHNOLOGY

William A. Grant
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"Voice Data Entry Applications At Texas Instruments"
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Texas Instruments, Inc.

SESSION VI-C MILLIMETER MEASUREMENTS/CALIBRATION CAPABILITIES

Algie L. Lance
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"Current NBS Metrology Capabilities And Limitations At Millimeter Wave Frequencies"
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SESSION VI-D MEASUREMENT POTPOURRI

Ray Kellick
Teledyne Systems Co.

"Software Product Assurance In The Metrology Lab"
Mark Kaufman
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"Life-Cycle Objective Measuring Of The Software Product"
Gerald E. Murine
Metriqs, Incorporated

"Using GIDEP To Improve Your Metrology Posture'
Edwin T. Richards
GIDEP Operations Center

SESSION I-B

DC AND LOW FREQUENCY METROLOGY

Edward Nemeroff
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THE SOLID-STATE VOLTAGE REFERENCE COMES OF AGE

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ABSTRACT

This paper will trace the development of the Zener reference diode and the solid-state reference units utilizing the device over the past 25 years. Diode characteristics, measurement techniques, device stability and the status of solid-state voltage standards will be discussed.

INTRODUCTION

The saturated standard cell has been used to maintain the unit of electromotive force for more than 75 years. When maintained at a constant temperature it has a long-term stability of 1 to 2 ppm per year but it is a delicate artifact and must be treated as such. Its most serious drawbacks are the time required to stabilize when subjected to temperature changes and the deleterious effects of currents in excess of a few microamperes. About 1955 interest in using the Zener diode as a voltage standard developed. Early work by Enslein [1] showed that certain Zener diodes had potential at the 100 ppm level. Within a few years solid-state voltage references, using Zener diodes, became the voltage reference for most industrial applications and found limited use in the laboratory as a replacement for the unsaturated cell. Since then, the state of the art has advanced to the point where solid-state voltage references are challenging the saturated standard cell as a reference standard at the 1 to 5 ppm level. This paper will review the four major areas in the development of the solid-state voltage reference, which are:

(1) the development of accurate techniques for measuring voltages in the range of 2 to 10 volts,

(2) the operating characteristics of Zener reference diodes,

(3) the voltage stability of the Zener reference diodes, and

(4) complete solid-state voltage references.

THE ZENER REFERENCE DIODE

The Zener diode is a nonlinear passive element in which the voltage drop across the device is nearly independent of the current, in its normal operating region. The relationship between the two is

$$dV(z)/dI(z) = R(z)$$

where $V(z)$ is the Zener voltage developed across the diode by the current, $I(z)$, and $R(z)$ the effective Zener impedance which, for reference devices is in the order of 5 to 30 ohms. Although Zener diodes can be made with breakdown voltages from two to several hundred volts only those in the 5 to 9 volt region have been considered as reference devices because of the temperature coefficient of voltage. For 4 volt diodes the temperature coefficient is -400 ppm/K and it increases, nonlineraly, to +1000 ppm/K for 40 volt devices. Even though diodes can be made to have a zero temperature coefficient, a better solution is to compensate them by placing one or more forward biased diodes in series with a Zener of the appropriate breakdown voltage [2]. Devices with temperature coefficients as low as 1 ppm/K can be manufactured at the 6, 8 and 9 volt levels. One of the earliest devices, the 1N430, was constructed by placing one Zener and two forward diodes in a single package. Rather than placing complete devices in a single package, individual dies were assembled as a single unit to r-educe the size of the finished device and improve its thermal characteristics. Early diodes were of the alloy type but by the early 1960's were replaced by the diffused junction devices. The latter yielded more stable devices, had better thermal properties, and were more easily manufactured.

Although voltage stability with respect to time is the most important property of a reference diode are other operating characteristics affect the performance as a voltage standard. The most important, the relationship between diode current, temperature and voltage, were studied by a number of investigators [1], [2], [3], [4], and [5]. Based on studies of typical reference Zener diodes Eicke [3] showed that:

(1) the change in diode voltage is very nearly proportional to the logarithm of the diode current;

(2) the change in voltage with respect to temperature can be described by a quadratic equation which usually has a maximum in the 25 to 65 deg. C region; and

(3) the first temperature coefficient (which is the dominant term) is proportional to the logarithm of the diode current.

A knowledge of the quantitative relationships between diode voltage, current and temperature permit the designer to reduce the effects of temperature on diode voltage by proper selection of the operating current.

Although the zener reference diode is a dc device its voltage is affected by the presence of small alternating currents. Eicke [3] studied this phenomenon and found for a number of types of reference diodes that:

(1) the dc offset is proportional to the square of the applied ac;

(2) the offset is always negative, that is it reduced the diode voltage;

(3) the mangitude of the effect is frequency dependent, diminishing with increasing frequency; and

(4) it is device dependent.

Field [6] also observed that certain solid-state voltages were also affected by ac applied to the output terminals. The further found that the offset caused by external alternating currents could be effectively eliminated by the use of filters on output.

Early investigators used noise measurements (in the 80 Hz to 10 kHz range) as a method for screening Zener diodes. For alloy type diodes Baker [4] found that noisy diodes were not stable but quiet ones were only potentially stable. Noise measurements on diffused junction devices showed little or no correlation between diode noise and stability [3]. The data, however, suggested that certain device defects could be detected by measuring diode noise as a function of current. Low frequency (below 20 Hz) noise was also of concern because of the affect on the measurement of diode voltage. This type of noise is usually caused by variations in the rate of heat transfer between the junction and its surroundings. Since the thermal emf of silicon with respect to copper is approximately 100 microvolts/K, small changes in junction temperature will result in significant changes in the diode voltage. The latter type is the most serious and can only be minimized by carefully controlling the thermal environment of the device.

MEASUREMENT TECHNIQUES

Diode stability studies were limited by the ability to make accurate measurement of diode voltages and most of the progress in improving the measurement process was the direct result of producing better solid-state voltage references. Truly "boot strap" metrology at its best! Early investigators employed the series-opposition method in which the small difference between the Zener under test and a calibrated standard (usually a group of unsaturated standard cells in series) was measured using a potentiometer. With this technique Baker and Nagy [4] and the author [3] were able to measure a variety of diodes with *an* uncertainty in the order of 1 to 10 ppm depending on the diode voltage. Measurements to these accuracies were time consuming and limited by the available instrumentation. Such techniques are adequate for research but do not lend themselves to studying more than a few diodes at any one time. The author explored other methods for making accurate diode voltage measurements [7], [8] but they are also limited to laboratory type measurements. Since diodes for reference use must be tested and individually selected, (a process which requires that many measurements be made efficiently on many devices) some type of automated or semi-automated method was needed. One such technique was described by Arnett [9] and *was* designed to select diodes of modest accuracy for use in a variety of measuring instruments. The availability of the 6 1/2 digit DVM and the microcomputer has made routine high accuracy measurements on Zener diodes and solid-state reference units practical.

Field [10] developed an automated measuring system capable of measuring voltages from 1 to 10 volts with an uncertainty of a few tenths of a ppm. It is comprised of a string of resistors, a constant voltage source, a 6 1/2 digit DVM, a low thermal switch, a desk-top computer and a technique for calibrating the complete system. The computer controlled low thermal switch, developed by at NBS [11] controls both the measuring system and select the unit to be measured. By calibrating the complete measuring system for each set of measurements it is not necessary to use state of the art components; they merely need be stable for the measuring period, usually 1 to 3 hours. Field has reported a one standard deviation overall uncertainty of 0.13 ppm relative to the U. S. legal volt.

ZENER DIODE STABILITY

For use as a reference standard, voltage stability with respect to time is the single most important parameter and data by early investigators

[3], [4] showed that diodes stable to approximately 20 ppm per year were possible by careful testing and selection. A reappraisal of Zener diodes in 1970 [12] indicated that devices fell into three general classes:

(1) those diodes which were stable within 10 to 30 days are either stable with time or drift at a low linear rate (less than 50 ppm/yr);

(2) those diodes which stabilize within 6 to 18 months and then behave as (1) above; and

(3) those diodes that continuously change with respect to time a relatively high drift rate and are not usable as high accuracy voltage reference.

Only stability tests can be used to classify a device. During these studies, two other important characteristics affecting overall stability were identified. When subjected to excursions of ambient temperature some devices showed an abrupt change in voltage ranging from less than a ppm to 50 ppm or more. In general the voltage changes diminished with subsequent temperature excursions. It was also observed that after a power interruption, the voltage tended to return to its initial voltage then drift to the value before the power was removed. The data suggested that the magnitude of these changes are related to the magnitude of the voltage change with time.' To improve the yield of reference grade devices manufacturers use a burn-in process which is designed to stabilize the device by subjecting it to an elevated temperature while under power. During the burn-in period (usually 1000 hours) voltage measurements are made and diodes are graded on the basis of the measurements. The complete operation is usually automated for efficiency. The burn-in process greatly improves the yield of stable diodes but does not completely solve the the temperature and turn-off problems. Therefore many diode users conduct further test and selection in order to obtain diodes meeting their requirements.

Experiments in which diodes were maintained at a constant temperature and powered only for very short periods of time (10 to 30 minutes) showed that the voltage with respect to time was stable to within less +5 ppm over a period of 2+ years [12]. For the three diodes reported the worst drift rate was about 5 ppmiyr and the mean of the three was approximately, without regard to sign, was about 2-3 ppm/yr. NBS sent three such devices to PTB in 1964 and the measurements at the two laboratories agreed to 1.3 ppm [13]. Richman [16], in the mid-1960's investigated the problem of selecting reference grade devices to be used in precision instrumentation and developed criteria for choosing stable diodes and conducted a field test of 49 reference units. He found that the average drift rate for all was nearly zero and that 82 percent had an absolute drift rate of 30 ppm/yr or less. By 1965 it was clear that the Zener diode had the potential as a high accuracy voltage standard not of the saturated cell class but certainly in the 5 to 30 ppm range.

THE SOLID-STATE VOLTAGE STANDARD

The Zener diode is a passive device which must be combined with a current source and other components to form a complete reference voltage source. By 1960 several solid-state replacement5 for unsaturated standard cells appeared on the market. Internally they used an unregulated dc power supply that drove a preregulator circuit consisting of one or more Zener diodes to develop a voltage about twice that of the reference diode. This regulated voltage was used to power the reference diode. A precision resistive voltage divider, across the diode produced the 1.018 and 1.019 volt outputs. This arrangement gave an overall regulation, at the output terminals, of a few ppm for a 10% change in line voltage. By 1965 there were a number units on the market, and in fact, two were used in the 1965-66 round robin conducted by the National Conference of Standards Laboratories and reported by Richardson [15]. Each was measured at NBS before and after the round robin. The net change for one was 11 ppm (three measurements) during the year required for the the unit to be measured at 19 laboratories east of the Mississippi River. The other showed a change of 75 ppm traveling to 19 laboratories west of the Mississippi River. A review of other data for the latter unit suggest that the unit was drifting with respect to time (about 1 yr.).

By 1966 commercial units with reported stabilities of 10 ppm/month appeared. In addition to the 1.018 and 1.019 volt outputs they also provide outputs of 1.000 volt and 1000 microvolt. The Zener preregulator was replaced by regulated power supplies and all critical elements including the resistive voltage divider were temperature controlled. With improved device selection and proper design, the short-term performance of the unit was comparable to that of the saturated standard cell. Using the data given in reference [13], for seven units the *mean* drift rate *was* -3.9 ppm/mo over a period of 209 days. The standard deviation of a single point for a linear fit of the data was about 0.9 ppm, clear indication that the unit could serve as an excellent working standard or a transport standard at the 2-3 ppm level. In spite of many possible applications for such a voltage reference unit5 many metrology laboratories were reluctant to use solid state voltage references.

In addition to the development of solid-state voltage reference units, Zener diodes are used in a wide variety of precision instruments. For a period of time, more interest was shown in this latter application than in developing a stand-a-lone voltage standard. Looking back, it is clear that the availability of good Zener reference diodes made possible many of the electronic instruments now routinely used to make high accuracy measurements. Other advances in the development of the solid-state voltage reference include the use of operational amplifiers in the output; operating the reference device at its zero temperature coefficient; and batteries to maintain continuous power. The advantages operational amplifiers are:

(1) the output voltage can be adjusted to any desired voltage, usually 10.0 volts; and

(2) allowing the unit to supply a small current without affecting is output voltage.

These two characteristics are particularly useful when calibrating automatic test equipment and other electronic instruments. By operating the diode at it point of zero temperature coefficient the need for special temperature control is eliminated and power requirements are reduced to the level that make battery operation practical. The last two types of solid-state references are in the the 3 to 10 ppm class. Voltage references of the type just discussed are most advantageously used as secondary standards, as transport standards, and working standards at remote locations such as the production line.

Each stage of the development of solid-state voltage reference seems to require about a decade. The sixties saw studies of devices and the replacement of the unsaturated standard cell. The seventies saw a maturing of the use of Zener diodes, the development of reference units in the 3-20 ppm stability class and the extensive use of stable Zener diodes in high accuracy digital instrumentation. The eigthies begin the et-a when the solid-state reference seriously challenges the saturated standard cell. Today there are four solid-state voltage references for which the makers claim performance of 5 ppm or better. The major goals seem to be, in order of present priorities; the development of a transportable solid-state reference to eliminate, the need to ship saturated standard cells; to serve as a working standard at accuracies approaching the saturated cell; and ultimately as a replacement for the saturated standard cell. All four voltage reference manufacturers have utilized the data accumulated over the past 20 years but interestingly each arrived at a reference unit that differs in overall design philosophy.

Both Koep [16] and Huntley Cl73 control the temperature of critical elements, keep the unit under power at all times, and use operational amplifiers to buffer the output. The former has opted to have an output voltage near the voltage of the reference diode, approximately 6.5 volts, while the latter provides a 10 volt output. Both have a 1.018 volt output for comparing directly against saturated standard cells. Data on commercial units show that day-to-day variations are comparable to saturated cells and drift rates in the order of a few tenths of a ppm per month have been reported by Huntley [17b]. Spreadbury [18] also uses an operational amplifier in the output stage and controls the temperature but only applies power to the reference diodes when actually using the unit as a reference. His reported data indicate performance in the 5 ppm region over a period of several months [18b]. Murray [19] reported on a unit that did not control the temperature of critical elements and reported similar results.

Both Huntley and Koep have used solid-state units as transport standards with excellent results. Huntley [20], [17b] implies that, using NBS Volt Transfer Program techniques, one can achieve a transfer uncertainty, at the ten volt level, comparable to that attained by the NBS VTP. Huntley Cl91 further discusses the feasibility of establishing a network of laboratories, maintaining the volt at the ten volt level, that are monitored using solid-state voltage references. Koep [20] reported the results of an international round robin in which the corrected difference between four national laboratories (NBS, NPL, NRC, and PTB) were approximately -1 ppm when referred to the original NBS measurements. This agreement is very good for a test requiring about 7 months. Finally, NBS [21] now offers a service to calibrate solid-state voltage references at both the standard cell level and at higher voltages using the measuring circuit developed by Field [10].

CONCLUSIONS

In the past 30 years the Zener diode and diode based commercial solid-state voltage reference standards have evolved to the point where they perform at a level comparable to the saturated standard cell. Even so, some of the problems that remain are:

(1) more field data to support the results already in hand, a problem that only time will resolve;

(2) the reluctance of standards laboratories to use these devices; and

(3) their relatively high cost.

However, the advantages far out weigh the problems just mentioned. Specifically soild-state voltage referenceas:

(1) can be constructed to provide voltages in the range of 1 to 10 volts;

(2) can provide current to an external load with little or no degradation in accuracy;

(3) are far more robust than the saturated standard cell; and

(4) are more more readily used by unskilled personnel.

Finally, as one of the earliest investigators in the field, the author is gratified to see that the solid-state voltage reference has come of age and will add a new dimension to accurate voltage measurements.

REFERENCES

[1] Enslein, K., "Characteristics of Silicon Junction Diodes as Precision Reference Device", IRE Trans. on Instrumentation, Vol. I-6, June 1957, pp. 105-18.

[2] Morganstern, L. I., "Temperature-Compensated Zener Diodes", Semiconductor Products, Vol. 5, No. 4, pp. 25-29, April 1962.

[3] Eicke, W. G, "The Operating Characteristics of Zener Diodes and Their Measurement", ISA Trans., Vol. 3, No.2, April 1964, pp. 93-99.

[4] Baker, R. P., Nagy, J., "An Investigation of Long-Term Stability of Zener Voltage References, IEEE Trans. on Inst., Vol I-9, No. 2, Sept. 1960, pp. 226-31.

[5] Chandler, J.A., The Characteristics and Applications of Zener (*Voltage* Reference) Diodes", Electronic Engineering, pp 78-86, Feb. 1960.

[6] Field, B. F., National Bureau of Standards, Private Communication.

[7] Eicke, W. G, "Making Precision Measurements of Zener Diode Voltages", Trans. Comm. and Electronics, Vol. 83, No. 74, Sept. 1964, pp 433-438.

[8] Eicke, W. G, "A Direct Reading Voltage Ratio Set", Masters Thesis, The George Washington University, Dec. 1964.

[9] Arnett, W., "Automatic DC Data Logging System", IRE Trans. on Instrumentation, Vol. I-11, Nos. 3 and 4, pp. 148-52, Dec. 1962.

[10] Field, B. F., "A Sub-ppm Automated One-to-ten DC Measurinq Systems", CPEM Digest, 1984

[11] Kleimann, R. E., Eicke, W.G, Unpublished Report, NBS.

Cl21 Eicke, W. G, "Reappraising the Zener Diode as a Reference and Transport Standard", Electronic Instrument Digest, pp 50-59, May 1970.

Cl31 Eicke, W. G, Ellis, H. H., "Sur la Stabilite Prolongee des Diodes Zener etalon", Comite Consultalif d'Electricite, 11* Session, pp 73-77, 1965.

[14] Richman, P., "Precision Zener References: Selection and Field Performance", ISA Preprint M2-2-MESTIND-67, ISA Conference, Oct. 1967.

Cl51 Richardson, S. C., "Status Report of the NCSL 1965-66 Measurement Comparison", Proc. of the 1966 Std. Lab Conf., NBS Misc. Pub. 291, pp.13-30, Jul. 1967.

[16a] Koep, K. J., "Voltage Reference Standards", Meas. and Control, Apr. 1979.

[16b] Technical Literature, Standards Reference Labs, Inc.

[17a] Huntley, L. E., Kletke, R. D., Penco, C., Aqy, D. L., "On an application for a Solid State Voltage Reference Standard , Digest-CPEM/1982, pp.O-8 to O-9.

[17b] Huntley, L. E., "The Fluke Direct Voltage Maintenance Program , Proc. 1984 Meas. Sci. Conf.

[18a] Spreadbury, P. J., "Ultra-Stable Portable Voltage Sources , IEE Con. Pub. 174, pp. 117-120.

[18b] Spreadbury, P. J., "A New Solid-State Voltage Standard", Digest-CPEM/82, p. O-10.

[19] Huntley, L. E., "A Distributed Artifact Standard of Voltage", IMTC/84, pp.39-43, Jan 17-18, 1984.

[20] Koep, K. J., Summary Report on an International Round Robin Test Conducted on a Solid State Voltage Standard , NCSL 1983 Workshop and Symposium, pp. II--9.1 to 11-9.22, July 18-21, 1983

[21] "Voltage Measurements Sec2(d),NBS Special Publication 250, p 36, act. 1982.

AUTOCAL - FROM INSTRUMENTS TO PORTABLE SYSTEMS

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INTRODUCTION

As more and more instruments, ATE's and calibrating devices incorporating Autocal are becoming available the full potential of automatic'calibration systems is being realised.

It is most important to emphasise that the advantage of Autocal is not merely that it improves efficiency but that it also enhances the quality and accuracy of our calibrations, and therefore of our measurements. As will be finally discussed it also opens up significant opportunities to re-think many of our traditional approaches to calibration problems.

AUTOCAL - WHAT IS IT?

Autocal provides electronic, usually software controlled, calibration of measurements. It replaces calibration charts with data-bases, potentiometers with digital computations, and in some cases true manual adjustments with Automatic ones. It does not remove the need for traceability and the controlled systematic transfer of measurements. It does vastly ease and simplify the transfer process whilst greatly improving transfer accuracy.

LINEAR AUTOCAL

In the example of fig. 1 a simple DMM gain correction pot. is replaced with processor controlled arithmetic. As can be seen the pot is replaced with a multiplier and calibration data stores in RAM. The mathematical form of the correction is identical.

SECOND ORDER AUTOCAL

In an AC calibrating instrument incorporating Autocal it is possible to provide a second order frequency response correction since the calibrator "knows" its output frequency at all times.

It can be shown that provided poles and zeros in the frequency response are well above the frequency of interest (say five times higher) then the error is proportional to $(f/fo)^2$ where fo is the effective -3dB point of a single pole response. In practice, during calibration the HF error is measured and the system pole fo calculated and stored in calibration memory. Subsequent operation uses this data and the actual frequency to compute $(f/fo)^2$ and make an automatic output correction. See Fig. 2.

AUTOMATIC PARAMETRIC ADJUSTMENT

In some circumstances the correction law is far too complex and yet the traditional mechanical adjustment is trivial. It is then sometimes possible to provide an "electronic servo" adjustment as in the example of trimming a DMM's frequency response. See Fig. 3.

MULTIPLE CALIBRATION POINTS

Autocal is so economic that it is possible to simply increase the number of calibration points - perhaps even to the extent of having one point for each increment of output. This, of course, has implications in the cost of calibration but can be very useful in overcoming unpredictable errors such as the frequency response of an AC calibrator in Fig. 4.

IMPROVED PERFORMANCE

All the above calibration corrections can be performed with covers on and therefore with the units in their normal use condition. The corrections can allow for high order variables that would be impractical with analog adjustments.

The net result is that high performance products owe their capabilities substantially to Autocal and would have to be degraded without it.

HISTORY OF AUTOCAL

Computer controlled sytems have incorporated software measurement "corrections" for some time but the first instrument (to my knowledge) with the self contained ability to provide calibration adjustment was the Fluke 8502. However, this was an option and therefore not an integral part of the instrument design or operation. The Datron 1061 was the first DMM to provide Autocal on all its calibration, requiring no manual adjustment at all for at least 5 years. Unfortunately although such instruments have been around for several years there has been no fully programmable multi-function calibrator of sufficient accuracy to provide the "hands-off" calibration that the DMM was designed for. Recently appropriate calibrators such as the Fluke 5440, Datron 4000 and 4200 have become available. Such instruments have been combined in a stand alone PC controlled package to provide total hands off calibration of Autocal DVMs and semi-automatic calibration of conventional products.

CALIBRATION SYSTEMS

Computer controlled calibration systems such as the Fluke system 10, Julie Lo-cost, and Fluke 7405 span many years. They have generally been expensive complex systems with limited accuracy and difficult programming Certainly the system cost has been a substantial "overhead" on the cost of the calibrators providing the basic performance. These first generation system have not been portable nor designed for the new range of Autocal instruments.

PORTABLE CALIBRATION

Traditionally calibration has been performed in the Calibration Laboratory by highly skilled personnel. The environment is controlled so that we can define and control the transfer uncertainties and the performance of the calibrating equipment. However, the instrument is normally operated in an uncontrolled environment which may be substantially different from that in the cal. lab. A classic example of this is the use of Instruments rack mounted in shop floor ATE systems.

Some calibration equipment is now designed to give good performance over a wide temperature range. The result is a much more stable environmental performance than the typical instrument to be calibrated.

Since such calibration equipment can be software controlled then the skill factor in calibrating the instrument is removed. The result is the ability to take the calibration to the ATE or other unit to be calibrated. This has several advantages.

1. Direct calibration of system resulting in better traceability.

2. Reduced transfer uncertainties

3. Reduced overall sensitivity to environmental differences

4. Possibility for system software to check and certify its own calibration.

5. Vastly reduced system downtime.

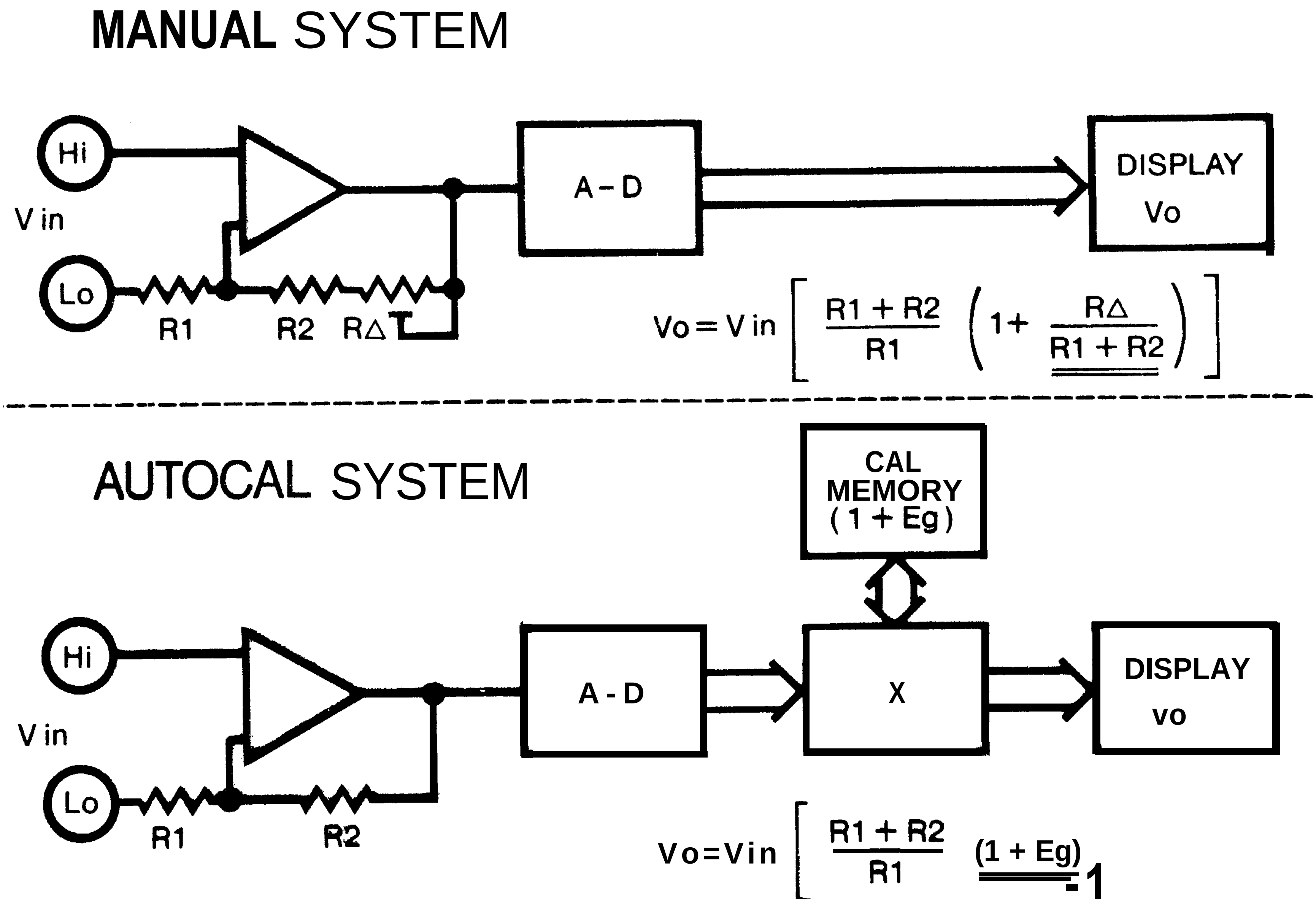
A highly accurate portable calibration system covering DC volts-and current, AC volts and current and resistance is shown in Fig. 5. It is capable of "shop floor" calibration under the control of it's IBM PC to accuracies of a few parts per million.

CONCLUSION AND FUTURE PROJECTIONS

Until now the greatest problem in a Calibration hierarchy has been in ensuring the accuracy of transfers. Autocal, through its lack of reliance on operator skills and its inherent capability of transfers to noise levels, removes this dependence.

This leads to a change of emphasis from specific calibration skills, which leads in turn to a complete re-appraisal of our overall calibration maintenance systems and programs.

The example discussed is in creating portable calibration but imaginative thinking unbounded by blind dogma can result in much better, more reliable measurement systems.



$$V_o = V_{in}\left[\frac{R1 + R2}{R1}\left(1 + \frac{R\Delta}{R1 + R2}\right)\right]$$

$$V_o = V_{in}\left[\frac{R1 + R2}{R1}\;(1 + Eg)^{-1}\right.$$

Fig. 1.

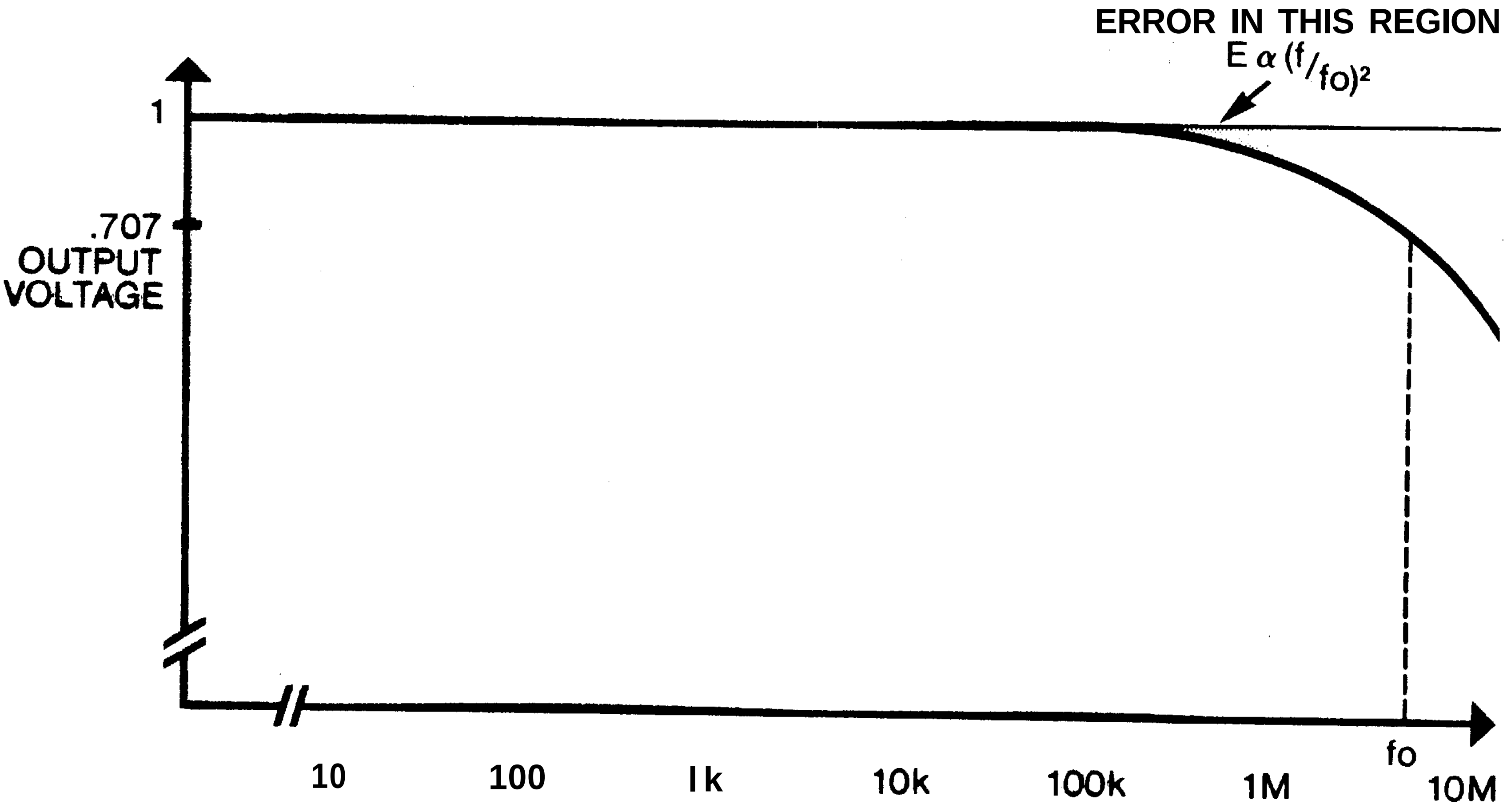

ERROR IN THIS REGION
E α (f/fo)²
1
.707
OUTPUT VOLTAGE
fo
10
100
1k
10k
100k
1M
10M

Fig. 2

OUTPUT FREQUENCY f

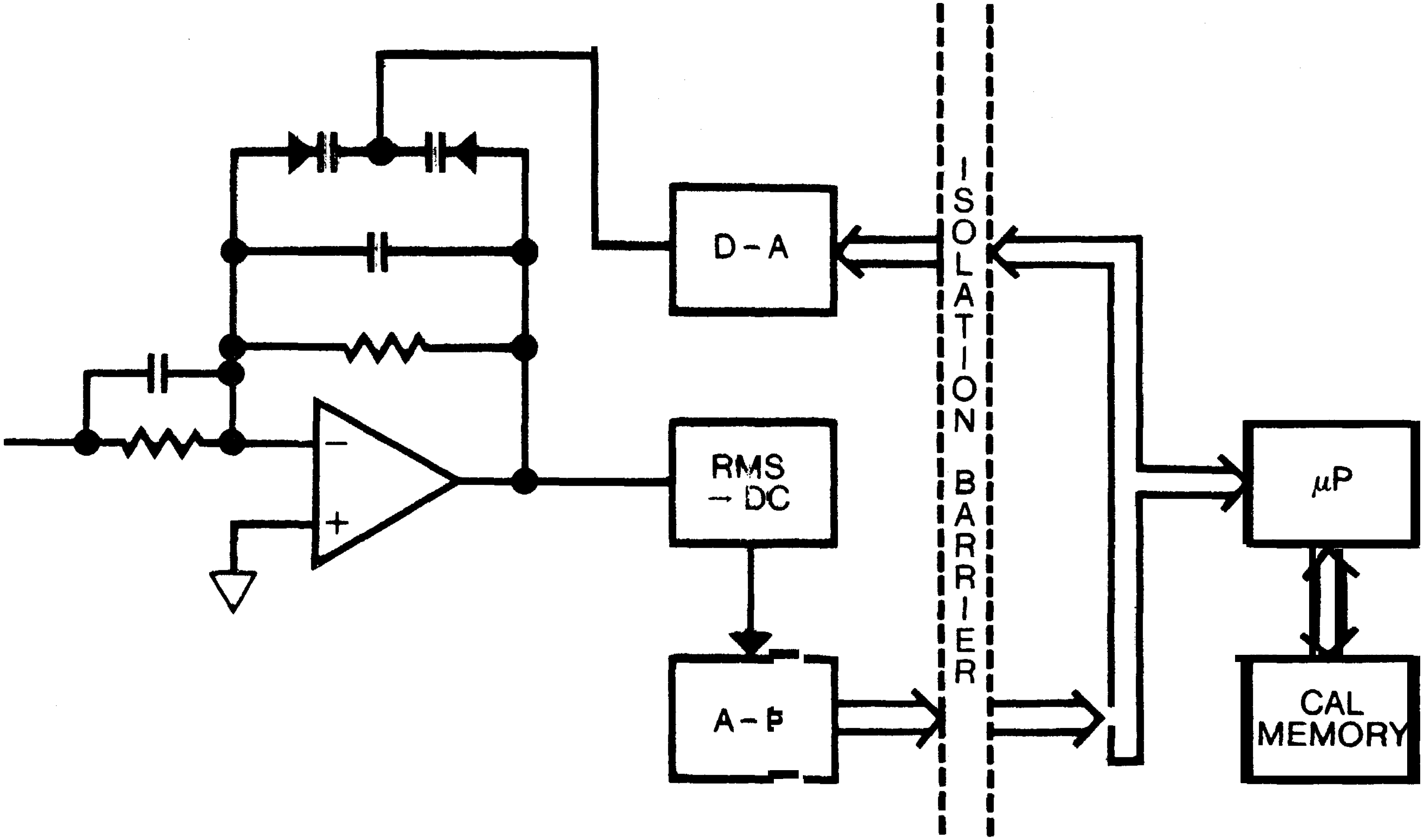


Fig. 3. HF VARICAP AUTOCAL BLOCK

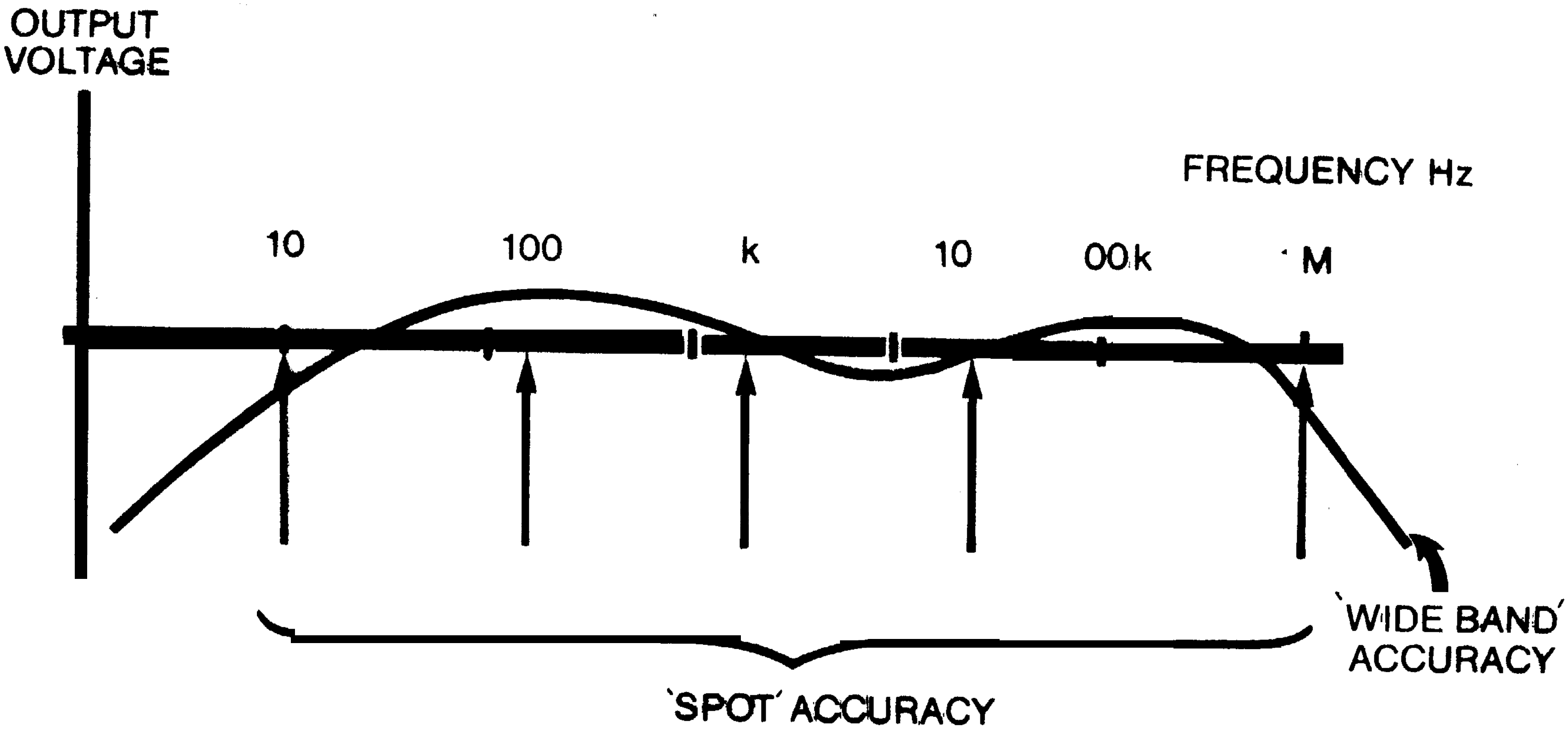


Fig. 4. 'SPOT' FREQUENCY CALIBRATION

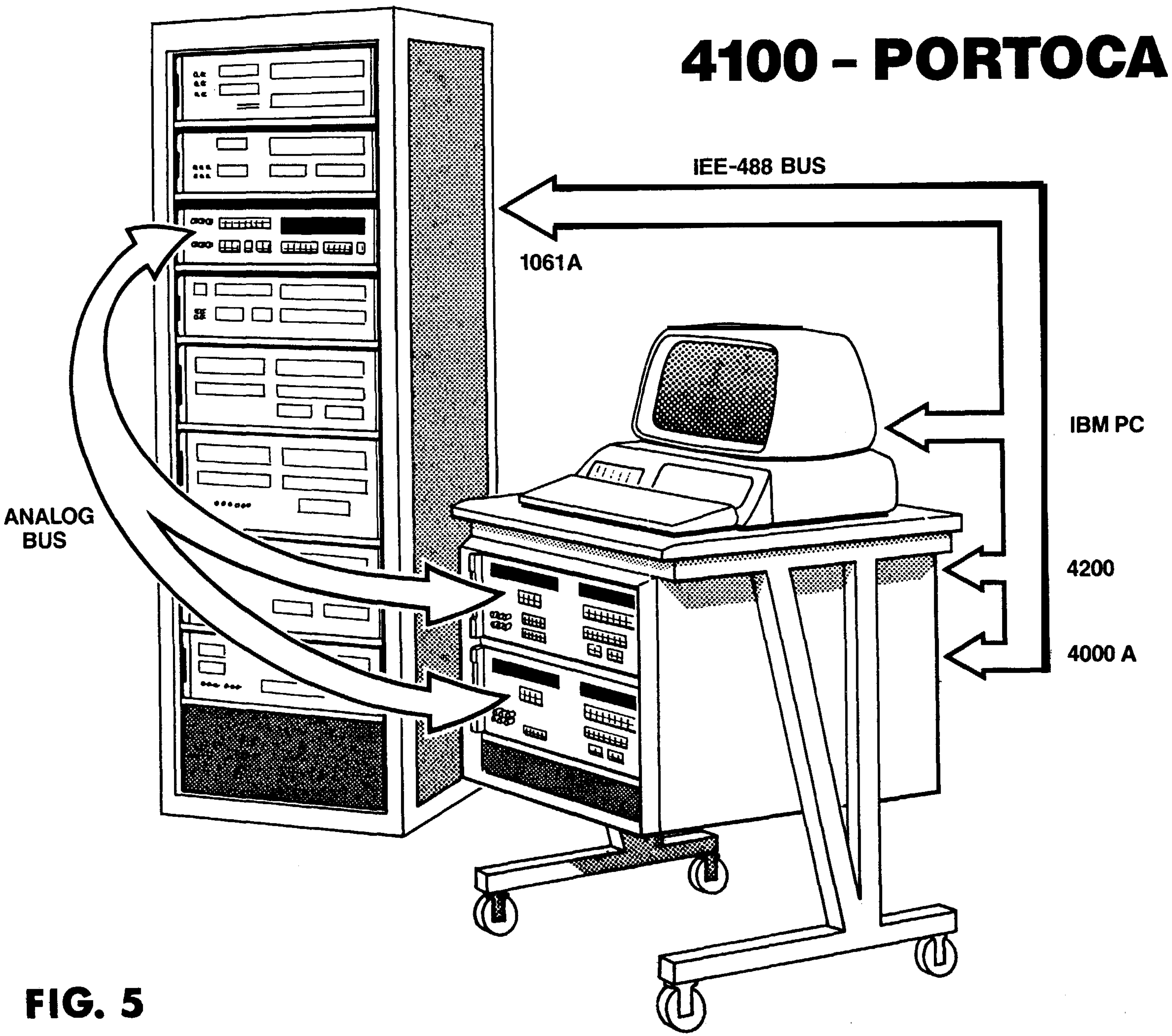


FIG. 5

A 50 PPM 47 HZ TO 63 HZ POWER STANDARD

Duane Brown,
Technical Support, R & D Department,
Guildline Instruments Ltd.

ABSTRACT

A micro based thermal wattmeter for the precision measurement of power over the 47 hertz to 63 hertz spectrum is described. It will operate up to 1000 hertz with reduced accuracy covering the power factor range of -1 through 0 to +1. The principle used is that of the AC/DC transfer principle, the main element being the differential multijunction thermal converter. The design has a resolution of 1 ppm and a direct reading full scale accuracy of 50 ppm.

The design has both current transformer (1A/5A), potential transformer (120 V/240 V) and direct 1 mA inputs. Methods may be employed using the direct 1 mA inputs to obtain the best results when measuring less than full scale inputs. The design is directly calibrated against an external 1 mA dc signal or an external 1 mA ac signal. Phase angle calibration is performed against a known capacitor.

INTRODUCTION

The measurement principle of the thermal wattmeter is described in a paper by N.L. Kusters (1) and L. Cox (1) of the National Research Council of Canada. The main element of the thermal wattmeter is a differential multijunction thermal converter (from here on referred to as DMJTC) from a design by F. Wilkins of the National Physical Laboratory in England.

The DMJTC has 400 thermocouples and two heaters as shown in Figure 1. The group of thermocouples on one heater are wired in series opposition to the group of thermocouples on the other heater. Thus if both the heaters are at the same temperature the output from the thermopile is zero. This design makes use of heater interchange to eliminate heater mismatch. The heaters are interchanged simultaneously to achieve a differential thermal multiplier.

Each heater responds to the square of the rms current flowing through it. The large number of thermocouples gives high output levels, (typically 40 mV for a 20 mA rms input). By keeping the current at a lower level it reduces the power levels in the two heaters and therefore reduces the temperature, approximately a 15K rise. The low current also reduces the output noise from the DMJTC.

This lower temperature rise plus the bifilar heaters with distributed thermocouples results in lower dc reversal errors and lower ac/dc transfer errors.

Other features of this thermal wattmeter are:

1) Automatic dc reference reversal.

2) Direct reading self balancing operation.

3) 4 ripple cancel circuit to improve the ac/dc transfer error.

4) Built-in input transformers.

AC/DC TRANSFER CIRCUIT DESCRIPTION

The thermal wattmeter is basically an AC/DC, 1 mA full scale input, transfer instrument.

It measures an unknown ac signal by subtracting a known dc signal from the unknown ac signal in the thermal converter. A feedback circuit adjusts the known dc signal to drive the thermal converter to null.

If the thermal converter was perfect with identical responses then the output as stated in (1) would be as follows:-

$$V_{dc} = K/T\int_0^T[(x+y)^2-(x-y)^2]dt \qquad (1)$$

$$= 4K\frac{1}{T}\int_0^T xy\,dt \qquad (2)$$

which is by definition real power.

The circuit diagram of the thermal converter multiplier is shown in Figure 2. The main element is the DMJTC with two heaters H1 and H2. The sum (x + y) is applied to heater H1 and the difference (x - y) is applied to heater H2. From (1) the output from both heaters is a function of the heater power.

$$(x+y)^2 = X^2+Y^2+2(xy)$$

$$(x-y)^2 = X^2+Y^2-2(xy)$$

where (xy) denotes the time average product

$$\frac{1}{T}\int_0^T xy\,dt$$

The output of the thermal converter is no longer a function of (xy) but also depends on the operating point $(X' + Y^2)$. This operating point makes the DMJTC ideal for measuring all power factors. The operating point of the thermal converter is set by superposition of Vref on the x input.

When the average input product is zero ((xy) = 0) the output of the DMJTC is not necessarily zero. This is due to heater mismatch. This heater mismatch or zero offset is eliminated by taking a second output O_R after reversing the Y input and taking as the final output the variation of the multiplier between normal and reverse settings. By taking the average of the two outputs

$$(O_N - O_R)/2$$

a thermal multiplier with zero output is realized.

Due to the long time constant of the thermal converter the reversing rate of the circuit is fairly slow. The thermal response is reduced by incorporating dc feedback (figure 3) to maintain thermal balance. Another advantage of the feedback circuit is its linear output, and it is this feedback which is actually measured.

CIRCUIT DETAILS

From Figure 4 we see that the ac and dc signals are superimposed on the x and y inputs. Xref is a constant 10 Vdc and Xvar is the variable dc that is adjusted to obtain a null from the thermal multiplier. The average ac input product is then equal to the dc input product since ac and dc signals do not correlate.

All associated amplifiers are rated for one milliamp rms full scale. The feedback path (Figure 4) consists of a proportional plus integral path. A delay switch is incorporated in front of the integrator which opens at approximately 100 milliseconds before the heaters reverse and closes 1/8 second after the heaters reverse. This allows the proportional or fast path to almost null the thermal converter without introducing a transient into the integrator thus allowing the integrator to settle quickly.

Unfortunately, the feedback is not always purely dc. There is some fundamental frequency. This fundamental frequency gets added to Y just as the dc part of the feedback adds to Y. The component of the feedback in phase with X gets multiplied' with X to give apparent power. A ripple cancel circuit was necessary, to subtract away any fundamental frequency ripple, to improve the ac/dc transfer error (Figure 5).

The phase of the fundamental ripple frequency reverses every time the heaters reverse or when the dc polarity reverses but not when both reverse together. This phase reversal gets demodulated by interchanging the positive and negative x inputs of an integrated circuit multiplier. This multiplier acts as a phase sensitive detector producing a signal whose dc average is proportional to the amount of fundamental ripple fed back in phase with x. An integrator takes the dc average and controls an automatic gain stage to input enough of the -x signal to subtract the in phase ripple in the feedback.

The dc reference (Figure 6) is derived from an internal solid state supply. The variable dc reference is a precision D/A converter operating on the pulse width principle. The logic produces a pulse from 0 to 999 micro seconds wide in one micro second increments producing an output voltage from 0 to 999 with each step equalling 10 mV dc.

The setting of Xvar is determined by switching the A/D to look at a 0.2% accurate integrated multiplier. The input to this multiplier comes directly from the x input of the thermal multiplier. The dc component is subtracted to leave only the ac component. Thus the output of the multiplier represents the first three digits of the seven digit reading.

Polarity reversal of the dc voltage reference averages out any dc offsets in the IC amplifiers. This eliminates any zero instabilities in the thermal multiplier circuit.

The clock signals that do the reversing are generated from a precision one second clock. This accurate clock signal becomes very useful for calibrating less accurate wattmeters. The Normal/Reverse and Plus/Minus clocks reverse every one second and two seconds respectively. These reversals are sinked to an input frequency zero crossing circuit. This reduces the possibility of internal clocks heating against any external inputs.

The A/D is a ±20,000 count ±2 V full scale converter. It is triggered to start a conversion only after the thermal converter has settled. The input integrate period of the A/D finishes measuring the feedback signal from the thermal multiplier just before the heaters reverse.

The input gain to the A/D is set up to equal a 500 millivolt difference between normal and reverse settings. This represents a 0.1% ac/dc difference which has the same weight as one step on the variable dc reference. Thus the ac/dc difference may reach 0.4% before the A/D will overrange asking to have the variable dc reference readjusted.

SOFTWARE

The program begins by setting the variable dc reference to output 5.00 Vdc. If the ac/dc difference is greater than 0.4% it will cause the A/D to overrange. The micro senses the overrange signal and switches the A/D to look at the 0.2% integrated circuit multiplier. This reading is then used to adjust the variable dc reference to within 0.2% of the ac/dc difference.

After the variable dc reference is set then the A/D returns to looking at the feedback circuit. All four readings (Normal plus, Reverse plus, Reverse minus and Normal minus) must then fall within the 0.4% level. Each of these four readings are stored in its own location as a five digit number, overwriting any previous similar A/D reading made four seconds earlier. After taking a reading the microprocessor subtracts Reverse from Normal readings and averages the two dc polarities giving the ac/dc difference.

Should the ac/dc difference be greater than 0.1% of full scale but not enough to overrange the A/D, then the program adjusts the variable dc by a few steps. It then subtracts this change from all four input readings such that the next A/D reading will fit in. This procedure allows tracking sampling inputs up to 0.2% of full scale per second without overranging.

The known dc setting of the variable dc gets added to the ac/dc difference as determined by the A/D to give a reading in the range of 1. This six digit reading can then pass through a switch selectable low pass digital filter having a 10 second time constant. This filter is intended for use when calibrating low noise, low drift ac power supplies or wattmeters. The digital filter takes nine times the old reading and adds the new reading to give it its 10 sec time constant. However, if the difference between the two readings new and old is greater than 100 ppm then the new reading is passed directly to the display.

CALIBRATION

The calibration of the wattmeter (Figure 7 and 8) involves adjusting the dc reference voltages Vref and Vvar. These two references can be calibrated either against a known 1 mA dc input or against a known 1 mA ac input.

To generate 1 mA dc requires a stable known dc source and known resistor to generate a known 1 mA dc signal. The output of the resistor is fed into the current input of the thermal wattmeter. At the same time the reference multiplier output, which sets the variable dc reference voltage, is set to 1.0 V ±1000 ppm. The variable reference is then adjusted to equal full scale ±10 ppm. With the variable reference calibrated the 1 mA dc input is removed. The fixed reference now gets calibrated against the variable reference such that the thermal wattmeter display also equals full scale ±10 ppm. The unit is now calibrated.

To calibrate the thermal wattmeter against a 1 mA ac signal requires the use of a precision 6-1/2 digit voltmeter, a known ac source and two known equal value resistors. First the precision voltmeter is connected between the Vref input and star ground on the thermal multiplier. Vref is then adjusted such that the voltmeter display indicates ±10 V ±10 ppm. The fixed voltage reference is then calibrated. The digital voltmeter is then removed. The output of the two known resistors are connected to the V and I inputs and the ac source is set to generate 1 mA ac through the resistors. The variable voltage Vvar then gets adjusted such that the thermal wattmeter display indicates the calculated value from the resistors and the ac source. The unit is then calibrated.

Phase angle calibration of the design requires the use of a known capacitor and a known resistor. The impedance of the capacitor should be approximately equal to the value of the known resistor. The dissipation of the capacitor should be zero or known. By connecting the output of the capacitor and resistor to the I and V inputs respectively and applying full scale voltage, the phase angle can be adjusted such that the thermal wattmeter display equals zero or the value of the known dissipation of the capacitor.

INPUT TRANSFORMERS

The thermal wattmeter uses amplifier aided current and potential transformers. Both the current transformer and the potential transformer are two stage amplifier aided devices. Amplifier aided transformers are well covered in many papers. This paper will concentrate more on calibrating the two transformers. This calibration procedure requires the use of a known power standard 120 V ac source and 1 A ac source and necessary equipment to prove the above two sources.

POTENTIAL TRANSFORMER

The potential transformer is best calibrated against the 120 V ac source and a known 120 kΩ resistor and capacitor. Connect the known resistor output to the current 1 mA input and apply 120 V ac to it and to the PT input. Adjust the magnitude of the PT such that the thermal wattmeter display equals the value of the known ac input voltage plus or minus the known deviation of the resistor. Substitute the known capacitor in place of the known resistor on the current 1 mA input. The phase of the potential transformer can then be adjusted such that the thermal wattmeter display equals zero plus or minus the known dissipation of the capacitor. The PT is then calibrated.

CURRENT TRANSFORMER

Current transformer calibration is best done against a known standard. This requires a known 1A current source with a known 1A quadrature output. By applying the known 1 A to the CT and the known 120 V ac to the PT one can adjust the magnitude of the CT such that the thermal wattmeter display equals the calculated known reading. By switching the current source to its quadrature output the phase angle of the CT can be adjusted such that the thermal wattmeter display equals zero.

APPLICATIONS

The precision clock along with a timer out signal makes the instrument ideal for calibrating other wattmeters. The unit will output a start pulse and stop pulse over a switch selectable period of ten, one hundred or one thousand seconds. In this mode the readings are accumulated to measure energy. Dividing the thermal wattmeter displayed reading by 3600 represents watt hours and by 36000 to represent kilowatt hours.

The thermal wattmeter is well suited for measuring power in circuits with distorted waveforms of current and voltage. Crest factors of three in current and voltage are possible. An additional area of use is the measurement of power at very low power factors such as the short circuit losses in large transformers or the losses in large shunt reactors.

It is not always necessary to use the CT and PT inputs. Improved accuracy and resolution for low level signals are possible using the one milliamp current and voltage inputs. External CT's and PT's with voltage outputs can be interfaced to the one milliamp current and voltage inputs of the thermal wattmeter through known resistors. These resistors can be selected such that the current output is 1 mA or full scale. Thus it is possible to read full scale even for a 10 V input.

CONCLUSION

The differential thermal wattmeter for the ac/dc transfer of power is based on the multijunction thermal converter. The thermal converter heaters are fully protected against burn out and crest factors of three in voltage and current waveforms are permissible without degradation of accuracy. Accuracy statements of 40 to 50 ppm are achievable with 100 microwatt resolution for all power factors.

The accuracy statements are limited to the 40 ppm - 50 ppm level at this time. This is mainly due to the drift of the internal voltage reference and inherent problems within the CT section. At this time I know of only NRC which can certify the wattmeter to the 50 ppm level and only for the 47 Hz to 63 Hz range.

The design has two ranges for input volts (120/240) and two ranges for current (1A/5A) along with the 1 mA inputs.

REFERENCES

(1) Kusters, Norbert 1 and Cox, Louis G. "The Development of an Automatic Reversing Differential Thermal Wattmeter." IEEE Transactions on Instrumentation and Measurement. Vol. IM-29, No. 4, Dec. 1980, pp 426-431.

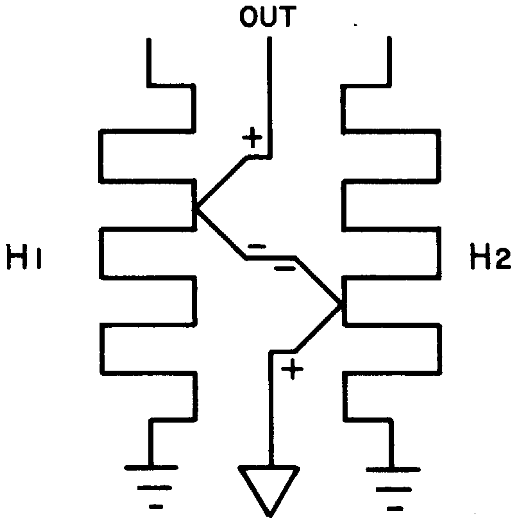


FIGURE
DMJTC

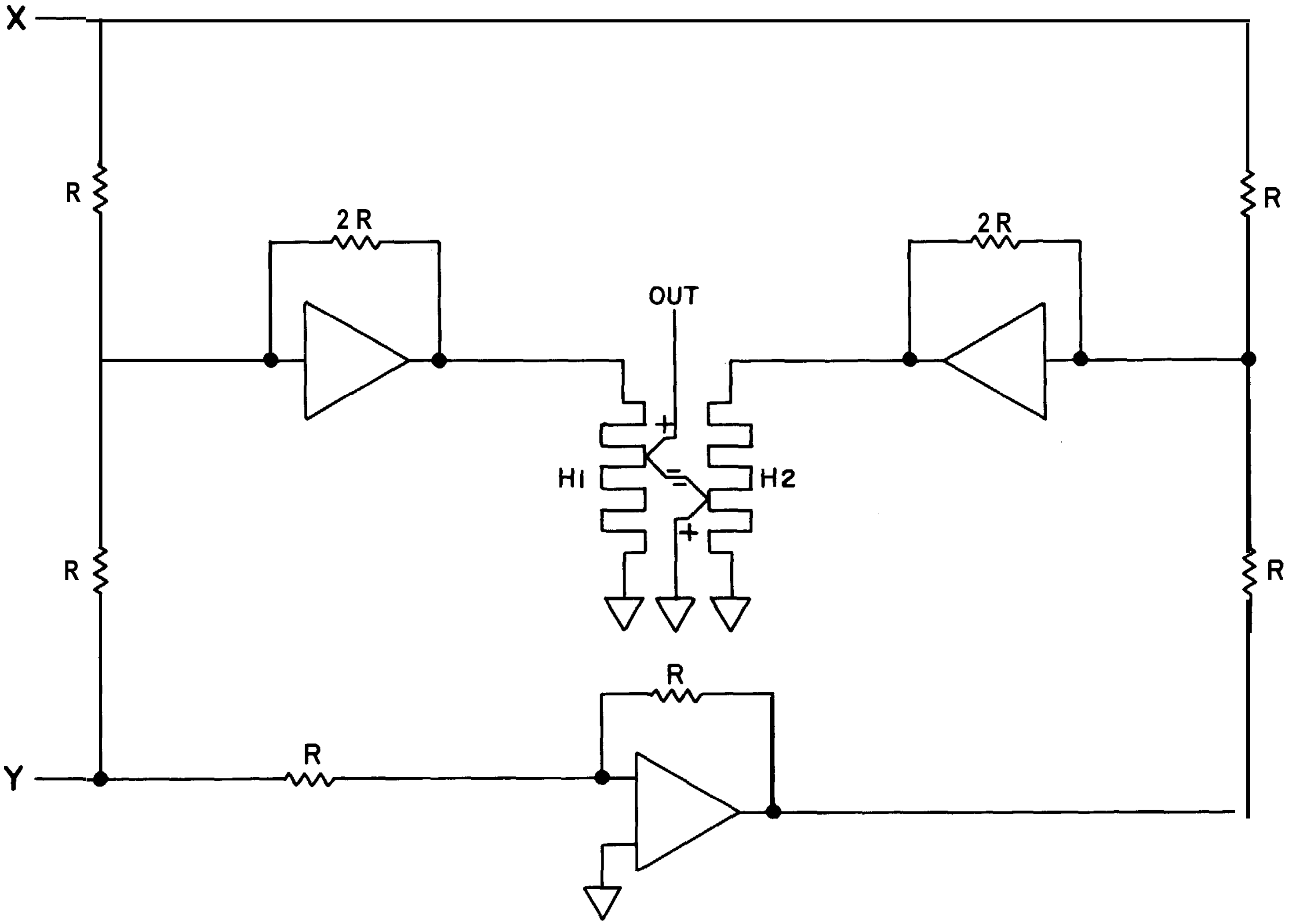


FIGURE 2
THERMAL MULTIPLIER

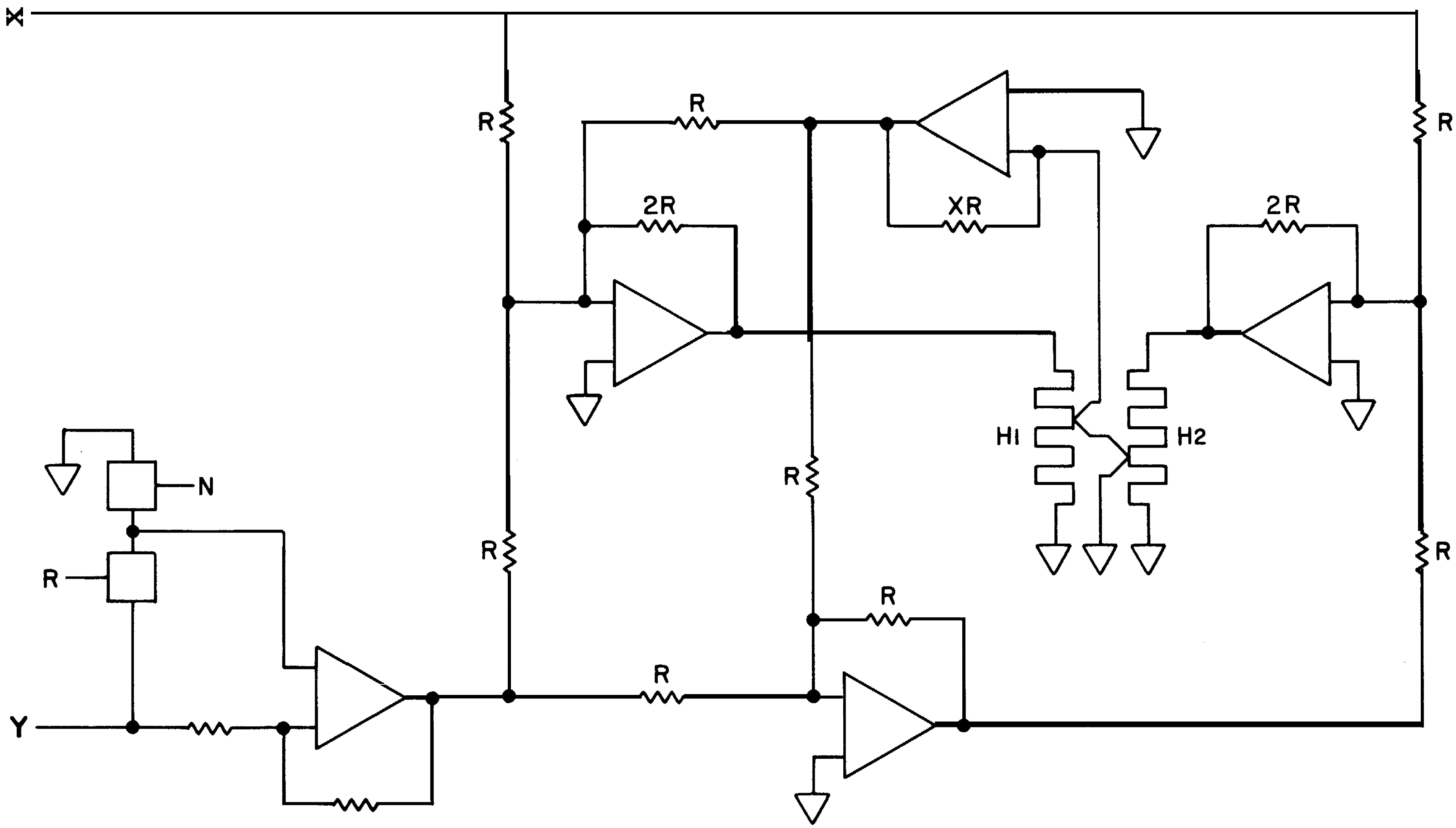


FIGURE 3
DC FEEDBACK

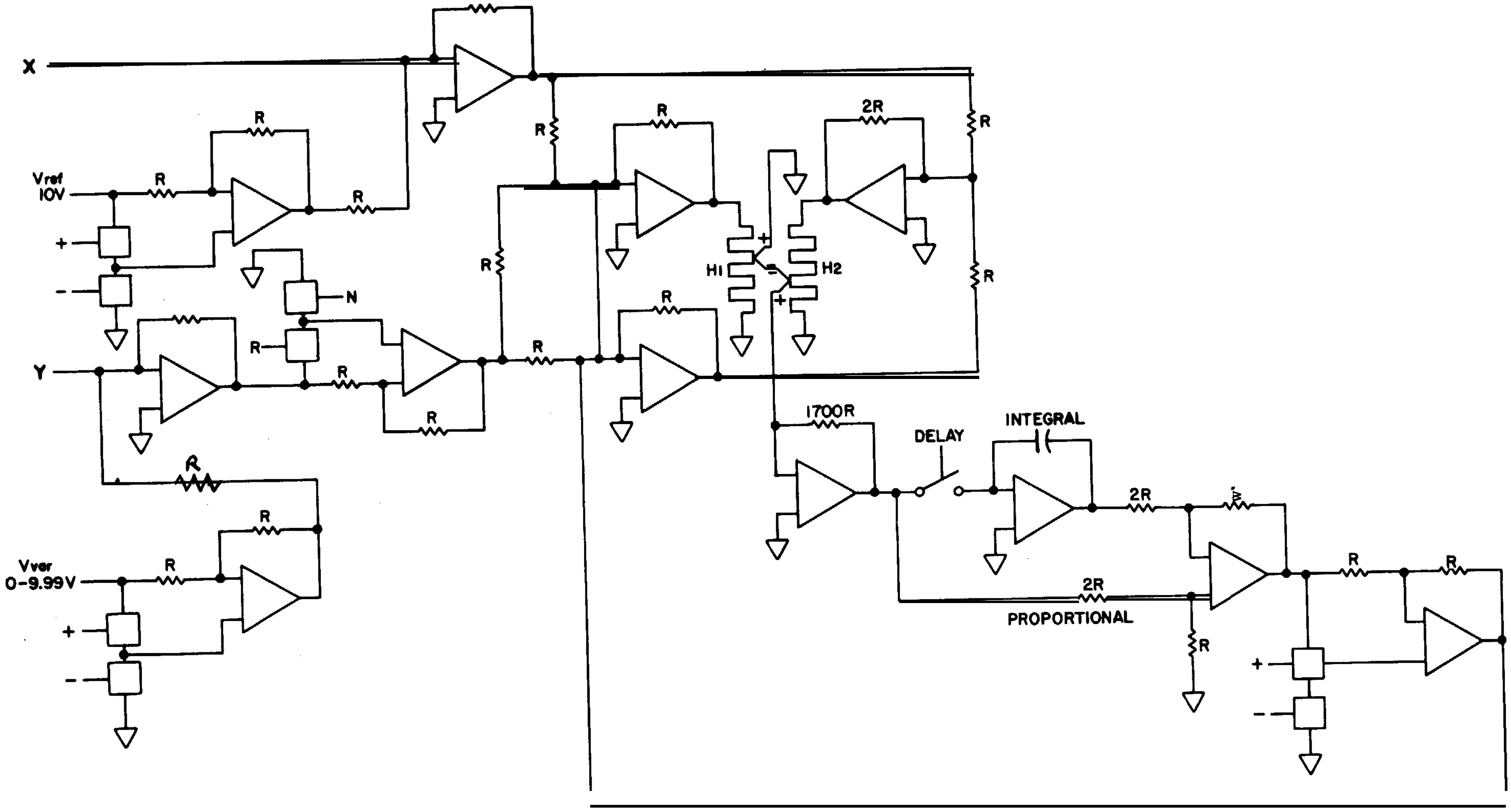


FIGURE 4
THERMAL MULTIPLIER WITH DC FEEDBACK

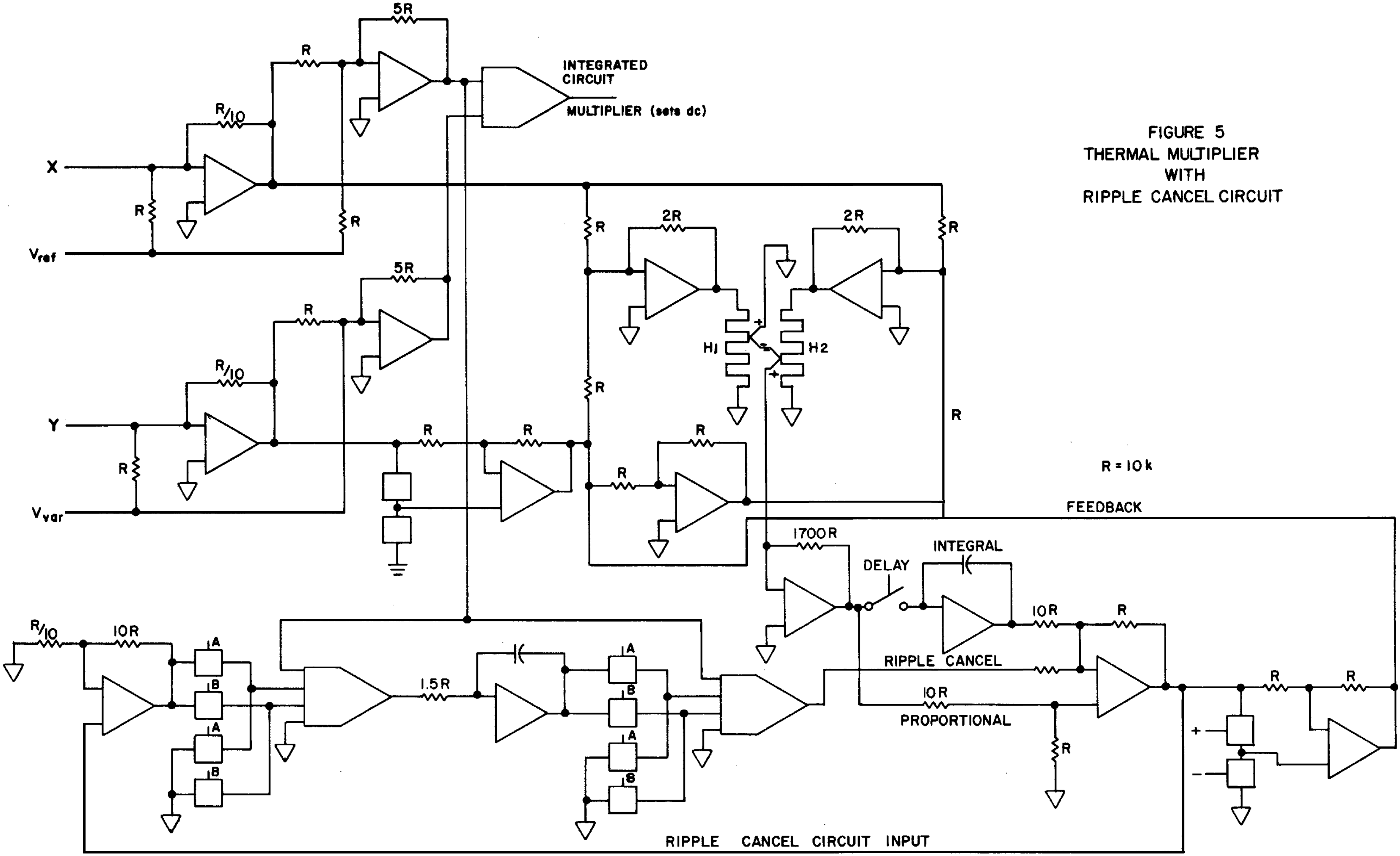


FIGURE 5
THERMAL MULTIPLIER
WITH
RIPPLE CANCEL CIRCUIT

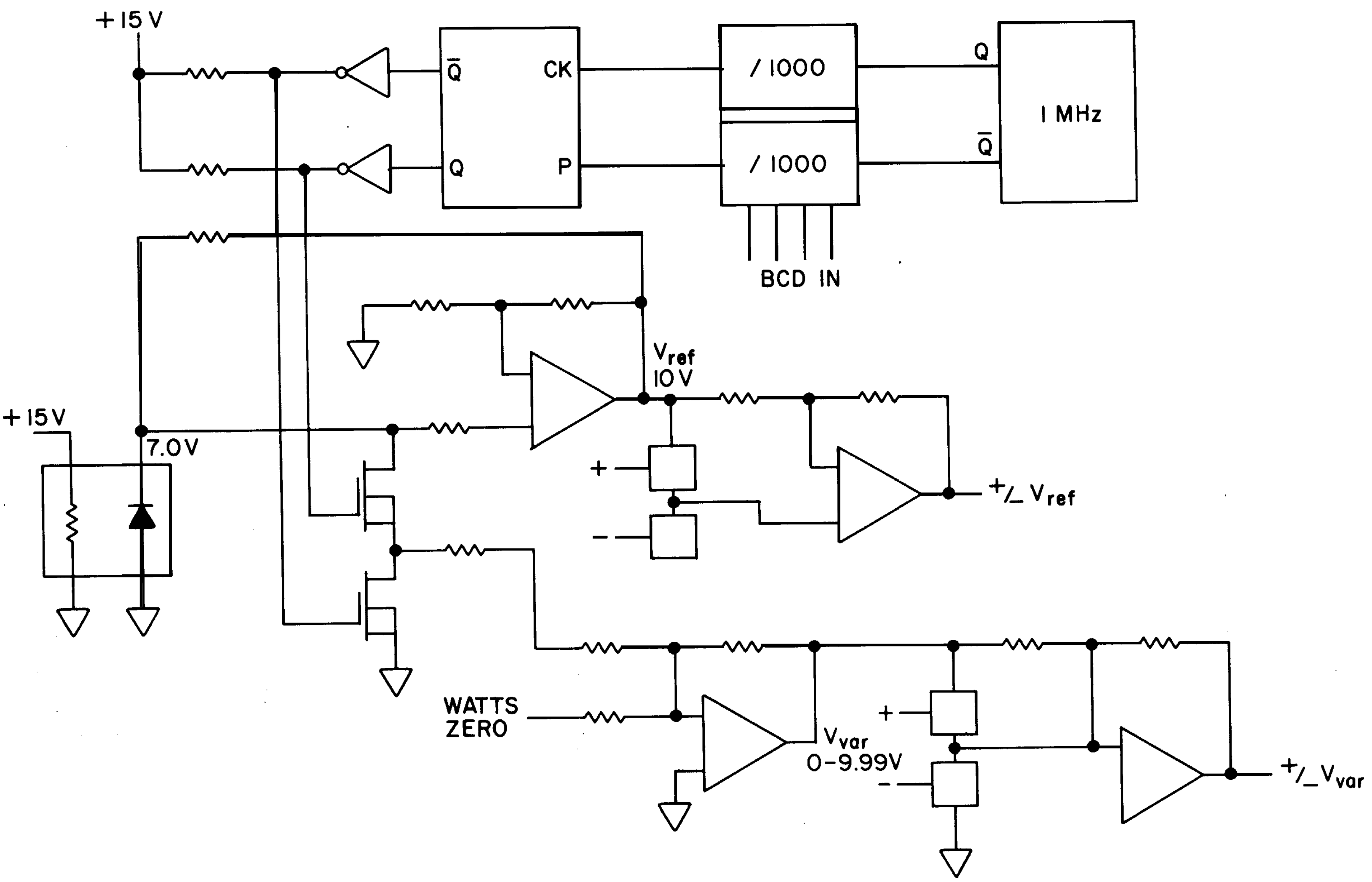


FIGURE 6
DC VOLTAGE REFERENCE

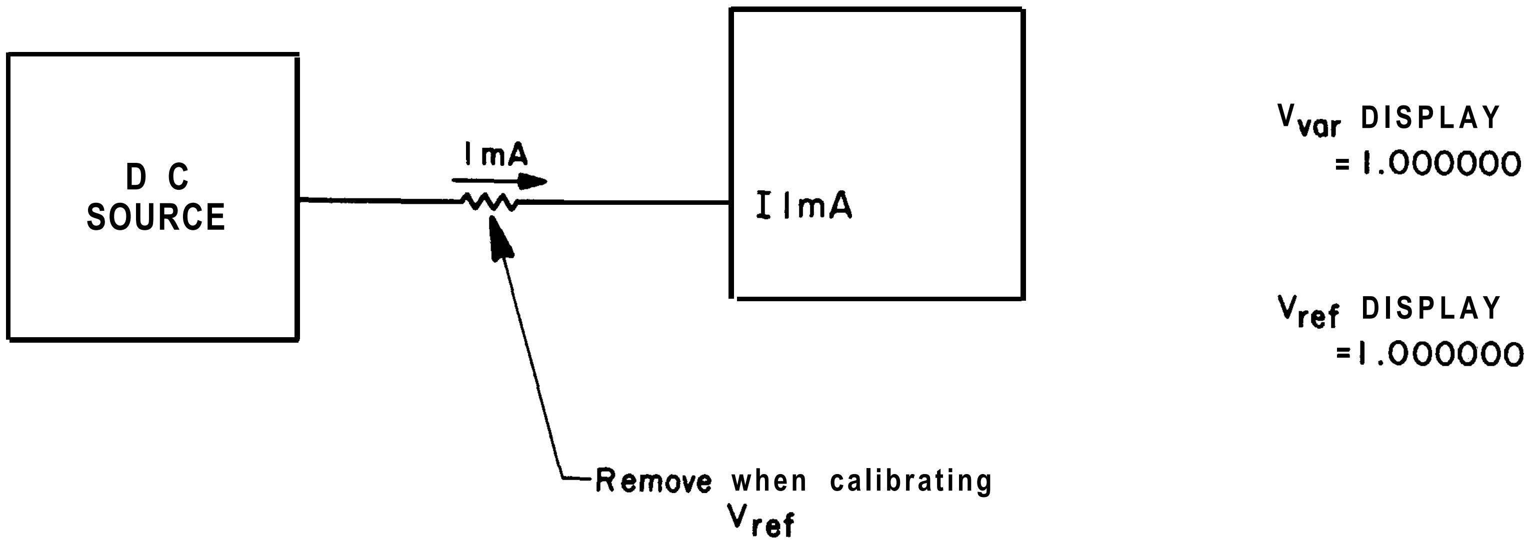
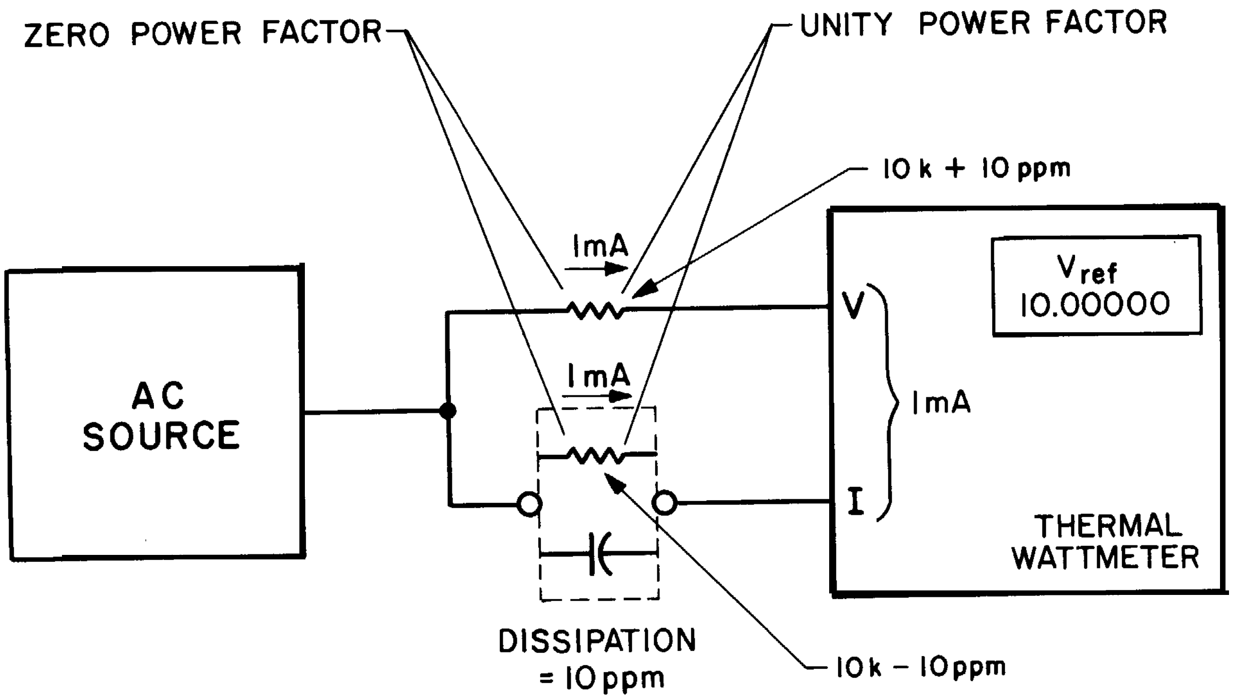


FIGURE 7
DC CALIBRATION



UNITY P.F.
DISPLAY
= .000000

ZERO P.F.
DISPLAY
=1.000000

FIGURE 8
AC 1mA CALIBRATION / PHASE ANGLE CALIBRATION

SESSION I-C

MEASUREMENT POTPOURRI I

James D. Tostensen
Lockheed Missiles & Space Co.

SPACE SHUTTLE TILE AUTOMATED DIMENSIONING

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Sunnyvale, California 94086

ABSTRACT

The re-entry of Space Vehicles into the atmosphere after completing missions in the orbit around the earth or the *moon* has been accomplished many times in the past two decades. Past man rated vehicles like, Mercury, Gemini and Apollo carried from one to three astronauts and were quite small and compact in size compared to the Space Shuttle Vehicle and required much less of an area to have re-entry insulation to protect the capsule and its occupants from the heat during re-entry. Insulation on past vehicles was an ablative type that actually charred and peeled away the dynamic heating of re-entry carrying the heat away from the capsule. These vehicles were used for only one mission.

Tiles manufactured by the Lockheed Missiles and Space Company, Space Systems Division, Thermal Protection System for use on the Space Shuttle Orbiter as a Thermal Protection System are designed to last up to 100 missions. The tile will keep the outer structure from melting and the internal compartments cool enough to enable human occupants to perform their duties comfortably during re-entry through the atmosphere.

Since each tile is equally important as another, the need to dimension them accurately to determine the best fit and relationship to surrounding tile is very important.

With the Space Shuttle Orbiter being larger in size than a Boeing 737 twin jet airliner, this gives one some idea of the area to be covered with tile. The Space Shuttle Orbiter cargo compartment is large enough (15'x15'x60') to carry the Mercury, Gemini and Apollo all at one time.

Since the Manufacturing process cycle is of key importance to maintaining the dimensional tolerance and strength requirements a short review of these processes will be presented prior to the dimensional part of the lecture material.

In the conclusion portion of the presentation several photographs of the vehicle tile Thermal Protection System will be shown after mission return to show the effects of dynamic heating and tile integrity.

The basic raw material is a short staple 99.7% pure amorphus silica fiber. The fibers are derived from common sand. Basic fibers are mixed into a slurry and cast into a block. From the block the tile shapes are numerically control machined. The tile are then coated on the designated areas with a silica frit coating and kilned at 2300 °F to fuse the coating to the tile basic material.

Identification of the tile is then-applied and they are forwarded for inspection. The dimensional relationship of one tile to the other is equally important to achieve the proper spacing for any movement and a breather path to the atmosphere. Master Dimensional Data is analyzed and transformed into N/C machining and dimensional standards computer tapes which are used to machine and measure the completed tiles.

INTRODUCTION

The dimensional measurement of the tiles are accomplished by utilizing a Mainframe Computer in which the tile standards are stored. Interfacing with the mainframe computer are four (4) Bendix-Cordax Coordinate Measuring machines. communications with the mainframe computer is accomplished by four (4) on station computers, Card Readers (IBM Cards), Cathode Ray Tube (CRT) and teletypes. IBM cards which are keypunched to indicate the tile part number and serial number are read into the card reader and call up the dimensional standards stored in the mainframe computer. The Bendix-Cordax equipment is equipped with a arming probe on the Z-axis which physically touches the tile to take measurement points.

When the measurement points are completed they will be analyzed by the computer and a accept/reject message is displayed on the CRT at the measurement station. The dimensions are then stored in the computer file and can be readily retrieved and copies obtained for analysis. The tile are then subsequently placed into Array Frame Assemblies (tools) and shimmed to meet the tile-to-tile space (gap) requirements. The Array Frame Assemblies are then packaged and shipped to the customers facility for installation on the Space Shuttle Orbiter.

BASIC MANUFACTURING PROCESSES

The basic raw material used to make the tile is a short staple 99.7% pure amorphus silica fiber. The fibers are derived from common sand. The Silica Fibers are mixed into a slurry and cast into several different sizes of production units. The production units are pre-dried in a microwave oven and then sintered in a kiln at 2250°F to fuse the fiber junctions for strength. The production units are cut into smaller sizes called cubes/ blanks from which specific tiles are numerically control machined. A masking process is then performed on the area of the tile to be coated. A coating consisting of silica frit, borosilicate and alcohol is used to coat tile specified areas, of the high temperature black tile. While a white silica compound with alumina oxide is used to coat the low temperature white tile.

After coating the tiles are air dried for several hours and then glazed at high temperature (2300°F) in a kiln to fuse the coating to the parent material. The tile are then vacuum waterproofed to resist moisture and identified on the coated surface with a part number and serial number.

TILE MEASUREMENT PROCESS

Master dimensional data (MD) is received from the customer on the tiles to be manufactured. The MD data is analyzed by the computer programmers and converted into data to machine and measure the tile. Engineering forwards this data to the Numerically Controlled Engineering Group who prepare the N/C tapes for driving the N/C machines to cut the tile shape. Quality Engineering also receives a set of measurement standards which are loaded into the Product Assurance computer to dimensionally inspect tile. After the tile has completed the manufacturing cycles, it is forwarded for inspection measurement.

The automated dimensional system utilized by Inspection consists of a Mainframe Computer linked to four (4) on station computers which drive the four (4) Coordinate Measuring Machines. The measuring equipment is operated by the use of a IBM Card Type Reader, Cathode Ray Tube Console Display and a Teletype. See Figure 1.

When the IBM card is fed into the Card Reader the tile part, dash and serial number are optically read and transmitted to the main frame computer. This information on the IBM card identifies the measurement standards for that tile and dimensions taken by the coordinate measuring machine of the tile will be compared to those in the computer standards.

The tiles are held in the measurement position by a vacuum fixture. The Cordax measurement machine is equipped with a Renshaw touch sensing probe on the Z-Axis column to detect the measurement touch Points without damaging the coated (Ceramic Glass like) surface. The number of measurement points taken on a typical tile are 41, nine points on each side equally spaced and five points on the top, as shown in Figure 2. These points are transmitted via the on station computer to the main frame computer where they are compared with the stored standards of the tile size. The main computer then transmits a message to the on station CRT which informs the operator of the accept/reject criteria. The operator can also obtain a copy of the measurements by activating a on station thermal printer built into the CRT console. This information is then utilized by Engineering to evaluate the tile application if it is under or oversize. Tolerance bands on the tile sides are plus or minus .008" and plus or minus .010" on the top surface, as shown in Figure 3.

Depending upon the tile configuration the number of measurement points taken will decrease or increase. The average time to dimension a simple tile on the Coordinate measuring equipment is 16 minutes. Tiles with curved sides and compound angles can take up to 30 minutes to dimension, due to extra machine movements and touch points necessary to cover the tile entire surface.

It might be noted that since the first shipset of tiles were delivered for the Columbia Orbiter 102 on which each tile was dimensionally checked, the number of tile now measured has declined. One of the main reasons for less of the tile being dimensionally inspected is close control of the Numerical Control Machining Tapes and also stability in the tile manufacturing processes. These conditions allow a sample measurement by family part numbers of the basic same configuration. Since the introduction of this system of control there have been no adverse conditions or reports of large numbers of out-of-tolerance tile and savings in dimensional inspection is appreciable.

Anytime a configuration or N/C Machining change is made the tile are dimensionally inspected to verify the change. A typical set up of a tile on the Coordinate Measuring Equipment is shown in Figure 4. Since the tiles are coated with a ceramic glass type material they are held in place for work operations by a vacuum table during the measurement process. Other key items in the dimensioning are the Arming Probe, Contact Probe and the positioning fixture. Each time the probe makes contact with the tile surface a signal is generated and sent via the on station computer to the mainframe computer for standards comparison.

The computer system is also utilized to store other inspected attributes on the tile. This data is also entered via a CRT console and card readers at different inspection stations. This data is indexed in the computer from a IBM card which is peculiar to each tile identifiable to a part number, dash number and serial number. Some other data entered and stored in the Computer Data System via the IBM card are visual, weights, dimensions and any special features such as radii, holes and recesses. Due to the requirements of having complete records and traceability from vehicle to vehicle should problems arise, almost dictates that a automated computer system be utilized for quick retrieval of all historical data.

The IBM (MB-09) card is actually the Shop Order Traveler which accompanies the tile through the entire Manufacturing and Inspection Cycle. The back side of the card is utilized to record all manufacturing processes, while the front side (shown in Figure 6) is primarily used to record Inspection data and for Engineering dispositions as required.

INSTALLATION OF TILE ON THE SPACE SHUTTLE

When the tile are installed on the Space Shuttle Orbiter vehicle, precise gaps are left between them to allow for any expansion or contraction and a breather path to the uncoated bottom and side of the tile is provided. These requirements establish the rather stringent plus and minus tolerances of the tile size. It would have been virtually impossible to manually dimension tile, due to the quantity, complex shape, fragility and the number of measurements required.

With an average of 41 measurements per tile and 32,000 tiles required for the Space shuttle that equates to 1,312,000 measurements per ship set of tiles.

Depending upon the area of the Shuttle Vehicle where the tile are installed the gaps will differ. The method by which the tile are attached to the Orbiter Vehicle is shown in the attached drawing (see Figure 5). The gap between the tile as mentioned before provides a breather path to the atmosphere and allows for movement and keeps them from making physical contact. If tile tend to be oversize or undersize it affects the gap distance and installation positioning. The installation illustration in Figure 5 shows the typical gap tolerances for the High Temperature and Low Temperature reusable tile insulation utilized on the Space Shuttle Orbiter.

The illustration also shows the method by which the tile are attached to the Space Shuttle outer structure, by utilizing RTV-560 and Nomex strain isolator pad (SIP) between the structure and the tile. Typical installation of tiles on the vehicle are somewhat indicated by the color of the outer surface. The black colored areas indicate the high temperature tiles. Some of the white colored areas are the low temperature tile, but later vehicles will also have thermal blankets which are white in color. For typical vehicle re-entry temperatures refer to Figure 7.

TILE CONDITION AFTER RE-ENTRY

A series of photographs were taken after re-entry and landing at Edwards Air Force Base to show the tile condition. To highlight the lecture several photos of key high and low temperature points on the vehicle will be shown and narrated to show the durability of the material and need for precise dimensioning. Since these photographs are in color they have not been reproduced and made a part of this paper. Precise color is needed in the photos to show tile condition. Photos to be shown will be of the Shuttle Orbiter Nose, Elevons, Body Flap, Wing Leading Edge, Fuselage Side, OMS Pod, Cockpit and Engines.

CONCLUSION:

Without the computer driven coordinate measuring equipment it would have been very costly to dimensionally evaluate the tile for the Space Shuttle Orbiter. Considering the number of data points to be recorded and filed, it would have been a paper nightmare. Secondly, the copying errors and transpositioning of numbers would have also been an error factor of some magnitude.

To manually dimension a tile with conventional measuring devices such as micrometers, calipers, height gages and other precision instruments would have been very costly and even in some cases impossible due to tile shapes. With a ceramic glass type coating the handling and instrument contact would also cause a hiqh percentage of damage.'

With millions of pieces of data to be recorded for historical purposes and the necessity for detailed traceability and retrieval in a timely manner, computers were the only answer. Manrated vehicles have stringent requirements for safety reasons and adequate precise data and records of both hardware and personnel performing those functions are essential to the program overall success.

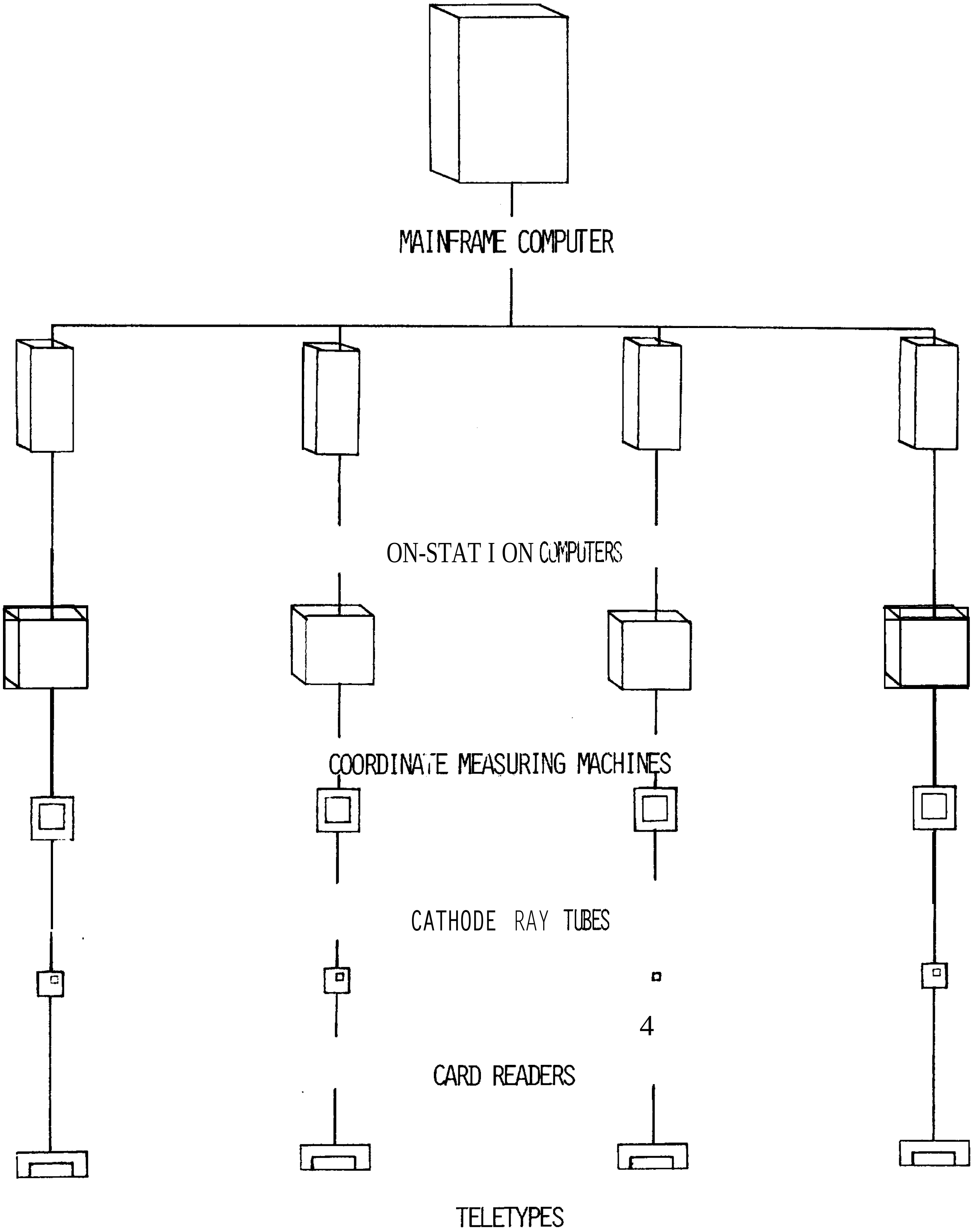
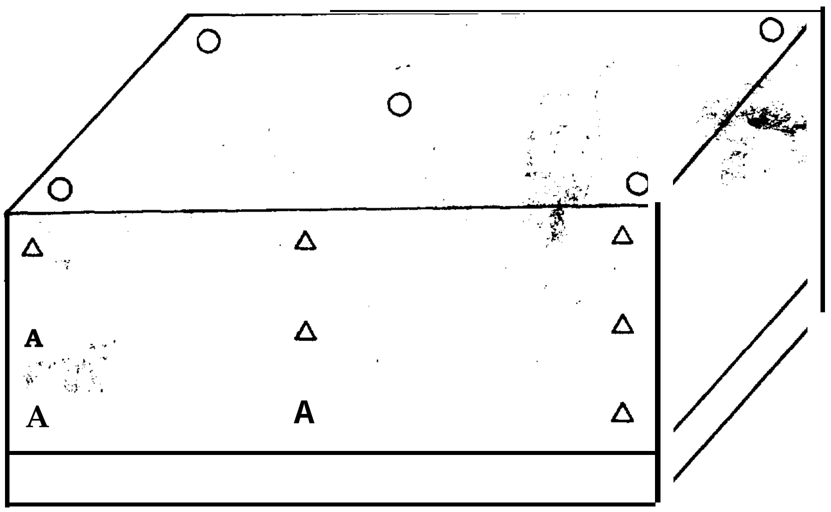


FIGURE 1

COORDINATE MEASURING SYSTEM

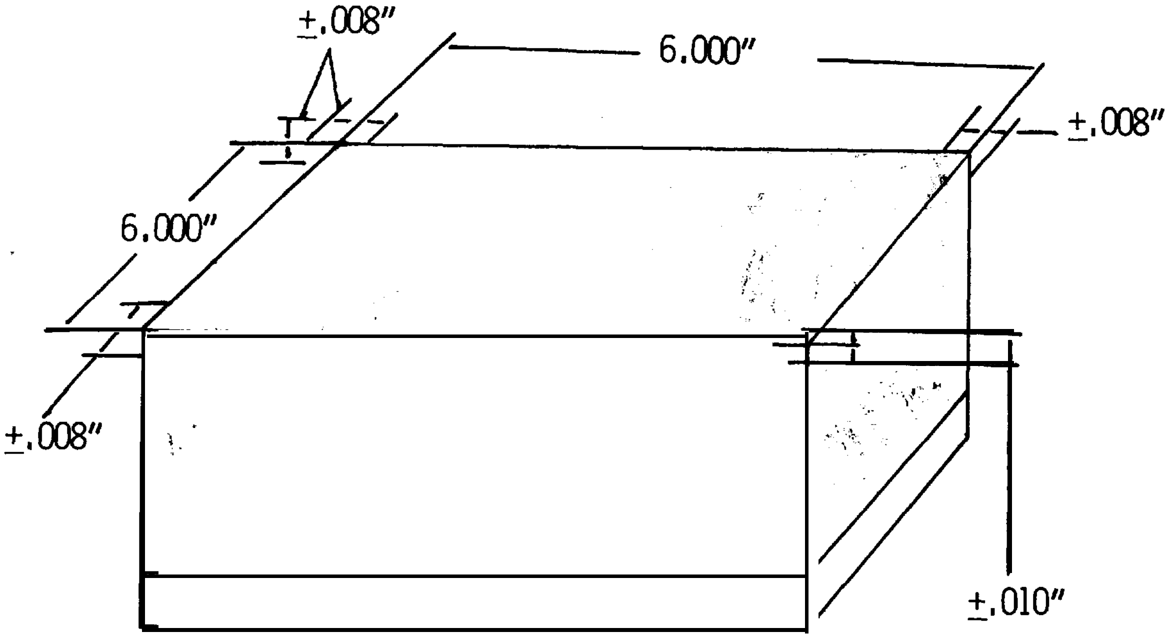


A TYPICAL TILE SIDE TOUCH POINTS (9)

○ TYPICAL TILE TOP TOUCH POINTS (5)

FIGURE 2

TILE MEASUREMENT POINTS



TYPICAL TILE TOLERANCES SIDES/TOPS

FIGURE 3

TYPICAL TILE TOLERANCES SIDES/TOPS

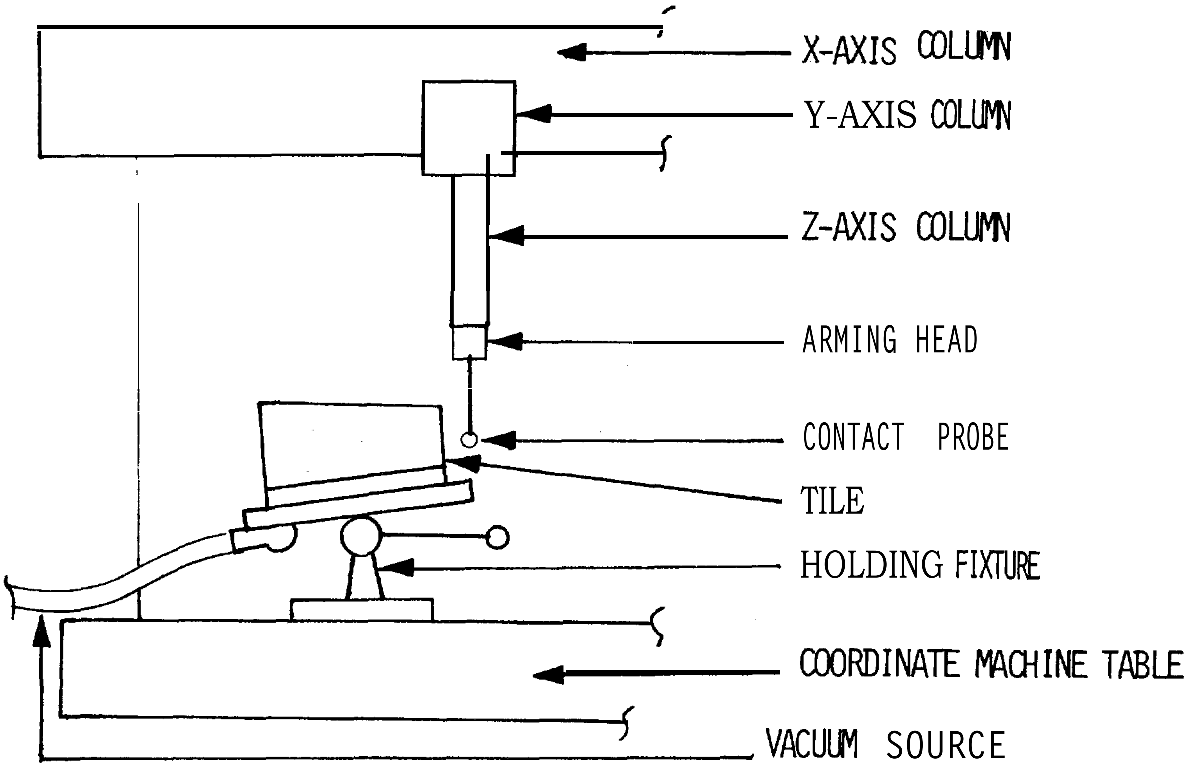
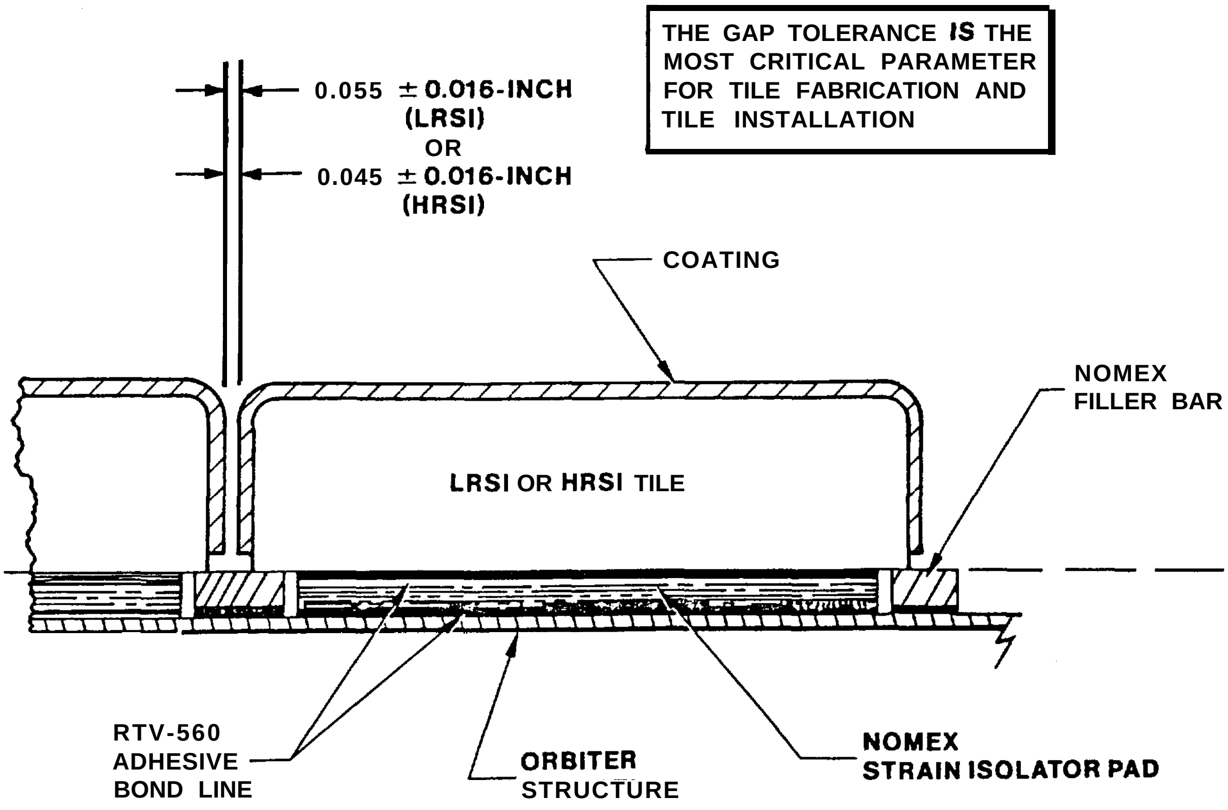


FIGURE 4

TILE MEASUREMENT SET UP

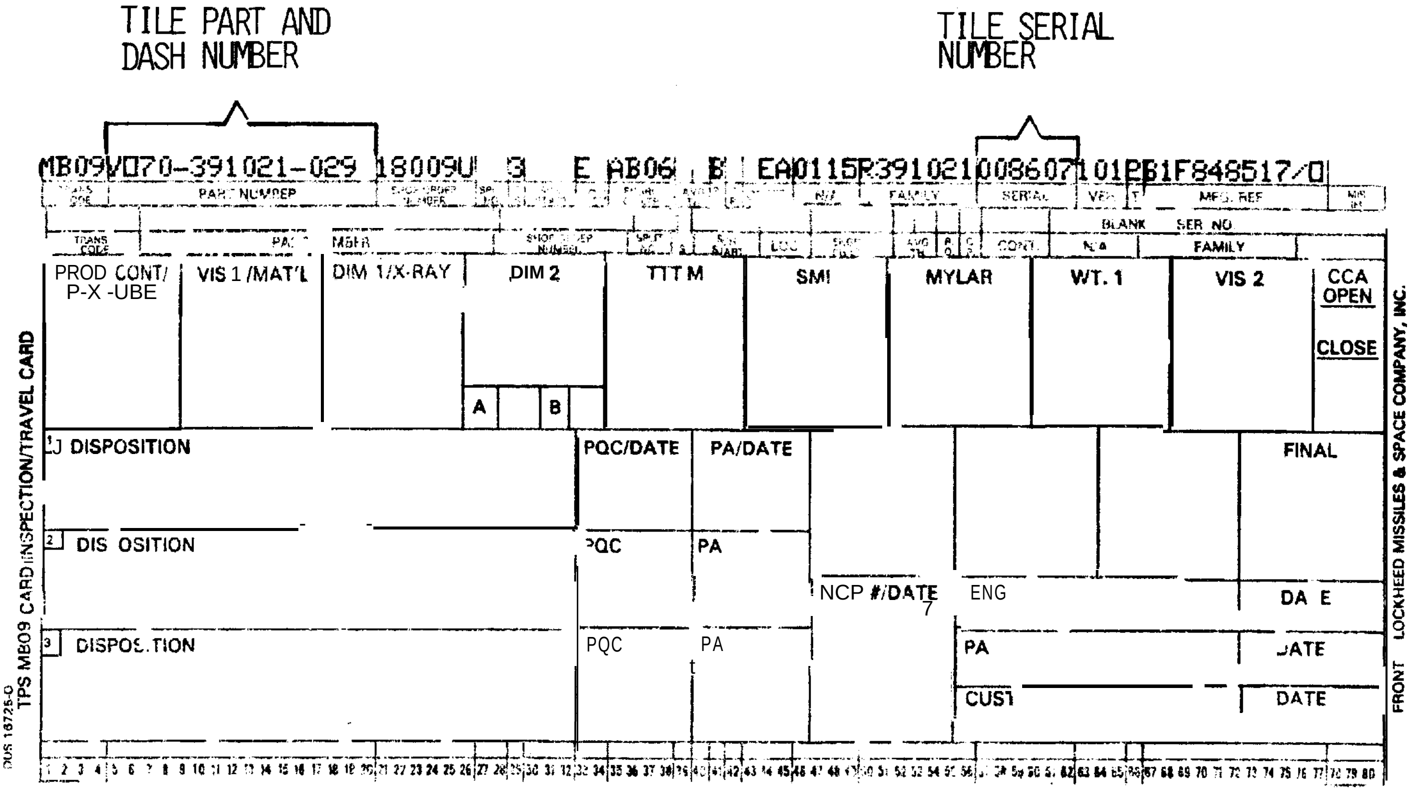


HRSI — CLASS 2 — HIGH TEMPERATURE TILE 1200°F to 2300” BLACK COATING (EMITTANCE IS OVER 0.8 AT 2300°F),

LRSI — -CLASS 1 — LOW TEMPERATURE TILE 750°F TO 1200°F WHITE COATING (EMITTANCE IS 0.65 AT 1200°F) COATING IS DESIGNED FOR LOW SOLAR ABSORBTANCEON ORBIT

FIGURE 5

TILE INSTALLATION ON THE ORBITER



MB09V070-391021-029 18009U 3 E AB06 B EA0115R391021008607101PB1F848517/0

TRANS CODE | PART NUMBER | SHOP ORDER NUMBER | SERIAL | VER | MFG. REF

TRANS CODE | PART NUMBER | SHOP ORDER NUMBER | SPLIT | LOC | AVG | CONT. | BLANK | SER NO | N/A | FAMILY

PROD CONT/ P-X -UBE	VIS 1 /MAT'L	DIM 1/X-RAY	DIM 2 A B	TTT M	SMI	MYLAR	WT. 1	VIS 2	CCA OPEN CLOSE

1 DISPOSITION	PQC/DATE	PA/DATE				FINAL
2 DISPOSITION	PQC	PA	NCP #/DATE	ENG		DATE
3 DISPOSITION	PQC	PA		PA		DATE
				CUST		DATE

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

TPS MB09 CARD/INSPECTION/TRAVEL CARD

FRONT LOCKHEED MISSILES & SPACE COMPANY, INC.

FIGURE 6

IBM (MB-09) CARD USED TO RECORD TILE HISTORICAL DATA

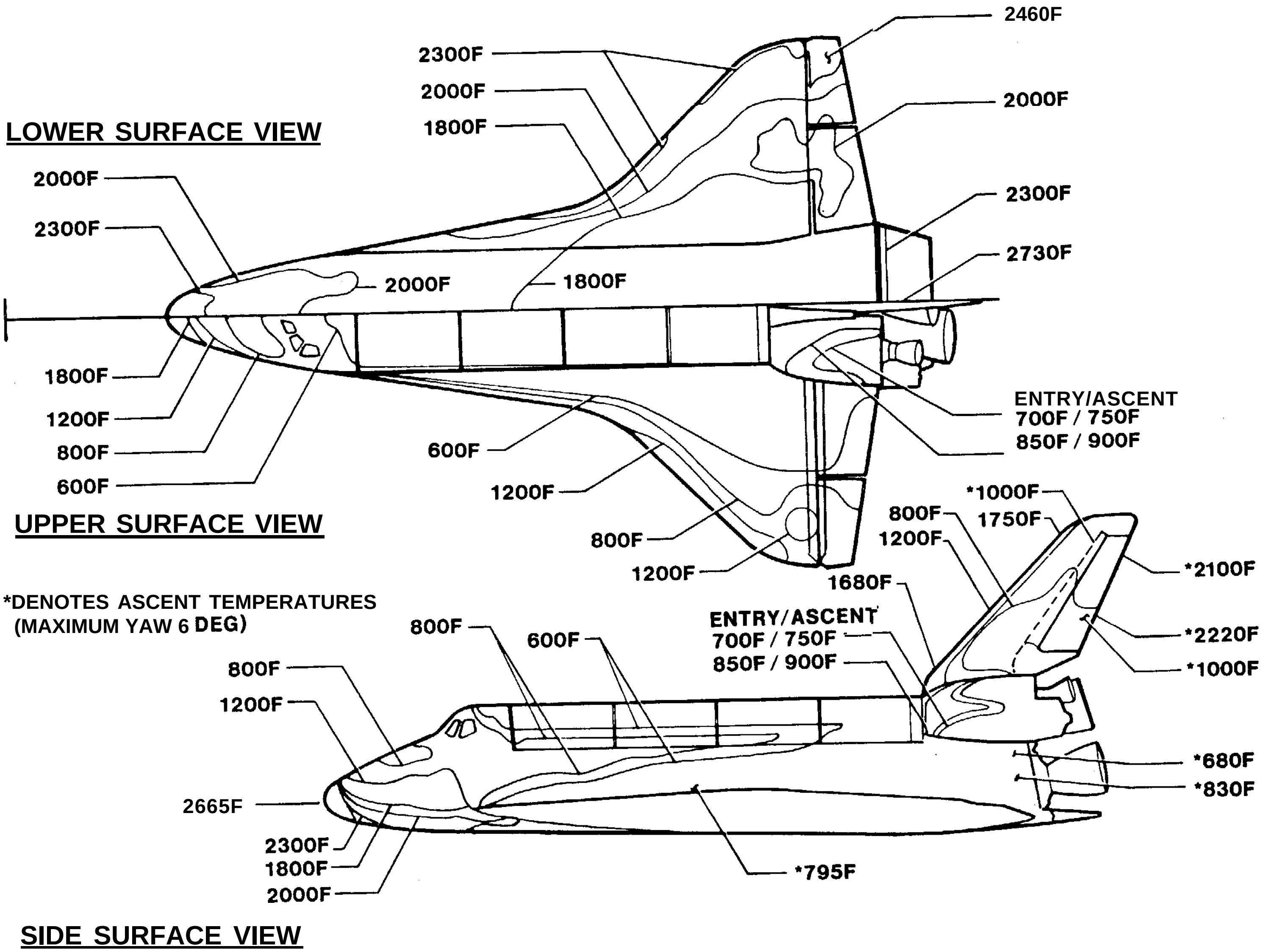


FIGURE 7

TYPICAL ORBITER RE-ENTRY TEMPERATURES

HIGH FREQUENCY AND STATIC CAPACITANCE KASUREMNT TECHNIQUE ON LINEAR PARAMETRIC TESTERS

L. Gutai, S. Hylroie, and T. Hazendonk
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ABSTRACT

The combined high frequency and static capacitance-voltage technique is a well-known tool in characterizing metal-oxide-semiconductor (MOS) structures. Understanding of the physics and controlling the properties of those structures have a great impact on the performance, yield and further development of MOS devices.

Due to the complexity of C-V characterization techinques and the lack of commerically available dedicated measurement systems the use of this powerful tool has been limited to research and development purposes only. Linear (DC) parametric test systems commonly used for process evaluation and device parameters extraction in production areas, however, can easily be adapted to perform those measurements.

This paper will discuss the additonal hardware and software required for the implementation of the high frequency and static capacitance-voltage technique on a Keithley Linear Parametric Test system.

The advantages of a C-V characterization technique built around a general purpose DC parametric tester over the commercially available standalone C-V measurement systems are higher throughput, increased data storage, increased data manipulation capabilities and integration with standard PCM testing used in production.

The hardware addition consists of a few items available off the shelf at moderate cost. The software architecture allows the use of the powerful computational resources, available in such systems, for process and device parameter exraction, further statistical analysis and modeling, as well as process equipment evaluation.

A new technique was developed to correct for measurement errors in the high frequency capacitance measurement due to the low quality factor of nonideal MOS capacitors. Examples of the application of this system in new process development, process trouble shooting and process equipment evaluation will be discussed.

INTRODUCTION

Semiconductor process and materials control have become an integral part of the semiconductor industry in recent years. Manufacturing more complex integrated circuits has placed increasing demands on technologies employed in wafer fabrication. Various process steps such as oxidation, implantation and masking have to be continuously evaluated in order to maintain the low variations between wafers and between sites on the same wafer. A small number of specially designed test circuits, process control monitors (PCM), are placed on each wafer and sophisticated measurements are carried out on them to monitor regular process steps, evaluate equipment performance, heip in new process development or trouble shooting (1). Triggered by this demand, the design, manufacturing and widespread use of a new family of test equipment, the DC parametric testers have evolved. The use of parametric testing within the semiconductor industry has literally exploded during the past few years (2).

These general purpose parametric testers are designed mainly for steady-state current and voltage measurements and are used in production areas. The demand for more sophisticated or special testing methods such as high frequency and static capacitance voltage measurements or mobile ion concentration determination in metal-oxide-semiconductor structures stimulated the development of dedicated testers for use in research and development environments.

Our goal here is to show the benefits of combining the advantages of the high throughput, large data management and storage capability of the commercial DC parametric testers with the advantages of dedicated test equipment. With the variety of available microcomputers and IEEE bus compatible electronic measurement instruments on today s market, it is relatively easy and economical to custom build a dedicated measurement set-up around an existing parametric tester. A further advantage of such a system is its compatibility with standard PCM testing as used in production.

The choice of the high frequency and static capacitance-voltage measurement techniques as an additional process control tool is justified by the unique properties of MOS capacitors in process characterization (3). The MOS capacitor has the advantages of simplicity of fabrication and of analysis. Since the fabrication of an MOS capacitor uses the same processing as the integrated circuit, it provides direct information on the actual process. **Another important feature of** using MOS capacitors in process characterization is that while parametric measurements performed on

MOS transistors provide information **on the combined** effects of different process steps, the **capacitance** voltage measurement reveals the role of the individual process steps separately.

SYSTEM DESCRIPTION

A)BLOCK DIAGRAM

The block diagram of the high frequency and static capacitance measurement system built around a Keithley Parametric Tester is shown in Fig. 1. The heavy arrows represent sensitive signal routes: high frequency measurement signal from the capacitance meter and low leakage connections to the elecrometer. The light arrows and the dashed lines represent the high level analog signals and the digital control connections, respectively.

A short description of the functions of each building block is given below.

The **METAL** SHIELDING box encloses the prober and the impedance box (which has to be situated close to the capacitor), providing shielding against electrical interference, induced static charge and light.

The **PROBECARD** provides mechanical support for **the** electrically shielded and teflon insulated capacitance probe and establishes electrical connections between the Keithley System and the C-V measurement setup.

The **IMPEDANCE** BOX serves as a **multiplexer between** the **high** frequency and static capacitance measurement instrumentation, decoupling one from the other. This also contains the circuitry to measure the high frequency equivalent series **resistance** of the **MOS** capacitor.

The KEITHLEY SYSTEM controlled **by the DEC PDP 11/34** mini-computer provides the DC biases for both the high frequency and static capacitance measurements and measures the analog outputs of the **Boonton** bridge and the Keithley 616 electrometer.

The ICS COUPLER, **used as** a listener only in this configuration, takes IEEE bus commands from the controller **(DEC** PDP **11/34) and outputs 10 x 4 bit** TTL signals to set the measurement ranges of the **Boonton 72B,** control the relays in the impedance box and operate the light source on the probecard necessary **for MOS capacitance measurements in inversion.**

The **1MHz** three terminal **BOONTON 72D** CAPACITANCE **METER** measures the parallel equivalent capacitance of an impedance with an accuracy of 0.25% **and** linearity of 0.1% provided that the quality factor of the capacitor is greater than 5. The **Boonton** bridge is inherently insensitive to parasitic capacitances between its high and low terminals and the ground terminal. These features combined with the impedance box attachment (described later in details) makes this measurement suitable for the high frequency capacitance measurement of a non-ideal **MOS** capacitor.

The KEITHLEY **ELECTROMETER** 616 is used as a buffer **amplifier** (input impedance greater than 10^{14} ohms and leakage current less than 10^{-15} **amperes)** to **measure** the charge on the **MOS capacitor** in the **static** capacitance-voltage measurements. The charge is determined by measuring the voltage drop on a known capacitor connected in series with the **MOS** capacitor.

The **JUNCTION BOX** contains all the analog and digital connections organized in a way that makes it easy to change the circuitry if necessary. A small power supply and driver **circuits** for the relays in the impedance box are placed here too.

B)MEASUREMENT CIRCUIT SCHEMATICS

The simplified circuit diagram of the measurement setup is shown in Fig. 2. for clarity, the digital control signal **and** relay drive routings are omitted.

(1) High Frequency Capacitance Measurement.

When relays RD and RC are closed and relay RS is open, the **Boonton 72B** capacitance meter measures the parallel equivalent capacitance of the **MOS** capacitor .

The DC bias is **applied between the** terminals **"LO** BIAS and HI **BIAS"**. The inductor L decouples the **1MHz** measurement signal from the electrometer circuitry. The tuned parallel LC circuit provides a means to apply the DC bias onto the **MOS** capacitor if the relay RC is open and compensates all the stray capacitances between the probe and **the** ground. (The elecrometer reading can be used to monitor the DC bias.) The D_1 and D2 silicon diodes prevent electrical breakdown in thin oxides by eliminating the voltage spikes generated by the Eoonton between its **high** terminal and **ground terminal during range changing.** For the 15mV **1MHz** measurement signal, the diodes represent a very high impedance and also limit the spikes to 0.7 volts. (This solution has the advantages **over** the common clamping diode circuit that it eliminates the need of an additonal power supply with voltages set every time slightly higher than the maximum blas voltage.1

(2) Static Capacitance Measurement.

When using a parametric tester, the obvious choice for quasi-static capacitance measurement is the charge-voltage technique **(4).** In this technique, the electric charge needed to raise the potential across a previously discharged **MOS** capacitor terminals to a predetermined value is measured **-** either directly with a coulomb meter or indirectly by measuring the voltage drop on a known **('standard)** **capacitor** connected in series with the **MOS** capacitor. This voltage drop can be measured with **a high input impedance low leakage current electrometer. In this case, a Keithley 616 electrometer was used in the buffer amplifier mode to measure the voltage drop on the CQ polystyrene capacitor terminals. The bias is applied across the series combination of the MOS capacitor and the polystyrene capacitor via the Boonton LO BIAS and "GROUND" terminals. For high resolution, the** Reed **relay RS is used to short the capacitor CQ before each step (true static** measurement). For all practical purposes, however, this initialization is needed only at the start of the voltage sweep. If the leakage of the system is less than 10^{-14} amperes, the quasi-static method (waiting between two subsequent biases only for the electrometer to settle) gives identical results to the "true" static measurement. During the measurement, the Reed relay RD is open to decouple the high frequency circuitry. The inductor L blocks the high frequency signal from the capacitance meter during the static capacitance measurement. Using a coulomb meter makes the measurement simpler because the whole applied bias voltage appears on the MOS capacitor terminals. In that case, however, one needs an auto-ranging coulomb meter.

Note that the electrometer input capacitance, the cable capacitance and CQ are connected parallel, thus their total known capacitance has to be determined in a separate calibration step. This is done automatically during the impedance box calibration (see: Calibration of the Impedance Box") and the static capacitance measurement is calibrated to the high frequency capacitance measurement.

C) SERIES RESISTANCE MEASUREMENT

When an impedance bridge is used, both components of a complex impedance can be determined. However, the Boonton 72B capacitance meter measures the equivalent parallel capacitance only. This disadvantage can be overcome by the use of a simple passive circuit as is shown in Fig. 3a, thus retaining the good qualities of the Boonton 728 capacitance meter (price vs. resolution). A known capacitor (C_0) with a relay across its terminals is connected in series with the unknown impedance (Z_2'). By taking two readings, one with the relay open resulting in a value CA and one with the relay closed resulting in a value C_B, both components of the impedance can be calculated.

When the relay is closed, the meter measures the parallel equivalent capacitance of the impedance of the MOS capacitor (Z_2 in Fig. 3a):

$$CB = C_S/(1+R_S^2\ C_S^2\ \omega^2), \qquad (1)$$

since stray capacitances from terminal "H" to ground and from terminal "L" to ground do not affect the Boonton reading.

When the relay is open, the effect of stray capacitance, C_1 (Fig. 311, cannot be ignored. This capacitance consists of the capacitance between relay terminal "B" and ground, the capacitance of the coaxial cable to the probe and the capacitance of the shielded probe itself.

The effect of this capacitance could, in theory, be canceled with a parallel LC circuit connected between node "B" and ground as is shown in Fig. 2. (The capacitor between "HI BIAS and ground isolates the DC bias from ground.) If the parallel combination of stray capacitance C_1 and the LC circuit is tuned to the measurement frequency, then no measurement signal flows from node "B" to ground. In the practical realization, however, there always exists a finite impedance between node "B" and ground. Moreover, this impedance changes when replacing the probe or the cable.

More detailed considerations show that the effect of the ohmic component of this impedance can be ignored. In the following derivation, we substitute this impedance by a capacitance C_1 arriving at the initial circuit in Fig. 3a.

In order to calculate the effect of capacitance C_1 on the Boonton reading, an equivalent circuit of the circuit in Fig. 3a is shown in Fig. 3b. (Y-Delta transformation.) It is well known from linear network theory that the two circuits are equivalent if:

$$Z_1=Z_2'+Z_3'+Z_2'Z_3'/Z_1'. \qquad (2)$$

The Boonton reads the parallel equivalent capacitance of impedance Z_1 and ignores the impedances from high terminal to ground and from low terminal to ground (Z_2 and Z_3, respectively).

Using the notations of Figs. 3a and 3b, one gets:

$$Z_1 = 1/(j\omega C_p + 1/R_p) \qquad Z_1' = 1/j\omega C_1$$

$$Z_2' = 1/j\omega C_S + R_S \qquad Z_3' = 1/j\omega C_0.$$

Substituting these values into Eq. 2:

$$C_A = C_p = \frac{C_S C_0(C_S+C_0+C_1)}{(C_S+C_0+C_1)^2+(C_0+C_1)^2 R_S{}^2 C_S{}^2 \omega^2}. \qquad (3)$$

From Eqs. (1) and (3), R_S and C_S can be expressed in terms of CA, CB, C_0, C_1, as follows:

$$C_S = (C_0+C_1)\left(\frac{(C_0+C_1)/C_B+1}{C_0/C_A-1}-1\right), \qquad (4)$$

$$R_S = \frac{(C_S/C_B-1)^{1/2}}{\omega C_S}. \qquad (5)$$

Typical values of CS and RS are 100 picofarads and 300 - 500 ohms, respectively.

Parasitic Effects of Adjacent Test Structures

On a typical PCH, there are several test structures, (transistors, guarding ring, etc) located close to the MOS capacitor. These structures are usually AC grounded-via the probes used for parametric testina of these structures (Fig.4). Due to the non-zero-series resistance of a practical MOS capacitor, the finite impedance, Z_1', between the common node of CS and RS and ground will introduce an error into the series resistance and capacitance measurement. We can model this impedance at the 1MHz measurement frequency by a parallel combination of a capacitance and resistance (C_1 and R_1 in Fig. 4b). The equivalent series capacitance and series resistance, C_M and R_M in Fig. 4c, respectively, can be caluclated substiuting the. actual values of impedances Z_1, Z_1', etc., into Eq. (2). According to

Fig. 4b:

$Z_1=1/j\omega C_M+R_M$ $\qquad Z_1'=1/(j\omega C_1+1/R_M)$

$Z_2'=R_S$ $\qquad Z_3'=1/j\omega Cs)$,

thus:

$$C_M=C_S/(1+R_S/R_1), \qquad (6)$$

$$R_M=R_S(1+C_1/C_S). \qquad (7)$$

During the part of the measurement when the MOS capacitor is in deep depletion, parasitic capacitances of a few picofarads result in a large error in RS; but since $R_1>>R_S$, the capacitance reading is less affected. The procedure is then to use Eq. (4) and (5) to calculate the measured C_S and RS and using their values in Eq. (6) and (7) as C_M and R_M to caluclate the corrected values. A simple solution to eliminate the effect of this parasitic capacitance and avoid the necessity of this correction is either to include a high resistor or a tuned parallel LC circuit between the extra probe and the AC grounded source or measurement instrument.

Calibration of the Impedance Box

To use the impedance box the values of CO and C_1 have to be determined. This can be done in a simple and accurate way without using any known standard calibration impedances.

If we replace the impedance Z_2' (in Fig. 3a) by an unknown pure capacitance, then $R_S=0$ and from Eq. (1) we get: $C_S=C_B$. Substituting this value into Eq. (3), a linear relationship results between the inverse of the two Boonton readings l/CA and $1/C_B$:

$$1/C_B=[C_0/(C_0+C_1)](1/C_A)+1/(C_0+C_1). \qquad (8)$$

Using different capacitors and plotting $1/C_B$ vs. $1/C_A$ a straight line results, from wich C_0 and C_1 can be determined. Note that the actual values of these capacitors are not needed, the only requirement is that they have to be constant between the two readings. (Stray capacitances between the probe and the chuck need not be considered: they add to the value of these capacitors.)

Error Calculation.

Eqs. (4) and (5) can be used to calculate the errors resulting in CS and RS. Assuming that the random errors in CO, Cl, CA and CB are independent and, in this particular case, are equal to 0.1%, the expected relative error in CS and Q (Q is the quality factor defined by $Q=(R_SC_S\omega)^{-1}$) are plotted in Figs. 5a and 5b as a function of C_0/C_S with Q as parameter. As can be seen from those graphs, this method gives good accuracy for the series capacitance, but is less accurate for series resistance measurement. However, in MOS C-V characterization the accurate value of the series capacitance rather than the series resistance is needed.

APPLICATIONS AND RESULTS

Typical high frequency (HF) and static (QV) capacitance-voltage characteristics of an MOS capacitor are shown in Fig. 6. The high frequency capacitance-voltage curve has been corrected for back side contact effects to coincide with the static capacitance measurement in the accumulation region . The interface state density distribution across the band-gap extracted from those curves is shown in Fig. 7. Performing these measurements lot by lot on a few PCMs on each wafer or on wafers with all-PCM structures, valuable information can be drawn regarding process variations or equipment peformance, respectively.

As an expample for process variation monitoring, the threshold voltage variation over a three month period is plotted in the uppermost graph in Fig. 8. These data have been extracted from measurements used on large area MOS transistors. The plot of this important device parameter indicats that considerable variations have occurred in certain process steps. To have a deeper insight to the underlying causes of those variations, different process papameters extracted from capacitance measurements are plotted in the next three rows in Fig. 8. These capacitance-voltage measurements have been carried out on MOS capacitors located adjacent to the MOS transistors used for transistor parameter measurements. Comparison of those plots gives the relative (w) and absolute (a) contributions of certain process parameter variations to the threshold voltage variation.

Examples for equipment performance evaluation are given in Figs. 9 and 10. Measuring the electrically active dopant concentration profile with the pulsed capacitance technique, a modification of the high-frequency capacitance-voltage method, the impurity concentration profiles on an implanted and unimplanted capacitor, located adjacent to each other, can be determined as is shown in Fig. 9a. The area between the two curves, the net implanted dose, was contour mapped in Fig. 9b. In Figs. 10a and 10b interface state distribution and oxide thickness are contour mapped.

The use of the combined high frequency and static capacitance-voltage techniques helps understanding the physics and controlling the properties of the MOS structures which, in turn, gives a means to control the performance, yield and further development of MOS and bipolar devices.

SUMMARY

Hardware modification and software package have been developed for performing high frequency and static capacitance-voltage measurements on a Keithley parametric tester. This measurement set-up has the advantages over more sophisticated and dedicated systems of higher speed, increased data storage and manipulation capability and compatibility with standard PCM testing. The system is simple to use either by engineers or operators and has proved accurate and reliable. Data collected and represented in ' various ways both in development and manufacturing environment can be very valuable in process and equipment evaluation, new process development and trouble shooting.

ACKNOWLEDGEMENT

The authors are greatly indebted to Steve Katzman for his valuable help in software development, to Joel Orona for building the hardware, to Jim Crawford for maintaining the Keithley system and to Irene Diazoni for carrying out most of the measurements.

REFERENCES

(1) Perloff, D. S., "Characterizing Process Nonuniformities On Large Diameter Wafers: An Overview", Silicon Processing, ASTM Special Publication 804 (ed. by D. C. Gupta), 1983, pp. 422-444.

(2) Evans, G. G., "Semconductor Parametric Testing: Yesterday, Today, and Tomorrow , Keithley Publication, 1983.

(3) Nicollian, E. H., Brews, 3. R., "MOS (Metal Oxide Semiconductor) Physics and Technology", John Wiley & Sons, 1982, pp. 1-11.

(4) Ibid., pp. 488-489 and 601-603.

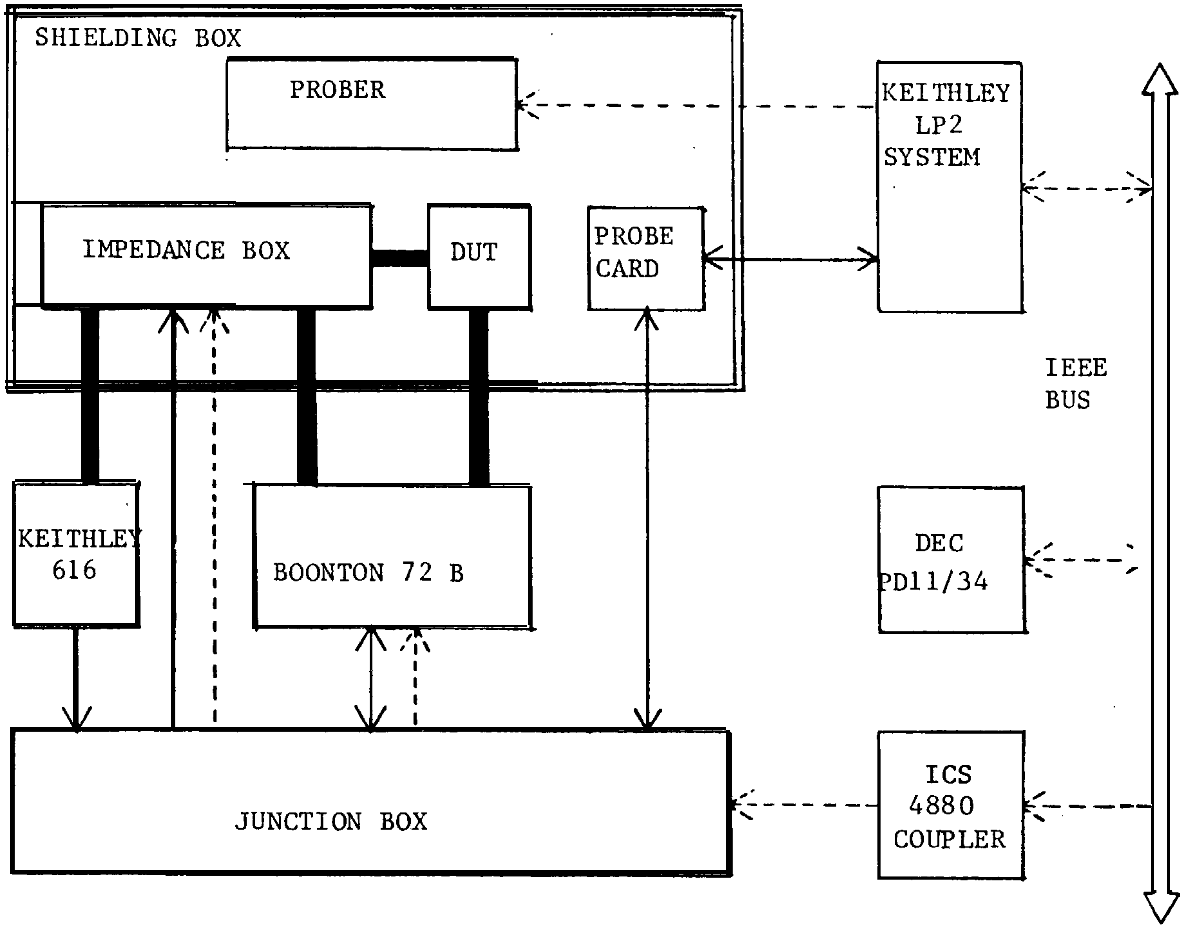


Fig. 1. High frequency and static capacitance-voltage measurement on Keithley parametric tester. Block diagram.

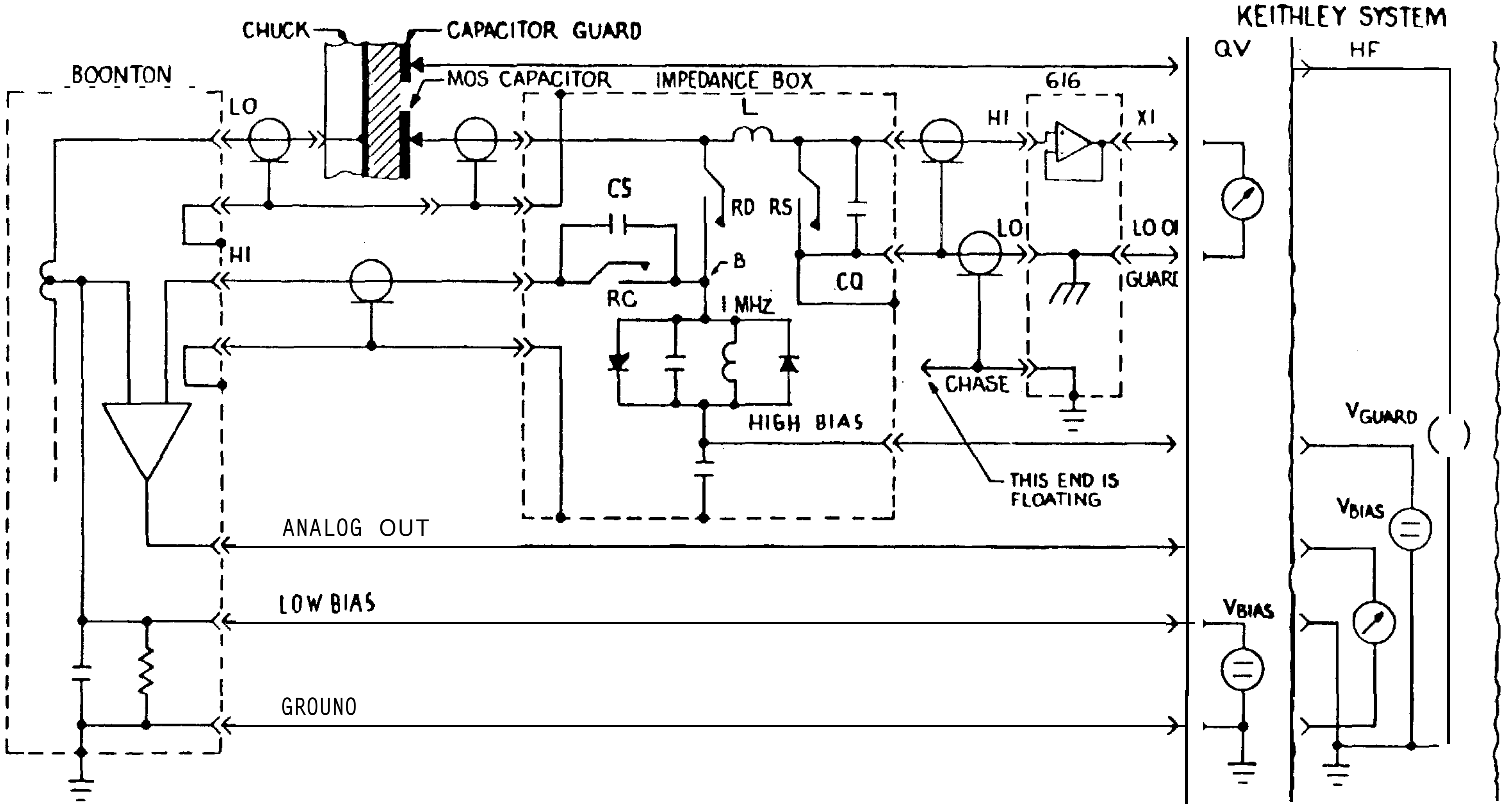
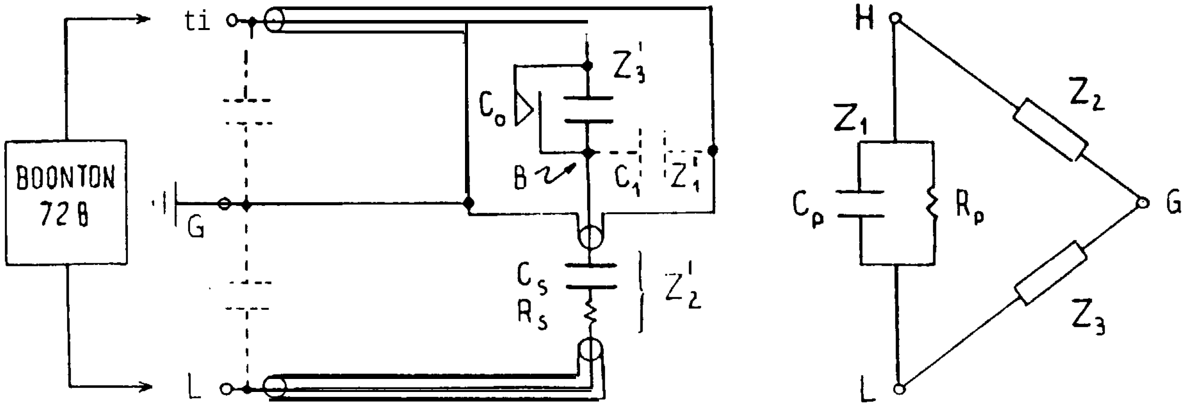


Fig. 2. Simplified signal routing schematic.



(a) (b)

Fig. 3. Auxiliary circuit for high frequency equivalent series resistence measurement. (a) Simplified measurement circuit. (b) Equivalent circuit of Fig. 3a.

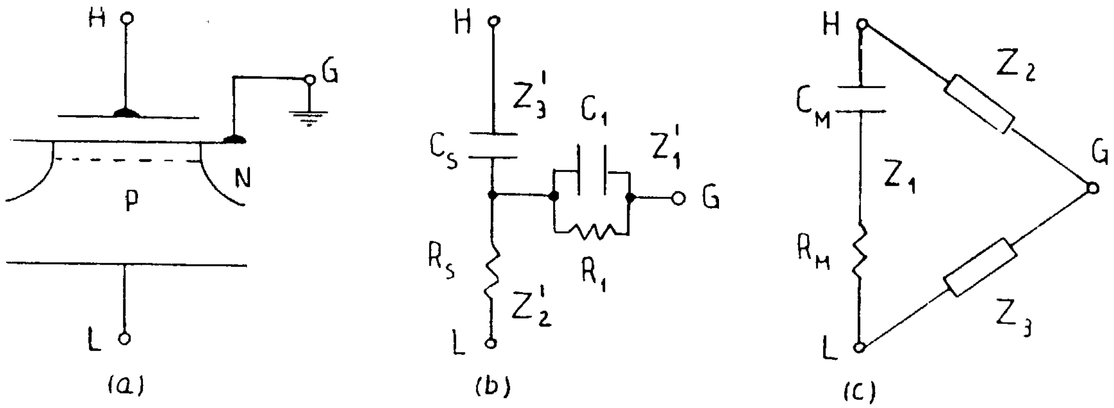


Fig. 4. The effect of adjacent test structures if the series resistance of MOS capacitor is not zero. (a) Test structure (MOS capacitor with a junction guard). (b) Circuit model. (c) Equivalent circuit of Fig. 4b.

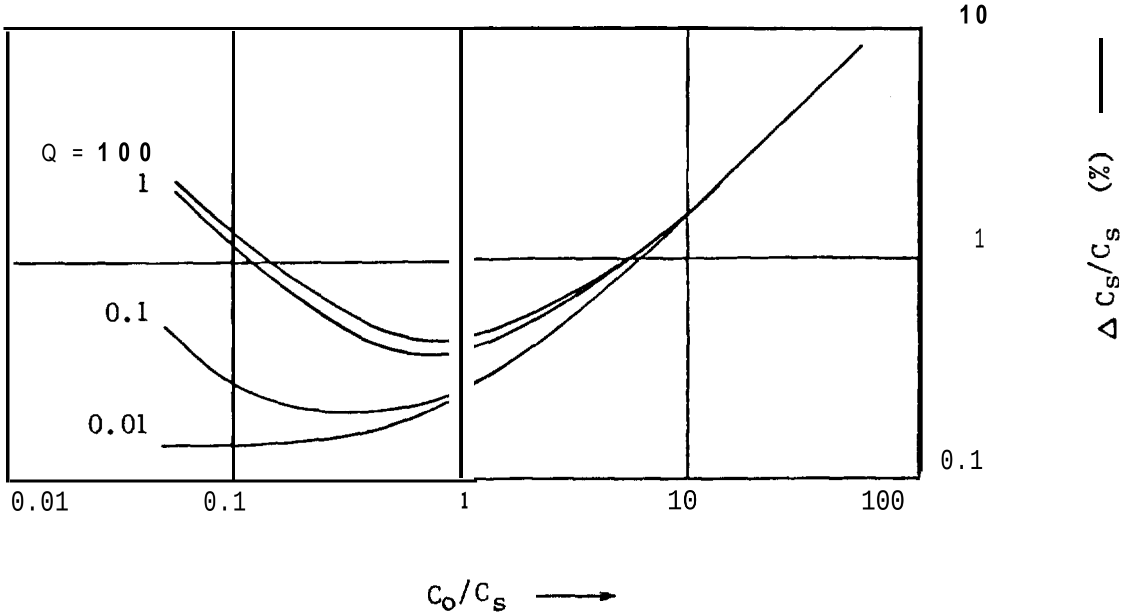


Fig. 5a. The relative error in the series capacitance, C_s, measured with the impedance box, as a function of C_o/C_s with the quality factor, Q, as parameter. $(Q = 1/(R_sC_s\omega))$.

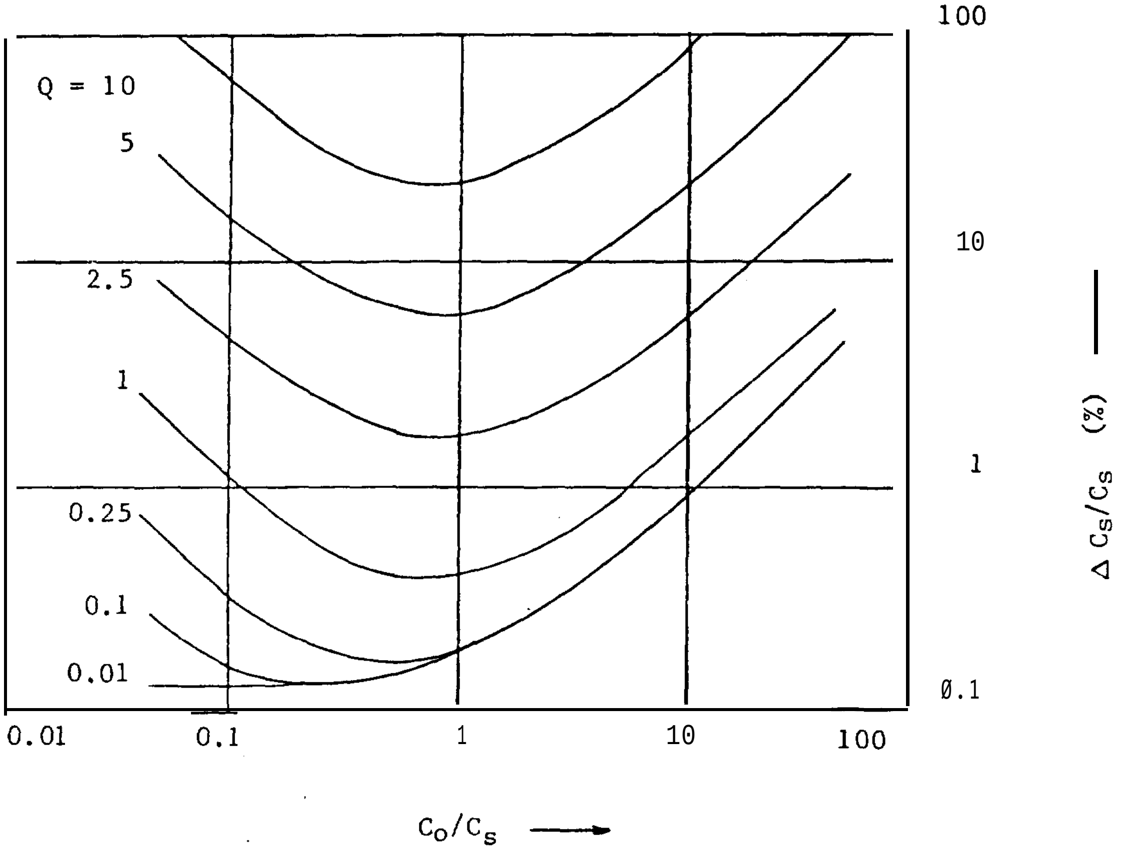


Fig. 5b. The relative error in the series resistance, R_s, measured with the impedance box, as a function of C_o/C_s with the quality factor, Q, as parameter.

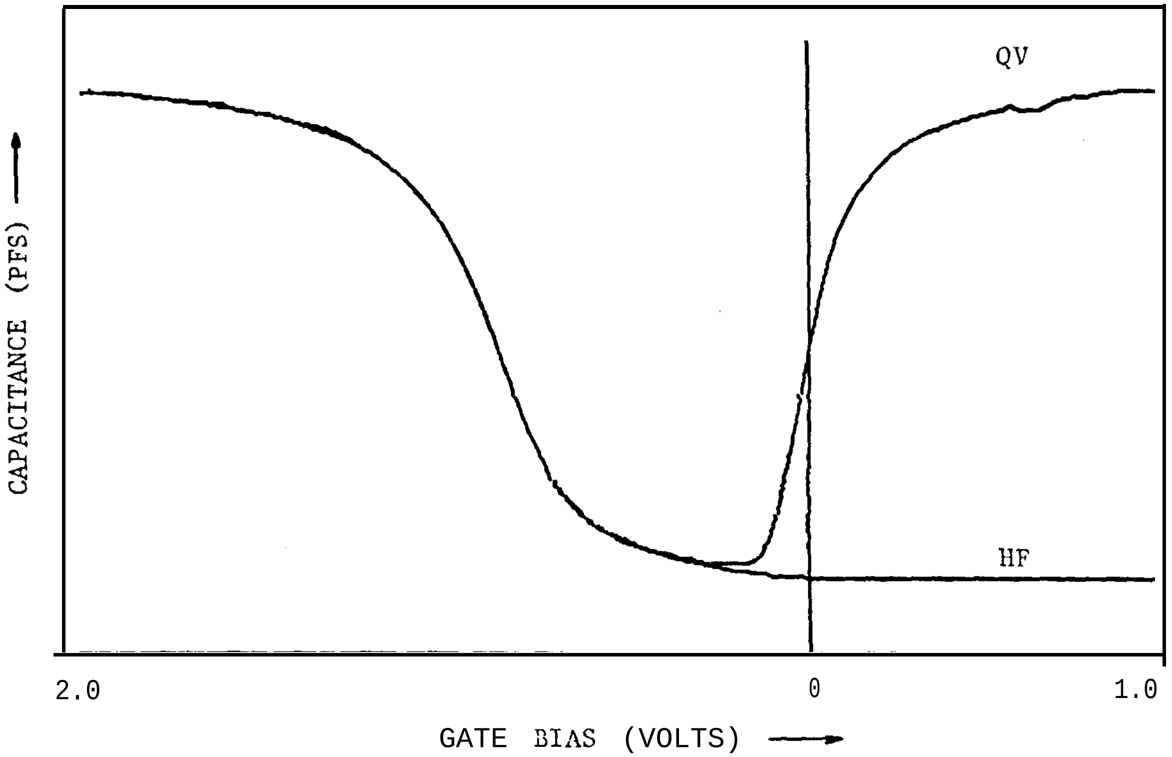


Fig. 6. Typical high frequency and static capacitance-voltage characteristics of an MOS capacitor.

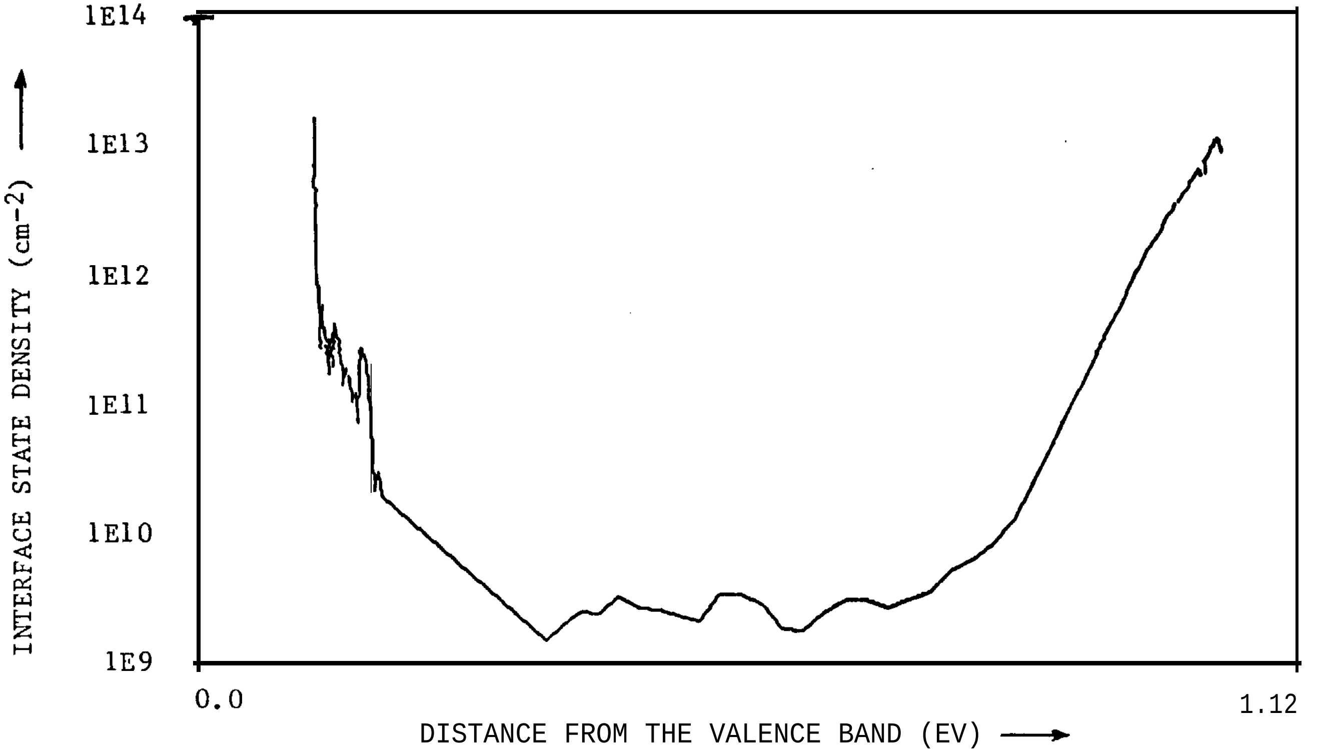


Fig. 7. Interface state density distribution.

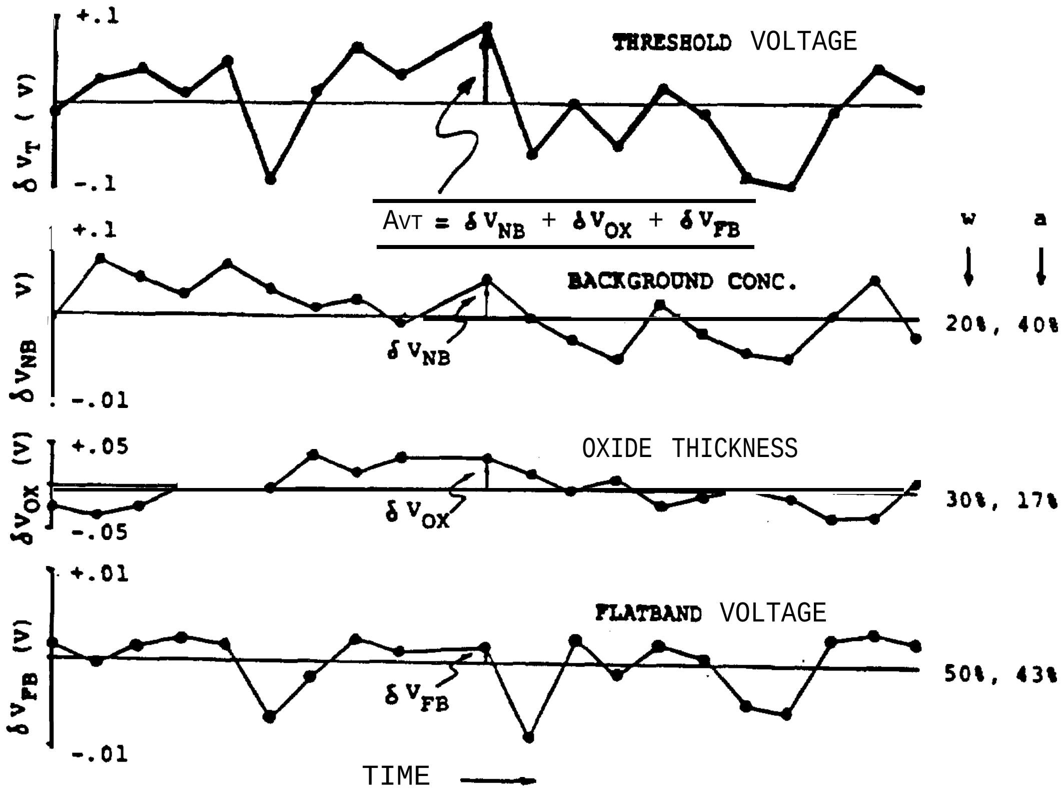


Fig. 8, Threshold voltage variation over a three month period (uppermost graph). The three subsequent graphs show the contribution (in volts) of process parameter variations to the threshold voltage variation.

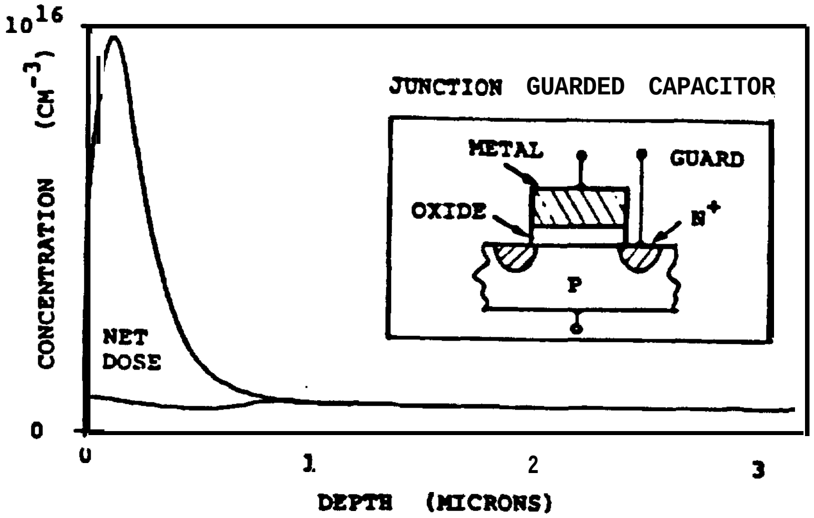


Fig. 9a. Implant dose concentration profile measured' by pulsed high frequency C-V technique on an implanted and unimplanted capacitor.

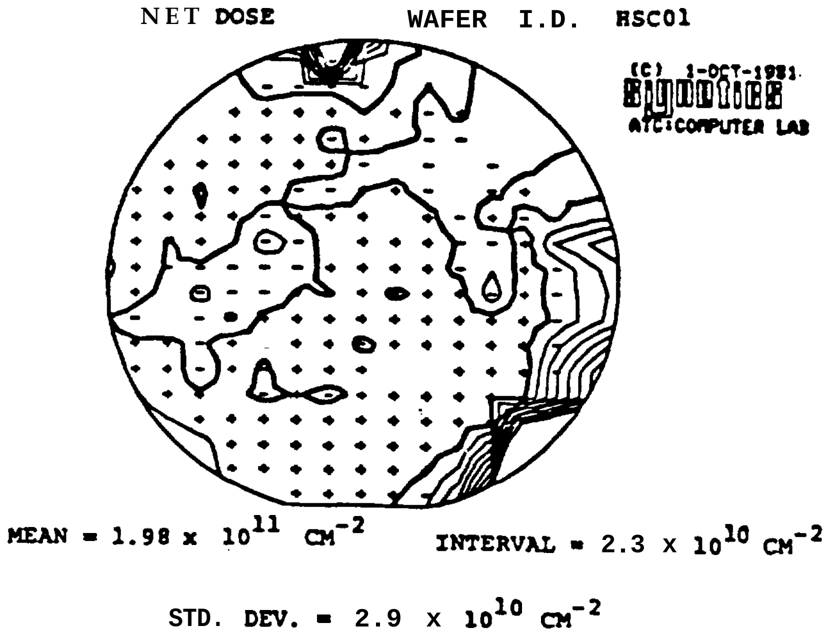


Fig. 9b. Net dose variation over a wafer. The profiles were measured on each site and the net dose was calculated according to Fig. 9a.

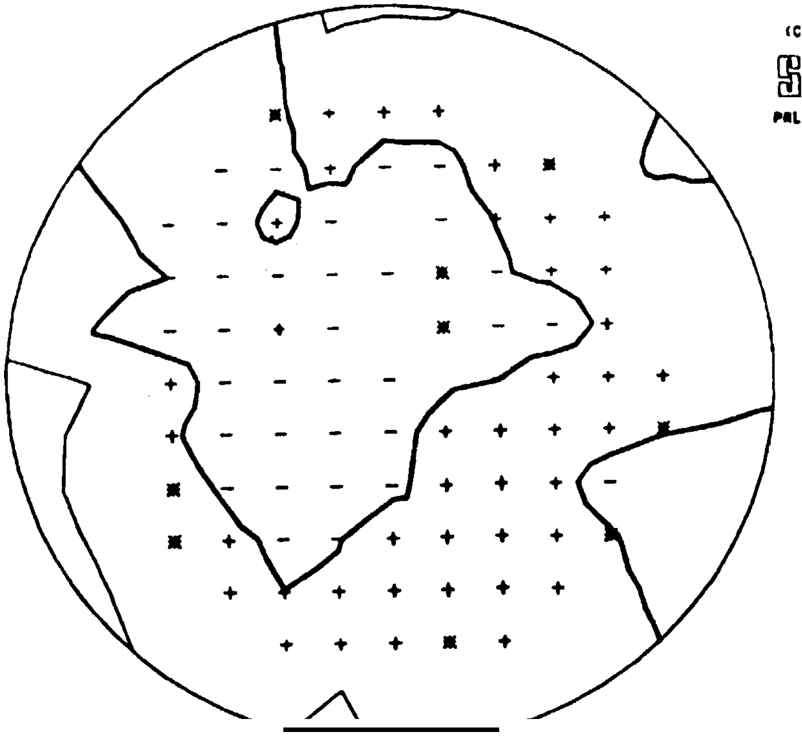


Fig. 10a. Contour map of the total number of interface states. Mean = 1.55E11 cm^{-2}, interval = 2.0E10 cm^{-2}.

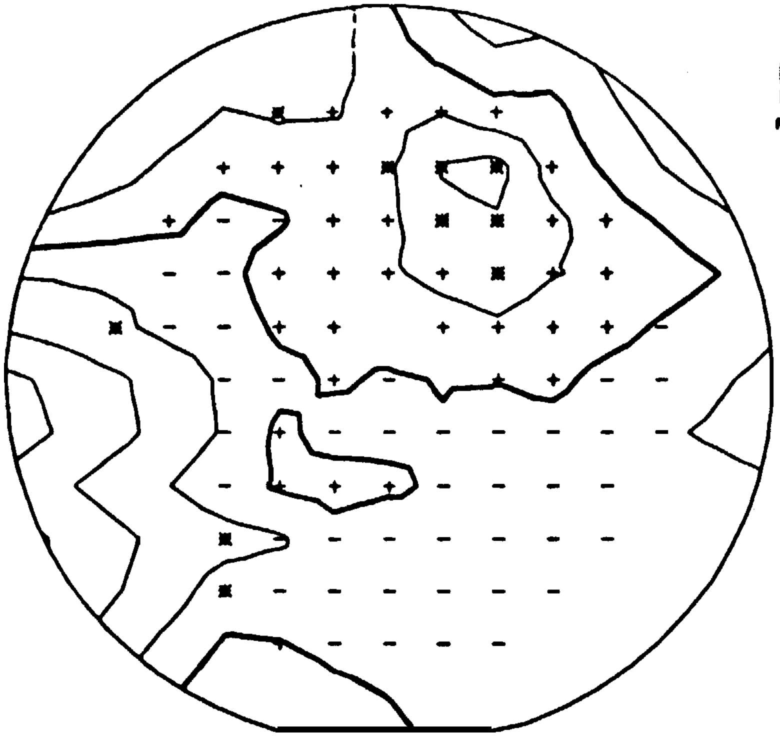


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Fig. 10b. Oxide thickness contour map.
Mean = 5450 Ångstrom, interval = 50 Ångstroms.
The oxide thickness was measured by the static capacitance-voltage technique.

STATIC SYNERGETICS ALGORITHM : A NEW VERSATILE TOOL FOR REAL-TIME QA WITH INTERACTIVE FEEDBACK TO PROCESS QC QUALITY AND YIELD OPTIMIZATION OF MATERIALS AND DEVICES

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ABSTRACT

The time-independent,static limit of Haken's (1) synergetics,the dynamics of pattern evolution out of chaos, in analogy with material,device,or system evolution out of input materials during processing,is used as a universal.scalable.reversible.mathematical algorithm and/or experimental model(not a theory nor process(specific)model) to provide a real-time,interactive quality assurance (QA) and feedback to quality-control (QC) to be coupled in parallel to a specific particular process theory or model. The input to processing QA and QC is its output,any of the complex, frequency-dependent electronic,electrical,dielectric, mechanical/viscoelastic,optical or magnetic property Functions of the processing produced defect/imperfection disorder distribution Pattern at that particular moment in the processing,the instantaneous Pattern input of an external radiation diffraction-pattern. The Algorithm provides a flexible versatile tool to relate processing induced defect distribution Pattern universally to Function/functional property performance,as designer and/or user specification,no matter however(model physics/chemistry,...specificity) in the processing the defects are produced,on the scales of material,device or system/IC. Additionally the Algorithm can be utilized in forward Pattern input-Function output, *or a* backward Function input-Pattern output to trace back from Function specification failure to defect distribution Pattern cause.

INTRODUCTION

Static Synergetics is a new subject. Its expression in a simple mathematical Algorithm provides a new tool with useful powers of material/device/system yield and quality optimization. It connects Pattern to Function in a universal,reversible,scalable mathematical algorithm or experimental model(experimental Pattern input - experimental Function output(in the forward direction) versus experimental Function input- experimental Pattern output(in the reverse direction),but is not a specific process mechanism/ process,defect type/physics/chemistry,...dependent theoretical model,and therein lies its advantages of universality,flexibility and versatility as a universal measurement tool of designer specified output Functions during processing.

At least four universal phenomena are understood by this Algorithm unification of/synthesis of the universal generalized-disorder collective-boson mode-softening universality-principle(G...P) (2) ,a generalization of the classic Brillouin(circa 1917-the father of solid state physics,and information/communications theory) concept of symmetry-breaking (Pattern),with the universal infra-red divergence principle (3) of Wigner and Dyson;

- Universal Functional Properties(experimental):
  - (1) ● 1/f flicker noise power spectrum
  - (2) ● 1//f dielectric(magnetic,mechanical) susceptibilities (4)
- Universal derived functional properties(experimental):

COMPLEX.FREQUENCY-DEPENDENT($w \ll 10^{11}$Hz.):

- A.C. electrical conductivity
- D.C. electrical conductivity
- Dielectric constant/function(relative dielectric permeability)
- Dielectric dispersion
- Dielectric dissipation/loss
- Dielectric response/susceptibility
- Dielectric loss tangent
- Capacitance
- Impedance
- Admittance
- Conductance
- Current flicker noise power spectrum
- Voltage flicker noise power spectrum
- Broadband FM signal-to-noise(S/N) ratio
- Optical refractive index
- Optical extinction coefficient
- Optical reflectivity

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(3) ● Universal Anderson localization(total internal reflection)(TIR)& Anderson transition

(4) ● Universal existence of multi-level system & associated low-temperature/frequency thermal(conductivity,specific heat,...) and acoustic,and...property anomalies(deviations from Debye theory predictions) in glasses, powders, . ..other disordered systems

The latter two are not utilized here.

How can we use these universal properties,explicit functions of process introduced defect disorder distribution Patterns via the Algorithm(to be calculated here)to analyze real-time interactively QA,providing feedback on material,device or system processing immediate testing to ascertain processed quality? In other words,can process introduced defect distributions be minimized,improved or even eliminated, thus optimizing product quality and yield? And,can this be done during a multi-step process,so that the specific defect distribution causing step can be identified,isolated and altered,rather than post-processing,where the steps are blurred together and nonseparable(for analysis nor alteration)? The key is the universality of the classic Brillouin symmetry-breaking that the defect disorder distribution performs in the material,device or system(IC) at whatever scales(or scale distribution) they occur at, *some set* of heterogeneous-disorder/clumping/clustering heirarchy wavevectors in the external radiation (X-ray,electron,neutron,microwave,ultrasonic,...) scattering-diffraction-pattern static-structure factor S(k) ie.at *some* configuration-space distribution of scales in configuration-space Fourier transform of $S(\underline{k})$, $g(\underline{r})$,a photomicrograph of the defect disorder.This latter will be dominated by the small-angle -scattering(SAS) diffraction-pattern from the heterogeneities/clumps/clusters of defects,$S_{SAS}(\underline{k})$

STATIC SYNERGETICS ALGORITHM

Static Synergetics allows derivation of explicit equations relating directly defect generalized-disorder (heterogeneous-disorder of the SAS) scattering(inelastic differential scattering cross-section,frequency averaged or unresolved)-diffraction-pattern morphology ie. static structure factor $S(k;\theta)$,implicitly a function of(through the particular specific process model) processing parameter set&deposition temperature T,deposition pressure P,deposition voltage V, concentration of jth solute/impurity species X_j,deposition current J,grain size R,...in some usually unknown functional form. Static Synergetics embodies three properties:

UNIVERSALITY-means that the Algorithm can be used on and is quite generally applicable to any and all defect distribution symmetry-breaking generalized-disorder introduced before,during or after processing,whatever type and however produced -this imparts great flexability and versatility in the use and application of the Algorithm.

REVERSIBILITY-means that the Algorithm can be used as an experimental model in either the forward (Pattern input-Function output) or reverse/backward(Function input-Pattern output) as a machine,, -in either direction the Algorithm works! -input diffraction-pattern $S_{SAS}(k;\theta)$-output Function F(w) or input Function F(w) - output diffraction-pattern $S_{SAS}(k;\theta)$, making Function also implicitly processing parameter/variable set 8 dependent: $F(k;\theta)$

SCALABILITY-means that the heterogeneous-disorder (defect distribution heirarchy Pattern)so critical for the infra-red divergence principle part of the Algorithm(as *seen in the* SAS dominated part of $S(k;\theta)$)can be considered as a low wavevector(long wavelength)scale with respect to total system,device or material sample size/dimensions/diameter. Thus microscopic defect distributions within a material may be treated equivalently to material defect distributions within a scaled up larger device,and in turn equivalently to a still further scaled up larger system (IC)/circuit,...

We list the Function/functional properties-Pattern morphology diffraction-pattern/static structure factor relations given by the Algorithm(rather than deriving them)derived previously$^{(5)}$,where $S(k;\theta)$ is related to defect configuration-space photomicrograph Patterg $g(\underline{r};\theta)$ Fourier transform by

$$S(\underline{k};\theta)= \bar{g}(\underline{r};\theta) \exp(-i\, \underline{k}\cdot \underline{r})\, d\underline{r} \qquad (1)$$

and we abbreviate inverse density of states/group velocity,totally containing diffraction-pattern/static structure factor $S(\underline{k};\theta)$ contribution to the Function/properties factor,

$$[2\,k\,S(k;\theta) - k^2\, \partial S(k;\theta)/\partial k]\,/S^2(k;\theta) = [\ldots] \qquad (2)$$

the critical exponent(universal) in universal l/f flicker noise power spectrum,and in *relaxation* response susceptibilities(dielectric,mechanical/visco-elastic/magnetic,...),the orgins of the universal electrical,dielectric,optical,...Functions listed.

$$n = g(w)/w = 1/v_g(w) = 1/v_g(k).(k^2/S(k))=[\ldots] \qquad (2')$$

COMPLEX, FREQUENCY-DEPENDENT , DIFFRACTION-PATTERN DEPENDENT , IMPLICITLY DEPOSITION (PROCESS) PARAMETER DEPENDENT :

A.C ELECTRICAL CONDUCTIVITY:

$$\sigma_{AC}(w;\theta)\cong\sigma_{DC}(0;\theta)+\epsilon_0/w^{(2m|V|^2/w\hbar^2)[\ldots]} \qquad (3)$$

DIELECTRIC CONSTANT/FUNCTION/RELATIVE PERMEABILITY):

$$\epsilon\,(w;\theta)\cong\epsilon_0\,[1+(1+i)/w^{(2m|V|^2/w\hbar^2)[\ldots]}] \qquad (4)$$

DIELECTRIC DISPERSION:

$$\epsilon'(w;\theta)\cong\epsilon_0[11++\,1l/w^{(2m|V|^2/w\hbar^2)[\ldots]}] \qquad (5)$$

DIELECTRIC DISSIPATION/LOSS:

$$\epsilon''(w;\theta)\cong\epsilon_0/w^{(2m|V|^2/w\hbar^2)[\ldots]} \qquad (6)$$

DIELECTRIC LOSS TANGENT:

$$\tan\delta(w;\theta)\cong\{1/w^{(2m|V|^2)/w\hbar^2)[\ldots]}\}/\{1+1/w^{(2m|V|^2/w\hbar^2)[\ldots]}\} \qquad (7)$$

DIELECTRIC RESPONSE:

$$\chi''(w;\theta)/\chi'(w;\theta) \cong \cot(n\pi/2)\,\phi(w;\theta)\text{(independent of w and }\theta) \qquad (8)$$

DIELECTRIC RELAXATION RESPONSE SUSCEPTIBILITIES:

$$\chi'(w;\theta)\cong \text{"1"}/w^{n(w;\theta)}\ ;\ \chi''(w;\theta)=\text{"1"}/w^{n(w;\theta)} \qquad (9)$$

$$n = g(w)\,/\,w$$

CAPACITANCE:

$$C(w;\theta) \cong (A/W)\epsilon_0[1 + (1+i)/w^{(2m|V|^2/w\hbar^2)[\ldots]}] \qquad (10)$$

IMPEDANCE:

$$Z(w;\theta) \cong R_0+ 1/iw(A\epsilon_0/W)[i/w^{(2m|V|^2)/w\hbar^2[\ldots]}+\{1+1/w^{(2m|V|^2/w\hbar^2)[\ldots]}\}] \qquad (11)$$

CONDUCTANCE:

$$G(w;\theta)\cong (A/W)\epsilon_0\,/w^{(2m|V|^2/w\hbar^2)[\ldots]} \qquad (12)$$

ADMITTANCE:

$$Y(w;\theta)\cong 1/\,Z(w;\theta) = 1/(11) \qquad (13)$$

OPTICAL REFRACTIVE INDEX:

$$N(w;\theta)\cong\epsilon_0^{1/2}\{1 + (1+i)\,/\,w^{(2m|V|^2/w\hbar^2)[\ldots]}\}^{1/2} \qquad (14)$$

which for nonzero extinction coeffieient becomes

$$N(w;\theta)+ i\,K(w;\theta) \cong \epsilon^{1/2}(w;\theta) =[\epsilon'(w;\theta) + i\,\epsilon''(w;\theta)]^{1/2} \qquad (15)$$

causing difficulty in deriving a simple functional law such as (14) without further equation relating $N(w;\theta)$ optical refractive index to $K(w;\theta)$ optical extinction coeffieient

l/f FLICKER NOISE UNIVERSAL POWER SPECTRUM:

$$P(w;\theta)\cong \text{"1"}/w^{n(w;\theta)}\cong\text{"1"}/w^{(2m|V|^2/w\hbar^2)[\ldots]} \qquad (16)$$

1/f VOLTAGE FLICKER NOISE POWER SPECTRUM:

$$P_V(w;\theta)=(4k_BT/g)\ /\ w^{(2m|V|^2/w\hbar^2)[\dots]} \qquad (17)$$

$$\vdots$$

in terms of geometrical factor g,where V is the voltage applied by electric field $\underline{E}=-\nabla V$,where m=ℏ=1 in atomic units, Very important is the realization that the approximate "≅" sign rather than actual equalities indicates that the Static Synergetic8 Algorithm is for FM properties only;the amplitude,the numerator of each expression,is not necessarily universal in magnitude and is not known explicitly as a function of defect symmetry-breaking diffraction-pattern/static structure factor S(k;θ),though Dutta and Horn,and Hooge(7) point out that the numerator amplitude/modulus is a universal constant γ=2 x 10^{-3},dimensionless,and seemingly universal AM for all semiconductors and metals.

Generally (3)-(17) can be summarized as

$$Q(k,w;\theta)=Q(w;\theta)=Q(g(w;\theta)/w=Q(\,[\dots]\,)=Q(S(k;\theta))=Q(\theta)$$
$$=Q(n(\theta)) \qquad (18)$$

for the generalized Function in terms of generalized Pattern Fourier transform diffraction-pattern S(k;θ) and hence in terms of the processing parameter set $\theta=\theta\{T,P,X_j,R,V,I,\dots)$ implicitly. These provide the coupling to process model specifics for particular processing equipment/systems.

Static Synergetics Algorithm *covers* the following frequency bands with FM Function calculation as explicit function of Pattern(diffraction-pattern)of symmetry-breaking and processing parameter/variable set:

very low frequency (VLF) : 10^{-5}Hz.-10^{0}Hz.
low frequency (LF) : 10^{0}Hz.-10^{+3}Hz.
audio frequency (AF) : 10^{+3}Hz.-10^{+5}Hz.
radio frequency (RF) : 10^{+5}Hz.-10^{+8}Hz.
short wave (SW) : 10^{+8}Hz.-10^{+10}Hz.
microwave-infra-red(MW)-(IR): 10^{+10}Hz.-10^{+12}Hz.

with a conservatively estimated cut-off in validity and applicability at the quantum/inter-band transition threshold limit of approximately 10^{11}Hz.,in the infra-red(IR) band. The Algorithm spans some 16 decades/orders of magnitude in applicability to calculation of relative FM electtical,dielectric,electronic (intra-band),noise and optical (and magnetic,mechanical/viscoelastic,...) Function properties,explicitly as functions of small-angle-scattering(SAS)defect diffraction-pattern. Above approximately 10^{+11}Hz.absorption edges of material specific quantum transitions occur and are untreatable by the Algorithm,though it has recently been proposed that local coordination number Pattern EXAFS data be tried as input to calculate higher frequency properties. But we caution that with no logical theory of inclusion of quantum processes in Static Synergetics,an essentially long wavelength limit approach(valid asymptotically in the low frequency limit),such attempts to extension to still higher frequency must be open to rigorous scrutiny;the linear density of states of the infra-red divergence principle becomes"universal"Gaussian with n≠1 for higher energies/frequencies. Yet the possibility exists for extension out of the low frequency/energy limit regime since the all important linear density of states(of the infrared divergence universality principle)is the low-frequency limit of a Gaussian density of states in general,first having been utilized(by Wigner and Dyson,and many successors)for nulear energy level structure in the Mev energy range, far above those applicable for solids and *other condensed* matter,and *on the other* side of the inter-bend transition quantum limit cut-off.Only the future will tell if successful extension into the near IR and visible spectral regimes is possible;some band-structure specificity will have to be introduced, changing the universal quality of the Algorithm.

Static Synergetics Algorithm summarizing equation set for generic Function properties as explicit functionsof Pattern morphology diffraction-pattern/static structure factor due to defect disorder symmetry-breaking S(k;θ),itself some implicit function of processing parameter set $\theta=\theta(T,P,X_j,R,V,J,\dots)$ measured during processing or known from some specific process model on some specific equipment,or by trial and error(the usual case):

$$Q(\theta)=Q(w;\theta)=Q(\ '(w;\theta),''(w;\theta))=Q(1/w^{n(S(k;\theta))}) \qquad (3)-(17)$$
$$n(\theta)=n(S(k;\theta))=|V|^2 g(w)/w=|V|^2/v_g(w),w=|V|^2/w\ .$$
$$\partial w(k;\theta)/\partial k = |V|^2/w.\partial(k^2/S(k;\theta))/\partial k \qquad (19)$$

the universal infra-red divergence principle,

$$g(\theta)=g(w;\theta)=1/\partial w(k;\theta)/\partial k=1/\partial(k^2/S(k;\theta)/\partial k \qquad (20)$$
$$w(\theta)=w(k;\theta)=\ k^2/S(k;\theta) \qquad (21)$$

the G. ..P generalized-Brillouin modulation principle

$$S(\theta)=S(k\theta)=\iiint \bar{g}(r;\theta)\ e^{-i\underline{k}\cdot\underline{r}}d^3r=S_{SAS}(k;\theta) \qquad (22)$$

This will be the basic equation set of the static Synergetics Algorithm,usable as an experimental model with proper experimental Pattern morphology diffraction-pattern S(k;θ) input,that dominated by small-engle-scattering(SAS) heterogeneity/clump/cluster-disorder dominated $S_{SAS}(k;\theta)$,resulting in Function property output Q(θ),or reversibly Function property input Q(θ)(deviation from desired designer specifications)resulting in Pattern morphology diffraction-pattern S(k;θ),this latter always dominated by defect clumping/clustering into heterogeneities.

We summarize equation set (18)-(22)in Figure 1 and in the following nested parentheses parameteric equation sets of the Algorithm:

$$\text{OUT} \leftarrow Q(\theta)=Q(n(\theta)\ )=Q(n(g(\theta)\ )\ )=Q(n(g(w(\theta))\ )\ )=Q(n(g(w(S(\theta))))) \qquad (23)$$

$$n(\theta)=n(g(\theta))=n(g(w(\theta)))=n(g(w(S(\theta)))) \qquad (24)$$
$$g(\theta)=g(w(\theta))=g(w(S(\theta))) \qquad (25)$$
$$w(\theta)=w(\underline{S}(\theta)) \qquad (26)$$
$$S(\theta)=S(\bar{g}(\theta)) \longleftarrow \text{IN} \qquad (27)$$

These form an algebraic heirarchy of nested but simple(only algebraic manipulations except for one local dericitive(in (2)),in the forward direction(machine)use of the Algorithm. Figure 2 summarizes their method of Algorithm use in an equation flowchart,as well as the inverse function nested parentheses equations of the Algorithm used in reverse/backward direction(machine)fashion,inputing Function and outputing back-calculated (heterogeneous-defect-disorder) diffraction-pattern Fourier transform of Pattern.This is obtained by reading nested equation set (23)-(27)with inverse functions from bottom to top(inverse = backwards machine):

$$\text{OUT} \leftarrow \bar{g}^{-1}(\theta) = \bar{g}^{-1}(S(\theta)) \qquad (28)$$
$$S^{-1}(\theta) = S^{-1}(w(\theta)) \qquad (29)$$

$$w^{-1}(\theta) = w^{-1}(g(\theta)) \qquad (30)$$

$$g^{-1}(\theta) = g^{-1}(n(\theta)) \qquad (31)$$

$$n^{-1}(\theta) = n^{-1}(Q(\theta)) \longleftarrow \text{IN} \qquad (32)$$

We must strongly emphasize that this Algorithm,culminating explicitly in one equation into which these nested sequences collapse,Function properties equation set (3)-(17),depending upon Function property desired to monitor continuously as function of processing variable/parameter set θ,always contains term (2) so that only two multiplications and one derivitive need be done with input data reducing data manipulation to the simplest minimum,facilitating rapid data processing through Algorithm. The input diffraction-pattern $S(k;\theta)$ may be utilized whatever the external radiation wavelengths chosen to resonate geometrically with aver&e inter-defect clump/cluster/heterogeneity size scale;X-rays,electrons,neutrons,laser photons(beam),microwaves,even ultrasound,...synchrotron radiation source photons(beam);all are candidates for external radiation diffraction-pattern source,depending upon the material/device/system(IC),and their availability for in-process utilization,and of course expense. However,since the SAS part of the diffraction-pattern will dominate the Algorithm(through its produced linear density of states),it must be preferentially experimentally measured,entailing the requirement of external radiation beam intensity(to make diffraction-pattern both local and intense enough to minimize diffraction-pattern detector counting times, and increase detector signal-to-noise(S/N)ratio to its maximum possible value,to minimize detection time for diffraction-pattern counting.Thus beams,especially synchrotron radiation and,more portably and less expensively,laser radiation(CW) in the appropriate geometrical resonance wavelength regime,and perhaps X-ray sources suitable for X-ray photolithography, should optimize use of the Algorithm since $S_{SAS}(k;\theta)$ at the small-angles,in the most forward-scattering direction,is hardest to resolve with the poorest signal-to-noise(S/N)ratio in detection. But with the development of small X-ray sources(Aracor,Micronix)and diffraction-pattern cameras for in-system ambient real-time use,currently being done for a host of processing deposition system types,such sources may soon be readily available "off-the-shel.f"accessories to processing systems, Very positively,the time scales involved can be exceedingly short;with current state-of-the-art synchrotron light sources(ex:SSRL at Stanford) $S_{SAS}(k;\theta)$ is measurable within a millisecond,with possible extension into the microsecond regime with the new wiggler magnets. Since the mathematical algorithm (23)-(27)in the forward direction or in the reverse direction (28)-(32) collapses into single expression (3)-(17) depending upon desired Function property to be calculated,and sinve all of these Functions involve calculation of function expression (2) with only simple algebrair and one derivitive numerical manipulations of input data $S_{SAS}(k;\theta)$ diffraction-pattern Pattern,data processing times of just a few milliseconds are contemplated,totally sufficient for repeated sampling during material/device/system processing of minutes to hours.Development of the in-system X-ray cameras mentioned earlier should open the use of the Algorithm to a wide-spectrum of in-plant processing QA and QC applications. Caution will have to be exercised to prevent intense beam radiation damage of the material/device/system being prooessed, and of course safety shielding considerations will be mandatory.

PROCESSING FLOWCHART AND MATHEMATICAL ALGORITHM

We now flowchart the Static Synergetics Algorithm used as a mathematical algorithm of an experimental model with universal,reversible and scalable features,as a computation machine,and with applicability as a new., versatile, flexible tool in processing quality assurance(QA) with real-time feedback,and when used in parallel with specific process model,as an interactive process quality control(QC) leading to optimized processing yield and quality in designer specification electrical, dielectric,electronic,optical,magnetic or mechanical Function properties. The flowchart,shown in Figure 3 is merely a different organization of the Static Synergetics Algorithm universal principles synthesized into the Algorithm,and the Pattern-Function connection they provide,as shown in Figure 1,reexpressed as the experimental model input-output mathematical algorithm of Figure 2. For this reason we have put all three figures close together at the end rather than in the text;their basic identity end equivalence,similarities and differences can be seen more clearly in juxtaposition.

Given the universal,scalable,reversible properties of this Static Synergetics Algorithm flowchart,how can we utilize it in a practical processing application,to optimize quality of material/device/system being grown/processed,while simultaneously optimizing acceptible quantitative yield,by optimizing processing real-time? Each processing step at each scale(micro to macro) should be amenable to the university of the Static Synergetics Algorithm used as an experimental model real-time as an internal form of quality assurance (QA) leading ti interactive processing quality control(QC). This should be applicable to optical,semiconductor,dielectric/ceramic/insulator,metal,alloy,magnetics,integrated circuits,integtated optics,fiber optics,optical storgae memory,ferrite,microwave material/device/MIC,...material/device/system processing. How can the flowchart of the Algorithm in Figure 3 be used and applied to real,practical processes,to yield real-time feedback QA and interactive QC,monitoring of designer specification Function properties of thin film processing quality and yield optimization? How can the forward Pattern-Function or reverse Function-Pattern connection of the Algorithm (in the latter,change in specific Function properties being real-time feedback QA monitored from designer specifications allows backcalculation of the defect heterogeneity/clumping/clustering responsible,its photomicrograph in configuration-space(its Pattern)or Fourier transform diffraotion-pattern change in k-diffraction-space)by triggering a reverse calculation diagnostic of defect distribution Pattern responsible for deviation from desired specifications of Function properties,the deviation from acceptable property tolerances (range)/variances,be utilized as a flexible,versatile tool for real-time feedback QA and interactive QC via process model and numerical/computer control and/or the motivated experienced fabrication technician/process sustaining engineer?

PROCESS REAL-TIME FEEDBACK INTERACTIVE QA ANALYSIS-QC CONTROL

Figure 3 figuratively illustrates this proceedure, utilizing the mathematical Algorithm as an experimental model,with diffraction-pattern input yield Function properties output(in the forward direction) or reversibly Function properties input yielding diffraction-pattern output(in the reverse direction),the lattera deviation from earlier(in the process)acceptable fon(ex:defect cluster growth,ageing,recrystallization,heat treatment,annealing,graingrowth,nucleation,...) . As Figure 2 illustrates,forward direction use(from bottom to top)relates processing parameter/variable set 8 dependent defect morphology/Pattern via its diffraction-pattern $S_{SAS}(k;\Theta)$ or Fourier transform configuration-space Pattern $g(\mathbf{r};\Theta)$ photomicrograph,to processing parameter/variable set Θ dependent Function properties Q(8). In the reverse direction (top to bottom) processing parameter/variable set Θ Function properties $Q(\Theta)$are used as input and related to calculated (deviations) in small-angle-scattering (SAS) diffraction-pattern $S_{SAS}(k;\Theta)$,from which the defect size distribution introduced detrimentally in processing since the last forward direction application of the Algorithm using the last $S_{SAS}(k;\Theta)$ measurement has deviated from an acceptable density and distribution morphology to stop producing acceptable designer specification Function properties Q(8) within the QA specified required processing/designer/end user Function specifications variance allowable. Figure 3 merely rewrites Figure 2,which in turn symbolized the Algorithm of Figure 1,in standard processing flowchart format(7). Reading the mathematical Algorithm part of the flowchart,itself in parallel with a processing specific process model(machine specific) physics/chemistry theory model,from bottom to top (forward direction):external processing variable/parameter set 8 determine(implicitly)any of the Function properties Q(8) via their effect upon Pattern morphology photomicrograph $\bar{g}(\Theta)$,hence upon diffraction-pattern $S_{SAS}(k;\Theta)$ through the(unknown)complicated physics/chemistry of that particular (deposition,heat treatment,dry etch,...)process. Working up the Algorithm (in the forward direction use) step-by-step,or alternatively jumping to collapsed Function properties expressions (3)-(17),one arrives at the Function properties Q(8) that the processing will impartto the particular material/device/system being processed, in that process step,it it continues in steady-state processing operation. The user of the Algorithm then evaluates whether the desired Function property set $\{Q(\Theta)\}$(any combination of (3)-(17))lies within the allowed variances from the designer specifications of Function properties. If satisfactory,all is allowed to proceed stead -state with occasional QA checks(as deemed *necessary*)via another group of diffraction-patterns(later on). If not satisfactory,or if the processing develops non-steady-state fluctuations/glitches(ex:power fluctuations,voltage fluctuations, current fluctuations,...in the fab plant)one then gingerly modifies some of the processing parameter/variable set$\{\Theta\}$to bring the desired Function property set$\{Q(\Theta)\}$ back into designer specifications allowed variances limits,verified by re-measuring $S_{SAS}(k;\Theta)$ diffraction-pattern or by taking a series of configuration-space photomicrographs(if that is feasible in-situ during processing,which diffraction is!). Real-time feedback interactive QA and QC have been achieved!

How does the user modify processing parameter set$\{\Theta\}$? This question fall outside the parvue of the Algorithm,in parallel with the it in the flowchart,and is not universal,being process specific. A proaess with a well understood and developed machine specific process model(process physics/chemistry specific; those details being included only in the model,not the Algorithm!)can be controllably and systematically modified by varying processing parameters/variables in a logical fashion,calculating expected results beforehand,and then implimenting these Algorithm predictions of Function properties/expected results through the process numerical computer controller during processing,real-time.Alternatively,the observant motivated quality conscious fabrication technician/sustaining process engineer can try different process modifications to keep the diffraction-pattern $S_{SAS}(k;\Theta)$ within some previously agreed and defined function form, thus effectively indirectly monitoring the desired material/device/system final Function properties indirectly. This is <u>indirect Measurement without direct measurement</u>! Pre-calibration must be performed,using the Algorithm. The latter description of the use of the Algorithm in converting QA to an interactive QC function is more hit-and-miss,but more realistic given the lack of real-time feedback of Function properties during processing currently "state-of-the-art". The former,if well understood and broken-in process model exists,converts QA(of the Algorithm) into QC in a most systematic,understood satisfactory manner. It can optimize productivity by maximizing yield quantitanively with Function properties within designer specifications for end-user needs. The designer and end-user are after all the customer of the processer.

The Static Synergetics Algorithm offers this real-time feedback QA and interactive QC during processing for the first time!This can be done without monitoring the desired Function properties directly, which may be impossible during processing,thus saving that difficult and process/machine specific task,if the user has a set of target designer specifications mandated,or even guessed at(or even cares how good the ouality of his output productivity is as opposed to the obsessive *concern* with quantitative yield numbers).So real-time feedback QA and interactive QC to optimize processing quantitative yield simultaneously with optimizing processing quality of product,is now possible with proper use of the Algorithm.as a flexible,versatile tool quite universally&if the desire is there in the user). Static Synergetics Algorithm embedding within a scheme in parallel with a specific process model,from process start-up to process scale-up,can perform these desired functions uniquely and very adequately,with indirect end-point Function monitoring/measurement. In actual in-process,i diffraction-pattern measurement is not feasable,the sample may be removed periodically for diffraction-pattern measurement/monitoring,to indirectly maseure/monitor desired final Function properties designer specifications compliance. This latter is impractical,but is still superior to to repeated set of Function properties measurement if many are designer specified foe end-user/customer use. The Algorithm can be applied *on any* scale processing,or On several scales simultaneously,if desired.Its Use is up to the inginuity,and needs,of the processer!

APPLICATIONS

PLASMA DEPOSITION/ETCHING:

Plasma striations/inhomogeneities during plasma deposition,etching,CVD,LPCVD,...can be analyzed end optimized/eliminated using the Algorithm(8)

SEMICONDUCTOR ELECTRONICS:

As Siegel(5) has stressed,the Kolbessen-Strunk(9) emphasis on empirical silicon(and extendable to 111-V and 11-V1 compound)semiconductor material/device/IC Function properties correlation with microscopic defect clusters/clumps/heterogeneities types and densities(and implicitly Patterns),can be borne to fruition via the Static Synergetics Algorithm,replacing correlation with analytic mathematical calculation ability.,independent of defect/process physics/chemistry specific processes/mechanisms/models.It reinforces&proves upon systematically and supplants empirical correlation(hit-and-miss)if used properly,in a total strategy of process QA and QC quality and yield optimization.(10) Compound 111-V's require this!

FIBER OPTICS:

Intrinsic fiber-losse(9),refractive index(core,...), extinction coeffieient,reflectivity,...can be real-time determined from inhomogeneity $S_{SAS}(k;\theta)$,optimizing quality in real-time feedback QA and interactive QC,and optimizing numerical yield.

ACOUSTO-OPTICS(& ELECTRO-OPTICS):

Defect distributions in signal-processing applications(9),surface-acoustic-wave(SAW)delay lines and devices, Bragg diffraction convolvers involving correlation and matched fiber detection,multichannel operation and chirp Fourier transform processors,acousto-optic memory devices(via acousto-phatorefraotive effect),memory-correlator devices,incoherent-light time-integrating,processors...can be treated in fabrication with the Algorithm at all scales,from material to device to circuit/system,to be real-time quality-assured and interactively quality-controlled to minimize loss/dissipation and maximize signal-to-noise(S/N)ratio,in operation of these defect dominated acousto optic(and electro-optic)products.

INTEGRATED OPTICS:

Dielectric waveguide materials and devices,defect driven residual Rayleigh scattering losses,other loss processes(microbending,bending,twist,interface, . ..),and S/N ration can be optimized in their Function properties,most importantly being loss minimization/transmission maximization. Total internal reflection,planar optical waveguides,channel optical waveguides,coupling to optical waveguides via prism couplers&rating couplers,tapered film couplers,end-fire or butt couplers,waveguides,waveguide lenses, (luneberg,grating or Fresnel,geodesic,...),waveguide mirrors,beam splitters,acousto-optic transducers(stepped-frequency,tilted-array,phased-array,chirped frequency,...);transducer arrays,detector/sensor arrays,RF spectrum analyzers,A-to-D converters,time integrating converters,high speed optical switching devices,dielectric waveguides,Bragg refleotion periodic waveguides,frequency multiplexers(chirped,gratings,grating directional couplers,...) planar waveguides(metal-clad,Bragg reflection,... ..are amenable to Static Synergetics Algorithm QA and interactive process model specific QC to maximize yield and S/N ratio,as well as numerical quantitative yield productivity.

In conclusion,the correct application of the Static Synergetics Algorithm to QA and QC in processing offers a new flexible,versatile tool to optimize quality and yieldsin a plethora of processing applications.

REFERENCES

1.H.Haken,Series in Synergetics,Springer-Verlag(1970)

2.E.Siegel,J.Noncryst.Sol.40,453(1980);Intl.Conf.on Lattioe Dynam.,Paris(1977)-pub.by Flammarion(1978)

3.K.L.Ngai,Comm.S.S.Phys.,9,4,127(1979);9,5,141(1980);NRL Rept.#3917(1979)

4.A.K.Jonscher,Contemp.Phys,24,1,75(1983);in Physics of Dielectric Solids,IOP#58,I.O.P.(1979);Chelsea College(U.of London)Dielectrics Group Handbook(79)

5.E.Siegel,Proc.Electrochem.Soc.83,8,497(1983);Electrochem.Soc.Mtg.,S.F.(1983);Lasers'83,S.F.(1983); MRS Fall(Boston)&Spring(S.F.)Mtgs.,(1984)&(1985)

6.P.Dutta and P.M.Horn,Rev.Mod.Phys.53,3,497(1981)

7.F.N.Hooge,Phys.Lett.A29,139(1969);P.Handel,Phys.Rev.A22,2,745(1980)

8.E.Siegel,Bull APS Plasma Div.Mtg.,L.A.(1983);IEEE Conf.on Plasma Science,S.D.(1983)

9.B.O.Kolbesen and M.Strunk,Solid State Devices(1980) IOP#57(1981);L.B.Jeunhomme,Single-Mode Fiber Optics,Marcel Dekker(1983);N.J.Berg and J.N.Lee,Acousto-Optic Signal Processing,Marcel Dekker(1983); A.Yariv & P.Yeh,Optical Waves in Crystals,Wiley(84)

10.GaAs compound semiconductors dominated by defects: S.-M.Liu and M.B.Das,UGIM Symp.,Texas A.&M.(1983); M.B.Das and J.M.Moore,IEEE Tr-Ed,21,247(1974);M.B. Das and P.K.Ghosh,IEEE Electron Dev.Lett.EDL-2,210,(1981);S.Miyazawa,Y.Ishii,S.Ishida,and Y.Nanishi, Appl.Phys.Lett.43,853(1983);Jpn.Jnl.Appl.Phys.22, L270(1983);21,L335(1982);R.T.Blunt,S.Clark and D.J.Stirland,IEEE Trans.Electron.Dev.ED-29,1039(1982);D.C.D'Avanzo,IEEE Trans.Elec.Dev.ED-29,1051 (1982).

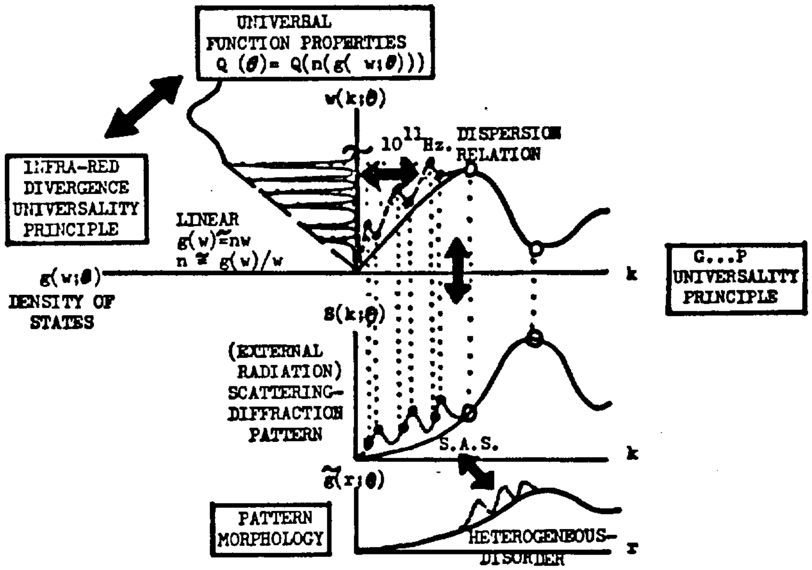

Figure 1. Pictorial Summary of Universal, Reversible, Scalable Static Synergetics As • Union of G...P — With Infra-Red Divergence Universality Principles to Relate Pattern Morphology to Universal Function (Dielectric, Electronic, Flicker Noise... (Magnetic, Mechanical...)) Properties

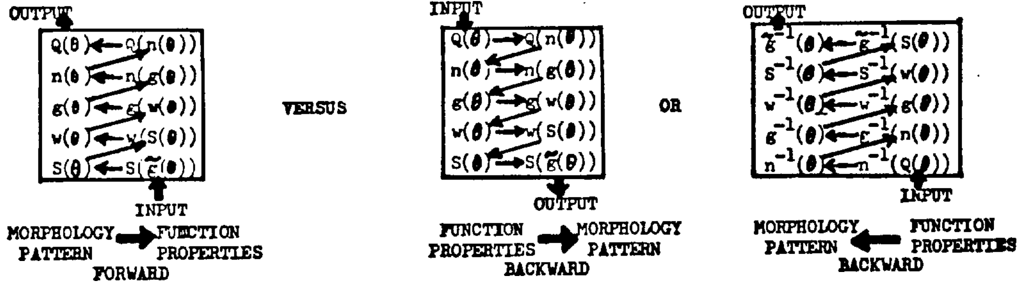

Figure 2. Static Synergetics Universal, Reversible, Scalable Mathematical Algorithm. Reversibility Allows Use of Algorithm and Flowcharts In Either Direction As Experimental Model

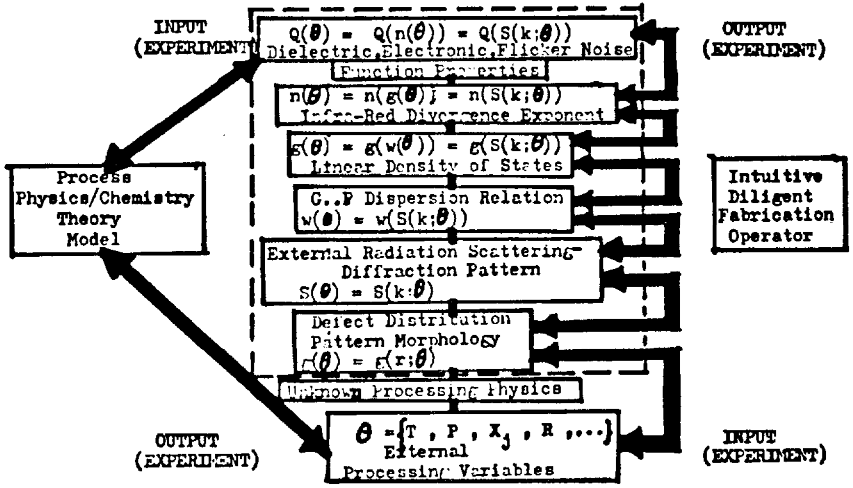

Figure 3. Processing Flowchart Of Static Synergetics Mathematical Algorithm As Experimental Model

MOBILE AUTOMATED CALIBRATION SYSTEMS FOR ON-SITE TESTING

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ABSTRACT

Calibration laboratories face some special problems in supplying calibration services to instrumentation fixed in place in test stations or stationary ATE in manufacturing areas. The same problems apply when instruments are secured in racks at large, complex test installations remote from the "cal lab . Dismantling instruments from these fixtures for transport to the calibration laboratory introduces unacceptable work stoppages and extra costs. To resolve this, cal labs often bring individual calibrators to the work location and make a temporary setup to perform the calibration. The recent. introduction of a series of mobile automated oscilloscope and meter calibrators, named CALCART by Ballantine Laboratories, Inc., provide the calibration laboratory faced with such requirements with a group of easily transportable configurations of calibrators with associated controllers, color displays, disk storage, and calibration software. These turnkey systems provide the calibration laboratory with the mobility needed to bring the cal lab on-site easily, to perform fast, efficient automated calibration on the largest population of instrumentation commonly in use in most facilities - oscilloscopes, voltmeters, current meters, ohmmeters, and multimeters. This paper describes a typical meter CALCART and discusses some of the direct and indirect benefits of mobile on-site automated calibration.

INTRODUCTION

Ballantine Laboratories, Inc., designs and manufactures a wide range of electronic instrumentation and calibration standards, many of which are interfaceable to the IEEE 488 Bus for automatic test applications. In the last two years we have launched four turnkey automated calibration systems, all driven by Ballantine COMPUTEST software run on bus compatible personal computers. The two most recent systems use an IBM PC and color CRT monitor as the controller and information display. These automated systems provide fast, quality controlled calibration of oscilloscopes and meters, verifying and documenting instrument performance versus published specifications, The free standing individual components are generally configured as conventional bench or work stations and used in fixed installations within the calibration laboratory. Units to be tested are brought to the system for calibration. When those units that reside in fixed installations are disemboweled from location and transported to the cal lab for this work, consternation reigns. The pragmatic solution is one that will accomplish the calibration task rapidly, directly on-site, and with optimum efficiency.

TRENDS IN AUTOMATED CALIBRATION

The contributions to company performance and profit made by any in-house calibration laboratory are difficult to value. Assurinq measurement integrity clearly makes a major impact on controlling the quality of design, manufacture, and final product. But, since a hard number cannot be put on this service, calibration is traditionally considered a necessary but non-productive overhead expense. Any action by a calibration laboratory manager that reduces this cost by savings in time or people, without degrading effectivity, is well received by management and shareholders alike.

In recent years, automating the calibration process has proven to be a viable way to achieve such savings. Automated calibration systems provide several advantages compared to manual methods. They speed the process, raise productivity, control the quality of the test, and can be operated by semi-skilled personnel where appropriate. They record data at quicker rates, and produce clear, well formatted documentation and calibration certificates immediately.

Many calibration laboratories have designed automated calibration systems and written the software in-house, but turnkey systems are now commercially available that save users countless hours of programming.

We entered this field with a series of automated systems designed to handle oscilloscopes and meters. Figure 1 illustrates a typical Ballantine computer controlled oscilloscope calibration system configured as a work station. The system's components are free-standing, and are moveable from the station to sites outside the laboratory with a reasonable amount of ease, if desired.

When taking this option, adequate bench space, often in short supply at a test site, needs to be found, and non-productive time must be spent in assembling and cabling the system before start-up.

Moving the calibration system to the site is often necessary when instruments are fixed in place in large test facilities structured to collect and process masses of data. Further, many ATE systems secure test instrumentation in stationary cabinetry. In such instances, the availability of a well designed, conveniently mobile automated calibration system eliminates costly, time-wasting removal of test gear and its transport to the cal lab, and the added expenses from test bed shutdowns, or, substitution of backup equipment.

AUTOMATED ON-SITE CALIBRATION SYSTEMS

Ballantine's "CALCART" concept responds to the increasing requirements for mobility in automated systems. Principal design requirements were that our COMPUTEST calibration systems be packaged into a cart on roller bearing casters allowing the system to be wheeled to a test site for in situ calibration tasks. The cart had to be rugged, and its weight, stability, and steerability suited to easy handling.by one technician when moving the CALCART through doorways, aisles, and around corners. Large, lockable, rubber-tired swivel casters were chosen to minimize shock when negotiating door sills or rough floors. Adequate ventilation was necessary to assure the proper environment for the on board calibration gear. Sliding printer shelves and drawers had to be secure during transit, and the system had to plug into a power outlet and be ready to operate within minutes of being rolled into position at the site. A CALCART configuration of our COMPUTEST Automated Meter Calibration System is shown in Figure 2. This version includes the following sources:

Current:

Ballantine 1620A AC/DC Transconductance Amplifier
± dc and ac current to 100A
AC signals to 1kHz @ 100A and 10kHz on low ranges
Basic accuracy: (dc)±(0.02% setting + 0.1% range)
(ac)±(0.15% setting + 0.1% range)

AC Voltage:

Fluke 5200A AC Voltage Calibrator
1mV to 110V (30Hz to 100kHz)
Basic accuracy:
± (0.05% setting +0.005% range) + 10uV

DC Voltage:

Valhalla 27018 DC Voltage Calibrator
1uV to 1200v
Basic accuracy: ±(10ppm setting + 4ppm range)

Other CALCART versions include ac voltage sources to 1000 Volts, and resistance sources. The system's COMPUTEST software automatically reconfigures itself for any combination of sources used. Completing the equipment inventory is an IBM PC with dual drive, an IBM Color Monitor, and a bi-directional printer. All components operate on the IEEE 488 Bus.

A companion CALCART (Figure 3) provides automated oscilloscope calibration capability, The calibrator in this system is a Ballantine 61278 Programmable Oscilloscope Calibrator, a unit that can check scopes with bandwidths up to state of the art 1GHz operation.

CALCART SOFTWARE

The COMPUTEST software provided with the system is designed for flexibility and ease of use. Operation is menu oriented, and graphics, prompts, and operator guidance are straightforward with color displays enhancing the man/machine interface. Calibrations can be performed on meters that are IEEE 488 talkers or talker-listeners; BCD talkers or talker/listeners; or non-IEEE/non-BCD (manual) units. Closed loop calibrations can be run on talker-listener instruments with minimal operator interaction. Figures 4 and 5 are typical displays available to the operator when the "view/edit" mode is selected. They review a previously prepared calibration sequence checking 4 DC voltage ranges on a 5½ digit multimeter, and within one of those ranges 3 different scale values. Figure 6 is the operator's calibrate menu shown before commencing a check, and Figure 7 is the display on completion of a series of checks. The UUT checked on this procedure was a 5½ digit system voltmeter, and the time taken to verify the calibration of 8 points on 4 ranges on dc voltage was approximately 8 seconds. A sample calibration certificate produced by the system is illustrated in Figure 8.

The software allows test procedures to be generated by the calibration engineer to any level of detail required by selecting functions to be checked from menus, and responding to information prompts and completing tables. Procedures are saved on disk for future recall when required. Tests can be full verifications, or limited to only those parameters used in the particular test setup being calibrated. Technicians can opt to make calibration adjustments on a "fail" flag if operating conditions and time permit, or the data can be stored for lab use when the unit is scheduled for removal and correction.

BENEFITS OF ON-SITE CALIBRATION

Servicing test sites with mobile automated calibration systems frequently allows calibration of a complete test station or ATE installation in a single visit. Although on-site calibration shuts down the test station, the time off-line is substantially less than would be spent if units were disassembled from cabinets or racks and transported to the cal lab for conventional bench calibration.

When a calibration technician is on-site, many opportunities are available to evaluate the integrity of the measurement process at the location. Direct contact with floor test personnel allows an accurate review of the quality of the testing, and misapplication or improper measurement techniques can be corrected quickly. When isolated within the calibration laboratory, this kind of transfer of measurement skills is difficult to affect. A second order benefit can result from these on the job training sessions.,. the number of instruments returned with problems may be reduced.

Fault reports that accompany units returned for regular cal lab maintenance are frequently short and incomplete, Face to face discussions can more clearly define an operational problem and shorten troubleshooting and calibration efforts.

CONCLUSION

Mobile automated calibration systems provide a practical solution to the problem of providing fast, efficient calibration service to fixed in place instrumentation. Downtime at test installations is minimized since test instrumentation can remain in place when calibration is performed on-site. Automated calibration procedures control the quality of testing, and speed record keeping and printout of calibration certificates. Faster calibrations reduce cal lab expense. Additionally, mobile systems can be transported in conventional small vans, to extend the availability of the calibration laboratory s services to distant divisions without investment in satellite laboratories.

FIGURE 1. BALLANTINE COMPUTEST 4003A AUTOMATED OSCILLOSCOPE CALIBRATION SYSTEM.

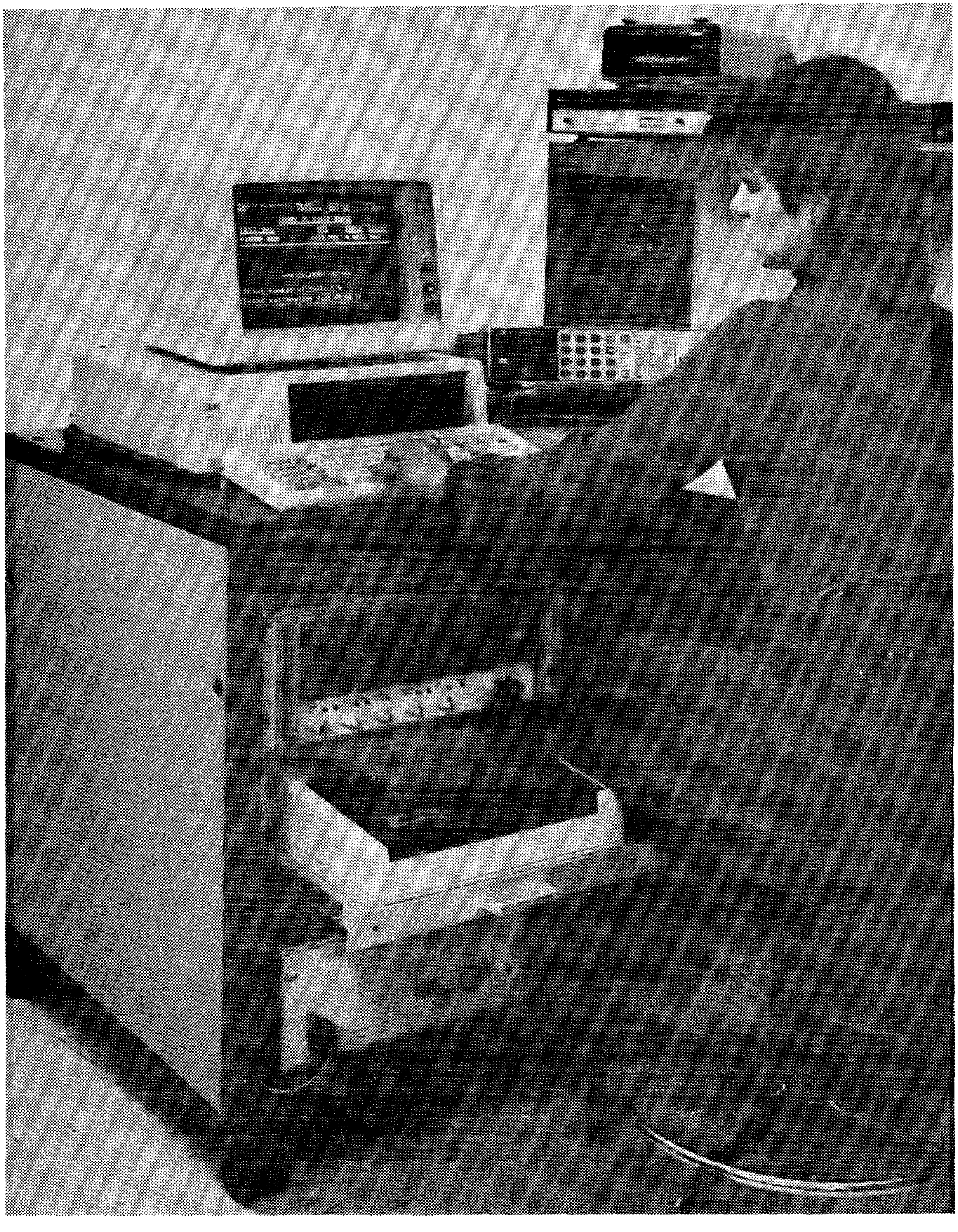


FIGURE 2. **BALLANTINE CALCART 4050A—MOD101**
MOBILE AUTOMATED METER CALIBRATION **SYSTEM.**

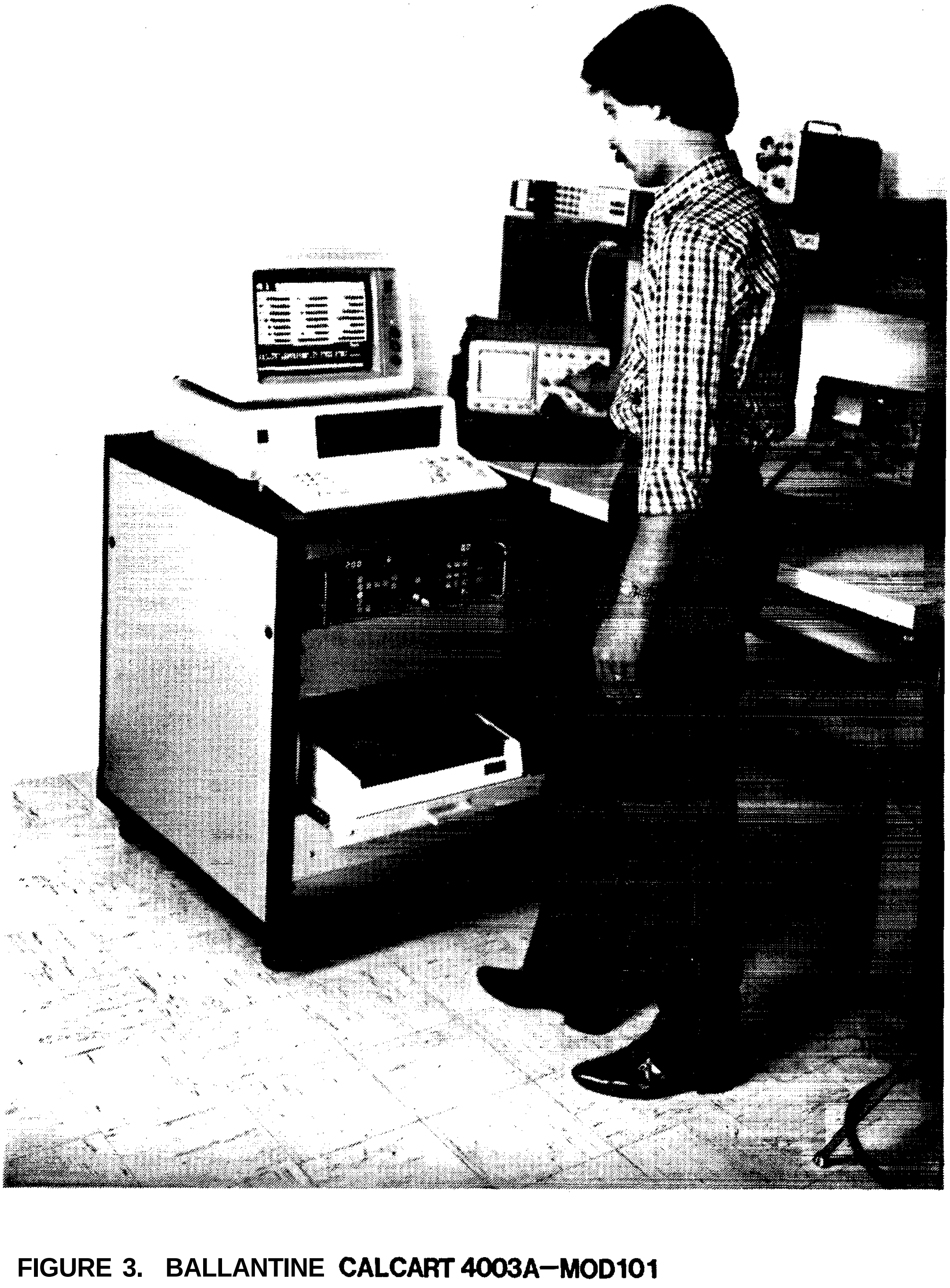
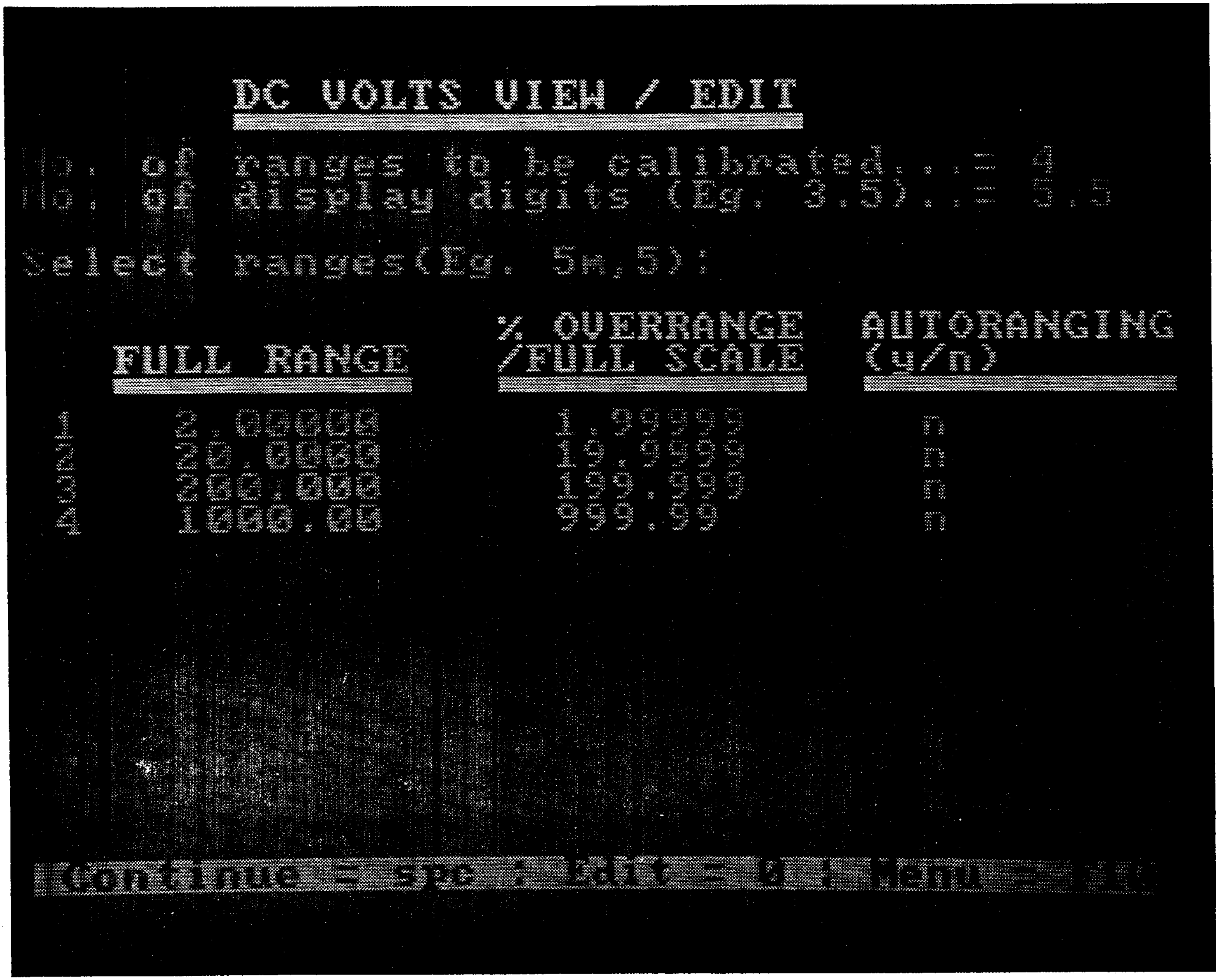
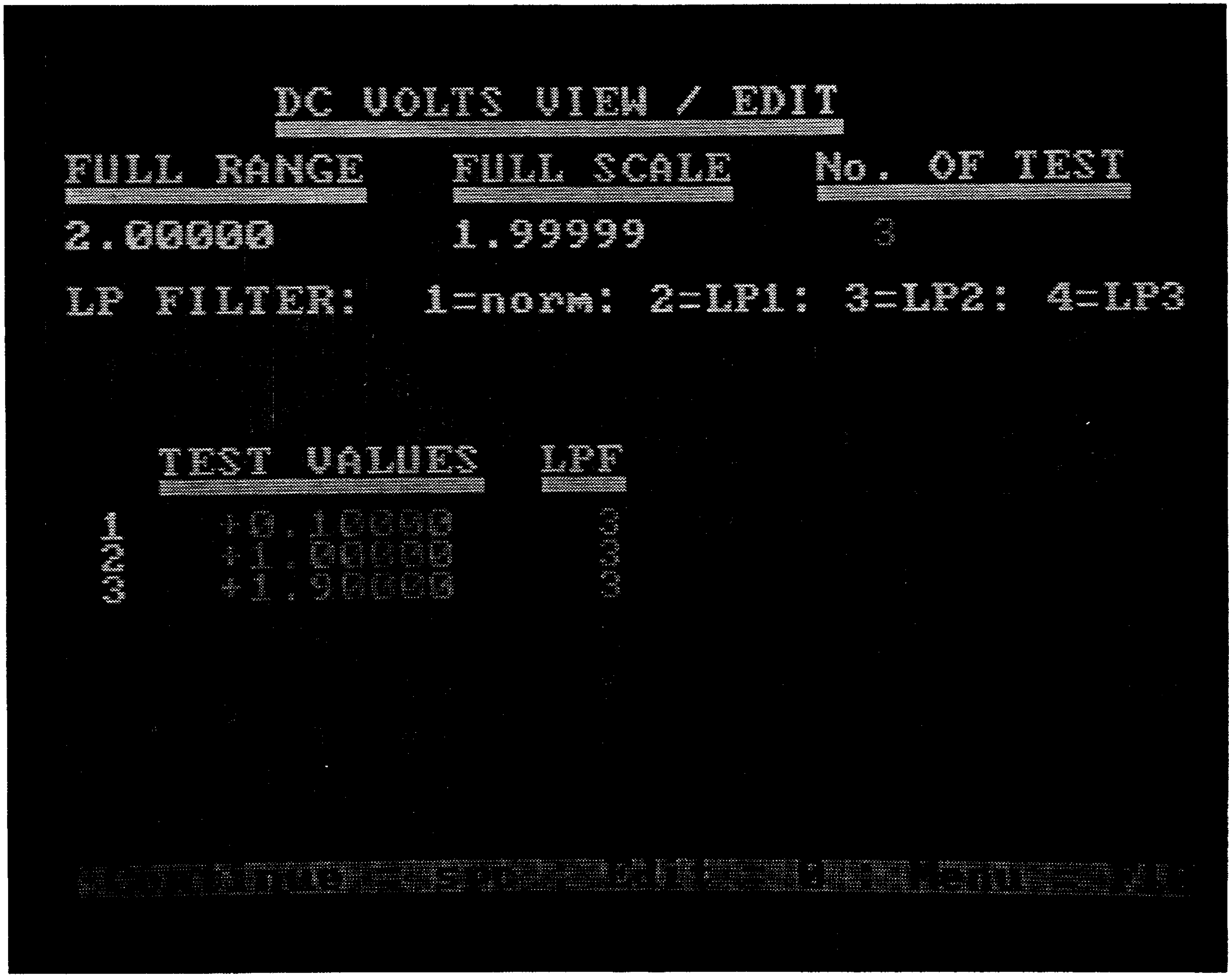


FIGURE 3. BALLANTINE **CALCART 4003A—MOD101**
MOBILE AUTOMATED OSCILLOSCOPE CALIBRATION SYSTEM.



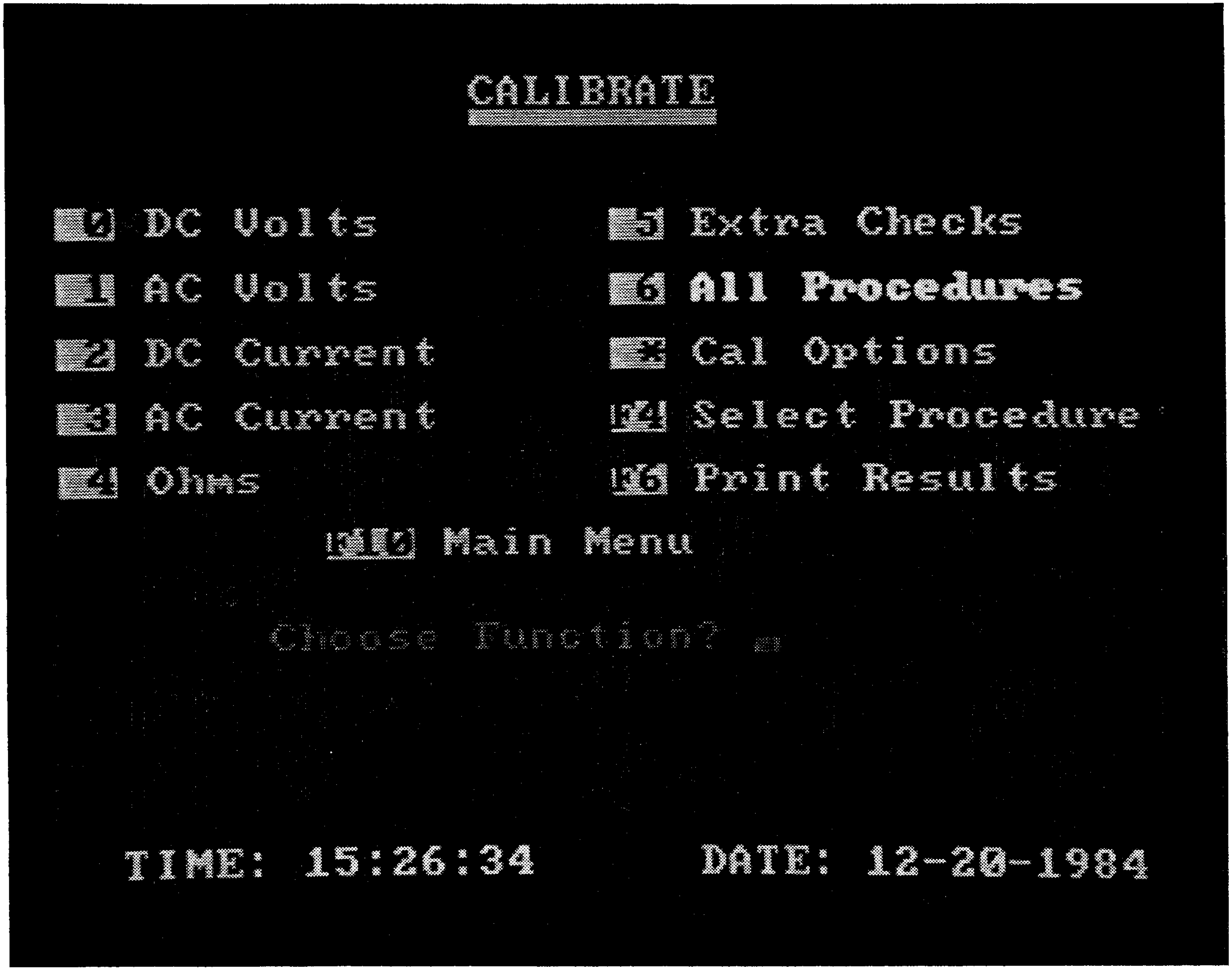
```
DC VOLTS VIEW / EDIT

No. of ranges to be calibrated..= 4
No. of display digits (Eg. 3.5)..= 5.5

Select ranges(Eg. 5m,5):

                      % OVERRANGE    AUTORANGING
     FULL RANGE       /FULL SCALE    (y/n)

 1    2.00000          1.99999          n
 2    20.0000          19.9999          n
 3    200.000          199.999          n
 4    1000.00          999.99           n

Continue = spc ; Edit = 0 ; Menu =
```

FIGURE 4. TYPICAL "VIEW—EDIT" DISPLAY OF a PROCEDURE SHOWING METER RANGES TO BE CALIBRATED.



```
          DC VOLTS VIEW / EDIT
FULL RANGE     FULL SCALE     No. OF TEST
2.00000        1.99999            3

LP FILTER:  1=norm: 2=LP1: 3=LP2: 4=LP3


     TEST VALUES    LPF
  1    +0.10000      3
  2    +1.00000      3
  3    +1.90000      3
```

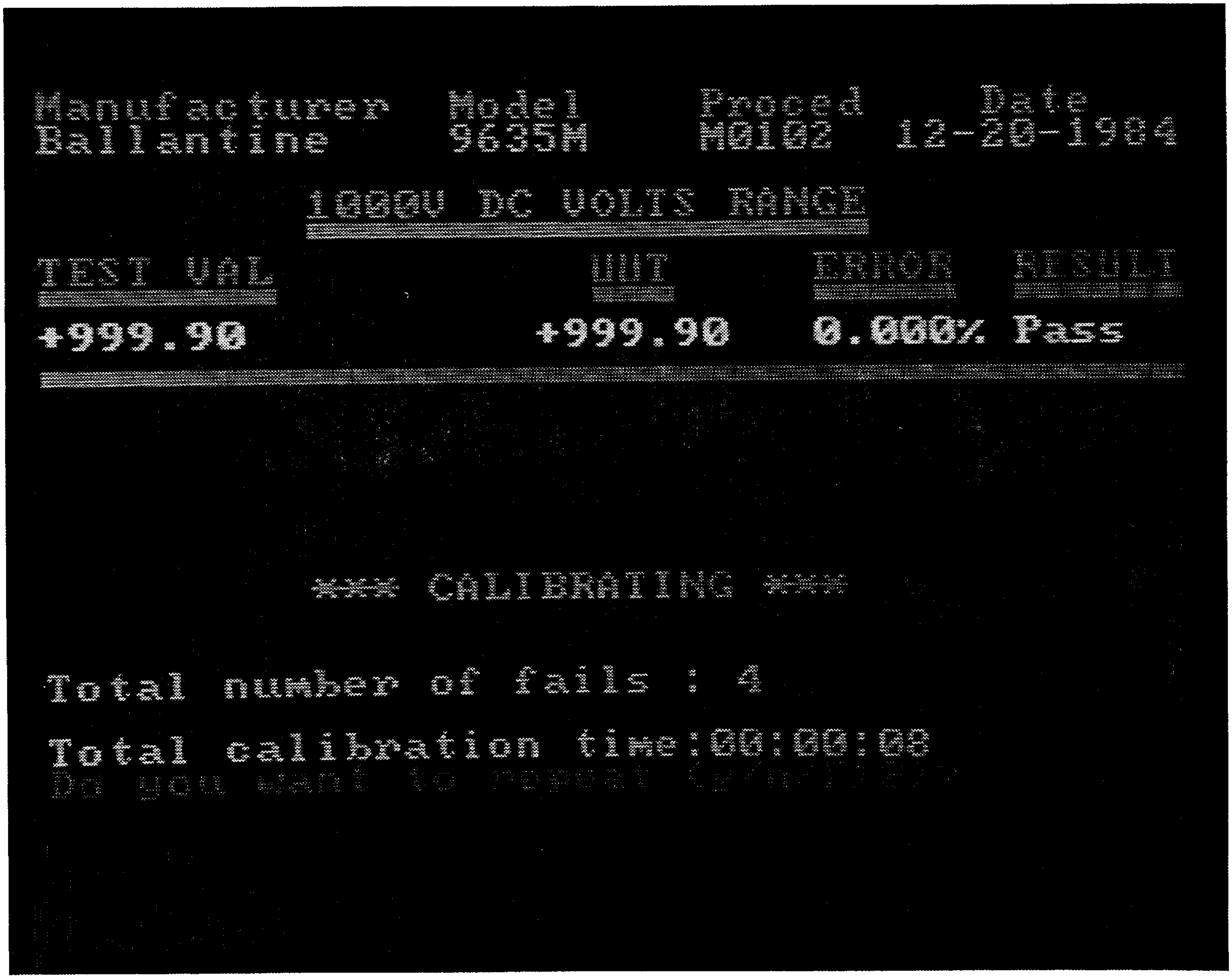
FIGURE 5. TYPICAL "VIEW—EDIT" DISPLAY OF A PROCEDURE SHOWING NUMBER OF TESTS AND FILTER MODES ON ONE RANGE TO BE CALIBRATED.



Choose Function?

TIME: 15:26:34 DATE: 12-20-1984

FIGURE 6. OPERATOR'S "CALIBRATE" MENU FOR a PROCEDURE TO CALIBRATE DC VOLTS MODE ONLY AND OPERATOR OPTIONS.



```
Manufacturer  Model    Proced   Date
Ballantine    9635M    M0102  12-20-1984

         1000V DC VOLTS RANGE

TEST VAL              UUT      ERROR   RESULT
+999.90             +999.90   0.000%  Pass


         *** CALIBRATING ***

Total number of fails : 4

Total calibration time:00:00:08
Do you want to repeat (y/n[illegible]
```

FIGURE 7. FINAL DISPLAY AFTER LAST TEST VALUE IN A PROCEDURE.

```
CERTIFICATE OF CALIBRATION
Scheduled recall calibration(6 mos.)



Manufacturer.....Ballantine          Procedure No.. . .M0102
Model No.. .......9635M              Operator.. . . . . . .M. Smith
Serial No.........54321              Date............12-20-1984

                          TEST         ACTUAL       ACCURACY  UUT      PASS/  COR
RANGE                     VALUE        UUT READING  LIMIT     ERROR    FAIL   ACT
=================================================================================
DC ML3 2V                 +0.10000     +0.10589     0.030%    5.090%   Fail   DV1
DC ML3 2V                 +1.00000     +1.00377     0.012%    0.377%   Fail   DV2
DC ML3 2V                 +1.90000     +1.90058     0.011%    0.031%   Fail   DV3
DC ML3 20V                +10.0000     +10.0007     0.011%    0.007%   Pass
DC ML3 20V                +19.9990     +20.0019     0.011%    0.014%   Fail   DV5
DC ML1 200V               +100.000     +100.005     0.011%    0.005%   Pass
DC ML1 200V               +199.990     +199.991     0.011%    0.000%   Pass
DC ML1 1000V              +999.90      +999.91      0.011%    0.001%   Pass
---------------------------------------------------------------------------------"


COMMENTS:
Return for recal check 6/20/85.


*  Indicates results after adjustments.
#  Indicates marginal pass.
Low pass filter codes:  L1=norm   L2=LP1   L3=LP2   L4=LP3.
Low frequency response codes:  F1=norm   F2=LP1   F3=LP2   F4=LP3.
Range codes:   M=Manual   A=Auto.


Total Calibration Time:00:00:08
Failed on 4 test(s).

Produced on a BALLANTINE COMPUTEST calibration system.


                                            ................ .........

                 COMPUTEST SYSTEM SPECIFICATIONS


FUNCTION          VALUE             % SETTING     % RANGE       OFFSET

DC VOLTS          1V-1200V          +/- 0.001     +/- 0.0004      -

AC VOLTS
10-30Hz.         1mV-1V            +/- 0.1                      10uV
 10-30Hz.         1V-1000V          +/- 0.1      +/- 0.005        -
 30Hz.-20KHz.     1mV-1V            +/- 0.02          -         10uV
 30Hz.-20KHz.     1V-1000V          +/- 0.02     +/- 0.002        -
 20-100KHz.       1mV-1V            +/- 0.05                    20uV
 20-100KHz.       1V-1000V          +/- 0.05     +/- 0.005        -
 0.1-1MHz.        1mV-1V            +/- 0.33                    30uV
 0.1-1MHz.        1V-1000V          +/- 0.33     +/- 0.033        -
VOLT FREQ.         100Hz.-100KHz.    +/- 1.0      +/-0.1           -
                  1MHz.            +/- 3.0      +/- 0.3          -

DC CURRENT         0-100A            +/- 0.02     +/- 0.02         -
AC CURRENT         0-100A            +/- 0.15     +/-0.1           -
(Current spec is related to input voltage spec)
```

A NON-SYSTEMS APPROACH
TO AUTOMATED CALIBRATION

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Newport News Shipbuilding
Newport News, VA

ABSTRACT:

Calibration of Test and Measuring Equipment (TME) has evolved from standard manual techniques to the use of highly automated calibration equipment and procedures. Several companies now manufacture such automated "stand alone" equipment with the needed software to perform calibrations of specific types of TME. More importantly, these basic packages can be supplemented, at a modest investment, with other ancillary equipment and additional software, to perform Automated Calibrations on a much wider selection of TME. The manufacturers have not, however, provided instructions and software for this expanded capacity, and as a result many well equipped laboratories which now have this equipment at their disposal are not using it in the most cost and tine effective manner, The users of TME want their equipment back in the field as soon as possible - tine is money - and Automated Calibration extended to its practical limit can be the best answer to that need.

INTRODUCTION:

Newport News Shipbuilding and Dry Dock Company (NNS) first embraced the concept of Automated Calibration in 1979 with the purchase of a Julie Research Labs LOCOST 106. It became readily apparent that Automated Calibration was the way of the future and we have since purchased another Automated Calibration System, the Ballantine Laboratories 4020A Oscilloscope Calibration System, installed in 1982.

The experience gained using the LOCOST 106 and the 4020A has convinced us to further automate our calibration facility. As part of this effort, all purchases of calibration equipment specify the IEEE-488 bus interface be included. The IEEE-488 bus is the standard adopted by instrument manufacturers.

Automated Calibration of the more common types of TME; voltmeters, ammeters, VOM, etc.; has proven to be cost effective. However, other types of TME are even more advantageously suited to Automated Calibration. Routine and time consuming calibrations are well suited for this concept.

The first attempt, at NNS, to implement this idea was to supplement the LOCOST 106 with an AC voltmeter and a non-IEEE-488 distortion analyzer. (The LOCOST 106 does not have AC voltage measurement capabilities.) With this ancillary equipment and the LOCOST 106 we were able to partially automate the calibration of Instrumentation Tape Recorders. The LOCOST 106 was used to source the AC voltage levels used as inputs to the input of the recorder channel under test. Output levels were monitored with the supplemental voltmeter, via the IEEE-488 bus. Distortion was measured manually and entered as a keyboard input. While not completely automated, the concept was used satisfactorily for several months. The scheduled use of the LOCOST 106 as a standard system prohibited further development.

The Ballantine Labs 4020A Oscilloscope Calibration System has the capabilities, among others, of sourcing, under IEEE-488 control, precise DC voltages. This has been used to calibrate DC voltmeters. Although not specifically designed for this function, it has had limited use. Again, further development was suspended due to use as a oscilloscope calibrator. These two trials, while not completely successful, has proven that the concepts of Automated Calibration should be further developed. To illustrate this method of expanding Automated Calibration, two different types of TME are to be discussed. These two types were chosen because of the repetition and tine required to do a manual calibration.

AUTOMATED CALIBRATION INSTRUMENTATION TAPE RECORDERS:

The application of Automated Calibration to Instrumentation Tape Recorders, for instance, has proven to be very cost effective without loss of quality. Instrumentation Tape Recorders typically have 4 to 14 channels. Each channel must be checked at each of the operating speeds of the recorder, for frequency response, distortion, S/N ratio, etc. Newer Instrumentation Tape Recorders are capable of being controlled remotely via the IEEE-488 bus. (With or without the IEEE-488 Interface, Automated Calibration of Tape Recorders is time saving.)

Four models of tape recorders have been adapted to Automated Calibration at NNS. Two of these models have IEEE-488 bus control; the Racal Store 4DS and the Store 141. The two remaining recorders, the Ampex PR-2200 and the PR-2300 require manual switch positioning to control speed.

The minimum equipment required to manually calibrate the tape recorders is as follows:

° Signal Generator
° Distortion Analyzer
° Voltmeter

For Automated Calibration of Tape Recorders the following equipment was selected:

° Signal Generator H-P 3325A
° Voltmeter H-P 34558
° Switch Driver H-P 11713
° Scanner (lab built)
° IEEE Controller H-P 86A, disk drives, printer (See Figure 1.)

All equipment listed above or an equivalent is available in many calibration labs, except the scanner which was lab built at NNS. (See Figure 2.) A substitute scanner may be available. The Switch Driver and scanner serve to route the inputs and outputs of the Tape Recorder under test to the proper locations. The scanner consists of two separate but similar sections. Each section consists of sixteen (16) SPDT relays driven by a 1 of 16 decoder (74154 IC). Each section is separately controlled by the 11713. The operating power is also derived from the 11713. Each section is identical except that the relays used on the inputs of the UUT ground the non selected input.

Signals are routed, via the scanner, to the channel under test and to the required measuring equipment. All data is taken by the controller and values obtained by the voltmeter under bus control are compared with stored constants. Data is printed with out-of-tolerance conditions noted on the printout.

The program which controls the equipment also monitors the status of the Tape Recorder under test. When close to end of tape, the operator is prompted to change the tape and the calibration continues. For the Racal Recorders this is the only operator action required.

Operation is similar for the Ampex Recorders. The operator is prompted to make the necessary operations on the Recorder. Again, all data is taken under computer control. (See Figure 3.)

Other types of recorders can be adapted to this type of calibration. Here at NNS, the next step is to include the H-P Tape Recorders in this program.

Like all automated systems, developing the software is the major time consuming effort in putting together an automated system. We, at NNS, have elected to write all computer programs in BASIC, which although slower than other languages, is well suited for this application because it is "user friendly". Technicians find the commands are easily understood and the programs simple to modify. Only about 650 lines of code are necessary for the Racal Recorders and 550 lines for the Ampex.

Experience over the past year has proven to us at NNS that the time required to calibrate a typical 14 channel recorder has been reduced by 80% without sacrificing quality.

AUTOMATED CALIBRATION
PANEL METER CALIBRATOR:

The Arbiter Systems Model 1040A Panel Meter Calibrator (PMC) is another prime candidate for Automated Calibration. While several specialized pieces of equipment are required, Automated Calibration is still cost effective. The PMC is capable of generating DC volts from 0.01 to 1000 volts, AC volts from 1.5 to 750 volts at 60 or 400 Hz, DC current from 0.0001 to 10 amps, AC current from 0.15 to 5 amps and is capable of generating phase shifted signals for use in checking synchroscopes, power factor and wattmeters. This is a very versatile unit.

To check all of these functions manually and to make the necessary adjustments and rechecks can take many hours. The purchase from Arbiter Systems of a Model 1048 PMC Calibration Unit, a 1040-950 Auto-Cal Module and a 1040-900 IEEE-488 Interface Module made Automated Calibration simple to achieve. The 1048 supplies loads and signal routing to the system voltmeter via the 1040-950 Auto-Cal Module. The 1040-900 IEEE-488 Interface Module allows the serial data bus of the PMC to be commanded and read by the IEEE-488 controller. (See Figure 4.)

Preliminary checks of the 1048 PMC Calibration Unit must be made prior to use to verify accuracies of internal resistors. This is done prior to each use of the 1048 and is included in the PMC software.

The program again is written in BASIC. The system is unique in that all calibration constants for the PMC are stored in non-volatile RAM. The software is written so as to update the stored constants on any function that is determined to be out-of-tolerance, and to recheck that function to verify accuracy.

Equipment required to manually calibrate the PMC is as follows:

° Digital Multimeter
° Decade Power Resistor
° Decade Resistor
° Shunt Box
° AC Differential Voltmeter (2 req'd)
° Distortion Analyzer
° Electronic Counter
° Current Shunt 0.1 ohm
° Phase Meter

- Current Shunt 0.1 ohm
- Phase Meter

The following ancillary equipment was selected for automating this procedure:

- H-P 86A Computer, disk drives, printer
- H-P 34558 Digital Multimeter
- H-P 339D Distortion Analyzer (not IEEE-488)
- Drantz 305 Phase Meter with 3008 plug in (not IEEE-488)
- Arbiter 1048 PMC Calibration Unit
- Arbiter 1040-900 IEEE-488 Interface Module
- Arbiter 1040-950 Auto-Cal Module

Note that some of this equipment is not IEEE-488 compatable but can be read by the system voltmeter via the 1040-950 Auto Cal Module.

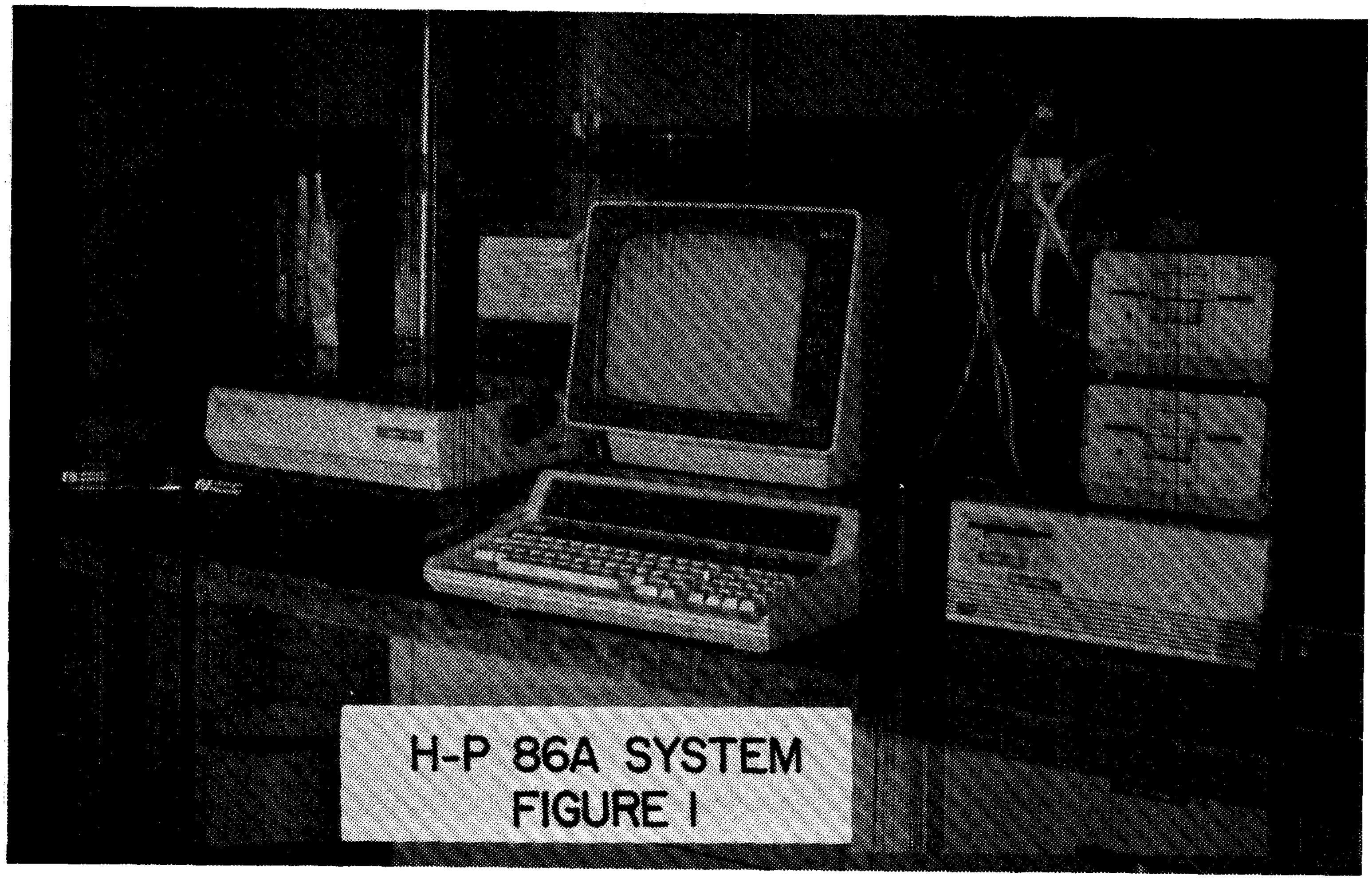
The PMC calibration time has been reduced by 85% using the Automated Calibration System.

SUMMARY AND CONCLUSIONS:

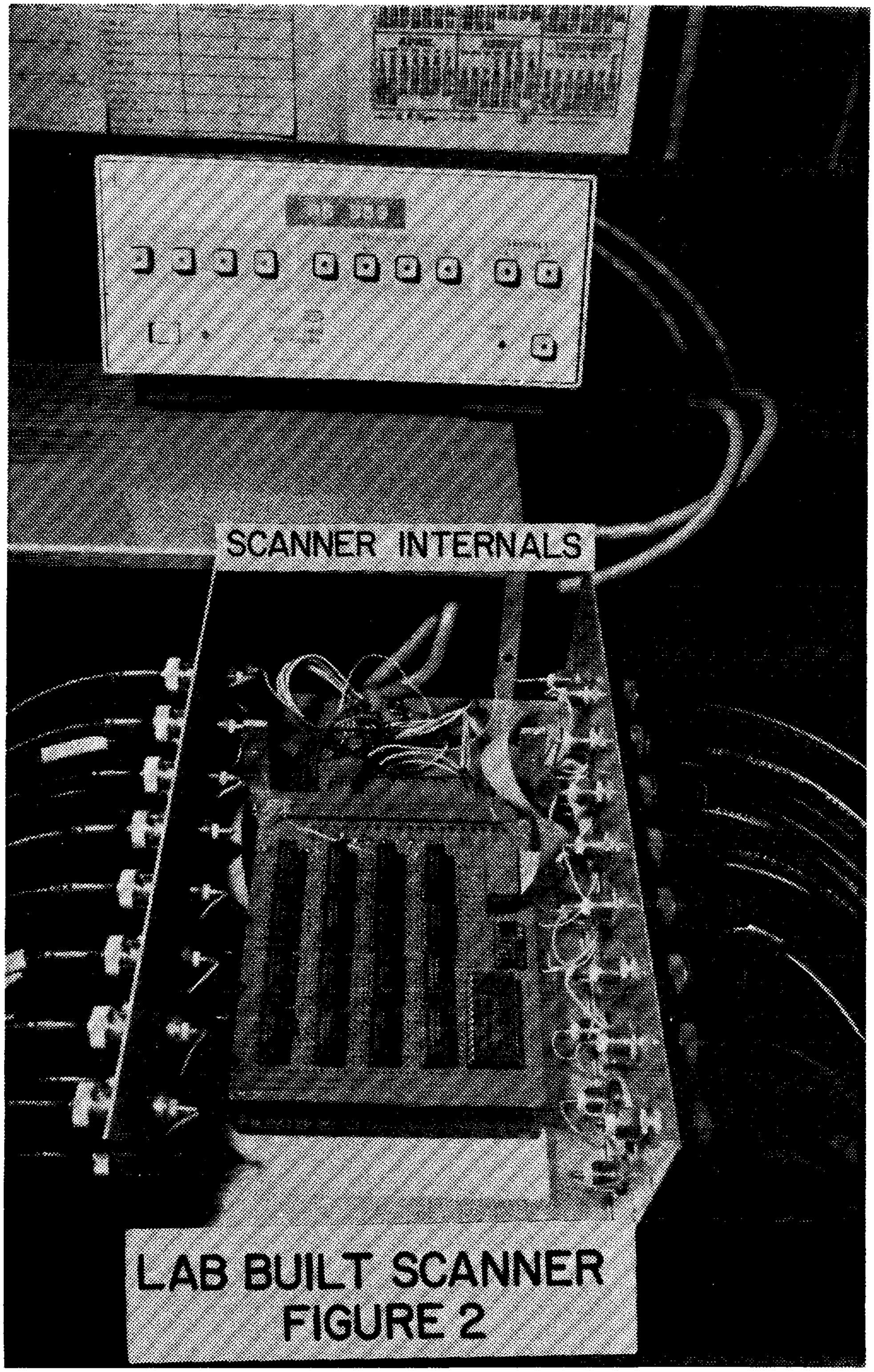
Both of the procedures presented here as illustrations were put together with equipment that was available in our lab, with the exception of the 1040-900 and the 1040-950. The cost of these two units was minimal and proved to be a worthwhile purchase. These concepts were tried, to prove or disprove, that Automated Calibration was adaptable to most any calibration procedure and that Automated Calibration is cost effective. The answer is a definite YES. Time savings were very significant even after software development time. The breakeven point on the Tape Recorders was on the forth unit and on the PMC, the third unit.

Automated Calibration should not be limited to those calibrations that are done by "dedicated systems" but should be limited only by imagination and equipment available. Think about your calibration efforts. Can you save time without loss of accuracy? Quality calibration should be foremost.

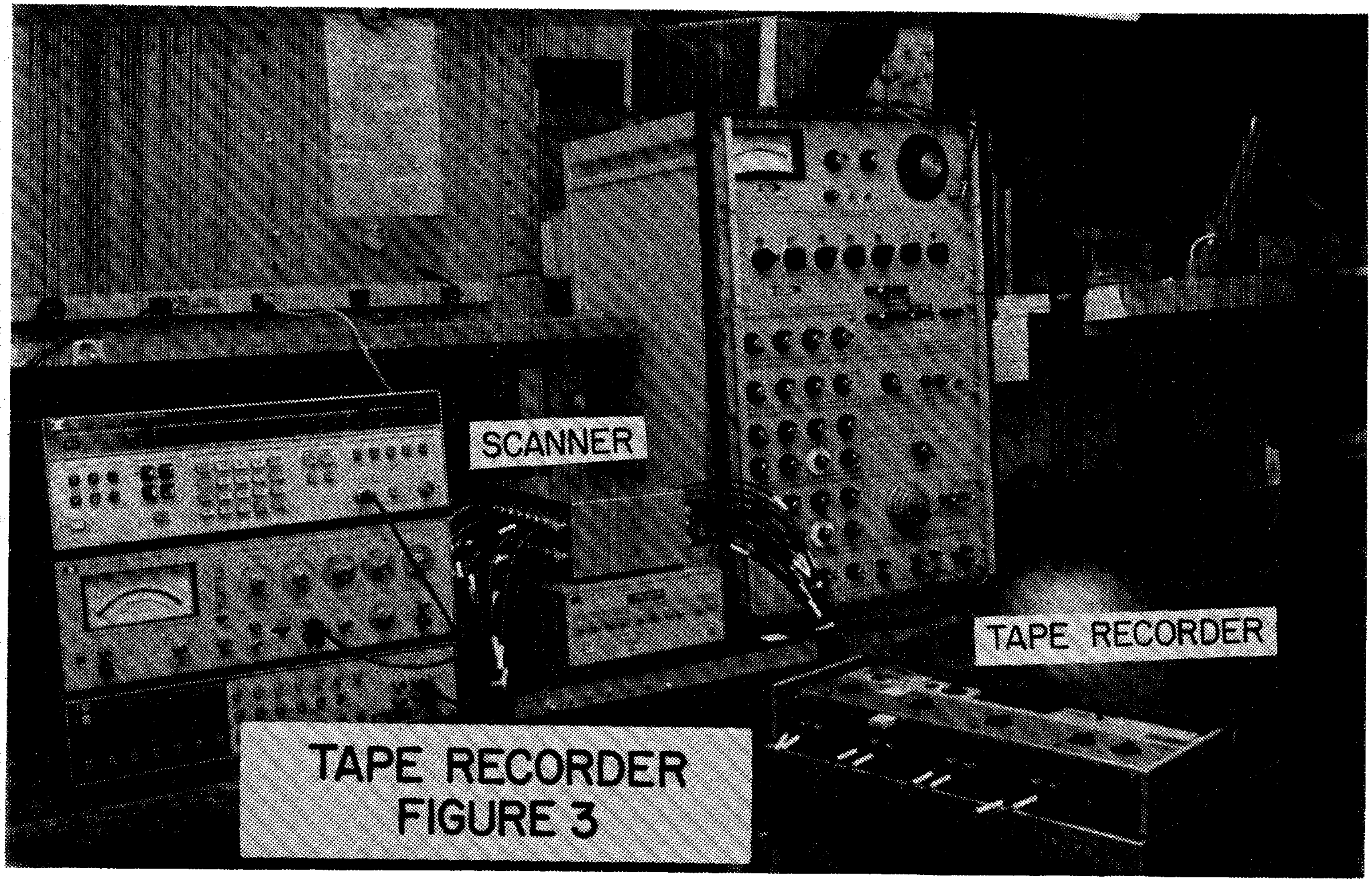
During development of the software to perform these tasks, much time and effort was spent that could have been avoided if instrument manufacturers would standardize the IEEE-488 commands. The IEEE-488 bus is well defined, now let's standardize the commands used.



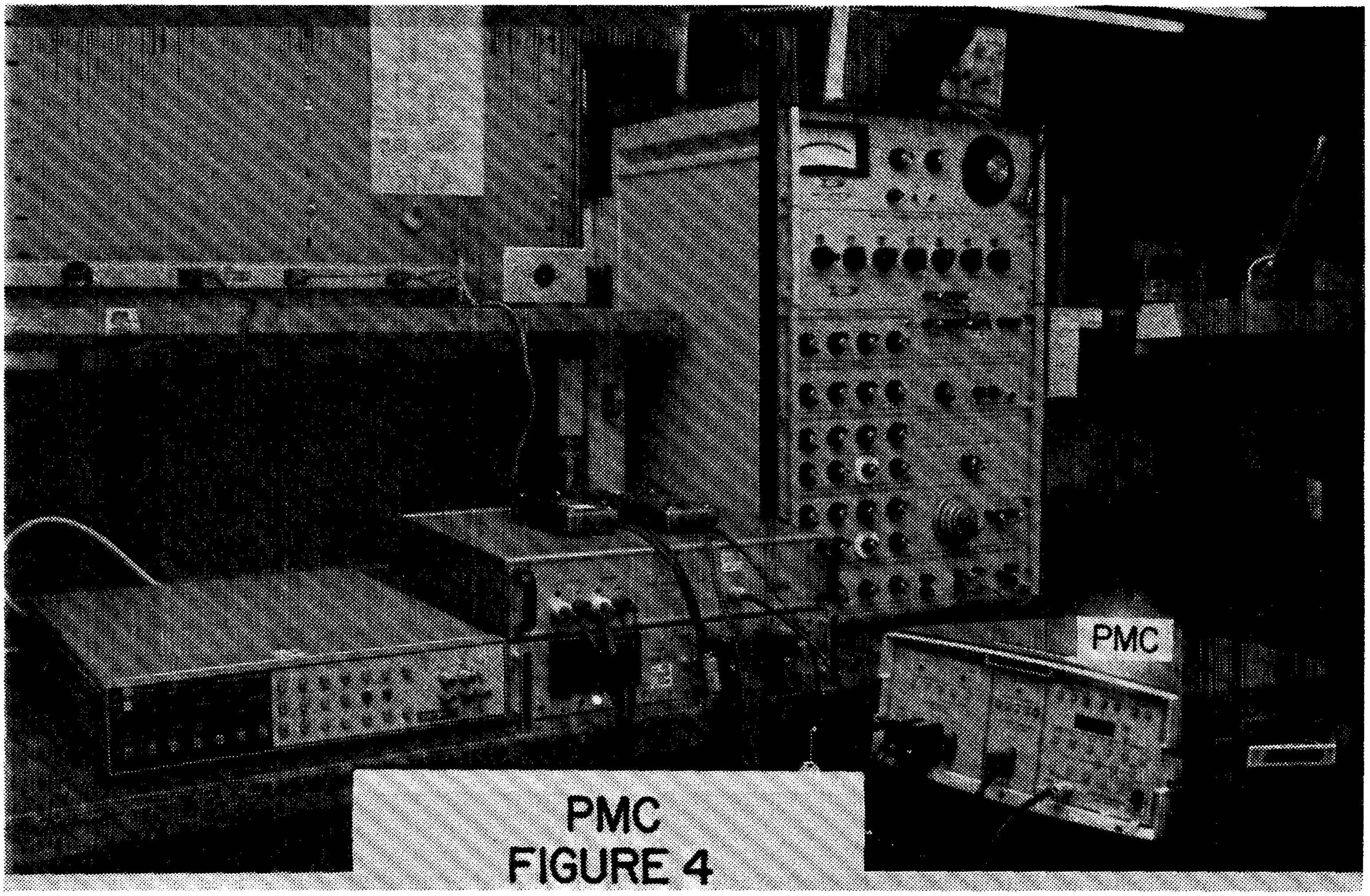
H-P 86A SYSTEM
FIGURE I



LAB BUILT SCANNER
FIGURE 2



TAPE RECORDER
FIGURE 3



PMC
FIGURE 4

SESSION I-D

CHANGES AND CHALLENGES IN AUTOMATED METROLOGY

Charles E. Weber
Grunman Aerospace

ADVANCED APPLICATIONS OF AUTOMATION IN THE CALIBRATION LABORATORY

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CHANGES AND CHALLENGES:

The, decade of the 80s is indeed a time of changes and challenges for the Grumman Aerospace Corporation. A massive investment of the resources of capital and talent is positioning the company in a leading role in aerospace technology. New aircraft programs such as the X-29 Advanced Technology Demonstrator, the F14D and A-6 update with virtually all new avionic systems, along with continuing improvements on the EA-6B, EF-111 and E-2C aircraft have demanded new and improved manufacturing, testing, and quality assurance methods. New business areas, such as the automatic test equipment field, where Grumman has become a major factor, and atomic fusion research have also presented the challenge of measuring, inspecting and testing new devices under new conditions.

The impact of new and changing programs on the company's calibration program has been a major challenge to meet. In addition, a further calibration challenge has been cost control. Meeting the calibration requirements of new technology at any cost is not acceptable in today's competitive environment. This statement is doubly true in Grumman Measurement Standard's case since this section not only supports corporate calibration needs but is also a major factor in the quality commercial calibration and repair services field. High costs would soon stop the company's growth in this area.

MEETING THE CHALLENGES:

Grumman Measurement Standards has met the technologic and economic challenges by implementing its own changes. New methods of calibration, new calibration systems and new standards of higher accuracy and broader range have been implemented or acquired. The results of our response to the challenges are clearly evident in the area of productivity. Productivity gains have averaged 7% per year over the last few years. At the same time quality levels have improved. Many of the technologic gains and a substantial portion of the economic and quality gains are directly attributable to the application of automation to the calibration process.

Basic Rules For Automation:

Grumman's approach to calibration automation has been guided by a few basic rules:

- Automate where it is an economic or technologic advantage
- Utilize "turnkey" systems wherever possible
- Work closely with system manufacturers
- Maintain diligent technical oversight and control over system operation to assure a high quality level
- Innovate and be creative — but be practical!

Prior Success:

Grumman Measurement Standards has a long history of successful calibration automation. Presently operating systems, which have previously been reported on[1] include those for calibrating:

- Pressure Transducers
- Thermocouples
- Digital and analog meters
- Voltage calibrators
- Current calibrators
- Resistance decades
- Resistance bridges
- Potentiometers
- Temperature indicators
- Current shunts

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[1] C. E. Weber, *"Calibration System Automation at Grumman Aerospace Corporation"*, Proceedings of the Measurement Science Conference, Palo Alto CA. January 1983.

- Voltage dividers
- Amplifiers
- Oscillators
- Function generators
- Pulse generators.

Continual upgrades have kept these systems in effective service.

NEW SYSTEMS

Grumman Measurement Standards has, during the past two years, purchased and/or developed 6 additional automated calibration systems for calibration of the following types of instruments:

- Surface plates
- Load cells
- Microwave components
- Microwave signal generators
- Microwave power sensors
- Oscilloscopes
- Standard resistors
- Standard cells
- Shunts.

In many instances the calibration process has been fully automated. In others the calibration process has been significantly aided by automation.

Surface Plate Calibration System:

Calibration of surface plates has been a challenge for a long time. Most are calibrated on site due to their size and weight. Using conventional techniques a series of measurements are made and data acquired. Processing and analyzing the data back at the laboratory takes considerable time. If some data seems questionable the field calibration crew has to return to the site and repeat the calibration.

An automated technique, presented in Fig. 1, is now employed utilizing a laser interferometer tied into a small computer. Data can now be acquired and analyzed in real time. Simple but costly measurement errors, such as picking up a bit of grit under the footpad of one of the reflectors, are quickly noticed and may be corrected immediately thus greatly reducing the need for repeat calibrations. The system utilizes a Hewlett Packard 5526A Laser and a Hewlett Packard software package run on an 85A computer. Data plots are provided both in numeric and contour form for the surface plate, see Fig. 2 and 3.

Laser interferometer measuring techniques are also utilized for calibration of precision linear devices such as the 100 in. Schwein barometer. Future applications, using an improved system, will extend automated laser calibration to multi-axis machine tools and measuring machines.

Load Cell Calibration System:

Load cells and other force measuring transducers are widely used in the aerospace industry. Strain gage type load cells predominate in Grumman's applications and are used extensively for static and fatigue testing of airframes.

Manual calibration of load cells involved a lengthy sequence of operator actions which necessarily had to be performed in the proper sequence to arrive at the correct results. All too often one or more steps were missed or done out of sequence resulting in erroneous data. This led to needlessly repeated calibrations.

Automating the calibration of load cells was a case of taking exception to the usual rules for automation. With no "off-the-shelf' systems available for this application, Grumman was forced to develop both hardware and software to accomplish this task (see Fig. 4).

The system, as presently configured, is automated to the extent of prompting the system operator to perform a specified test sequence while the system is automatically acquiring and processing the test data.

The computer directs the operator to select a standard of comparable range and sensitivity to the test article and to mount the units in the test fixture. A force range of 0 to 10,000 lb can be applied in either tension or compression mode. A series of zero load measurements and resistance calibration equivalent value (RCEV) tests are performed automatically to assure that the circuits are electrically operational. By responding to "touch screen" commands, as illustrated in Figure 5, the operator exercises the transducers to prepare them for calibration and then performs two calibration runs from zero to full scale and back to zero. At each test point, the system samples the excitation voltage and output voltage of the transducers. A least squares solution is performed on this information which provides the sensitivity, deviation, repeatability and hysteresis data necessary for the user of the transducer.

System uncertainty is still under evaluation. However it appears to be better than 0.2 % .

Microwave Component and Signal Generator System:

A custom designed system for calibration of microwave components and active microwave devices was purchased from Microtel, a division of Adams-Russell (see Fig. 6). The Microtel System designed for Grumman provides the following capabilities:

- Attenuation measurement to 100 dB from.10 MHz to 18 GHz

- VSWR measurement
- Frequency measurement
- Power measurement
- Modulation measurement.

The system consists of a Microtel 1295 Receiver and a Microtel SC-811 Signal Generator, each frequency controlled by a Microtel FS-1000 Synthesizer. A Boonton 82AD Modulation Meter, Hewlett Packard 436A Power Meter and an EIP 548A Frequency Counter provide the modulation, power and frequency measurements necessary for signal generator calibration. For component calibration, a set of special Wiltron bridges is employed for VSWR measurement. Considerable effort was put into selecting special, well matched attenuators, adapters and cables to minimize the measurement uncertainties.

Initial software was provided by Microtel. Grumman has extensively modified it to meet our particular requirements. This system is performing exceptionally well. Calibration times for broadband microwave components have been reduced by up to 90%. Signal generator calibration times have been reduced by over 50%.

A set of check standards is being used to monitor the performance of the system. Attenuators of 3 and 60 dB and reflection coefficient standards of approximately 0, 0.2 and 0.34 are available in N, SMA and APC7 connector styles, both male and female where applicable to validate system performance. Repeatability and measurement agreement with traceable standards have consistently been better than 0.05 dB/10 dB over the short time the check standards have been available. It is anticipated that longer term testing will allow us to significantly reduce system uncertainties.

Microwave Power Sensor System:

The Weinschel System II Power Meter System presented in Fig. 7 was purchased for calibration of power sensors. This system came complete with software for use with power sensors utilizing power meters having GPIB capability. Power sensors requiring power meters having an analog voltage output can also be calibrated with this system. However, accomplishing this did require software revisions by Grumman. At present, thermistor, bolometer and thermocouple type sensors are calibrated with equal ease.

Calibration time has been cut in some cases by up to 95%. The average time for a calibration, which consists of three runs with the unit connected in different positions, is accomplished in approximately 20 minutes.

The stability and repeatability of the system have been very good. Two Hewlett Packard 8478A Thermistor Mounts have been used as check standards on a monthly basis. The data shows a spread of less than 1% in the measured calibration factors.

Primary Resistance/Voltage System:

The success of Grumman's commercial calibration service venture has brought with it an increasing workload of basic electrical standards. This raised the challenge of calibrating such units at a reasonable cost, using a minimum of increasingly scarce "primary laboratory" labor.

The Julie Research LOCOST "Mini System", utilizing the same software as its big brother, has been successfully applied to the calibration of standard resistors, shunts, thermal converters and standard cells.

The system, when applied to basic standards, provides a quick, accurate means of comparison between NBS calibrated reference standards and units submitted for test.

In its low resistance comparison configuration (see Fig. 8) resolution of 0.01 parts per million are achieved with uncertainties shown to be approximately 0.5 part per million at the Thomas one ohm level.

Achieving this accuracy level was a trial and error task during which a number of digital multimeters, current sources, switches and other components were tried and found wanting until the final configuration was arrived at. The present system, when used for resistance comparisons below 100 ohms, utilizes a JRL DM1060 digital multimeter fed by an extremely stable JRL 100: 1 gain buffer amplifier. A very high quality transfer switch was found to switch the input connections to the amplifier. Since the low resistance measurements are performed over a short but still significant timespan a very stable current source is required. A JRL DCS106 100 ampere unit was found to be sufficiently stable to allow comparisons to less than 1 part per million.

For 100 ohms and higher resistance comparisons, the DMM is used as a direct reading, 4 wire ohmmeter. Resolution again is 0.01 PPM with transfer uncertainty of approximately 1 PPM.

Oscilloscope System:

Oscilloscopes and their related plug-ins represent the single largest group of instruments in the workload of the Measurement Standards electrical calibration section.

Automation of a large workload such as this is always an attractive endeavor economically. Unfortunately the metrologist's road to automating oscilloscope calibration has been long and rough. Over the years a number of different systems have been proposed to meet this challenging task and abandoned by various companies or agencies. Finally, hardware designed for the Navy MECCA program, teamed with user friendly software, made automation of this task feasible.

Following an evaluation process, Grumman obtained two Ballantine 4002A Automated Oscilloscope Calibration System (see Fig. 9). After overcoming some early hardware and software problems, the laboratories have found the system to be very effective. Calibration times have been reduced by 25 to 50% for most models calibrated.

Software was provided with the system and in its present configuration is very easy to use for the system operator. Unique calibration programs have been generated for approximately 300 oscilloscope or plug-in models.

HOW FAR CAN THE AUTOMATION OF CALIBRATION GO?

At last count, approximately 37% of the calibrations performed by Grumman Measurement Standards have been automated (see Fig. 10). The remaining 63% of the workload would seem to be an inviting target for automation. However, there are many items for which no practical automated calibration methods have been developed. For example the largest segment of the remaining non-automated workload is an assortment of small inspection tools such as micrometers, calipers, thread gages, hole gages, etc. It is anticipated that the use of such instruments will decrease due to the emphasis on quality. assurance methods built in as integral parts of automated manufacturing and assembly processes rather than traditional inspection methods of products. In spite of this trend, there is no doubt that a large volume of these tools will remain in the calibration workload for the foreseeable future.

The answer to the question therefore is not clear. Certainly, some of the instrument types presently not calibrated by automated methods will be picked up as existing systems are upgraded in performance. However, many other types are waiting for those new or better ideas which undoubtably will come along. One need only look back 10 years to see the great strides made in automated metrology by people with imagination, to conclude that such progress will continue.

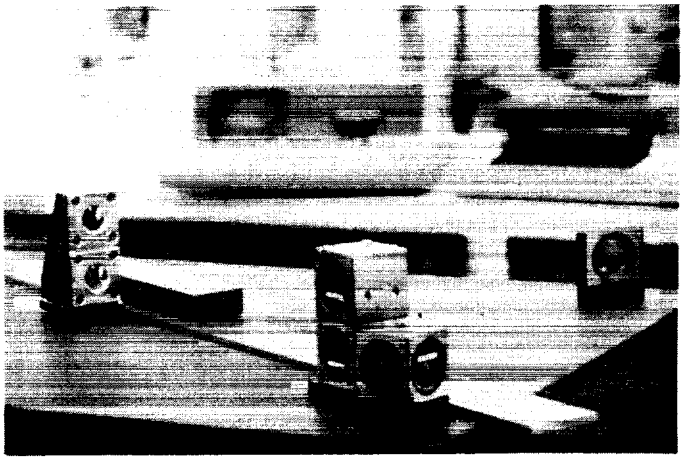
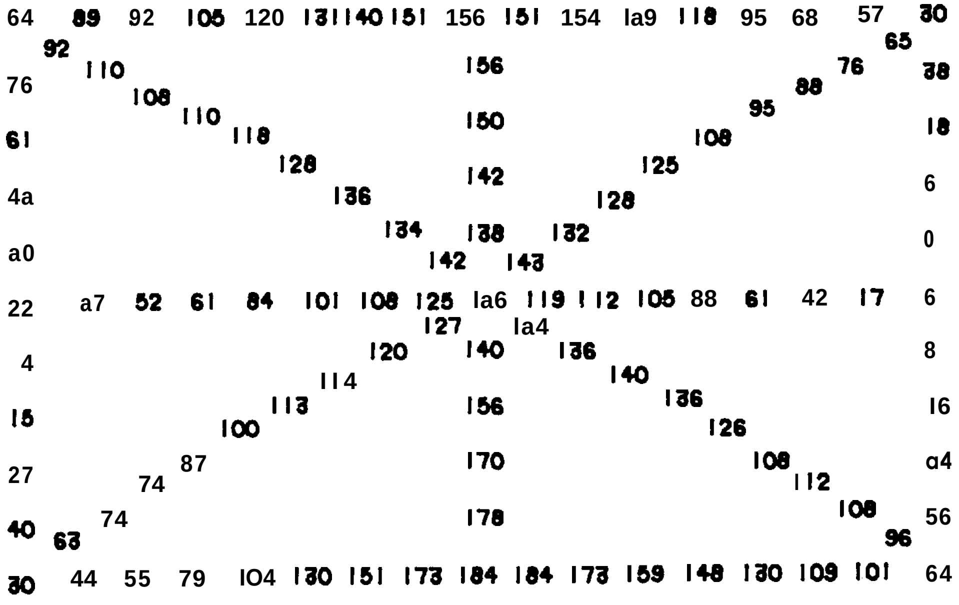


Fig. 1 Automated Surface Plate Calibration



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                            134      138      132
a0                             142      143                                0
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                                   127      la4
4                               120      140      136                      8
                             114                     140
15                        113            156              136              16
                      100                                     126
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Fig. 2 Surface Plate Numeric Plot

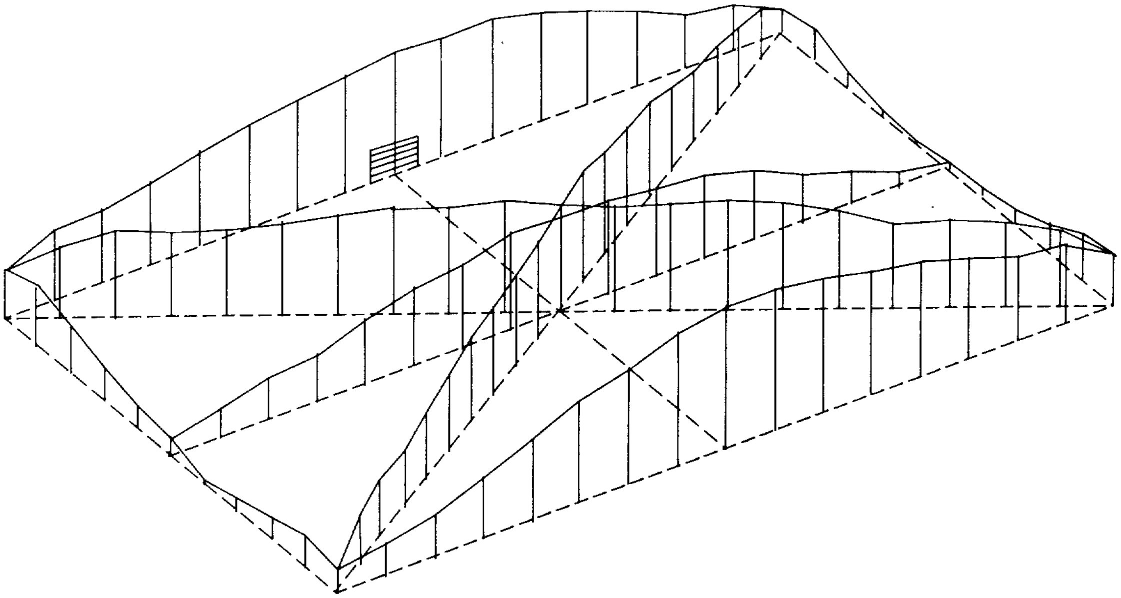

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Fig. 3 Surface Plate Contour Plot

Fig. 4 Load Cell System Fabrication

Fig. 5 Load Cell System Control Console

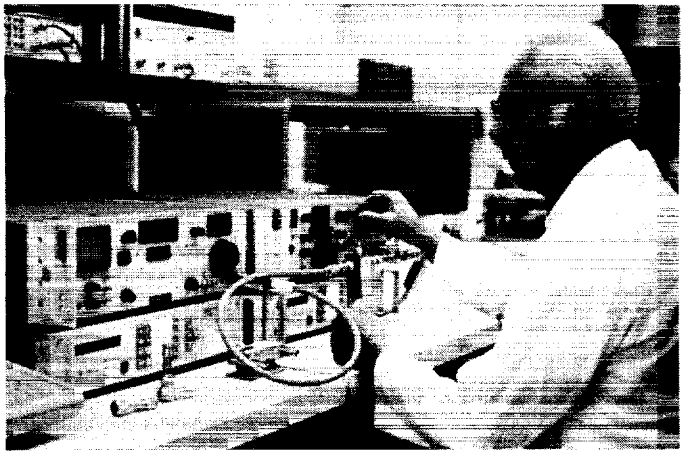

Fig. 6 Automated Microwave Calibration System

Fig. 7 Automated Microwave Power Sensor Calibration System

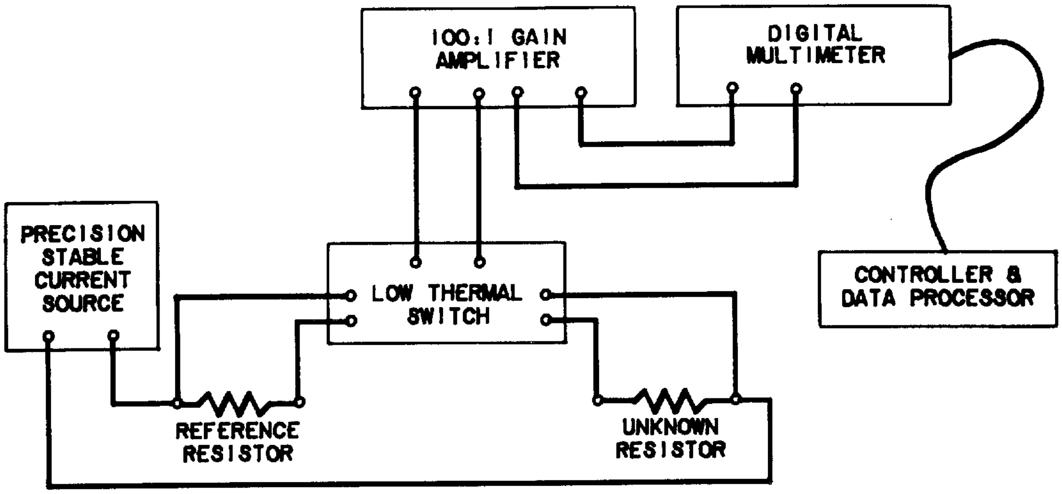

Fig. 8 Automation of Low Value Resistance Calibration

Fig. 9 Automated Oscilloscope Calibration System

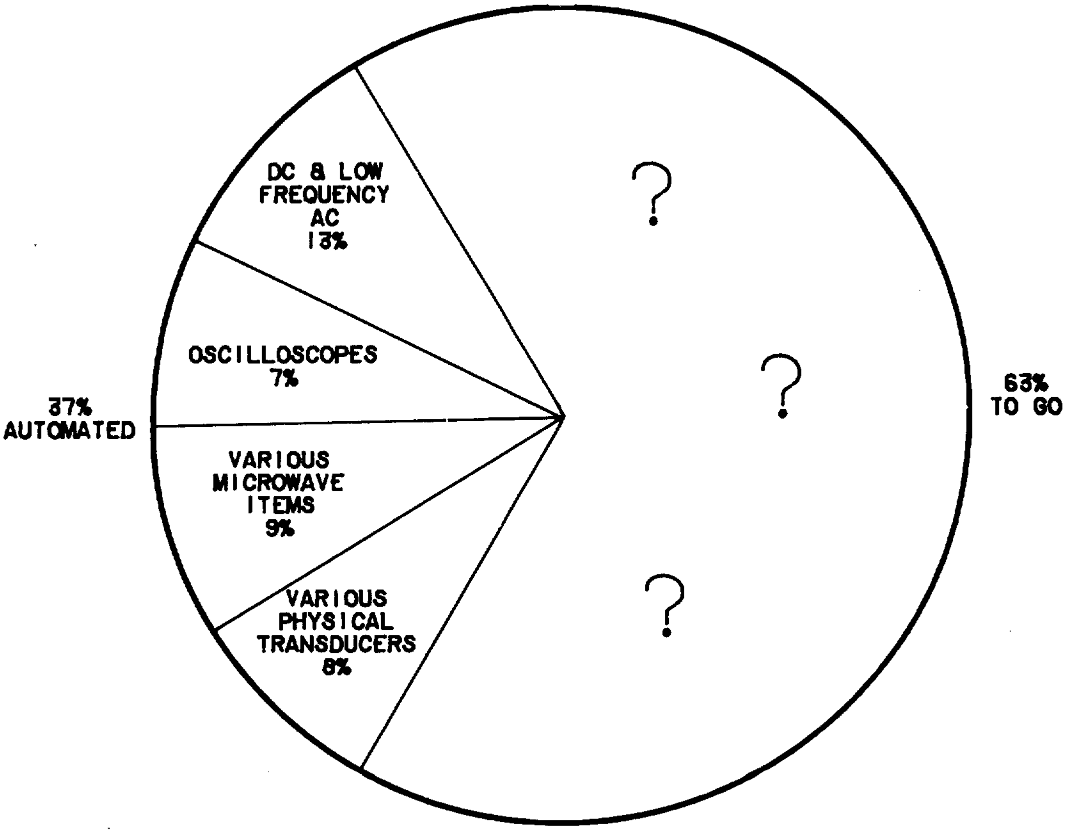

Fig. 10 How Far Can Automation Go?

SESSION II-A

BASIS FOR MEASUREMENTS WHEN THERE IS NOT A NATIONAL STANDARD OR NATIONALLY ACCEPTED MEASUREMENT PROCESS

Selden **McKnight**
USAF Director of Metrology

COPING WITH NON-EXISTENT NATIONAL STANDARDS - AN NBS PERSPECTIVE

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ABSTRACT

The act establishing the US National Bureau of Standards (NBS) lists as a principal function to undertake The custody, maintenance, and development of the national standards of measurement and the provision of means and methods for making measurements consistent with those standards.. .." For many common measurements, calibration laboratories can achieve traceability to national standards by utilizing measurement services provided by NBS. High-level calibration laboratories typically provide calibrations for lower level laboratories in a hierarchical fashion so that measurements at the working level can ultimately be related to national standards. Measurement inconsistencies may develop where national measurement standards do not exist or where measurement services are unavailable from NBS. This paper outlines from NBS perspective the nature of the resulting problems and discusses how they may be resolved.

INTRODUCTION

The act establishing the US National Bureau of Standards (NBS) lists as a principal function to undertake The custody, maintenance, and development of the national standards of measurement, and the provision of means and methods for making measurements consistent with those standards.. . ." For many common measurements, calibration laboratories can achieve traceability to national standards by utilizing measurement services provided by NBS. High-level calibration laboratories typically provide calibrations for lower level laboratories in a hierarchical fashion so that measurements at the working level can ultimately be related to national standards. Measurement inconsistencies may develop where national measurement standards do not exist or where measurement services are unavailable from NBS.

Measurement services provided by NBS to facilitate traceability to national standards include

- o Calibrations and Special Tests (1)
- o Standard Reference Materials (2)
- o Measurement Assurance Program Services (1,3)

For many types of common measurements, e.g. mass, length, temperature, and dc voltage. NBS maintains national standards and provides convenient measurement services. Reference 1 lists several hundred different calibration and special test services available from NBS, and reference 2 lists over 900 different Standard Reference Materials (SRMs) available from the Bureau.

In spite of this plethora of available NBS services, there are a variety of measurements for which NBS, in most cases, does not provide services. Examples are:

Workplace Measurements:

NBS generally focuses its attention on providing services to support the highest level standards laboratories rather than working level measurements. Thus, for example, NBS does not calibrate torque wrenches or bench volt-ohmmeters, since such devices can easily be calibrated to the required level of accuracy by laboratories that utilize NBS services to calibrate primary standards. Similarly, NBS provides accurately analyzed gas SRMs to the pollution control community to facilitate quality control in the production of large quantities of commercial gas reference materials used on a daily basis to calibrate air pollution measuring instruments.

Highly-derived Units:

There is no need for NBS to provide services for units easily derived from base units. For example, NBS does not need to provide velocity calibration services because NBS does provide services for length and time, two fundamental SI units that can be measured to very high accuracies. Those who must calibrate speedometers can utilize these length and time services to derive velocity calibrations.

Certain Ranges of Parameters:

Where a given quantity must be measured over many decades, NBS of ten provides services at one or a few reference points. Thus, while NBS does provide calibration services for microwave parameters such as power and attenuation, these services are only available for certain power levels and for certain ranges of frequencies. NBS SRMs for trace elements in a matrix may be provided only at one level of concentration.

PRIORITIES FOR NBS SERVICES

At no time in its history has NBS ever attempted to provide measurement services for all types of measurements nor would we ever expect to do so at some future date. The number of different kinds of measurements is simply too great. NBS must continually reassess the current mix of services that we do provide and strive to optimize it,

Because of the time required to develop new measurement services, NBS must anticipate future developments. The Federal budget process is such that when a need for a new measurement standard is identified, it typically takes a minimum of 2-3 years before new funding actually becomes available. Where a problem is deemed sufficiently important, reprogramming may be used, that is, work in some existing measurement service area will be terminated in order to free up resources to attack the new requirement, In some cases funding from some other government agency may become available to develop a new standard. Once work begins, it may take 2-3 years of R&D to develop a new standard and verify the technical integrity of the associated service. Thus NBS must anticipate now what services will be needed 5 or 6 years hence if they are to be available when needed.

Often NBS is successful in anticipating needs. For example, several years ago NBS decided that optical fiber measurements were likely to become important and we were able to reprogram a small amount of resources. A research program was begun to develop optical fiber measurement standards and services. This work is now bearing fruit, and it is clear that the decision to pursue this course was a good one. Some times we fail to identify a standards need early enough, but more often, we identify the need but have difficulty locating funding to carry out the R&D required to address the need.

NBS strives to gather up-to-date information from the communities it serves in order to plan future services. Documents such as the NCSL National Measurement Requirements Survey (4) are invaluable for this purpose.

COPING WITH NON-EXISTENT NATIONAL STANDARDS

The ultimate purpose in having national standards of measurement is to minimize measurement errors so that different organizations or individuals measuring the same item will achieve consistent results and produce credible data. The significance of NBS reference standards becomes more clear when we consider how errors affect measurements.

The errors associated with any measurement can be divided into two categories:

- o Random error (imprecision)
- o Systematic error (bias or offset)

(References 3 and 5 provide more detailed information on these two types of error.)

National measurement standards and NBS measurement services provide a means for quantifying (and usually for reducing) the uncertainty of measurement arising from systematic errors, but the random error contribution of a given laboratory s measurement process to the uncertainty of its measurements will be present whether or not national standards exist. Figure 1 and the example described below, which it illustrates, clarify this point.

Consider a hypothetical case that is a simplified version of an actual situation. Suppose industry is interested in measuring microwave/millimeter wave attenuation in some frequency band for which NBS services are not available. Because it is not possible to send a standard attenuator to NBS for calibration in this band, some other approach to achieving consistent measurements must be found. A logical first step in determining how large measurement disagreements between companies are would be to select a high quality attenuator thought to be stable and reproducible and circulate it to interested laboratories to be measured in an interlaboratory round-robin .

Figure 1 illustrates how the data might look if 4 companies took turns making attenuation measurements on this standard attenutator. Each firm measures the attenutation at the specified frequency or frequencies several times, connecting and reconnecting the attenuator for each measurement. (The data might well differ if the measurements were repeated at a different frequency or at much higher or lower power levels.)

There is a certain amount of scatter in the measurements of each company (random error) but the size of the random error varies considerably among the 4 companies. The mean of the measurements of each company would normally be reported as each company s best estimate of the value of the attenuator. The true value of the attenuation is shown by the dashed line, but of course none of the participants in this experiment has any way of knowing what that true value is.

A logical approach to solving the problem of the lack of NBS services for this measurement would be to define the accepted value of the attenuation of the attenuator as the group mean or average of the values determined by the 4 participants. The uncertainty statement would, of course, have to reflect the wide varation in values obtained by the laboratories. In this example, it is clear from the figure that the group mean would be higher than the true value. If a second round of measurements were carried out, each participant could correct the new values obtained by the offset of that participants previous measurements from the group mean determined in the first comparison. Presumably, this would lead to considerably better agreement in the second experiment, although the entire group would be offset from the true value. For actual situations of this kind, guidelines are available for determining how to weight the data from the various participants, how to treat outliers, etc.

If the measurement process in each laboratory is stable, the groups results should quickly converge so that each member would get nearly the same answer when measuring an attenutator of this type at this frequency and power level. The magnitude of the random error or scatter in the measurements of each company would be expected to remain about the same if the experiment were repeated several times.

Note that the previous paragraph begins with If the measurement process in each laboratory is stable. ..". In fact, a key step in this approach is to ensure that each participating laboratory has achieved a state of statistical control within the laboratory before the round-robin with the other labortories begins. The *term state* of statistical control means *a* condition where the precision achieved in a given laboratory is stable and predictable from one set of measurements to the next and where sudden unpredictable shifts in the mean do not occur. Reference 3 describes how one determines whether or not a state of statistical control has been achieved.

Note that in the example above, it is possible for the group to achieve consistent measurements of attenuation even though the whole group may be offset from the true value. Whether or not this offset is a problem depends on the nature of the measurements being made. For some types of measurements, it is only necesssary to have consistency within a given organization or group of laboratories. If so, the method for obtaining a group consensus described above, might be all that is needed. Such an approach works rather well for small groups of participants, however, it would quickly become unwieldy if there were 150 companies that needed to have consistent measurements for this kind of attentuator. If these measurements also needed to be consistent with attentuation measurements made in other countries, the small group consensus method would also be difficult to use. In such circumstances, it is clearly advantageous to have a central organization such as the National Bureau of Standards take responsibility for determining what the true value is and coordinating these measurements with national standards laboratories in other countries.

The example described above is very close to an actual situation. NBS does not currently provide calibration services in the millimeter wave band from 40-50 GHz. Several defense contractors who must make measurements in this range have banded together to carry out experiments to achieve measurement consistency within the group. NBS is helping with the design of the experiments, the analysis of the data , and the selection of measurement methods. There is a consensus among the participants that this approach is the best available *given* current constraints.

For some types of measurements for which national standards do not exist in the U.S., it may be possible to utilize measurement services from other friendly nations such as Canada or the U.K. NBS can provide addresses and phone numbers of national standards laboratories in other countries for those who wish to explore the availability of particular services. Some countries attach surcharges (e.g. 100%) to services provided to parties outside the country, but even when these surcharges are considered, the cost of services from other countries is often comparable to that of NBS services since some other countries subsidize the cost of measurement services provided by the national laboratory.

SUMMARY AND CONCLUSIONS

- It is unlikely that NBS could ever provide all of the measurement services that people need nor maintain all of the national standards that might be convenient.

- It is important to communicate standards needs to NBS so that NBS plans can realistically reflect the current needs of the measurement community. NBS needs to know what standards you need, why you need them, and what the impact will be if these standards are not available.

- Industry and government laboratories that must make measurements for which national standards and/or services are unavailable must still find ways of achieving measurement consistency. In some cases services from other countries may be an option.

- Laboratories that wish to achieve measurement consistency for a given type of measurement for which no standards exist should consider banding together to carry out experiments of the kind described in this paper. Organizations such as IEEE, ASTM, NCSL, EIA, and others can play a role in sponsoring such groups. NBS should be invited to participate in such groups, and within the constraints of available resources can often provide consulting services to help ensure the success of the experiments.

o National measurement standards provide a way of reducing systematic errors or offsets to acceptable levels but do not directly provide a way of reducing random error, which can only be done by each laboratory. Group interactions of the kind described in this paper can help group members achieve measurement consistency , but persistent offsets from the true value may still exist.

o Data generated by interlaboratory round-robins should be carefully documented for future reference. Statistical control methods should be utilize to analyize the data and establish realistic uncertainty statements for each participant.

REFERENCES

1. Calibration and Related Measurement Services of the National Bureau of Standards , NBS Special Publication 250 (and Appendices thereto), updated periodically. Current edition available from the NBS Office of Physical Measurement Services, Gaithersburg, MD 20899. For a recent update to this publication, refer to McClendon, L.T., and Kirby, R. K. (Editors); NBS Physical Measurement Services Status Report , NBSIR 84-2875, May 1984. (Available from same address.)

2. NBS Standard Reference Materials Catalog , NBS Special Publication 260 (and supplements there to), updated periodically. Current edition available from the NBS Office of Standard Reference Materials, Gai thersburg, MD 20899.

3. Belanger, B. C. (Part I, May 1984) and Croarkin, M. C. (Part II, April 1984) Measurement Assurance Programs , NBS Special Publication 676.

4. Caldwell, D. H., Editor, 1982 National Measurement Requirements Survey , National Conference of Standards Laboratories Report #NMRC 83-01, May 1983.

5. ANSI/ASQC Standard Ml-19XX, American National Standard for Calibration Systems (see Appendix - Quantifying Calibration Errors).

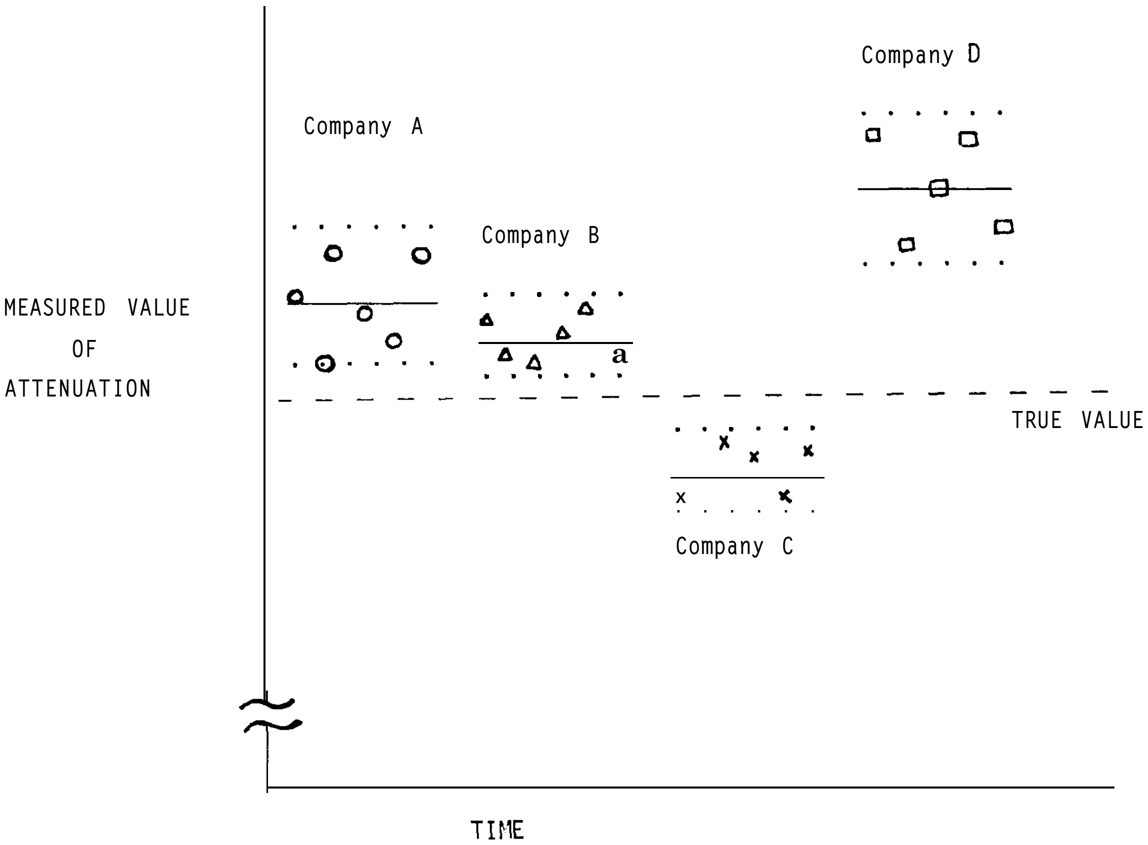

Figure 1. Data from a hypothetical intercomparison of attenuation measurements

SESSION II-B

NEW DEVELOPMENTS IN TEMPERATURE IN NBS AND INDUSTRY

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Lockheed Missiles & Space Co.

STATUS OF THE INTERNATIONAL TEMPERATURE SCALE

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ABSTRACT

In June 1984 the Consultative Committee on Thermometry met in Sevres, France. Representatives from many laboratories throughout the world reported on recent developments in high accuracy temperature measurements. Significant progress has been made in many areas, including: (1) improved realization of the thermodynamic temperature scale; (2) improved fixed points; and (3) improved fitting techniques for platinum resistance thermometers. This article will summarize these results and thus indicate the status of the international temperature scale presently in use.

INTRODUCTION

The ultimate responsibility for international standards of measurement rests with the General Conference on Weights and Measures (GCWM). It meets at the International Bureau of Weights and Measures, which is located on a heavily wooded hill overlooking Paris. To assist it in assessing developments in standards, the GCWM sponsors several consultative committees which generally meet every two years. The Consultative Committee on Thermometry (CCT) last met in June 1984 and I was honored to serve as the U.S. Delegate. This article contains a brief report to the attendees of the Measurement Science Conference on several topics in temperature standards that were discussed at the 1984 CCT meeting. It is intended to provide some perspective on the status of temperature scales to the practitioners of thermometry in science, engineering, and standards.

The GCWM currently acknowledges two international temperature scales. The mature IPTS-68 enjoys the full and formal sanction of the GCWM; it begins at 13.81 K and has no upper bound. The EPT-76 is a provisional scale, designated by the GCWM to serve as the basis for international thermoinetry from 0.5 K to 30 K until the IPTS-68 is replaced. The logical structure of both scales is the same: values of temperature are assigned to a set of well-defined fixed points and a prescription is given for calibrating specified interpolation devices using the fixed points. The third and very important feature of the scales is that they be as close as possible to the thermodynamic Kelvin (i.e., the "absolute") scale as other conditions (e.g., "smoothness","high precision) permit. This last feature imposes on the scientific community a continuing responsibility for conducting thermometry experiments with the best possible thermodynamic accuracy so that the resulting scales are meaningful.

This report on the 1984 CCT meeting will address specifically the latest developments in these three salient features of the temperature scales. We will start with a discussion of the thermodynamic accuracy of the two scales as we now understand it, then proceed to a treatment of the fixed points, and finish with a discussion of interpolation devices.

THERMODYNAMIC ACCURACY OF IPTS-68 AND EPT-76

Ultimately, a thermodynamically accurate measurement of temperature must rest on the application of a physical law which unambiguously relates some measured quantity to temperature. Such laws are surprisingly sparse; to date only a trio has been used in careful temperature measurements. These are the ideal gas law, black body radiation, and Nyquist *noise.*

A recurring question at the CCT meeting in assessing the thermodynamic accuracy of the international temperature scales is: How do the latest results using these different laws compare? Secondly, if there is a consensus among these results which can be believed, how do the scales being used now (i.e., IPTS-68 and EPT-76) deviate from that consensus?

With the help of documents presented during the CCT meeting, we can phrase eloquent answers to these questions in graphical form. In Figure 1 we display the results for the region extending from 0 K to 273 K, while the data from 273 K (0 °C) to 1337 K (1064 °C) are shown in Figure 2. We have chosen to present the results in two graphs because the ordinates differ by about a factor of 50 in the two different temperature regions. These figures represent my somewhat imaginative attempt to include information discussed at the CCT meeting as well as some previous results reported in the literature. Individual data points are not shown; instead the shaded band in each figure defines the region into which all the data fall. Individual contributors and their institutions are not identified because much of the work is in press and because proper acknowledgement would unduly lengthen this article. The figures will be discussed instead in terms of the physical laws used to obtain the data. These two figures are intended only to serve as a rough indication of the status of the temperature scale. More accurate summaries will undoubtedly appear (1). The reader may be assured, however, that the likelihood is small that the figures will change significantly in subsequent treatments.

Consider now the temperature region described in Fig. 1. On the ordinate we plot the difference $T-T_i$, where T is taken as the best estimate to the thermodynamic temperature scale and where T_i refers to temperatures defined by the EPT-76 ($i=76$) or by the IPTS-68 ($i=68$). The consensus of the measurements is immediately apparent (i.e., the black band) as is the inaccuracy of these temperature scales. In the region defined by EPT-76, measurements were made using gas thermometry at one national standards laboratory from 2.4 K - 28 K, gas thermometry at a second from 14 K - 100 K, gas thermometry at a third from 14 K - 300 K, and noise thermometry at a fourth institution from 2 K - 4 K. The region below 2 K was defined by extrapolation and by self-consistency of the vapor pressure of He^3 and He^4. There has not been much recent activity in this region, so that only one paper was submitted to the CCT in 1984 and it concerned itself with the agreement of the EPT-76 with preceding scales.

In the region in Fig. 1 defined by the IPTS-68, a truly impressive amount of data has been taken and compared. The results are based - with the exception of a single data point near 83 K taken with a noise thermometer -entirely on gas thermometry . Data from four laboratories fall within the shaded band in Fig. 1, which is a remarkable consensus indeed. The only improvement to these data which might be achieved would be to include more measurements based on noise thermometry. We argue that measurements based on two physical laws can inspire more confidence in the accuracy of the results than can measurements based on a <u>single</u> physical law, because systematic effects are varied more significantly in the former case.

In Fig. 2 we have plotted the estimated thermodynamic inaccuracy of the IPTS-68 at high temperatures. Note that the vertical scale for Fig. 2 is coarser than that of Fig. 1, reflecting the fact that the discrepancies increase at higher temperatures. Note also that convention specifies the use of a capital T as an abbreviation for temperature when the unit K is used, while t is used for °C. From 0 °C to 460 °C the curve was defined until very recently by only one laboratory's gas thermometer measurements. At the CCT meeting, confirmation of these gas thermometer results from 0 °C to 140 °C (defined by the black band) was achieved using a total radiation thermometer. In the temperature region extending from 140 °C to 460 °C, the gas thermometer results stand alone; the dark band indicates the internal consistency of the gas thermometer data. In the region from 460 °C to 630 °C, new measurements from two laboratories using spectral radiation thermometers were reported to the CCT and were used to define the curve in Fig. 2 for that region. Finally, data using two radiation thermometers and one noise thermometer were used to define the curve appearing in Fig. 2 at its upper extremity. All of these measurements had been reported much earlier than the CCT meeting; no new measurements in this range were reported.

FIXED POINTS

In Table I, we list the fixed points used to define the EPT-76 (●), those used to define the IPTS-68(*) and certain other fixed points (undesignated) which are under consideration for use in a future international temperature scale.

The five superconductive transition points, a relatively new entry into the list, have stimulated a question: Since samples of these materials have been generated to date by only one laboratory, what would be the reference temperatures obtained from samples generated by another? The question may be phrased alternatively as: How closely do the samples measured thus far represent the natural superconducting transition temperature for each material? During the CCT meeting, results were presented for several samples of each material made in the U.S.A., the USSR, and Czechoslovakia. With the exception of one sample exhibiting a broad superconductive transition (and thus discountable), the spread in the transition temperatures was found to be less than 0.5 mK for each material. These data represent a partial answer to the question posed, but clearly more data will be needed before a conclusion can be reached as to how satisfactorily superconductors can provide temperature fixed points. At the same meeting, a few other papers discussed the influence of impurity and of measurement technique on the measured transition temperatures of superconductors.

Another issue regarding fixed points that confronts the CCT is the evaluation of triple points and the replacement of the boiling point of a given material by a nearby triple point of another substance. In general, a triple point is to be preferred for reasons of precision and convenience over a boiling point because a pressure measurement tube must be provided for measurement of the latter while the former may be contained in a completely sealed cell. The CCT sponsored a six-year study in which forty-one sealed cells containing seven different materials were measured by thermometrists in nine laboratories. Three of these materials (Ar, O_2 and equilibrium H_2) are already defining fixed points on IPTS-68, and this study indicated the quality of results achievable with sealed cells. Broadly speaking, the triple points of different samples of Ar and H_2 were found to differ by as much as 0.6 mK, while the spread was two times larger for O_2.

Several cells providing the Ne triple point were examined; measured temperatures of different cells spread by approximately 0.6 mK. The triple point of Ne is being considered as a replacement for its boiling point which is only 2.5 K higher and which presently enjoys the status as an IPTS-68 defining point.

A few measurements on N_2, deuterium and methane were obtained, but the results are rather inconelusive. It would appear that, if some care is taken to assure the purity of the gas, these triple points can come under strong consideration by the CCT as defining points for the scale.

In addition to this experimental study of triple points, the CCT earlier commissioned a compilation and critical evaluation of the data available for many (over 30) materials with phase transitions occurring in the temperature region from 13 K to 3700 K. The CCT has now received this report and has asked that it be published (2). In addition to this document, separate papers submitted to the CCT reported on new measurements of In, CH_4, Ga, Hg, 02, Ar.

INTERPOLATION DEVICES

A discussion of this topic divides itself naturally into four categories corresponding to four temperature ranges.

The first is defined by EPT-76. Debates as to the proper or most useful interpolation device for this region have persisted almost from the day EPT-76 was inaugurated. For the past eight years the CCT has discussed various options which have included gas thermometers, paramagnetic thermometers, and vapor pressure of He^3 and He^4, as well as RhFe alloy resistors. No one candidate seems to stand above the others when all desirable characteristics (thermometric precision, small size, simple measurement instrumentation, simple interpolation equation, commercial availability,...) are considered. At the last CCT meeting the only discussion of this topic centered on a paper which proposed specific properties envisioned for the gas thermometer. The debate seems far from over, but clearly all candidates are possible and any one may be adopted with confidence by a laboratory desirous of establishing EPT-76 in situ.

In the second temperature range, 13 K to 273 K, the situation is very much different. The standard platinum resistance thermometer has reigned as the interpolat ion instrument of choice for many years. Four papers at the CCT meeting embellished the reputation of this device even more and indicated that still better precision may now be achieved with standard platinum resistance thermometers. Arranging the papers in a logical sequence, the first took the temperature scale defined by Fig. 1, smoothed it and showed that a particular thermometer could be fitted to the data with a maximum deviation no larger than 0.3 mK over the full range. A second paper indicated that, when several other platinum resistance thermometers were calibrated versus the first using only eight fixed points, the fitted deviations corresponded only to ±0.2 mK. Leaving out one strategic fixed point increased the residuals to ±1.0 mK, as was shown in a third paper. A fourth paper indicated that platinum resistance thermometers made by five different manufacturers, when compared, showed greater deviations in the behavior (perhaps a factor of 2 or 3) than those reported in the third paper. This last result notwithstanding, it appears that platinum resistance thermometers all conform incredibly well to a universal function of temperature and that differences are equivalent at most to ±1mK throughout this range. The platinum resistance thermometer in this temperature range is undisputably the most precise thermometric instrument available.

In the third temperature range, 273 K to 903 K, the same standard platinum resistance thermometer is also recommended for interpolation. Its excellent precision in this range has been demonstrated by many earlier studies and has not received attention in recent years. No information was therefore discussed at this CCT meeting.

We pass finally to a discussion of the range from 904 K to 1330 K. IPTS-68 is defined here by standard thermocouples. It has been an interest of the CCT for several years to consider redefining this range with an instrument possessing better precision than the standard thermocouple (-0.1 to 0.2 K).

At this CCT meeting an impressive amount of data (11 papers) was reported on the stability of several platinum resistance thermometers prepared especially for high temperature service. Most of the resistors tested were supplied by China following the CCT meeting two years earlier, in response to a request by the CCT for more detailed study of the thermometers. The studies also involved a few thermometers that were produced in the U.S.A. A number of problems were identified, including contamination, electrical leakage, and the fact that not all laboratories observed the same types or extent of instabilities in their thermometers. In studying the data, one has the impression that it is a somewhat premature, but not an especially bold assertion that high temperature platinum resistance thermometers, owing to their superior performance (by a factor of 10), eventually will supplant the standard thermocouple in this temperature region.

SUMMARY AND CONCLUSIONS

It will be the prerogative of the GCWM to construct the next international temperature scale based on data such as we have discussed in this article. Unconstrained, however, by the formal responsibilities and obligations of this body, we may advance a few predictions as to the probable features of the new scale. As for thermodynamic accuracy, most of the research (except possibly for noise thermometry) has been completed below 273 K, while more experiments are called for in regions above 273 K. Further studies of some superconductive transitions and triple points will be necessary before a complete set of reference points can be chosen. Though choice of a single interpolation device below 30 K may yet be difficult, the platinum resistance thermometer appears to be the undisputed choice from 30 K to 1337 K.

It would thus appear that the main body of the next temperature scale has already been cast; what remains is a careful crafting of some of the details.

ACKNOWLEDGEMENT

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REFERENCES

(1) The CCT has charged one of its working groups with the responsibility of constructing an interim table of the deviations of EPT-76 and IPTS-68 from the thermodynamic scale. The report will appear in Metrologia.

(2) Bedford, R.E., Bonnier, G., Maas, H., and Pavese, F., Recommended Values of Temperature For a Selected Set of Secondary Reference Points", Metrologia, Vol. 20, 1984.

TABLE I. Defining fixed points of IPTS-68 and of EPT-76, and some secondary reference points.

Equilibrium State	T_{68}(K)	T_{76}(K)
●Cd superconducting transition point		0.519
● Zn superconducting transition point		0.851
● Al superconducting transition point		1.1796
●In superconducting transition point		3.4145
● ^{4}He boiling point		4.2221
● Pb superconducting transition point		7.1999
*●Triple point of equilibrium hydrogen	13.81	13.8044
*●Boiling point of equilibrium hydrogen at 25/76 standard atmosphere	17.042	17.0373
*●Boiling point of equilibrium hydrogen	20.28	20.2734
● Ne triple point	24.5622	24.5591
*●Ne boiling point	27.102	27.102
		t_{68}(°C)
*O_2 triple point	54.361	-218.789
N_2 triple point	63.146	-210.004
N_2 boiling point	77.344	-195.806
*Ar triple point	83.798	-189.352
*O_2 condensation point	90.188	-182.962
Kr triple point	115.764	-157.386
*H_2O triple point	273.16	0.01
Ga triple point	302.924	29.774
*H_2O boiling point	373.15	100
*Sn freezing point	505.1181	231.9681
*Zn freezing point	692.73	419.58
Sb freezing point	903.905	630.755
Al freezing point	933.61	660.46
*Ag freezing point	1235.08	961.93
*Au freezing point	1337.58	1064.43
Cu freezing point	1358.03	1084.88
Ni freezing point	1728	1455
Co freezing point	1768	1495
Pd freezing point	1827	1554
Pt freezing point	2042	1769
Rh freezing point	2236	1963
Ir freezing point	2720	2447
W freezing point	3695	3422

*Defining point on IPTS-68.
@Defining point on EPT-76.

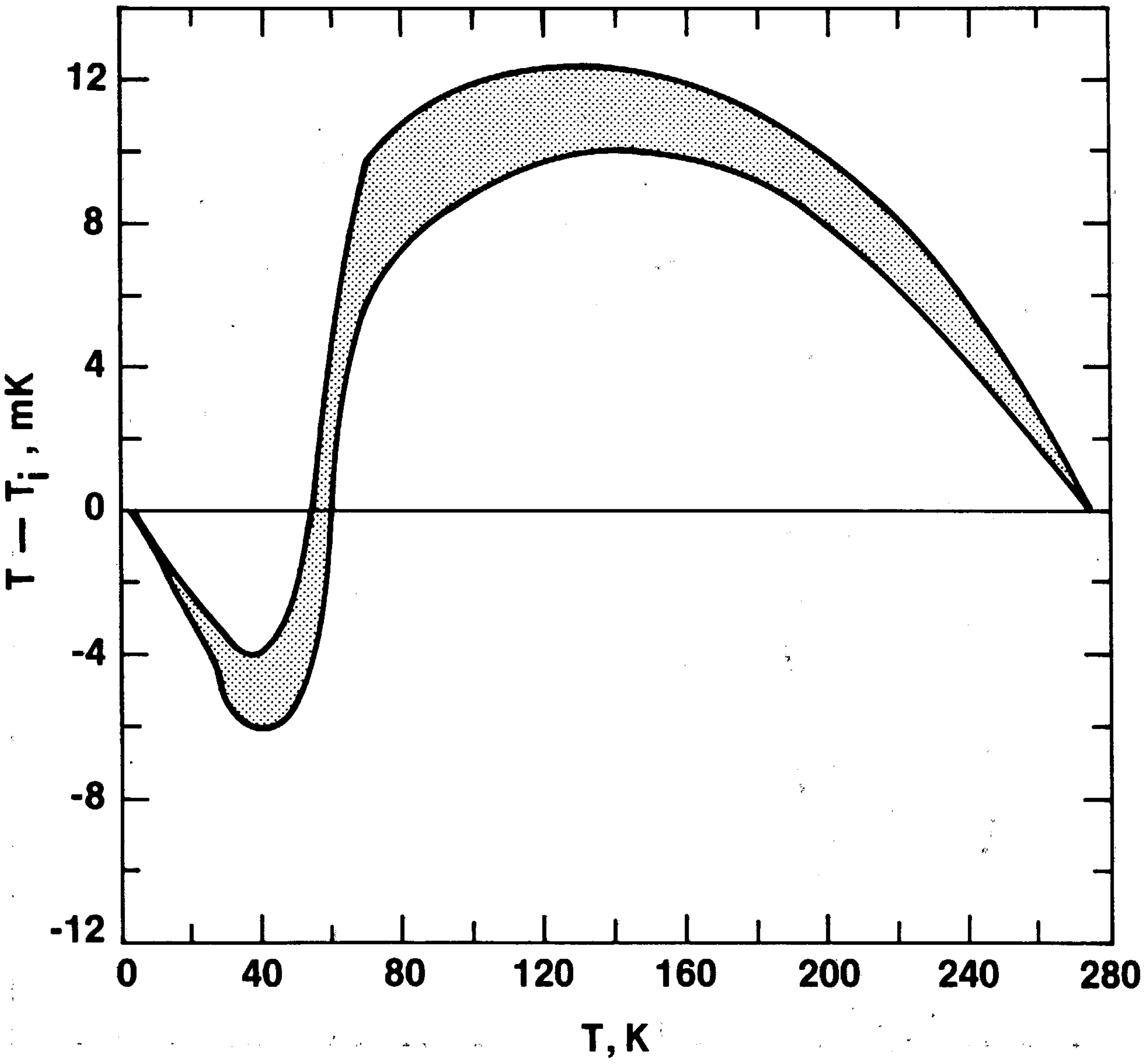

Figure 1. Deviation of EPT-76 and IPTS-68.

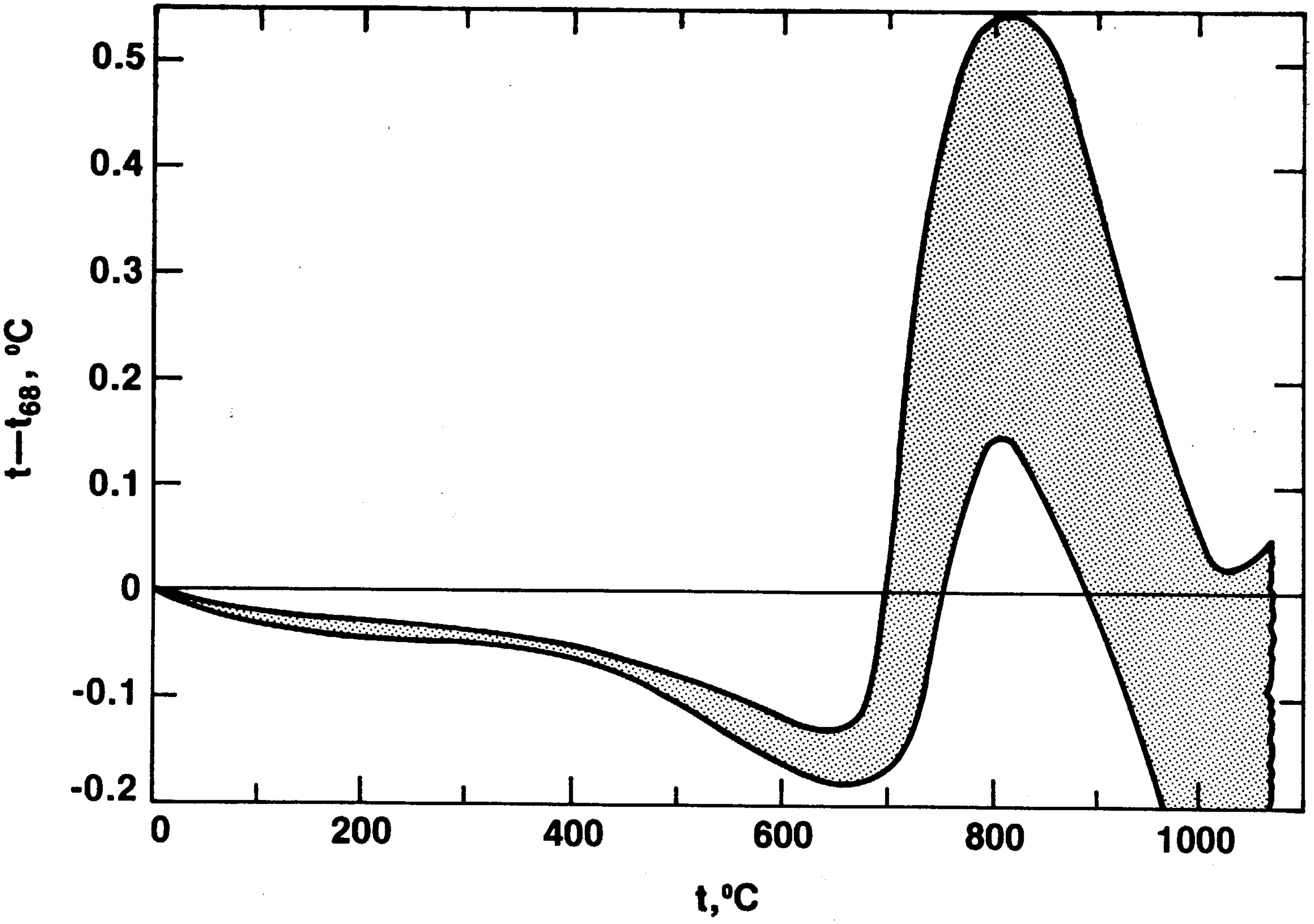

Figure 2. Deviation of IPTS-68.

SESSION II-C

STATISTICAL CONCEPTS-MEASUREMENT PROCESS UNCERTAINTY ANALYSIS

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USE OF TRIMMED MEANS IN MANUFACTURING PRODUCTION

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ABSTRACT

Line engineers want to use techniques whose statistical properties remain reasonably constant for data typical in manufacturing production (outliers in the data). Identifying and trimming outliers from each side of a data-distribution curve has been an approach used intuitively by line engineers for a long time to analyze data. The trimmed mean is obtained from a data set by removing a specified percentage (e.g., 10%) of observations from each side of the distribution. An application of trimmed means to a manufacturing process will be examined in this paper.

INTRODUCTION

To optimally control manufacturing processes, line engineers are continually faced with the responsibility of making decisions based on manufacturing process data. This paper will analyze the case of data distributions that have outliers (long-tailed distributions). Beckman and Cook (1) have written an excellent article on the history of statistical work done in this area. Outlier distributions are common in manufacturing. This paper proposes a statistical technique based on trimmed means to apply to these distributions. The trimmed mean obtained by removing a specified percentage of observations from each side of a data-distribution curve.

Line engineers want to use techniques whose statistical properties remain reasonably constant for data typical in manufacturing. In statistics, a technique is evaluated on the basis of two criteria: validity and sensitivity, and the evaluation is made relative to a specific model, usually the normal distribution. However, in manufacturing process data where outliers are common, the validity and sensitivity of the techniques will sometimes differ greatly from the values calculated based on normal distribution. Techniques whose statistical properties remain reasonably constant for distributions that differ from the normal are called robust. The trimmed mean is a robust statistic. An analysis of robust statistics is given by Huber (2).

Identifying and trimming outliers from each side of a data-distribution curve to analyze data has been an approach that line engineers have used intuitively for a long time. It is only within the last 20 years that this technique has been formally evaluated and shown to give results that are robust for validity and sensitivity. This paper will examine an application of trimmed means to a manufacturing problem. A comparison between statistical techniques based on all the data available and trimmed means will be made to show how different conclusions can be drawn from the data and how results based on trimmed means more closely match the results line engineers might expect to obtain.

BASICS OF TRIMMED MEANS

The trimmed mean is defined as the mean obtained from trimming off a % of the observations from each side of a data-distribution curve. We will use the notation T(a) to denote the α% trimmed mean, for example, T(10) will denote 10% trimmed mean. The mean of a data distribution is defined as T(0) and the median as T(50). We will use the following set of 20 numbers to show how the trimmed mean is calculated: 30, 32, 33. 35, 40, 42, 43, 45, 50, 52, 56, 60, 63, 65, 70, 72, 73, 78, 79, and 80. To calculate T(a) for various values of a, the data has to be arranged in numerical order first. Table 1 shows the value of the trimmed mean for the following trimming percentages: 0, 5, 10, 20, 30, 40, and 50. The trimmed mean, therefore, is simply calculated as the usual arithmetic mean after a% of the observations has been removed from the tails.

The standard deviation of the trimmed mean, S_T, is defined to be:

$$S_T = \sqrt{[(n-1)S_W^2/(h-1)]}$$

where n is the original sample size, S_W is the winsorized standard deviation, and h is the trimmed sample size. Tukey and McLaughlin (3) explain the use of the winsorized standard deviation with the trimmed mean. The winsorized standard deviation is obtained when the values of the trimmed data are replaced by the values of the data points next in line for trimming, after one or more points are removed from each side of the distribution. This set of values is then used in the common way to calculate the standard deviation. The following example illustrates the calculation of the trimmed standard deviation. The 10% trimmed standard deviation, S_{10}, is calculated for the data shown in Table 1. As you can see, the following values remain after trimming 10%: 33. 35, 40, 42. 43. 45. 50, 52, 56, 60. 63. 65. 70. 72. 73, and 78. To determine the winsorized standard deviation, we must first winsorize the data set by adding the values 33. 33, 78, and 78 to the above values; then deviation is calculated in the usual manner, which gives SW = 16.446. Therefore,

$$S = \sqrt{[19(16.446)^2/16]}$$

$$= 17.937$$

STATISTICAL ANALYSIS USING ALL THE DATA

Let's assume that a line engineer has to evaluate three different mixtures (concentrations) of raw materials to determine if any of the mixtures is capable of producing an average viscosity between 22.5 and 23.5 centipoise (cp), based on the data shown in Table 2. [Cornell (4) and Snee (5) explain how to conduct mixture experiments.] Figure 1 is a box plot [Tukey (6)] of the data showing that an extreme observation (a possible outlier is the value in the circle) exists for mixture 3. At this point, the engineer should determine whether this value is an outlier or not, but, for comparison purposes later, we will use all the data to perform the statistical analysis.

We performed a one-way analysis of variance [ANOVA--Snedecor and Cochran (7)] using the figures listed in Table 2 and the result is given in Table 3. Using a 5% significance level, the three mixtures were declared significantly different. We then used the Fisher least-significant difference [LSD--Snedecor and Cochran (7)] multiple-comparison test to determine how significantly different each mixture is from the other two. Although many multiple-comparison tests exist in the statistics literature, we chose the LSD test because it is relatively simple to calculate and is a powerful test [Carmer and Swanson (8)]. This test is a two-step procedure, in which individual pairs of population means are compared. In the first step, a one-way ANOVA is performed. If its result does not reject the null hypothesis (no difference between mixtures) at the 5% significance level, the procedure stops and we conclude that there is insufficient evidence to support differences between population means. If the result of the first step rejects the null hypothesis, we proceed to the second step of the procedure, called the protected LSD procedure). In this step, we apply the two-sample t-test to every pair of means. The LSD statistic is then

$$LSD = t_{\alpha,n-K} \sqrt{[2(MSE)/r]}$$

where $t_{a.\ n-K}$ is defined in a table of critical values that correspond to a significance level of α% and to degrees of freedom equal to the total number of samples minus the number of treatments, MSE is the mean square error obtained from the appropriate ANOVA table, and r is the number of replicates per treatment. Calculating the equation yields

$$LSD = t_{0.05,21} \sqrt{[2(1.763)/8]}$$

$$= 2.080 \sqrt{[2(1.763)/8]}$$

$$= 1.38$$

We then arrange the means of the three mixtures shown in Table 2 in descending order: 24.71, 23.32, and 21.96 for mixtures 1, 2, and 3, respectively. Next. we calculate the difference between the means and if it is greater than the LSD value of 1.38, the two means are declared significantly different at the 5% level. In our example, because the difference between mixtures 1 and 2 is 1.39 (24.71-23.32), the two mixtures are significantly different at the 5% level. A similar calculation for mixtures 2 and 3 shows that the difference is not.

A better method to illustrate the results of multiple-comparison tests is using graphics. Andrews, Snee, and Sarner (9) discuss this method. For the purpose of graphically showing our test, we define the least-significant interval (LSI) as

$$LSI = \bar{x} \pm LSD/2$$

where $\bar{x}$ is the treatment mean and LSD is as defined above. In our graph two mixtures are declared significantly different if no overlap exists between their respective LSIs. Figure 2 shows the LSIs for the three mixtures, from which we note that mixtures 2 and 3 are not significantly different at the 5% level. To determine if any mixture satisfies the specification that the average viscosity be between 22.5 and 23.5 cp. we draw a standard-interval line on the chart at 22.5 and 23.5. If a comparison between the standard interval and the LSI for each of the three mixtures shows that the LSI does not overlap the standard interval, the mixture does not meet the specification; otherwise, it does. Figure 3 illustrates graphically that mixtures 2 and 3 meet the specification.

STATISTICAL ANALYSIS USING 10% TRIMMED DATA

As you will recall from Figure 1, we labeled as an extreme observation the value in the circle for mixture 3. For this analysis, we used a trimmed mean with a trimming percentage of 10% [T(10)]. Hoaglin, Mosteller, and Tukey (10) have conducted studies to determine what effect trimming different percentages has for different data distributions. Table 4 shows the result of trimming 10% (one observation) from each side of the data distribution given in Table 2 after it has been put in numerical sequence. The trimmed mean, x_{t_i} (i=1,2,3), for each of the three mixtures is given at the end of the table. Figure 4 is a box plot of the viscosity for the trimmed data shown in Table 4, from which you can immediately see that the difference between mixtures is more pronounced than that shown in Figure 2 (all data), especially between mixtures 2 and 3.

A study by Yuen and Dixon (11) using the Monte Carlo simulation shows that a two-sample, trimmed-t statistic can be approximated by a student's distribution with degrees of freedom corresponding to the reduced sample. The loss in power when trimmed-t is used is small under exact normality, but the gain may be appreciably larger for long-tailed distributions. If we extend the results of the study to more than two means, then the ANOVA technique based on trimmed means yields satisfactory results.

Table 5 gives the results of the ANOVA for 10% trimmed data. As in the earlier analysis, the F test is significant at the 5% level. As previously, the LSD test is employed to determine which mixtures are significantly different. The LSD value is calculated to be:

$$\text{LSD} = 2.131\sqrt{[2(0.71)/6]}$$

$$= 1.04.$$

The LSI is defined as:

$$\text{LSI} = \bar{x}_{t_i} \pm \text{LSD}/Z$$

$$= \bar{x}_{t_i} \pm 0.71,$$

where $\bar{x}_{t_i}$ is the trimmed mean for each of the three mixtures. Figure 5 is the graph of the LSI for the 10% trimmed data. The results of this graph show that all three mixtures are significantly different from each other. Figure 6 is a comparison of the LSIs and the specifications, showing that only mixture 2 meets the specification.

COMPARISONS OF THE TWO STATISTICAL APPROACHES

A comparison of the LSIs for all the data (Figure 2) and for the 10% trimmed data (Figure 5) shows that mixtures 2 and 3 are significantly different at the 5% level for the trimmed data but not for all the data. The reason for this difference is the outlier that exists in the untrimmed data for mixture 3, as shown in Figure 1.

A comparison of the LSIs and the specification also shows different results: using all the data shows that both mixtures 2 and 3 meet the specification, while the 10% trimmed data shows that only mixture 2 does.

SUMMARY AND CONCLUSION

The example presented in this paper has shown the different results obtained when using trimmed means instead of means based on all the data. When outliers are present, they affect the results of the analysis if they are not taken into account. Trimming the data before any statistical analysis is performed eliminates this problem while keeping the analysis fairly robust. The results so obtained will usually match the engineer's intuitive results more closely than those based on all the data when outliers exist.

REFERENCES

(1) Beckman. R. J. and Cook, R. D., "Outlier....s," Technometrics. Vol. 25. No. 2, May 1983, pp. 119-149.

(2) Huber, P. J., Robust Statistics. John Wiley and Sons, Inc., New York, New York. 1981.

(3) Tukey, J. W. and McLaughlin. D. H., "Less Vulnerable Confidence and Significance Procedures for Location Based on a Single Sample: Trimming/Winsorization 1," Sankya. Series ii, Vol. 25, 1963, pp. 331-352.

(4) Cornell, J. A. Experiments with Mixtures: Design, Models, and Analysis of Mixture Data. John Wiley and Sons, Inc., New York, New York, 1981.

(5) Snee, R. D. "Design and Analysis of Mixture Experiments," Journal of Quality Technology. Vol. 3, No. 4, October 1971, pp. 159-169.

(6) Tukey, J. W. Exploratory Data Analysis. Addison-Wesley, Reading, Massachusetts, 1977.

(7) Snedecor, G. W. and Cochran, W. G., Statistical Methods. Iowa State University Press, Ames, Iowa, Seventh Edition, 1980.

(8) Carmer, S. G. and Swanson, M. R., "An Evaluation of Ten Multiple Comparison Procedures by Monte Carlo Methods," Biometrika. Vol. 68, No. 341, March 1973, pp. 66-74.

(9) Andrews, H. P., Snee, R. D., and Sarner, M. H., "Graphical Display of Means," The American Statistician, Vol. 34, No. 4, November 1980, pp. 195-199.

(ID) Hoaglin, D. C., Mosteller, F., and Tukey, J. W., Understanding Robust and Exploratory Data Analysis. John Wiley and Sons, Inc., New York, New York, 1981.

(II) Yuen, K. K. and Dixon, W. J., "The Appropriate Behavior and Performance of the Two-Sample Trimmed t," Biometrika. Vol. 60, No. 2, 1973, pp. 369-374.

	Trimming Percentage						
Observation	0	5	10	20	30	40	50
1	30						
2	32	32					
3	33	33	33				
4	35	35	35				
5	40	40	40	40			
6	42	42	42	42			
7	43	43	43	43	43		
8	45	45	45	45	45		
9	50	50	50	50	50	50	
10	52	52	52	52	52	52	52
11	56	56	56	56	56	56	56
12	60	60	60	60	60	60	
13	63	63	63	63	63		
14	65	65	65	65	65		
15	70	70	70	70			
16	72	72	72	72			
17	73	73	73	73			
18	78	78	78				
19	79	79					
20	80						
T(α)	54.9	54.89	54.81	54.83	54.25	54.5	54.0

Table 1. Trimmed Means for Various Trimming Percentages

	Mixture 1	Mixture 2 (in cp)	Mixture 3
	22.02	21.49	20.33
	23.83	22.67	21.67
	26.67	24.62	24.67
	25.38	24.18	22.45
	25.49	22.78	22.29
	23.50	22.56	21.95
	25.90	24.46	20.49
	24.89	23.79	21.81
Treatment mean:	x1 = 24.71	x2 = 23.32	x3 = 21.96

Table 2. Viscosity Results for All Data

Source	Degrees of Freedom (df)	Sum of Squares	Mean Square	F
Mixture	2	30.306	15.153	8.59
Error	21	37.030	1.763	

where df is the degrees of freedom, the mixture df equals the number of mixtures minus 1, which equals 2 (3-1=2), and error df is equal to the total df (24-1=23) minus the mixture df. which equals 21 (23-2=21). The value of the F ratio is found by dividing the mean square of the mixture (15.153) by the mean square df error (1.763), resulting in an F value of 8.59.

Table 3. ANOVA for All Data

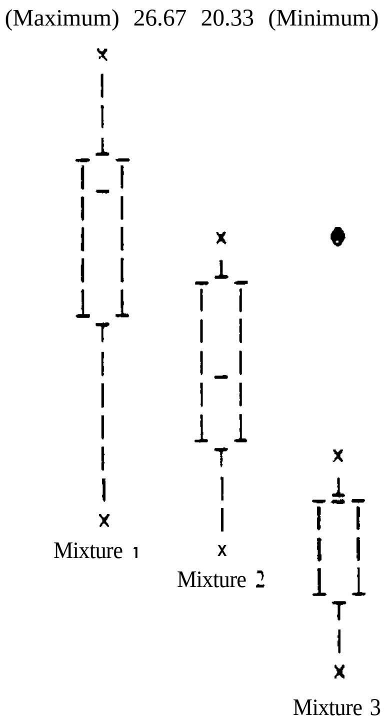
	Mixture 1	Mixture 2	Mixture 3
	23.83	22.67	21.67
	25.38	24.18	22.45
	25.49	22.78	22.29
	23.50	22.56	21.95
	25.90	24.46	20.49
	24.89	23.79	21.81
Trimmed mean:	x_{T2} = 24.83	x_{T2} = 23.41	x_{T3} = 21.78

Table 4. Viscosity Results for 10% Trimmed Data

Source	Degrees of Freedom (df)	Sum of Squares	Mean Square	F
Mixture	2	28.041	14.02	19.88
Error	15	10.577	0.71	

where the error df is equal to the total df (18-1=17).

Table 5. ANOVA for 10% Trimmed Data



A box plot is obtained by calculating the lower and upper quartiles and the median of each mixture, and then plotting these values as shown. In the box plots, the ends of the rectangular box represent the lower and upper quartiles (this distance is called the interquartile distance) and the horizontal line in the box represents the median. The crosses represent the largest and smallest data values that fall between the edge of the box and the interquartile distance measured out from the side of the box. Box values outside 1.5 times the interquartile distance are denoted with a darkened circle.

Figure 1. Box Plot of Viscosity Results for All Data

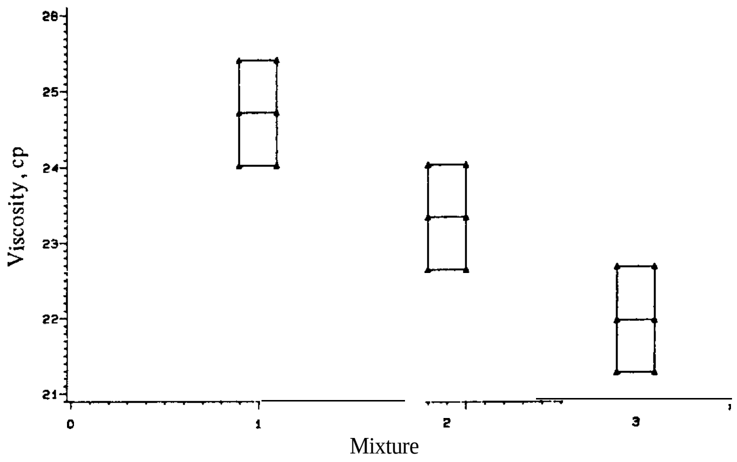


Figure 2. Least-Significant Intervals for All Data

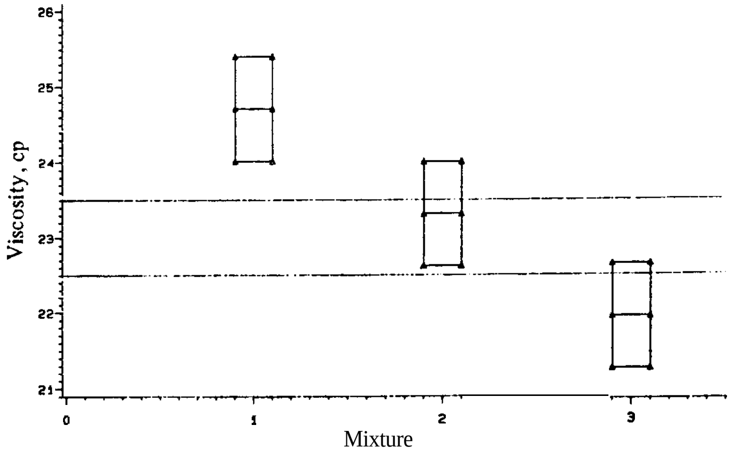


Figure 3. Least-Significant Intervals for All Data--Comparison with Specifications

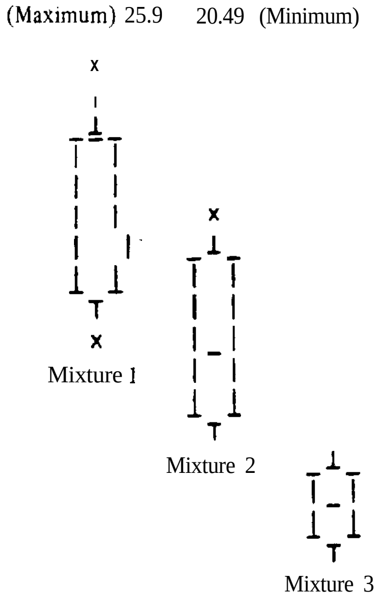


Figure 4. Box Plot of Viscosity Results for 10% Trimmed Data

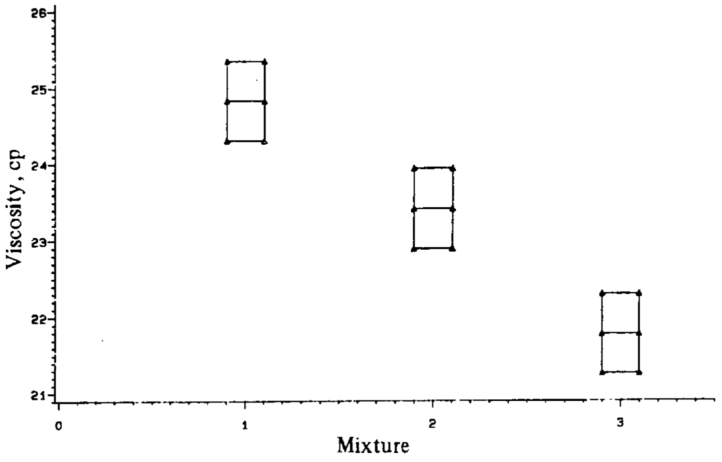


Figure 5. Least-Significant Intervals for 10% Trimmed Data

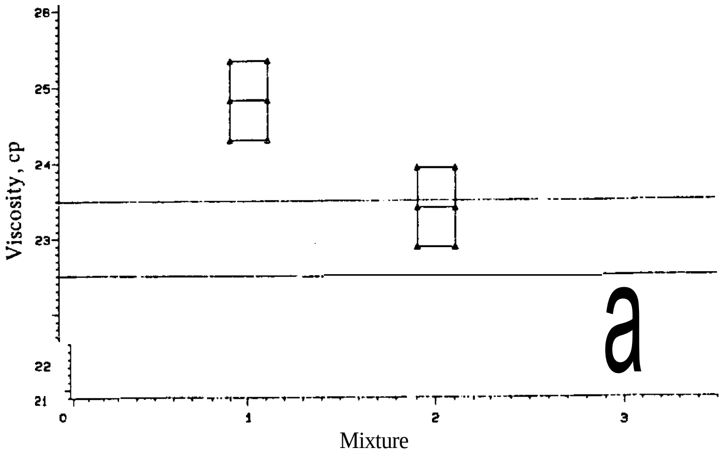


Figure 6. Least-Significant Intervals for 10% Trimmed Data--Comparison with Specifications

AN AUTOMATED ENVIRONMENTAL MONITORING AND ALARM SYSTEM FOR METROLOGY LABORATORIES - A WAY TO DO WHAT YOU SAY!

David R. Workman, Group Leader - Metrology Engineering
Martin Marietta - Denver Aerospace (MMDA)

ABSTRACT

Operation of a metrology system in conformance with MIL-STD-45662 and other applicable specifications requires that calibration environment conditions must either be maintained within specified tolerances or reported as a part of the test instrument performance data. Because it is not practical to record environmental data on all workload, a common practice is to establish a laboratory "normal" environment specification with proviso that calibrations may be performed only when the laboratory meets these requirements. When exceeded, environment must be noted and judgement made as to whether or not conditions will adversely affect the calibration process on an individual item basis. The calibration technician is normally held responsible for monitoring the environment and assuring that subject mandates are being maintained.

With common methodology, it is virtually impossible for technicians to know for sure if working conditions meet specifications. This is particularly true in regards to the critical parameters of temperature and humidity which can contribute significant process errors and result in equipment damage under extreme conditions. It has been noted during tours of many metrology laboratories that instruments used to monitor these parameters were incapable of either assuring specifications or alerting technician personnel when "out of spec." conditions exist. This results in situations where high probality exists that calibrations are being performed under conditions which are in direct violation of both MIL-STD-45662 and company policies.

This paper describes a solution for the specified problems which has been installed at the Martin Marietta-Denver Aerospace (MMDA) Metrology Laboratory in the form of an Automated Environmental Monitor and Alarm System.

DISCUSSION

The subject of environmental control problems is an aspect of Metrology System operation which is seldom publicized outside of an individuals' own company. On the other hand, it has been noted to be a popular "off the record" topic during unofficial meetings of metrology personnel. Observations and experience have indicated that virtually all metrology systems exhibit similiar problems relative to maintaining adequate system environment. While metrologists are righteous and verbose concerning their calibration methodology, standards and traceability, indications are that virtually all organizations have some kind of "dirty linen" where the integrity aspects of their process is related to the environmental system and specifications. This anomaly is not due to lack of cognizance on the part of metrologists as much as it is the result of conditions which are usually beyond their control.

In a typical metrology situation:

a. Metrology engineering establishes specifications for environmental system operation based on standards and contractual requirements, which are designed to minimize adverse effects on the calibration process.

b. Company facilities engineers, who are not normally cognizant of metrology system requirements, design and arrange for construction of the system; usually on a "lowest bidder" basis.

c. Metrology system standards for company operation are written on the basis of agreed upon requirements and design specifications deemed necessary for contractual conformance.

d. The "low bid" contractor installs a system which functions but is either incapable of proper performance without re-work or else marginally meets specifications.

e. Due to combinations of bad design, inadequate control systems, malfunctions and periodic plant maintenance shutdowns, the metrology lab must function under conditions which are less than acceptable for sustained legitimate operation.

f. Metrology supervision "dumps" the problems in the lap of the technician by assigning responsibility for assuring integrity to the individual performing the calibration; but often does not provide the training or equipment necessary to accomplish the assignment.

g- As an overall result, the metrology laboratory must attempt to maintain a productive and legitimate operation under conditions which are ofttimes in direct violation of of their written mandates.

From an honest standpoint, there are no "bad guys" in the above scenario in that all parties are serving the company interests to the best of their abilities. On the other hand, the situation results in conditions under which it can be reliably predicated that periodic environment control system malfunctions are inevitable. While lacking control of the situation, responsibility must still be borne by metrology personnel to assure that knowledge is maintained concerning what the conditions are and respond as required in conformance with their documented procedures.

At present, the mainstays of environmental monitoring in most laboratories are Temperature/ Humidity recorders in circular or strip chart formats. For the most part, these devices have measurement accuracies of ± 2% of span on a 0 to 100 degree F scale (+ 2 degrees F or 1.11 degrees C). Typical laboratory operating environment specifications range from ± (0.5 to 2.0) degrees C. It has been interesting to note that metrologists who would be righteously indignant at the suggestion of calibrating with standards having the same or less accuracy than the device they are testing, routinely base the environmental validity of their operation on instruments having accuracies the same as or worse than the specifications they are attempting to maintain.

Beside the fact that doubt exists relative to the ability of many observed laboratories to measure their specifications, an equally important problem relates to whether or not individuals working within a given system are aware when an out of tolerance condition exists. It has been further noted that many individuals are not cognizant of the performance specifications they are directly responsible for and often do not know what to do when tolerances are exceeded. From a practical standpoint, it has been observed that unless individuals are made aware of the fact that they are calibrating under conditions which do not meet specifications and given specific directions as to what to do, they will not respond or react to environmental changes, unless the conditions produce personal discomfort. This statement is not made in criticism as it is simply the result of the fact that technicians are normally engrossed in productive efforts and oblivious of their surroundings.

In the Denver Aerospace Metrology Laboratory, the stated problems were addressed in 1980 with steps taken to correct them in the new metrology lab then scheduled for construction. An overall solution was indicated to be a computer controlled environmental monitoring system with alarm provisions to alert employees when out of tolerance conditions exist. Despite high levels of management support and problem awareness, budget limitations resulted in the cancellation of the needed capability from the original construction. As such, the required system was not made available for use when the new lab was made operational in April, 1983. Despite this setback, funding was again requested with procurement and installation made in the mid-year 1984 time frame.

SYSTEM DESIGN REQUIREMENTS

At the outset, it was realized that a system of the type required to sustain the subject requirements would not be inexpensive. Because "integrity" is difficult to sell as a sole justification, economic factors would be necessary considerations. Analysis of prevailant operating practices and the fact that the design of the new facility required the monitoring of 12 specific areas, gave proof to the fact that not only would the requested system provide the technical capability necessary for legitimate operation, but would actually save enough in terms of supplies and technician maintenance time for chart recorders to pay for the system in short order. It was further realized that when procured, a powerful tool would be available which offered potential for numerous other laboratory support applications. While the system was requested and justified solely on the basis of environmental monitoring requirements, other applications were considered in the design stage in order to provide the company with maximum utilization potential.

Fundamental environmental monitoring requirements for the metrology system include the following:

1. Temperature
2. Humidity
3. Ambient Pressure
4. Light Levels
5. Radiation
6. Dust Count
7. AC Power Systems
8. Vibration
9. Acoustic Levels

While theoretical capability exists to monitor all of the listed parameters with computer access and data analysis, from a practical standpoint it was realized in the design and procurement stages that attempting to activate all of the indicated capabilities at once would be both technically and economically infeasible. For this reason, it was determined that only the critical areas of temperature and humidity monitoring would be initially addressed; with the understanding that inherent capability existed in the system, given adequate transducers, to establish monitoring capability for the other parameters at a future date.

Because critical temperature parameters include voltage and resistance reference baths, along with area ambient measurements, it was decided to locate the Data Acquisition System in the Electrical Standards Reference Laboratory to provide bath access. Likewise, this was necessitated by the fact that reference bath stability resolution of 0.001 degrees is required; which could only be tested with Platinum

Resistance Thermometers (PRT's) and this type of sensor does not function well with long lead wires.

Temperature and Humidity specifications for normal laboratory operation are as follows:

General Laboratory Areas

Temperature 23 + 1.5 degrees C (73.4 ± 2.7 degrees F)
Humidity 20 to 55%

Reference Laboratory and Balance Room

Temperature 23 ± 1.0 degrees C (73.4 ± 1.8 degrees F)
Humidity 35 to 55% with a 45% nominal setting

Alignment Laboratory

Temperature 20 ± 1.0 degrees C (68.0 ± 1.8 degrees F)
Humidity 20 to 55%

TEMPERATURE AND HUMIDITY TRNASDUCER SYSTEMS

Analysis of temperature requirements indicates that on a 4:1 ratio basis, in order for the subject specification to be verified, a temperature measurement system with uncertainty no greater than ± 0.25 degrees C would be required. While not specified except for limits, it was determined that a ± 5% overall humidity measurement capability would be acceptable.

As previously indicated and illustrated on the Metrology Laboratory layout (Fig. 1), there are 12 identified areas which must be monitored. Two important considerations requiring address were:

1. Selection of a transducer system which would verify system specifications.
2. How to mount the transducers to provide the best approximation of temperature environment at the work station.

The selected course of action was to procure zone monitor transducers which would be capable of both temperature and humidity monitoring with built-in signal processing electronics to simplify data analysis. The device selected was a VAISALA Model HMP 112Y having the following specifications:

Temperature Measurement

Temperature Sensor: Pt 100 1/3 DIN 43760
Temperature Range: -40 to +80 degrees C
Output Voltage: 10 mV/degree C
Accuracy: ± 0.3 degrees C

Humidity Measurement

Humidity Sensor: Humicap
Humidity Range: 0 to 100%
Output Voltage: 10 mV/ %
Accuracy: ± 2.0 % RH (0 to 80%RH)

While the ± 0.3 C temperature accuracy did not meet the indicated requirement of ± 0.25C it was rationalized that when adjusted for system operation and normalized at the nominal levels, overall system accuracy of ± 0.2 C would be obtainable. This rationalization was later proven to be correct during system verification tests.

An important problem which needed to be solved in the design stages was how best to mount the transducers in order to verify the actual working level temperature environment. Because of temperature gradients, it is accepted that the temperature where a transducer is mounted may or not be the same as where the technician is working. As a result, - it was determined that regardless of mounting location, the transducers would be adjusted to read the temperature at a designated reference location working level. Two types of mounting are used, Ceiling Mount (Fig.2) and Wall Mount (Fig.3).

As an afterthought, it was realized that it would be desirable to have monitors at all locations so that the temperature and humidity environments could be verified at the work stations. This is easily accomplished with the selected type of transducer and consists of adding only a low cost dual digital meter assembly, calibrated and scaled to read out directly in temperature and humidity as shown in Fig. 3. Efforts are currently being made to fabricate and install these monitors in all referenced areas.

SUPERVISORS PANEL

All zone transducer outputs are fed to the Supervisors Panel shown in Fig. 4. This assembly acts as a selectable readout for all lab areas. The panel is located adjacent to the control box for the Reference and Balance Laboratory air conditioning systems to facilitate ease of test and adjustment by maintenance personnel. The assembly also acts as a junction box for all signal leads; which are fed from this location to the data acquisition system in the Electrical Reference Laboratory. This panel also is the location of the environment status lights and audible signal system alarm.

DATA ACQUISITION SYSTEM

The Data Acquisition System, shown in Fig. 5 is a HP 30548 mounted in a desk console along with a HP 87 Controller and a HP 9133XV Floppy/ Winchester Disc Drive for data storage. The system has a storage capability of 10.5 Mbyte, of which approximately 7 Mbyte is required for a years environmental performance data. An overall diagram of the entire system is shown in Fig. 6. As indicated, the system not only monitors the laboratory environment and critical reference baths but also acts as the controller for the automatic voltage reference test setup for comparing Saturated Cell and Zener Voltage References. While this portion of the system has not been fully activated, system software is being prepared and when operational, it will perform all critical comparisons automatically at night to avoid the effects of personnel in the area. Preliminary evaluations of the automated cell comparator have indicated capability for 3 Sigma uncertainties in the region of 1 nV with the developed configuration.

While it is theoretically possible to continuously scan and monitor the area transducers, it was determined that 15 minute scanning intervals would be adequate to verify environmental system operation. This interval was selected in order to minimize wear on the scanning system relays and allow time between tests to perform other operations.

As shown on the attached 24 hour system report, hourly reports are provided for all identified areas which indicate the Mean, High and Low temperatures and humidities plus a 24 hour summation. All data are derived from the scanned 4 test per hour series.

Besides a daily operations report, the system has capability for real time identification of zones and parameters which are not meeting tolerances. Notification of out of tolerance conditions is given to laboratory personnel by activation of a timed audible alarm, visual change from Green to Red light condition at the Supervisors Panel and computer readout of the zone and parameters which are not neeting specifications. Alerts are also provided when the system out of tolerance condition is corrected.

An ongoing concern relative to operation of the subject capability is that knowledge of the calibration system environment is required during both work periods and times when the laboratory is unattended. This is particularly true when related to scheduled and unscheduled system air conditioning and power shutdowns. A primary requisite is that the monitoring system must maintain operation during these shutdowns in order to obtain data for evaluation of their affects on system performance. This is another reason why the Data Acquisition System was installed in the Reference Laboratory, as it is powered, along with the Master Voltage Reference, from a 2500 VA battery operated UPS system.

ENVIRONMENTAL AWARENESS

While it is felt that the described capability meets all of the instrumentation requirements necessary for support of critical environmental specifications in the Martin Marietta - Denver Aerospace Metrology Laboratory system, it must be emphasized that without an operating system which is capable of properly using the achieved capabilities, its value would be minimized. What has been found to be of equal importance is the achievement of a state of "Environmental Awareness" on the part of all laboratory personnel. Even with the described capabilities, it has been determined that achievement of this awareness is an ongoing process which requires both technician and supervisory cognizance. In summation, even with what is believed to be a "State of the Art" Environmental Monitor and Alarm System, maintenance of a legitimate metrology system remains an ultimate responsibility of the metrologist.

DISCUSSION OF OVERALL INDUSTRY REQUIREMENTS

As previously indicated, it is believed that conformance with documented environmental specifications is an industry wide problem which affects not only metrology systems but also test and receiving inspection areas. The overall problem stems from the fact that cognizant individuals know what is supposed to be done and their documentation reflects the fact that they are doing it. In practice, because of facility limitations, inadequate environmental monitoring/alarm systems and lack of individual awareness coupled with schedule and productivity requirements, there is likelehood that large quantities of workload are being processed industry wide in direct violation of specified contractual requirements.

A fundamental rule of both metrology and quality control systems is that "You must say what you do and do what you say". If the problems associated with test environment are as widespread as believed, the situation is a "Sleeping Giant" which awaits only higher inspection cognizance; because indications are that many organizations are not "doing what they say".

It should be noted that, while technically and economically justified for the Denver Aerospace operation, a computerized data acquisition system is not a mandatory requirement for legitimate operation. On an overall basis, the industry solution lies more in the development and implementation of programs which are carried out as documented.

Using MIL-STD-45662 and MIL-HDBK-52A as base requirements, the following are mandatory environmental requirements for metrology systems:

MIL-STD-45662

5.3 Environmental Controls. Measuring and test equipment and measurements standards shall be calibrated and utilized in an environment controlled to the extent necessary to assure continued measurements of required accuracy giving due consideration to temperature, humidity, vibration, cleanliness, and other controllable factors affecting precision measurement. When applicable, compensating corrections shall be applied to calibration results obtained in an environment which departs from standard conditions.

In simplified interpretation, this states that a metrology operation must establish and maintain environmental standards of performance which will not adversely affect the performance of calibration. It further states that if the environment differs from what is deemed to be a standard environment corrections will be applied as required.

MIL-HDBK-52A Paragraph (C) further states "The Government representative shall ascertain that all measurement standards and measuring and test equipment applicable to the contract are calibrated and/or utilized in an area in which the contractor has provided controls for environmental conditions to the degree necessary to assure measurements of the specified accuracy."

It is interesting to note that if this statement is taken verbatum it would indicate that if a given level of control is required and mandatory to accomplish a legitimate calibration, the same level would be required in the area where utilized. It is further interesting to note that because on-site calibrations are normally made in areas lacking environmental control, by definition, the whole concept of on-site calibration is not in conformance with the precepts of MIL-HDBK-52A. Carrying the situation to the ridiculous, it could be interpreted to mean that it is illegal to make measurements outdoors because there is no environmental control.

Despite the possible range of interpretations relative to Government Standards, the situation breaks down to the fact that given the basic guidelines outlined in MIL-STD-45662, a contractor must document what he believes to be a legitimate standard of performance and if the supervising inspection agency concurs that the company specifications are acceptable, these are what the contractors performance will be judged on. As such, companies are far more prone to "hang" themselves with their own documents than is the customer with a governing standard. As a general comment, many metrology systems place themselves in jeapordy by documenting environmental specifications of performance based more on what they would like them to be than what they are and compound the situation by stating requirements they have no capability to test. A prime example of this type of specification is temperature rate of change which is often specified but, seldom evidenced as an operational test capability.

As an overall suggestion, it would seem advisable, if an organization wishes to avoid trouble, to closely examine their own specifications and assure that it is both possible to meet them and conformance exists to what is stated. It must be noted that it is far easier to add requirements as needed, than it is to explain items which are claimed but not supported.

In addition, because it is recognized that there will be times when the system will not meet specifications, a fallback plan is necessary to relate what can and what can not be done under adverse conditions. As specifically related to temperature, it is recognized that not all calibrations require a tight reference laboratory specification. As an example of this situation is the general purpose power supply which may have low accuracy specifications and because of non-critical standard requirements can be reliably calibrated in a ± 5 degree range from standard environment. In other cases, it is possible where calibration reports are issued, to merely document the test temperature. In other words, in order to accomplish a legitimate program, more is required than the establishment of simple environmental specifications, as it is necessary to look at all workload, considering both the effects on the test instrument and standard and establish realistic environment requirements based on the type of work being accomplished.

The second factor of legitimate performance, assuming that a realistic company standard and fallback plan are in existence, is that it must be known at all times how the operating conditions relate to the specifications. In order to accomplish this action for critical parameters, equipment must be available that is capable of measuring the designated parameter to the required accuracy. Because it is recognized that technicians can not spend their time productively and stare at environmental monitors, subject devices should also include provision for HI and LO limit alarms to provide indications when a system exceeds standard specifications and when it returns to an in tolerance condition. This coupled with proper company standards and employee indoctrination will, for the most part, satisfy the requirements for sustained legitimate operation.

An example of the type of device required is the Temperature Monitor / Alarm system shown in Fig. 7. It should be noted that it is this instrument which allowed for legitimate temperature system operation in the Denver Aerospace Metrology Laboratory from the 1980 time frame, when anomalies were discovered, until 1984 when the automated system was installed.

The third accepted requirement for maintenance of a legitimate metrology system is that customers usually require records of system performance. Existing temperature and humidity recorders are usually more than adequate to sustain this function so long as it is clearly understood that, if existing systems are not capable of verifying tolerances, they are used only for the purpose of indicating long term trends in system operation. Where other less critical parameters are concerned, log books of performance tests will normally suffice.

In summation, the following check list is given for establishment of a legitimate laboratory environment system:

1. Examine system documentation and assure that stated requirements are realistic and can be supported.
2. Develop a "Fall Back Plan" and document what can and can not be done under out of tolerance conditions.
3. Obtain instrumentation that is capable of monitoring critical parameters and providing alarm when conditions exceed tolerances as determined by local needs.
4. Keep comprehensive records of system performance.
5. Assure that all involved individuals are adequately indoctrinated relative to system requirements and know what is required for maintenance of legitimate system operation.

CONCLUSION

Because of the design and complexity of the MMDA Metrology Laboratory, installation of the described system was deemed to be the only course of action which would provide a legitimate and cost effective long term solution to local environment monitoring and alarm requirements. Upon examination of one's own requirements, it is possible that others may require similiar systems to sustain operation and if such is the case, the MMDA Metrology System offers proof of benefits for having such a capability.

As a final note and point of concern, because observations of questionable integrity have been noted industry wide relating to environmental system specifications, it is strongly suggested that all concerned should take a close look at their own systems and assure that they are "Saying what they do and doing what they say".

ACKNOWLEDGEMENTS

The writer wishes to express appreciation to Martin Management and in particular to B.T. Rotruck, R.C. Schaller and R.E. Hannum whose cognizance and continued support have made the solution of difficult problems possible.

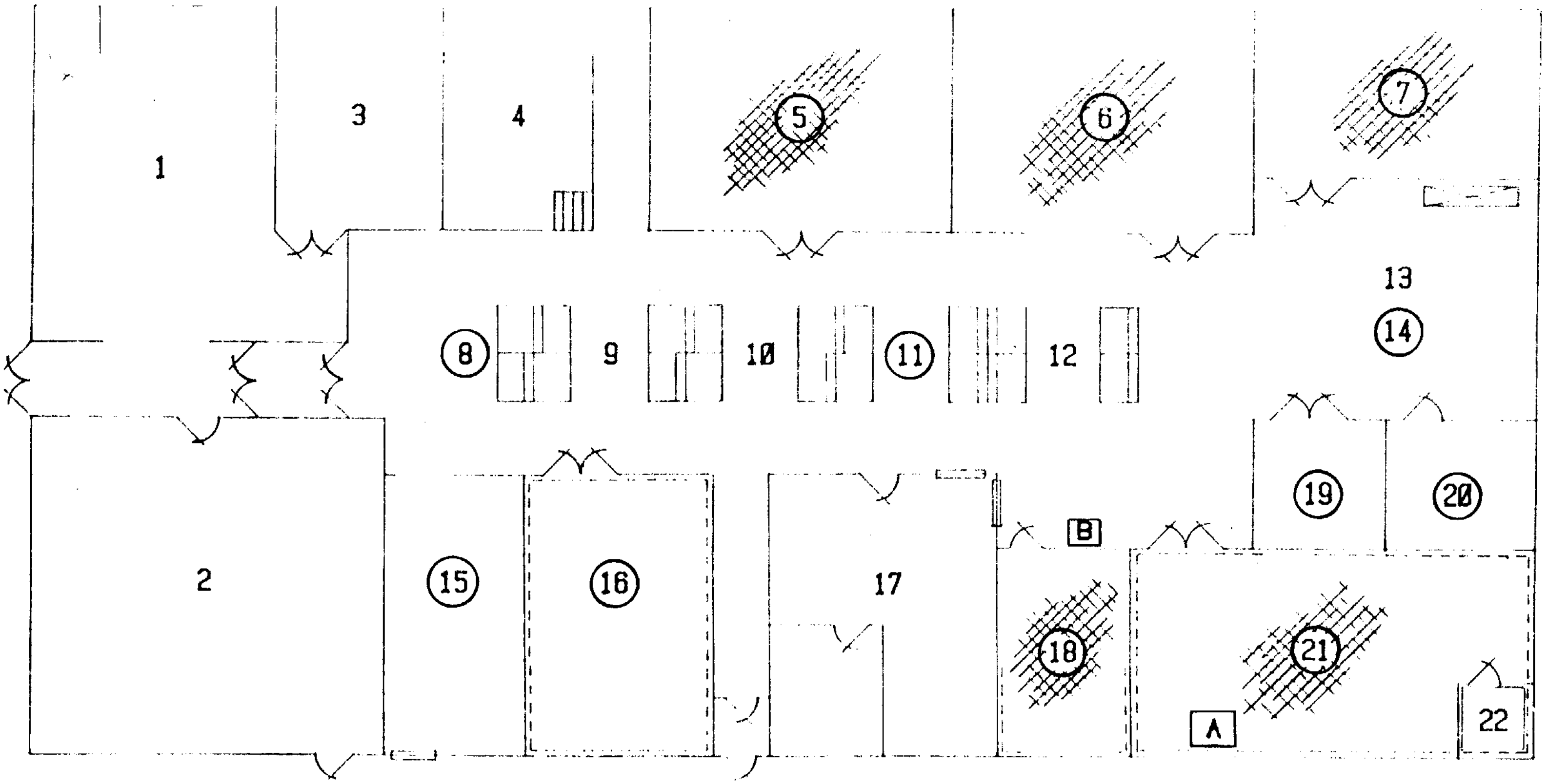
In addition to the above, a note of special appreciation and commendation is given to J.R. Yablonski, who has functioned in the capacity of Engineering Technician on all development projects the writer has been involved in to date. It is safe to say that without the support and expertise of the subject individual, many projects would still be only "paper" reality.

AUTHOR RESUME

David R. Workman is currently functioning as the Group Leader of the Martin Marietta - Denver Aerospace Engineering staff where he has been employed since 1980. Prior to joining Martin, he was employed by SIMCO Electronics, Homestake Mining Co. and Lockheed Missiles and Space Co. Background includes more than 25 years of Metrology Engineering and independent business management.

The subject individual is the author of numerous publications relating to a wide range of Metrology topics, has participated in ANSI Standard Writing Groups and taught Microwave Measurements at San Jose City College, Evening Extension, for 10 years. Mr. Workman is currently active in PMA and NCSL with past association in other professional societies including IES and PMS.

MARTIN-MARIETTA, DENVER AEROSPACE DIVISION METROLOGY LABORATORY



1 INCOMING/OUTGOING EQUIPMENT
2 EQUIPMENT CONTROL CENTER
3 EQUIPMENT CLEANING
4 FORCE CALIBRATION
5 OPTICAL ALIGNMENT CALIBRATION
6 PRESSURE & VACUUM CALIBRATION
7 VIBRATION CALIBRATION
8 ELECTRO-MECHANICAL CALIBRATION
9 GENERAL ELECTRONICS CALIBRATION
10 AC/DC CALIBRATION
11 AC/DC CALIBRATION
12 AC/DC CALIBRATION
13 TEMPERATURE CALIBRATION
14 TORQUE CALIBRATION
15 OSCILLOSCOPE CALIBRATION
16 RF & COMMUNICATIONS
17 METROLOGY SUPERVISION & ENGINEERING
18 MASS CALIBRATION
19 PARTICLE COUNTER CALIBRATION
20 HIGH VOLTAGE CALIBRATION
21 ELECTRICAL REFERENCE LABORATORY
22 MAGNETICS CALIBRATION

A. ENVIRONMENTAL MONITOR SYSTEM
B. SUPERVISORS LAB MONITOR/ALARM

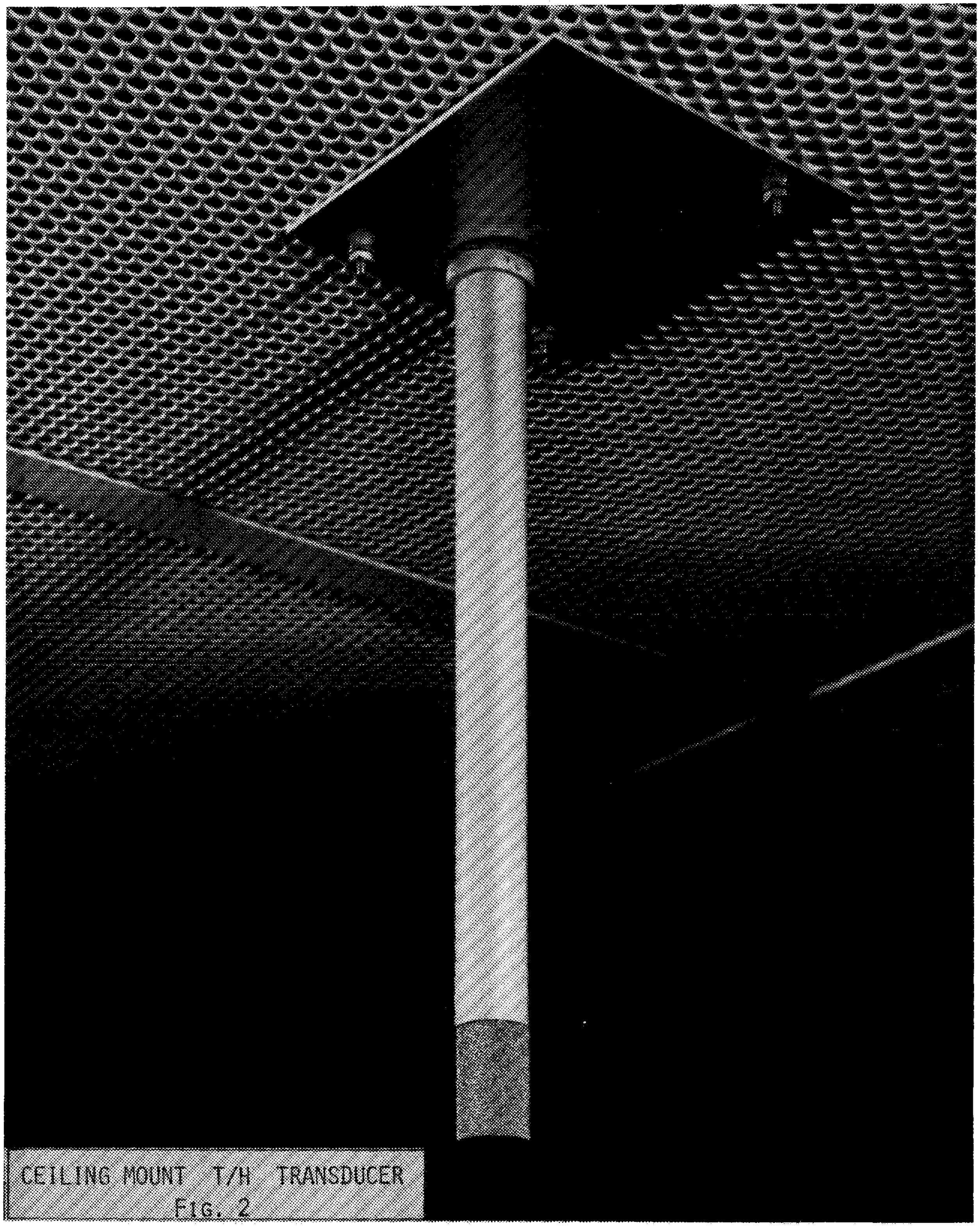
LEGEND

- - - -
RF SHIELDING

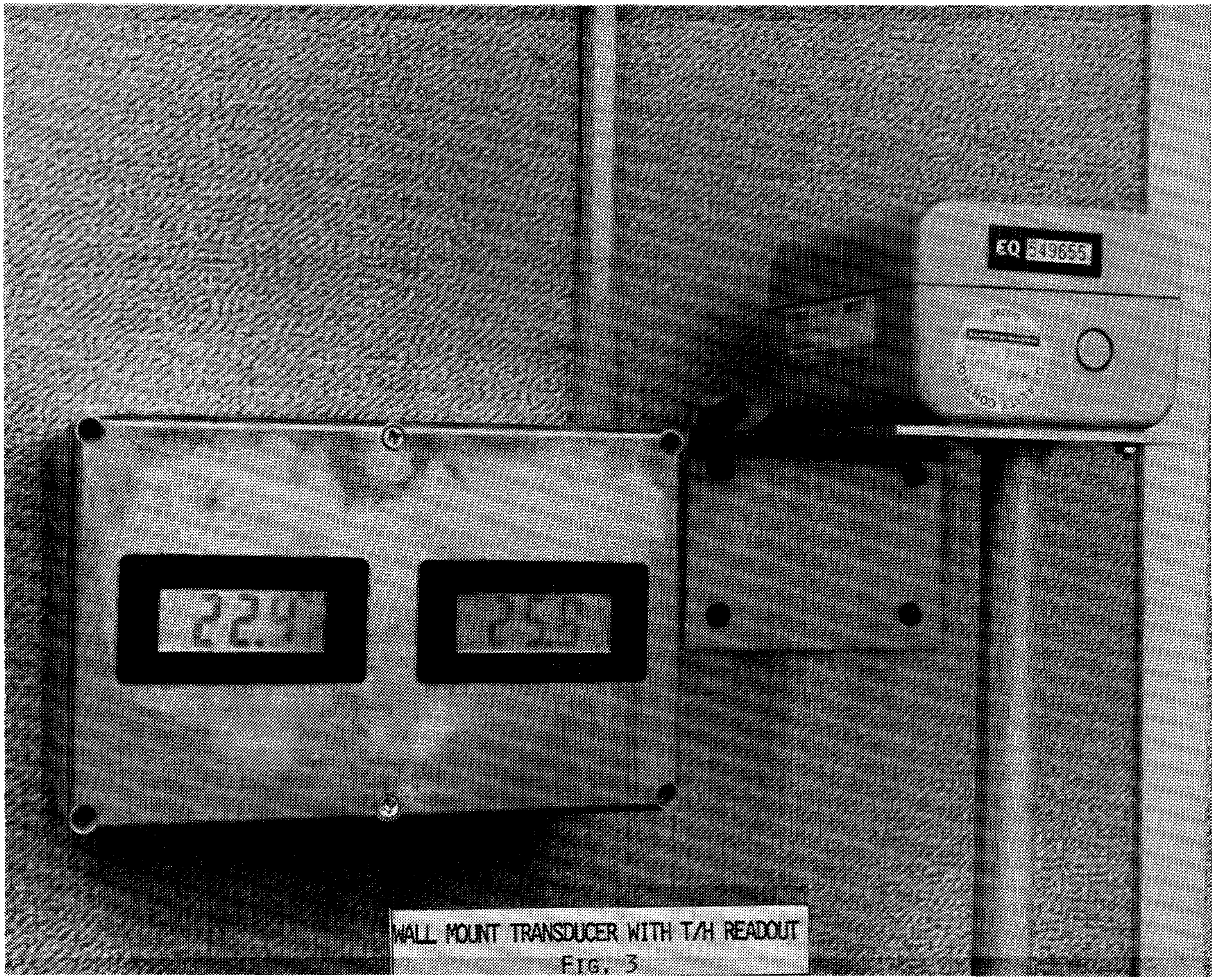
. . . .
MAGNETIC SHIELDING

▨
SEISMIC ISOLATION

FIG. 1

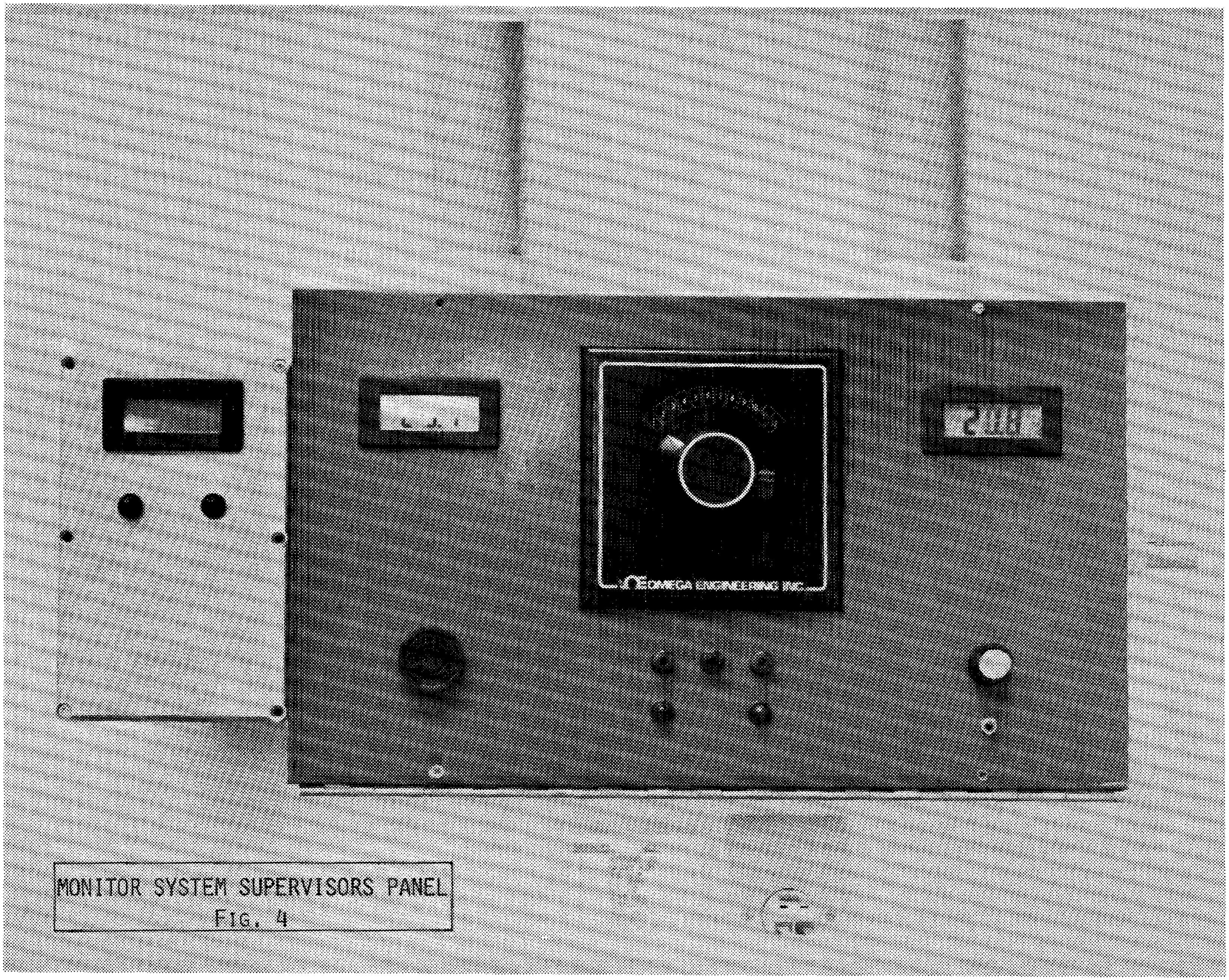


CEILING MOUNT T/H TRANSDUCER
FIG. 2

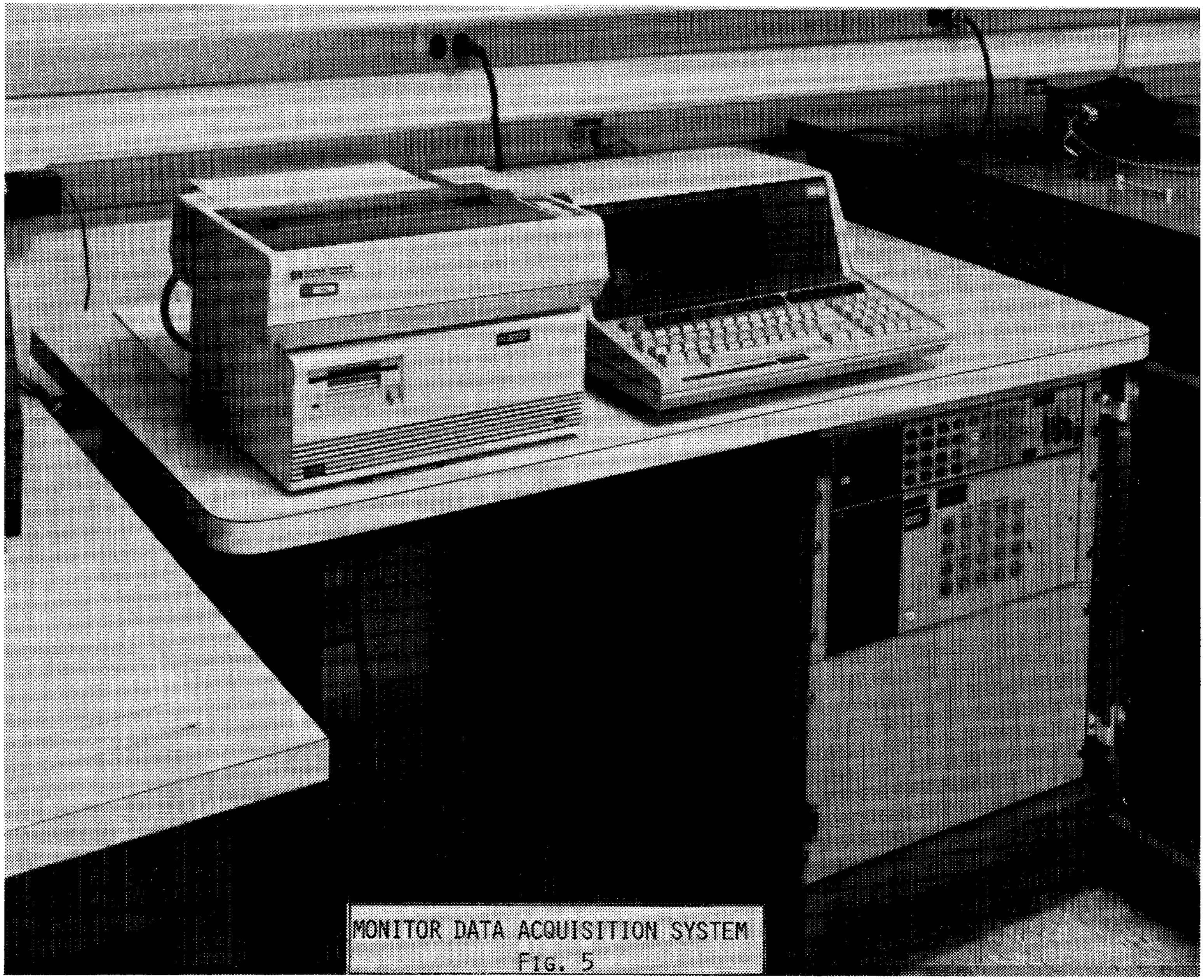


WALL MOUNT TRANSDUCER WITH T/H READOUT

FIG. 3

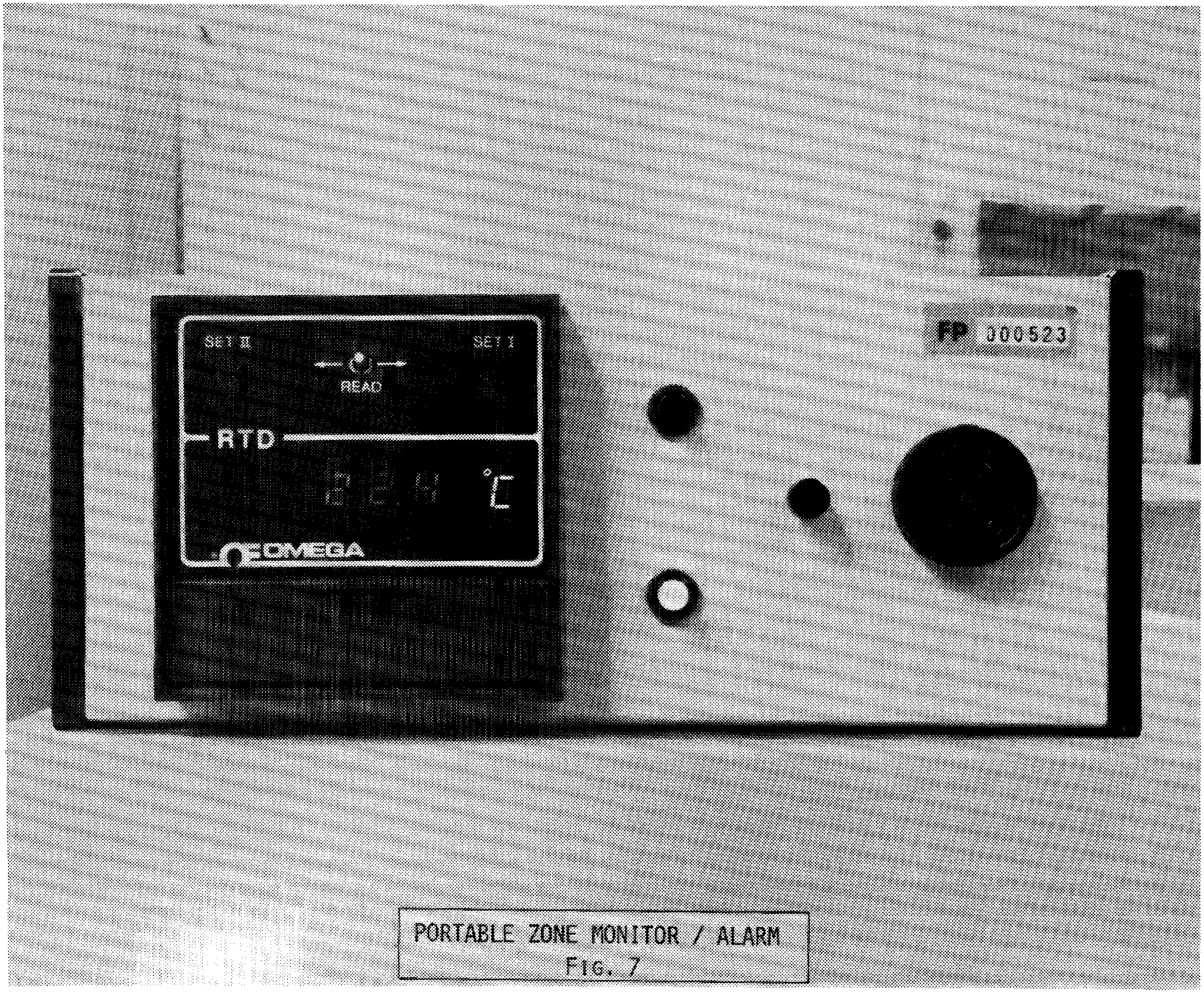


MONITOR SYSTEM SUPERVISORS PANEL
FIG. 4

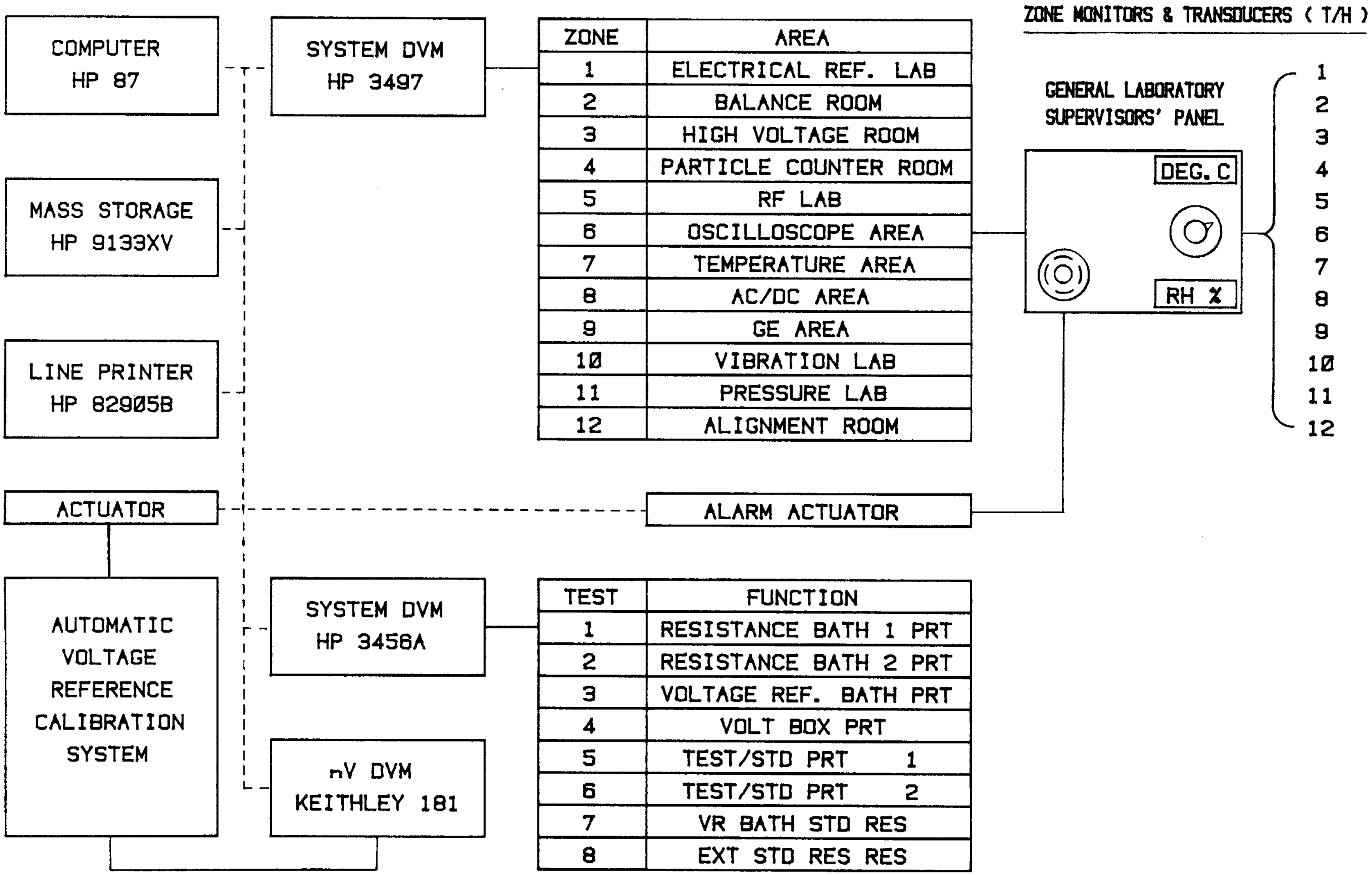


MONITOR DATA ACQUISITION SYSTEM

Fig. 5



PORTABLE ZONE MONITOR / ALARM
Fig. 7



ZONE	AREA
1	ELECTRICAL REF. LAB
2	BALANCE ROOM
3	HIGH VOLTAGE ROOM
4	PARTICLE COUNTER ROOM
5	RF LAB
6	OSCILLOSCOPE AREA
7	TEMPERATURE AREA
8	AC/DC AREA
9	GE AREA
10	VIBRATION LAB
11	PRESSURE LAB
12	ALIGNMENT ROOM

TEST	FUNCTION
1	RESISTANCE BATH 1 PRT
2	RESISTANCE BATH 2 PRT
3	VOLTAGE REF. BATH PRT
4	VOLT BOX PRT
5	TEST/STD PRT 1
6	TEST/STD PRT 2
7	VR BATH STD RES
8	EXT STD RES RES

MARTIN MARIETTA-DENVER AEROSPACE METROLOGY LABORATORY
ENVIRONMENTAL MONITOR SYSTEM
FIG. 6

DENVER AEROSPACE METROLOGY LABORATORY ENVIRONMENT DAILY REPORT
FOR
DATE:11/10/84 DAY:SATURDAY DAY OF YEAR:315 WORKWEEK:45

ZONE	LABORATORY AREA	PARAMETER	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00
1	REFERENCE LAB	TEMP.AVG. C	23.08	23.08	23.13	23.13	23.16	23.19	23.15	23.13	23.06	23.06	23.04	22.99	22.99
		HI C	23.11	23.11	23.17	23.16	23.17	23.22	23.18	23.16	23.14	23.09	23.07	23.01	23.02
		LO C	23.06	23.06	23.09	23.11	23.15	23.18	23.13	23.12	22.98	23.04	23.01	22.96	22.98
		HUM. AVG. %	40.8	41.1	40.3	40.1	38.3	37.3	37.8	39.5	41.9	42.8	42.7	44.5	45.3
		HUM. HI %	42	41.9	40.9	40.8	39.4	37.8	38.9	40.1	43.7	43.2	43.7	45.1	46.8
		HUM. LO %	39.9	40.7	39.8	39.7	37.5	37	37.4	39.1	39.4	42.4	42.1	44	44.4
2	BALANCE LAB	TEMP.AVG. C	22.01	21.94	21.87	21.92	21.88	22.15	22.46	22.62	22.73	22.78	22.79	22.84	22.86
		HI C	22.05	21.98	21.9	21.94	21.92	22.34	22.51	22.66	22.79	22.8	22.81	22.85	22.88
		LO C	21.97	21.9	21.86	21.92	21.85	21.92	22.4	22.6	22.66	22.76	22.76	22.84	22.84
		HUM. AVG. %	40.8	41.3	40.8	40.4	38.6	36.8	36.5	37.8	39.9	40.6	40.5	42	42.8
		HUM. HI %	42.4	42	41.4	41.3	39.8	37.1	37.6	38.2	41.5	41	41.3	42.5	44.3
		HUM. LO %	39.7	40.9	40.3	40	37.9	36.2	36	37.3	37.8	40.4	40	41.5	42
3	HIGH VOLTAGE LAB	TEMP.AVG. C	21.75	21.64	21.57	21.51	21.46	21.54	21.71	21.79	21.91	22.06	22.2	22.23	22.25
		HI C	21.79	21.69	21.61	21.54	21.5	21.64	21.74	21.83	21.99	22.11	22.22	22.26	22.27
		LO C	21.7	21.59	21.53	21.48	21.44	21.46	21.67	21.76	21.84	22.02	22.19	22.22	22.23
		HUM. AVG. %	30.4	30.9	30.9	31	30.7	29.8	29.3	29.5	30	30.1	29.6	29.6	29.7
		HUM. HI %	30.5	31	31	31.1	31	30.2	29.5	29.7	30.3	30.2	29.8	29.7	30
		HUM. LO %	30.3	30.7	30.9	31	30.4	29.6	29.2	29.4	29.8	30	29.5	29.6	29.6
4	PARTICLE LAB	TEMP.AVG. C	23.89	23.79	23.72	23.66	23.61	23.74	23.95	24.05	24.13	24.18	24.23	24.28	24.31
		HI C	23.93	23.83	23.76	23.71	23.66	23.86	23.99	24.1	24.18	24.21	24.26	24.3	24.33
		LO C	23.83	23.74	23.69	23.64	23.58	23.63	23.92	24.02	24.09	24.16	24.23	24.27	24.28
		HUM. AVG. %	30	30.2	30.3	30.3	30.1	29.4	29	29.2	29.6	29.8	29.5	29.6	29.7
		HUM. HI %	30.1	30.3	30.4	30.4	30.3	29.7	29.2	29.3	29.8	29.9	29.6	29.7	29.9
		HUM. LO %	29.9	30.2	30.2	30.3	29.9	29.3	29	29.1	29.3	29.8	29.5	29.6	29.6
5	RF LAB	TEMP.AVG. C	22.04	22.06	22.06	22.09	22.09	22.11	22.12	22.1	22.07	21.96	21.95	21.94	21.91
		HI C	22.06	22.11	22.1	22.17	22.18	22.17	22.21	22.18	22.08	22.06	22.13	21.98	22.15
		LO C	22.01	22.04	22.04	22.03	22	22.05	22.03	22.05	22.06	21.85	21.86	21.9	21.81
		HUM. AVG. %	33.7	33.8	33.7	33.6	33.4	33	32.9	32.9	33.4	33.6	33.6	33.8	34
		HUM. HI %	33.9	33.9	33.8	33.7	33.7	33.2	33.1	33.2	33.7	33.7	33.9	34	34.3
		HUM. LO %	33.7	33.7	33.7	33.5	33.3	33	32.8	32.7	33.3	33.4	33.3	33.8	33.6
6	SCOPE CAL AREA	TEMP.AVG. C	22.5	22.45	22.49	22.52	22.53	22.49	22.52	22.49	22.52	22.55	22.5	22.52	22.53
		HI C	22.56	22.5	22.55	22.57	22.58	22.53	22.6	22.55	22.59	22.66	22.7	22.68	22.6
		LO C	22.47	22.39	22.45	22.45	22.49	22.46	22.46	22.45	22.48	22.43	22.31	22.36	22.48
		HUM. AVG. %	33	33.2	33.1	32.9	32.7	32.4	32.1	32.3	32.8	32.7	32.8	32.9	33
		HUM. HI %	33.1	33.3	33.2	33	32.9	32.5	32.3	32.6	33.1	32.9	33.1	33.2	33.2
		HUM. LO %	32.9	33.1	33	32.9	32.5	32.3	32.1	32.2	32.5	32.5	32.5	32.8	32.9

DENVER AEROSPACE METROLOGY LABORATORY ENVIRONMENT DAILY REPORT
FOR
DATE:11/10/84 DAY:SATURDAY DAY OF YEAR:315 WORKWEEK:45

ZONE	LABORATORY AREA	PARAMETER	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00
7	TEMPERATURE AREA	TEMP.AVG. C	22.76	22.78	22.73	22.85	22.78	22.72	22.76	22.76	22.37	22.58	22.97	22.96	22.9
		HI C	23.05	23.05	22.98	23.1	22.91	23.1	23.04	23.09	23.15	22.79	23	23.08	22.94
		LO C	22.58	22.46	22.52	22.62	22.57	22.48	22.47	22.42	22.61	22.4	22.93	22.83	22.8
		HUM. AVG. %	33.1	33.2	33.2	33	32.7	32.2	32	32.4	32.9	33.7	33.1	33	33.2
		HUM. HI %	33.5	33.8	33.5	33.4	33.1	32.7	32.6	33	33.6	34.1	33.3	33.2	33.7
		HUM. LO %	32.5	32.7	32.8	32.6	32.1	31.6	31.8	32	32.5	33.6	32.9	32.9	33
8	AC/DC CAL AREA	TEMP.AVG. C	22.57	22.59	22.6	22.62	22.6	22.72	22.66	22.6	22.59	22.66	22.81	22.73	22.63
		HI C	22.62	22.62	22.62	22.66	22.66	22.8	22.69	22.69	22.66	22.68	22.86	22.91	22.75
		LO C	22.53	22.56	22.58	22.58	22.56	22.65	22.61	22.53	22.55	22.65	22.78	22.64	22.56
		HUM. AVG. %	33.6	33.7	33.5	33.4	32.9	32.3	32.4	32.9	33.6	33.8	33.4	33.7	33.9
		HUM. HI %	33.8	33.8	33.8	33.7	33.3	32.5	32.6	33.1	33.9	33.9	33.6	33.8	34.2
		HUM. LO %	33.4	33.7	33.4	33.3	32.4	32	32.3	32.7	33.1	33.8	33.3	33.5	33.4
9	GE/FORCE AREA	TEMP.AVG. C	22.56	22.49	22.54	22.56	22.59	22.79	22.94	23.02	23.05	23.11	23.04	23.05	23.09
		HI C	22.59	22.55	22.59	22.63	22.72	22.85	23.01	23.05	23.12	23.15	23.09	23.12	23.14
		LO C	22.53	22.46	22.47	22.48	22.48	22.75	22.9	22.99	23.01	23.08	23.01	23.01	23.02
		HUM. AVG. %	31.9	32.2	32.1	32	31.6	30.8	30.4	30.4	30.8	30.8	31	31	31
		HUM. HI %	32.1	32.3	32.1	32.2	31.9	31	30.6	30.6	30.9	31	31.2	31.2	31.3
		HUM. LO %	31.8	32.2	32.1	31.9	31.4	30.7	30.2	30.3	30.5	30.7	30.8	30.8	30.8
10	VIBRATION LAB	TEMP.AVG. C	22.17	22.18	22.19	22.18	22.16	22.25	22.14	22.15	22.07	22.14	22.27	22.36	22.18
		HI C	22.2	22.24	22.25	22.24	22.23	22.34	22.24	22.26	22.19	22.27	22.38	22.39	22.3
		LO C	22.14	22.14	22.14	22.12	22.1	22.16	22.04	22.11	22.01	22.09	22.16	22.32	22.08
		HUM. AVG. %	32.2	32.3	32.1	32.2	31.8	31.1	31.2	31.6	32.4	32.5	32	32.1	32.5
		HUM. HI %	32.3	32.4	32.3	32.3	32	31.3	31.5	31.8	32.9	32.7	32.2	32.1	32.9
		HUM. LO %	32.1	32.2	32	32.1	31.6	31.1	31.1	31.3	31.8	32.3	31.8	32.1	32.1
11	PRESSURE LAB	TEMP.AVG. C	22.19	22.14	22.62	22.31	22.25	22.62	22.43	22.46	22.47	22.5	22.37	22.4	22.42
		HI C	22.23	22.2	22.76	22.39	22.35	22.76	22.47	22.53	22.63	22.56	22.41	22.44	22.49
		LO C	22.14	22.1	22.34	22.25	22.18	22.48	22.4	22.44	22.24	22.42	22.34	22.38	22.35
		HUM. AVG. %	32.7	32.9	32	32.5	32.2	31.1	31.3	31.7	32.1	32.2	32.3	32.4	32.5
		HUM. HI %	32.9	33	32.5	32.7	32.5	31.4	31.4	32.2	32.3	32.4	32.4	32.5	32.8
		HUM. LO %	32.6	32.8	31.8	32.4	32	30.9	31.3	31.5	31.9	32.2	32.2	32.3	32.3
12	ALIGNMENT LAB	TEMP.AVG. C	20.5	20.52	20.5	20.52	20.53	20.52	20.52	20.51	20.51	20.54	20.54	20.57	20.55
		HI C	20.52	20.54	20.52	20.53	20.54	20.55	20.55	20.53	20.52	20.57	20.58	20.6	20.57
		LO C	20.49	20.5	20.48	20.51	20.52	20.51	20.5	20.51	20.51	20.52	20.5	20.56	20.53
		HUM. AVG. %	27.3	27.3	27	27	26.4	25.6	24.9	24.6	24.7	24.3	24.2	24.2	24.1
		HUM. HI %	27.5	27.4	27.1	27.1	26.9	25.7	25.2	24.8	25	24.4	24.3	24.3	24.3
		HUM. LO %	27.2	27.2	27	27	26	25.5	24.7	24.6	24.5	24.3	24.1	24.1	24

DENVER AEROSPACE METROLOGY LABORATORY ENVIRONMENT DAILY REPORT
FOR
DATE: 11/10/84 DAY: SATURDAY DAY OF YEAR: 315 WORKWEEK: 45

ZONE	LABORATORY AREA	PARAMETER	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	MEAN
1	REFERENCE LAB	TEMP.AVG. C	22.99	22.95	23	22.96	22.93	22.89	22.92	22.93	22.94	22.93	22.98	22.94	23.02
		HI C	23.02	22.98	23.03	23.06	22.95	22.95	22.98	23.01	22.98	22.97	23.03	22.99	23.22
		LO C	22.98	22.94	22.99	22.88	22.92	22.85	22.9	22.89	22.92	22.87	22.93	22.93	22.85
		HUM. AVG. %	45.3	47.4	46.8	46.2	47	46.9	46.6	46.4	46.6	46.7	47	46.5	43.6
		HUM. HI %	46.8	48	47.4	46.6	47.2	47.3	47.1	47	47	46.8	47.2	46.7	48
		HUM. LO %	44.4	47	45.4	45.7	46.6	46.4	46.2	46.2	46.3	46.7	46.8	46.4	37
2	BALANCE LAB	TEMP.AVG. C	22.86	22.88	22.88	22.85	22.87	22.85	22.88	22.9	22.89	22.86	22.89	22.87	22.6
		HI C	22.88	22.9	22.9	22.89	22.91	22.88	22.9	22.93	22.9	22.89	22.91	22.89	22.93
		LO C	22.84	22.86	22.85	22.8	22.83	22.83	22.86	22.88	22.88	22.84	22.88	22.86	21.85
		HUM. AVG. %	42.8	44.7	44.4	43.7	44.3	44.1	43.9	43.7	43.9	44.1	44.5	43.9	41.8
		HUM. HI %	44.3	45.4	44.9	44	44.6	44.4	44.3	44.4	44.3	44.3	44.8	44.1	45.4
		HUM. LO %	42	44.3	43.4	43.3	44	43.7	43.4	43.4	43.6	43.9	44.2	43.7	36
3	HIGH VOLTAGE LAB	TEMP.AVG. C	22.25	22.27	22.28	22.25	22.24	22.2	22.17	22.15	22.14	22.12	22.1	22.09	21.98
		HI C	22.27	22.29	22.3	22.26	22.25	22.22	22.19	22.18	22.15	22.13	22.12	22.11	22.3
		LO C	22.23	22.27	22.27	22.24	22.22	22.19	22.15	22.13	22.13	22.11	22.09	22.09	21.44
		HUM. AVG. %	29.7	30.5	30.9	30.7	30.7	30.9	30.9	31.1	31.3	31.4	31.8	31.7	30.5
		HUM. HI %	30	30.8	31	31.1	30.9	31	31	31.2	31.4	31.6	32	31.8	32
		HUM. LO %	29.6	30.4	30.8	30.5	30.6	30.8	30.9	31	31.3	31.4	31.7	31.7	29.2
4	PARTICLE LAB	TEMP.AVG. C	24.31	24.35	24.37	24.34	24.35	24.31	24.33	24.33	24.32	24.32	24.3	24.32	24.13
		HI C	24.33	24.37	24.4	24.38	24.38	24.35	24.36	24.34	24.34	24.34	24.33	24.35	24.4
		LO C	24.28	24.33	24.35	24.31	24.33	24.3	24.31	24.32	24.32	24.3	24.29	24.29	23.58
		HUM. AVG. %	29.7	30.2	30.4	30.3	30.2	30.4	30.3	30.4	30.6	30.6	30.9	30.7	30
		HUM. HI %	29.9	30.5	30.5	30.6	30.4	30.5	30.4	30.5	30.6	30.7	31	30.8	31
		HUM. LO %	29.6	30	30.4	30.2	30.2	30.3	30.3	30.4	30.6	30.6	30.8	30.7	29
5	RF LAB	TEMP.AVG. C	21.91	21.93	21.87	21.88	21.87	21.92	22.09	22.1	22.11	22.12	22.09	22.11	22.02
		HI C	22.15	22	22.01	22	21.92	22.1	22.21	22.21	22.21	22.23	22.2	22.22	22.23
		LO C	21.81	21.8	21.78	21.77	21.77	21.75	21.97	22.03	22	21.99	22	22.01	21.75
		HUM. AVG. %	34	34.6	34.7	34.5	34.5	34	34	33.8	34	34.1	34.2	34.2	33.8
		HUM. HI %	34.3	35	34.8	34.7	34.7	34.5	34.3	34	34.2	34.4	34.5	34.4	35
		HUM. LO %	33.6	34.3	34.7	34.4	34.4	33.7	33.8	33.7	33.9	33.9	34	34	32.7
6	SCOPE CAL AREA	TEMP.AVG. C	22.53	22.5	22.46	22.53	22.54	22.53	22.46	22.46	22.5	22.57	22.54	22.58	22.51
		HI C	22.6	22.72	22.57	22.58	22.64	22.65	22.57	22.65	22.66	22.71	22.62	22.71	22.72
		LO C	22.48	22.32	22.37	22.48	22.45	22.39	22.35	22.28	22.35	22.43	22.46	22.5	22.28
		HUM. AVG. %	33	33.7	33.8	33.5	33.4	33.2	33.5	33.3	33.5	33.4	33.6	33.6	33.1
		HUM. HI %	33.2	33.9	34.1	33.6	33.6	33.5	33.7	33.8	33.9	33.6	33.8	33.8	34.1
		HUM. LO %	32.9	33.5	33.6	33.4	33.3	32.9	33.4	33	33.3	33.2	33.5	33.4	32.1

DENVER AEROSPACE METROLOGY LABORATORY ENVIRONMENT DAILY REPORT
FOR
DATE: 11/10/84 DAY: SATURDAY DAY OF YEAR: 315 WORKWEEK: 45

ZONE	LABORATORY AREA	PARAMETER	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	MEAN
7	TEMPERATURE AREA	TEMP.AVG. C	22.9	22.83	22.65	22.59	22.84	22.62	22.9	22.67	22.83	22.79	22.73	22.72	22.78
		HI C	22.94	22.87	22.89	22.67	23.06	22.88	23.09	23.01	23.05	23.02	23.03	22.93	23.15
		LO C	22.8	22.76	22.81	22.49	22.45	22.52	22.63	22.47	22.53	22.48	22.56	22.58	22.4
		HUM. AVG. %	33.2	34	34.4	34.4	34.4	34.5	34.2	34.7	34.4	34.6	35	34.8	33.6
		HUM. HI %	33.7	34.2	34.7	34.6	34.7	34.7	34.7	34.9	34.9	35	35.2	35.1	35.2
		HUM. LO %	33	34	34.2	34.3	34	34.2	33.8	34.6	34.2	34.1	34.8	34.6	31.6
8	AC/DC CAL AREA	TEMP.AVG. C	22.63	22.73	22.63	22.54	22.7	22.62	22.66	22.68	22.68	22.65	22.56	22.65	22.64
		HI C	22.75	22.78	22.77	22.59	22.83	22.7	22.73	22.69	22.73	22.73	22.72	22.72	22.91
		LO C	22.56	22.66	22.57	22.48	22.61	22.58	22.56	22.67	22.62	22.57	22.57	22.59	22.48
		HUM. AVG. %	33.9	34.5	34.9	34.8	34.5	34.6	34.4	34.5	34.6	34.7	35.1	35	33.9
		HUM. HI %	34.2	34.6	35	35.1	34.8	34.8	34.6	34.8	34.8	34.9	35.3	35.1	35.3
		HUM. LO %	33.4	34.3	34.8	34.6	34.2	34.3	34.3	34.3	34.5	34.6	34.8	34.9	32
9	GE/FORCE AREA	TEMP.AVG. C	23.09	23.21	23.17	23.04	23.09	23.11	23.11	23.12	23.06	23.1	23.13	23.09	22.96
		HI C	23.14	23.23	23.24	23.07	23.13	23.14	23.13	23.16	23.09	23.12	23.2	23.15	23.24
		LO C	23.02	23.2	23.06	23.03	23.03	23.06	23.09	23.08	23.02	23.1	23.08	23.04	22.46
		HUM. AVG. %	31	31.3	31.5	31.5	31.5	31.1	31.4	31.3	31.5	31.4	31.5	31.6	31.3
		HUM. HI %	31.3	31.5	31.8	31.7	31.8	31.3	31.6	31.5	31.9	31.6	31.7	31.7	32.3
		HUM. LO %	30.8	31.2	31.3	31.3	31.4	31	31.3	31.1	31.4	31.4	31.5	31.6	30.2
10	VIBRATION LAB	TEMP.AVG. C	22.18	22.29	22.2	22.23	22.24	22.2	22.12	22.22	22.22	22.18	22.16	22.2	22.19
		HI C	22.3	22.31	22.31	22.37	22.33	22.29	22.13	22.35	22.26	22.26	22.22	22.28	22.39
		LO C	22.08	22.27	22.15	22.12	22.15	22.15	22.11	22.1	22.18	22.11	22.11	22.09	22.01
		HUM. AVG. %	32.5	33	33.3	33	33.1	33.2	33.4	33.3	33.5	33.6	34	33.8	32.6
		HUM. HI %	32.9	33.3	33.5	33.2	33.4	33.5	33.5	33.6	33.6	33.8	34.2	34.1	34.2
		HUM. LO %	32.1	32.9	33.2	32.8	33	33	33.4	33.1	33.4	33.5	33.9	33.7	31.1
11	PRESSURE LAB	TEMP.AVG. C	22.42	22.53	22.38	22.45	22.48	22.33	22.32	22.4	22.32	22.37	22.52	22.35	22.4
		HI C	22.49	22.58	22.56	22.65	22.67	22.42	22.41	22.55	22.35	22.71	22.55	22.62	22.76
		LO C	22.35	22.5	22.27	22.24	22.37	22.3	22.24	22.31	22.28	22.21	22.48	22.2	22.1
		HUM. AVG. %	32.5	32.9	33.4	32.9	33	33.3	33.4	33.3	33.6	33.6	33.6	33.8	32.6
		HUM. HI %	32.8	33.2	33.6	33.3	33.4	33.4	33.6	33.5	33.7	33.9	33.7	34	34
		HUM. LO %	32.3	32.8	33.2	32.7	32.7	33.1	33.3	33	33.6	33.1	33.5	33.4	30.9
12	ALIGNMENT LAB	TEMP.AVG. C	20.55	20.56	20.56	20.56	20.54	20.52	20.53	20.54	20.53	20.52	20.52	20.52	20.53
		HI C	20.57	20.59	20.57	20.57	20.56	20.53	20.55	20.56	20.54	20.56	20.55	20.54	20.6
		LO C	20.53	20.55	20.55	20.56	20.53	20.51	20.51	20.53	20.53	20.51	20.51	20.49	20.48
		HUM. AVG. %	24.1	24.6	24.6	24.7	25.4	25.7	25.9	26.1	26.5	26.6	26.7	26.7	25.6
		HUM. HI %	24.3	24.7	24.8	25.1	25.8	25.8	26.2	26.3	26.6	26.7	26.7	26.7	27.5
		HUM. LO %	24	24.6	24.6	24.5	24.8	25.6	25.8	26.1	26.5	26.6	26.7	26.7	24

SESSION II-D

THE EFFECTS OF DATA NETWORKS ON CALIBRATION

Frank Capell
John Fluke Mfg., Inc.

SESSION III-A

BASIS FOR MEASUREMENTS WHEN THERE IS NOT A NATIONAL STANDARD OR NATIONALLY ACCEPTED MEASUREMENT PROCESS (PANEL SESSION)

Selden McKnight
U.S. Air Force Director of Metrology

SESSION III-B

NEW DEVELOPMENTS IN TEMPERATURE IN NBS AND INDUSTRY

Dr. Klaus Jaeger
Lockheed Missiles & Space Co.

CRYOGENIC THERMOMETER CALIBRATION SYSTEM

JANUARY 18, 1985

PREPAREDBY
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ROCKWELL INTERNATIONAL CORPORATION
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FOR PRESENTATION TO
1985 MEASUREMENT SCIENCE CONFERENCE
SANTA CLARA, CALIFORNIA

JANUARY 17-18, 1985

ABSTRACT

This paper describes a system developed to calibrate thermometers at cryogenic temperatures. The temperature range of the system is from 1.2 to 330 Kelvin. The techniques used for automation of the system data acquisition and data reduction are described as well as future plans to provide improvements to the system.

INTRODUCTION

Rockwell International Corporation has entered into a significant new business area requiring the production of state-of-the-art devices that detect (sense) radiation at low energy levels. These devices perform most efficiently at cryogenic temperatures. A critical factor in their performance is the ability to sense and control their operating temperature; hence, the importance of the capablity to calibrate temperature sensors at the product operating temperature.

BACKGROUND

The need for a low temperature calibration capability was recognized during the Company's 1978-79 annual forecast of new capital equipment requirements because of the vigor of the R&D programs beginning to surface and the requests for calibration being received by the Metrology Laboratory. Temperature calibration depends upon the ability to produce a suitably stable environment. Without this ability it was not possible to comply with the early requests for low temperature calibration. However, it soon became apparent that there would be a continuing need to have a complete capability to calibrate thermometers at very low temperatures. The forecast for capital expenditures was amended to include funds for "Cryogenic Temperature Calibration" and studies were made to define the essential characteristics of a system for producing the temperatures required, including the standards and complementary instrumentation essential for calibration.

A significant result of the initial user surveys was that an inordinately large quantity of sensors would require calibration and subsequent re-calibration at periodic intervals. Limitations of the range of temperatures to be spanned by a given usage would aid in the efficiency of calibration; however, the time required for each sensor to be individually calibrated would still be excessive. Therefore, the ability to calibrate groups of sensors was included into the specifications for a calibration system. Further, the system was to be automated to the greatest possible extent to permit the accumulation of the data necessary for the generation of fitted functions that represent the performance of a sensor throughout a range of temperatures.

Procurement of the system was authorized for the 1982 Fiscal Year. The order was placed in April of 1982 and the system was delivered to Rockwell International in January of 1983.

SYSTEM DESCRIPTION

Preliminary discussions with potential suppliers had shown that only one of the qualified sources had indicated a firm interest in providing the system envisioned by Rockwell. A "turnkey" system concept resulted from the ensuing negotiations to define the system specifications. This system (Figure 1), which has been in operation since early 1983, is capable of calibrating up to 20 sensors with four-terminal connections over a temperature range from 1.2 Kelvin (K) to in excess of 300 K. The system is manually controlled from 1.2 to 4.2 K and automatically controlled from 4.2 to 300 K. Helium is used as the cryogen for temperatures from 1.2 to -80 K and Nitrogen is used from 80 to 300 K.

SYSTEM OPERATION

Control of the system (Figure 2) is provided by a dedicated HP9836 Computer that collects the data required, using an HP3497 Data Acquisition Control System. Individual setpoint temperatures are selected by the computer in ascending order as a calibration progresses, then delivered over the IEEE-488 bus to a Lakeshore Cryotronics Model DRC80C Temperature Controller that applies power to heaters in the Cryostat to establish the calibration temperature of the sample probe. Once the temperature has stabilized sufficiently, computer controlled data acquisition begins. A constant current source, a digital voltmeter, standards and the sensors being calibrated are the sources for data.

A significant feature of this calibration system is the manner in which the software and instrumentation interact to derive a data package (Figure 3). After a temperature is established, it is monitored continuously until a predetermined stability is verified; a stability of +/- 10 milli-Kelvin (mK) is the criteria used in the software at this time. When the system is stable, the control remains with the DRC80C but is no longer monitored by the computer. One of two internal temperature standards, using the constant current source at the proper current, is monitored by the digital voltmeter. Using an algorithm stored in the software, the temperature of the sample is established. While this temperature may vary slightly from that displayed by the controller, +/- 0.5 K, it will be sufficiently close to the desired calibration temperature to be satisfactory. Another factor that is monitored is the drift rate of the sample probe temperature. This also must be within a preset value, typically less than 10 mK per minute. When the drift rate has been satisfied a required number of sample times, the characteristics of the sensor being calibrated are measured. The standard readings, using both forward and reverse currents, are saved; then the current is applied to the sensor, in the forward and reverse directions, and either the resistance or voitage measured according to the kind of device being calibrated. In the case of a resistive device; Germanium Resistance Thermometer (GRT), the voltage drop across the device is a measure of the resistance if the current is known. For this reason, the bus-controlled current source incorporates a unique variation. There are four built-in precision resistors; 100, 1000, 10,000, and 100,000 ohms, that are in-series with the various constant current ranges of the source. Before and after each readng of either the standard or the test sensor, the voltage drop across the standard resistor is taken to calculate the actual current being applied to the device being measured. A benefit of this design is that the calibration of the current source relies upon measurements of the precision resistors because they are more stable than active devices and may be analyzed by means of control charts, etc., to assure their stability. In the case of voltage sensitive devices, diodes, etc., the current source is critical; however,the voltage measurements are only made in one direction. Completion of the data set for a sensor is accomplished by re-reading the standard's forward and reverse current to obtain a second temperature after the sensor values are stored. At each test temperature, commonly at 5 K intervals, up to 20 sensors may be evaluated. The resulting data sets are stored in a file for data reduction after all of the values are obtained.

The standards, permanently mounted on the sample probe, consist of a GRT and a PRT that have been calibrated by the National Bureau of Standards (NBS). The GRT is usable from 1 to 30 K and the PRT is usable from 14 to over 300 K. Implementation of the NBS calibrations required the ability to use the measured resistance of the standard to establish the calibration temperature. For the GRT, the NBS calibration provides on orthonormal least squares fit of polynominal of the form:

$$LOG,,, R_N = SUM\ A_{J,N} (LOG_{10}\ T)^J$$

for J from 0 to N, N= P, P+ 1,P+2 . . . .

The NBS polynomial provides resistance as a function of temperature; therefore, it was necessary to generate a similar Polynomial giving temperature as a function of resistance. A Polynomial fitingroutine, prepared for use with HP9836 for normal data reduction, was first used with the original NBS data to reproduce the 15th order polynomial supplied by the NBS Report of calibration. This was used to test the agreement with the NBS solution. When the NBS weighting was applied to the data, the Rockwell and NBS solutions were quite similar (Figure 4). Inverting the data, a polynomial of the form:

$$LOG,,\ T_N = SUM\ A_{J,N} (LOG_{10} R)^J$$

for J from 0 to N, N = P, P+ 1,P+ 2 . . . . .

was created using the original NBS raw data. With a 16th order polynomial, the agreement of the original data has an index of fit of 0.999 999 999 and differences between the measured and calculated values equal to or less than 0.6 mK.

The PRT calibration report supplied by the NBS is given in the conventional IPTS-68 format and is not readily converted into a usable format for the system software. Therefore, the polynomial fitting routine was set up using data points extracted frm the NBS tabular values of resistance versus temperature at 5 K intervals from 13 to 340 K. The shape of the function at the lower temperatures precluded a simple polynomial and the range covered was difficult to fit so the raw data was separated into two groups. The lower segment was fitted to a function of the form:

$$LOG_{10}\ T = SUM\ A_{J,N} (LOG_{10} R)^J$$

for J from 0 to N, N = P, P+ 1, P+ 2 . . . .

and the upper segment fitted to:

$$T = SUM\ A_{J,N} R^J$$

for J from 0 to N, N = P, P+ 1,P+2 . . .

Tables of T versus R were generated to test the validity of the fits and found to conform to the original NBS tabulation to better than 0.1 mK in every point examined.

Use of the polynomials in the calibration system software involves the selection of breakpoints that direct the measurement of temperature to the GRT when it is below 25 K and to the PRT for temperatures from 25+ to 340 K. A secondary breakpoint is defined when using the PRT that uses the LOG function from 25 to 80 K and the simpler function from 80 to 340 K.

The calibration probe, (Figure 5), is designed to accomodate 20 sensors in a four-terminal configuration. The removable mounting block contains drilled cavities suitable for most of the standard configurations of thermometers and may be replaced with other blocks to accept special devices. Above the mounting block is a terminal block for connection of the sensors to the wire harness. An adiabatic shield with a heater encloses the mounting block. A helium pot is located above the mounting block assembly outside of the shield. Surrounding the adiabatic shield and mounting block assembly is a vacuum jacket sealed wth Woods metal. During operation the vacuum jacket is alternately filled wth helium gas for heat transfer or evacuated to assist in temperature control. The helium pot is filled with liquid helium and partially evacuated to control temperatures when calibrations below 4.2 K are to be performed.

Not considering measuring time, loading and unloading the system with sensors requires about one working day. Improvements to the mounting techniques are being investigated with one thought being to revise the connection system to the terminals by eliminating the soldering. The system in use at the NBS has a flexible connector with female pins as the termination on the mounting block and the device being calibrated is provided with crimped-on male pins to plug into the connector. This approach results in significant gains in the loading process as well as reduction of the incidence of shorts and miss-wired connetions.

While operation of the system follows well-established techniques that have been described elsewhere (References I-5); its effective use requires a familiarization period. Since the system was received, the Rockwell Metrology Laboratory has been able to complete the calibration of more than 200 PRT's and over 75 Diode's Unfortunately, the occurrence of re-calibration has not offered the opportunity to compare calibrations for the same article enough times to evaluate the long term performance of the system or to evaluate the long term trends for devices being calibrated.

DATA REDUCTION

All of the data obtained during the calibration of a set of sensors is stored in files on floppy disks. When sufficient data has been obtained to provide a complete calibration, the files are closed and prepared for data reduction by a second set of software.

The data reduction software, supplied to Rockwell by the manufacturer of the calibration system, has been highly modified by the Metrology Laboratory staff. The resulting program, THERM (figure 6), collates the data from the original files, groups it by individual sensor and sorts it to arrange the data in ascending values of temperature. Each sensor file may then be examined to delete obviously erroneous values or to add values obtained from other sources. When a file is acceptable for further manipulation, weighting functions may be applied; if the weighting is not changed, the default value for weight is one. The relative precision of each of the data points is considered in calculating the relative weight of each point during the subsequent calculation. A fitting function that is suitable for the particular type of sensor is selected from the menu (Figures 6,7,8,9). Then the sensor data is fitted to the function to the degree necessary to provide the "best fit". Best fit is determined by the program and provided with the display of the coefficients for the polynomial. Experience with the calibration of different types of sensors has shown that the degree of fit required for the sensors is an indication of the quality of the data taken during the calibration. Establishing the polynomial for the correct function is the first element. With the polynomial, sets of tables (Figure. 11) are prepared for the sensor that show the actual relationship of temperature versus resistance or voltage in increments of temperature. The increments are selectable to suit the application. If desired, it is also possible to invert the data and fit functions that yield resistance or voltage versus temperature and to generate tables in appropriate increments. Some of our customers use their calibrated sensors in automated systems. We are able then to provide them with the polynomial coefficients (Figure 12) to use in their software directly, thereby eliminating the need to translate tables while conducting their tests or other operations.

STANDARDS CALIBRATION

Recalibration of the standards permanently mounted in the calibration probe will be performed using two standards that are also available at Rockwell. One of these standards, a capsule type PRT, has a calibration history, while the other, a Rhodium Iron Thermometer was only recently calibrated by the NBS. A second mounting block has been fabricated for the Rhodium Iron Thermometer (RIT) and the capsule type PRT (CPRT) for recalibration of the permanently installed standard GRT an PRT. The recalibration will be manually controlled rather than automatically because the instrumentation used for the RIT and CPRT is not capable of interfacing with a computer. Resistance measurements of the RIT and CPRT are made with Guildline Model 9975 Direct Current Comparator Resistance Bridge after stabilizing the setpoint temperature in the cryostat to within 1 mk. At least 30 measurement temperatures will be required for both the PRT and the GRT. Other standards available at Rockwell for verifying the continued validity of calibration data are SRM-767, Superconductive Fixed Points from the NBS and an Argon Triple Point Cell, at 83.798 K. Neither SRM nor the Argon TP have been operated by Rockwell at this time and it is planned to request the services of the NBS to calibrate the Argon TP before using it for calibration.

CONCLUSION AND FUTURE PLANS

The calibration of thermometers at cryogenic temperatures is an expensive demanding task. The equipment is complex and the skills required to use it are difficult to acquire. However, with the increasing use of cryogens to improve the performance of electronic devices it is necessary to acquire these skills and to extend the capability to calibrate thermometers into the cryogenic region. There'is a direct relationship between the accuracy of a thermometers calibration and the performance of equipment at very low temperature. Increasing the accuracy of low temperature calibration in a industrial metrology laboratory such as Rockwell's is not entirely based upon the ability of the NBS to calibrate the standards. Within the laboratory, there must be a dedication to the proper use of the standards; and the application of control techniques are vital to the continued success of the calibration activity. At Rockwell the use of control standards within the calibration process is encouraged and will be applied to this new facility. Further, the acquisition and use of new additional fixed point standards is in our planning for the future.

Presently, we are delivering calibrated thermometers with a stated accuracy of only + /- 0.1 K; due in part to the in-stability of the system. As we gain familiarity with the operating characteristics of the system, we are able to improve temperature stability. This will aid in improving our accuracy when the system is re-calibrated. Within the next three months, after a recalibration, we will re-analyze the system characteristics and, based upon the precision of the data gathered during system usage should be able to improve our accuracy statements to at least + /- 0.01 mK. The reported calibration accuracy will, however continue to be based upon the device stabilities, etc. Also, an improved temperature controller has been provided by Lakeshore Cryotronics that should help in improving the stability. This new controller, DRC-82C, provides variable power modes for heater operation that improve the temperature stability.

ACKNOWLEDGEMENTS

I am grateful to David Allen for his efforts in creating the data reduction software that is a major contribution to the successful use of this calibration system and also for his efforts in revising the software used for system operation. W.G. Pierce and J. Krause of Lakeshore Cryotronics were very supportive as the suppliers of the system by continually relaying their experience with a similar system in their facility.

REFERENCES

1. C.G.M. Kirby, Automation of a Thermometer Calibration Facility, Temperature Its Measurement and Control in Science and Industry, Volume 5, 1982
2. M.H. Cooper, Jr., R. L. Anderson and CA. Mossman, Automated Temperature Measurements from -183 to 2300 C, Temperature Its Measurement and Control in Science and Industry, Volume 5, 1982
3. Craig T. Van Degrift ad Robert S. Kaeser, Automation of Measurements in a Low Temperature Laboratory, Temperature Its Measurement and Control in Science and Industry, Volume 5, 1982
4. E.R. Pfeiffer and R.S. Kaeser, Realization of the 1976 Provisional 0.5K to 30K Temperature Scale at the National Bureau of Standards, Temperature Its Measurement and Control In Science and Industry, Volume 5, 1982
5. M. Durieux and R.L. Rusby, Helium Vapor Pressure Equations on the EPT-76, Metrologia 19, 67-72 (1983)

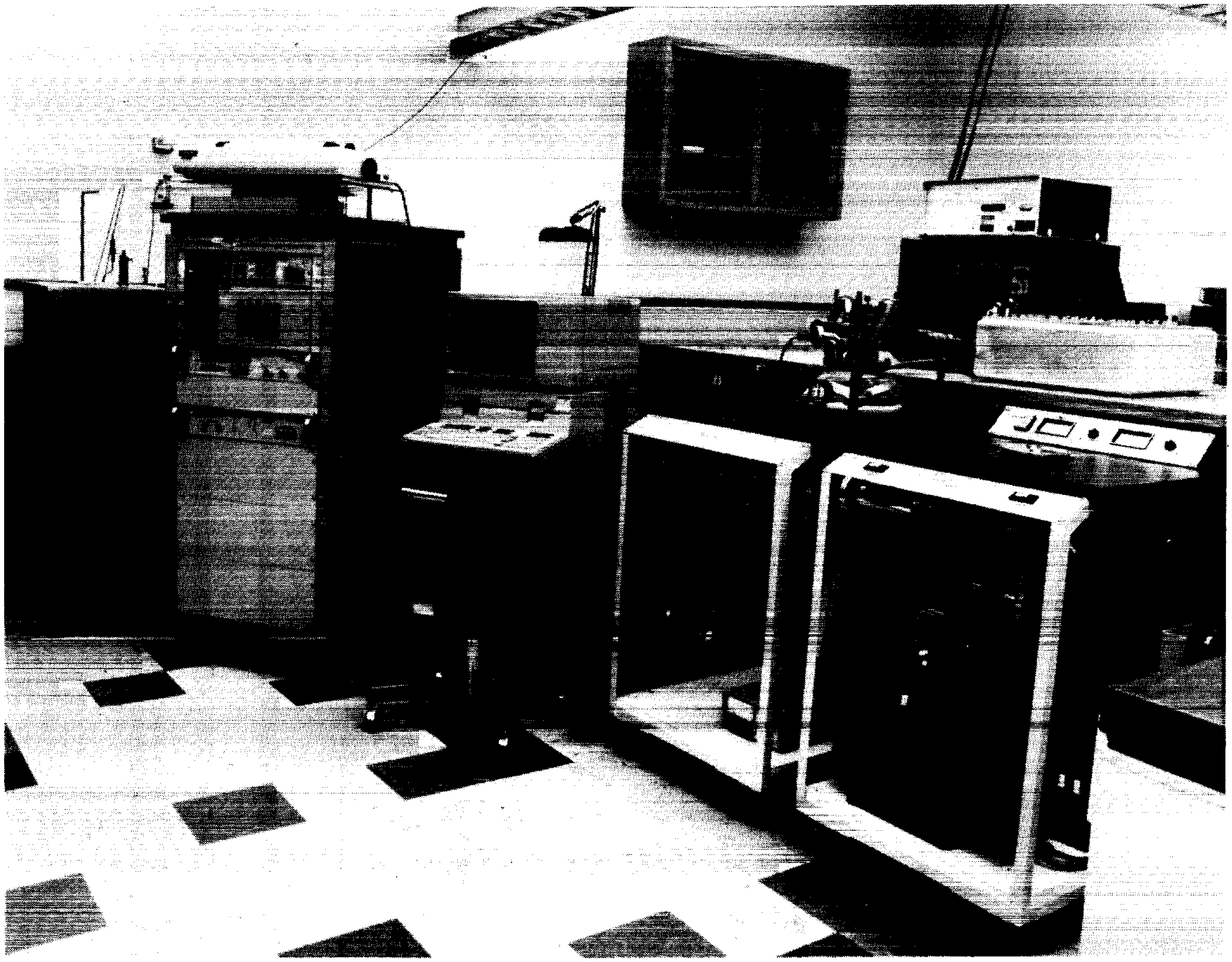


Figure 1. Cryogenic Thermometer Calibration System

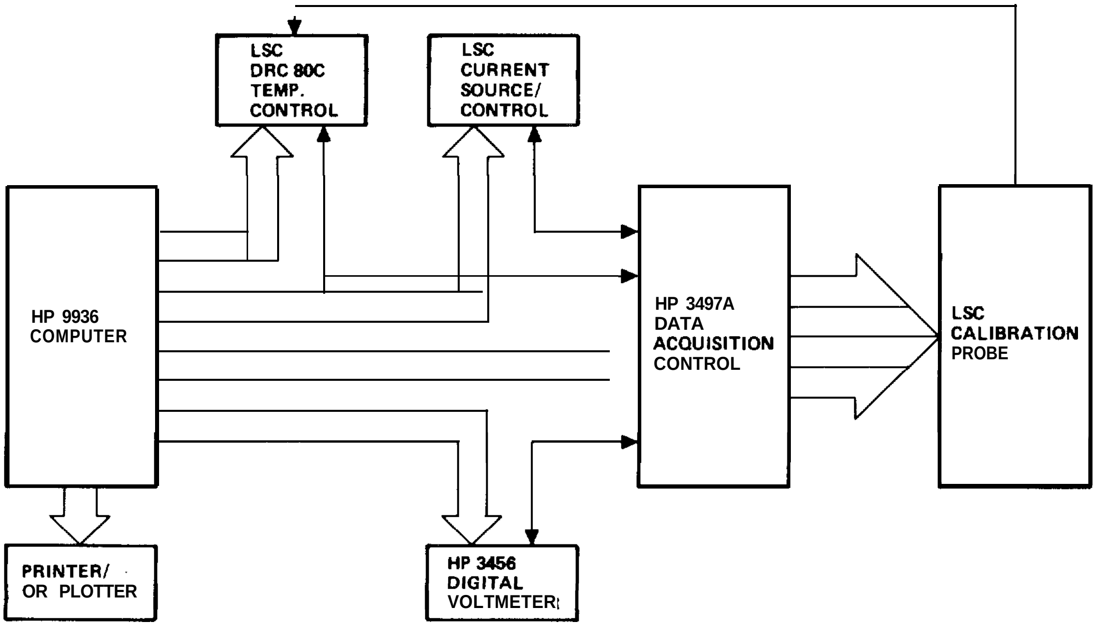


Figure 2. System Block Diagram

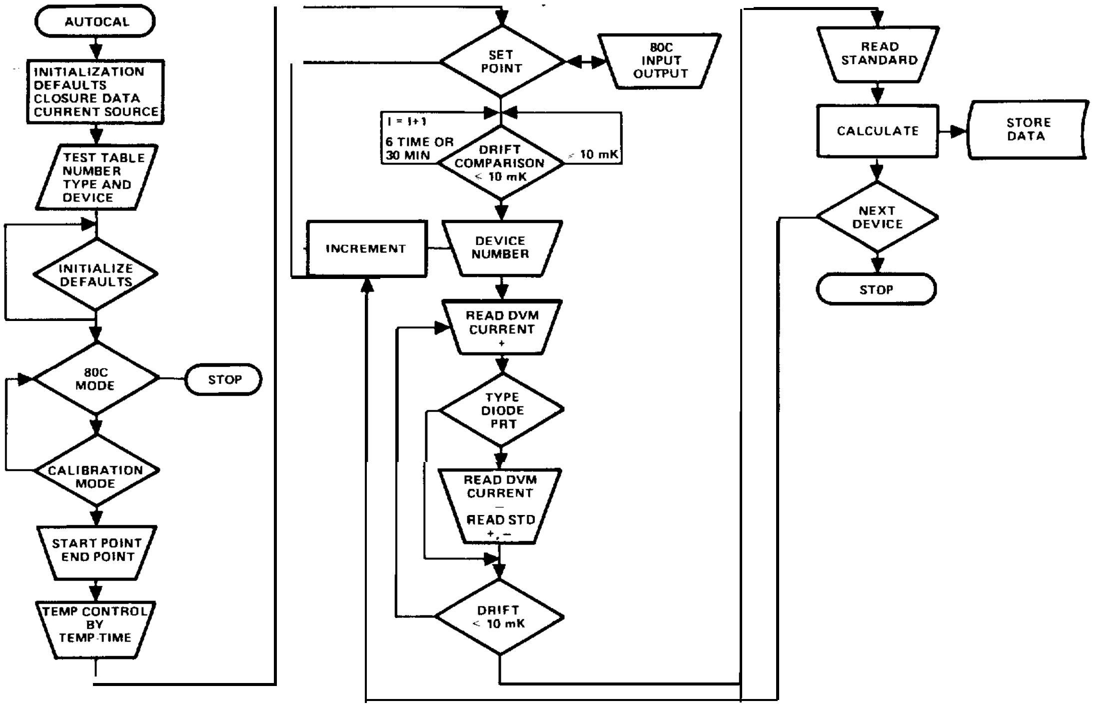


Figure 3. Flow Chart AUTOCAL

```
DEGREE OF CURVE FIT =  15
     INDEX OF DETERM =  .999999929425

COEFFICIENTS

A 0   =  5.2402896937
A 1   = -4.53313378774
A 2   =  7.67871029665
A 3   = -86.0186811258
A 4   =  784.106898492
A 5   = -4574.25512326
A 6   =  17866.4370161
A 7   = -48436.23425
A 8   =  93234.6918485
A 9   = -128907.733857
A 10  =  128162.842668
A 11  = -90691.9933131
A 12  =  44520.3021614
A 13  = -14400.4010205
A 14  =  2759.25508638
A 15  = -237.227068776

TEMPERATURE      WEIGHT     RESISTANCE        RESISTANCE
  KELVIN                     MEASURED          EQUATION

   1.01370         .06     163598.00000      163588.47627
   1.09995         .07     115208.00000      115243.35494
   1.17960         .08      86525.00000       86489.21187
   1.20004         .09      80713.00000       80705.76639
   1.30005         .11      58826.00000       58851.70141
  18.00073       66.60         29.71535          29.71679
  19.00018       79.30         26.43061          26.43041
  20.00067       93.20         23.72907          23.72847
  21.00018      108.00         21.47950          21.47828
  22.00135      125.00         19.57499          19.57484
  23.00184      142.00         17.94985          17.95018
```

```
Order of fi? = 15
                                     Standard
              Coefficients          Deviation     Ratio

A 0 = 0.52402896951903D+01         0.80224D-03   6532.07
A 1 =-0.45331344715407D+01         0.74646D-01     60.73
A 2 = 0.76787306045970D+01         0.21087D+01      3.64
A 3 =-0.86018940828661D+02         0.27625D+02      3.11
A 4 = 0.78410886387705D+03         0.20749D+03      3.78
A 5 =-0.45742648983497D+04         0.99661D+03      4.59
A 6 = 0.17866470633203D+05         0.32612D+04      5.48
A 7 =-0.48436316581395D+05         0.75557D+04      6.41
A 8 = 0.93234837977873D+05         0.12679D+05      7.35
A 9 =-0.12890792335636D+06         0.15576D+05      8.28
A10 = 0.12816302201407D+06         0.14010D+05      9.15
A11 =-0.90692115713362D+05         0.91212D+04      9.94
A12 = 0.44520360780614D+05         0.41826D+04     10.64
A13 =-0.14400419702653D+05         0.12810D+04     11.24
A14 = 0.27592586431654D+04         0.23516D+03     11.73
A15 =-0.23722737474424D+03         0.19567D+02     12.12

Standard Deviation of Fit =  0.183612E-04 log Ohms

    T            R        R Calculated    Delta R     Delta T    .   Weight
 Kelvin5       Ohms           Ohms          Ohms      mKelvins
 1.0137  163598.000000 163588.475563    9.524437      0.013     0.05960
 1.1000  115208.000000 115243.353426  -35.353426     -0.081     0.06740
 1.1796   86525.000000  86489.211559   35.788441      0.121     0.08340
 1.2000   80713.000000  80705.766290    7.233710      0.027     0.08810
 1.3001   58826.000000  58851.701851  -25.701851      0.147     0.11400
18.0007      29.715350      3.716787   -0.001437     -0.395    66.59999
19.0002      26.430610     26.430408    0.000202      0.069    79.29999
20.0007      23.729070     23.728468    0.000602      0.245    93.20000
21.0002      21.479500     21.478276    0.001224      0.593   108.00000
21.0014      19.574990     19.574836    0.000154      0.088   125.00000
23.0018      17.949850     17.950179   -0.000329     -0.219   142.00000
```

Figure 4. NBS — Rockwell Data Analysis

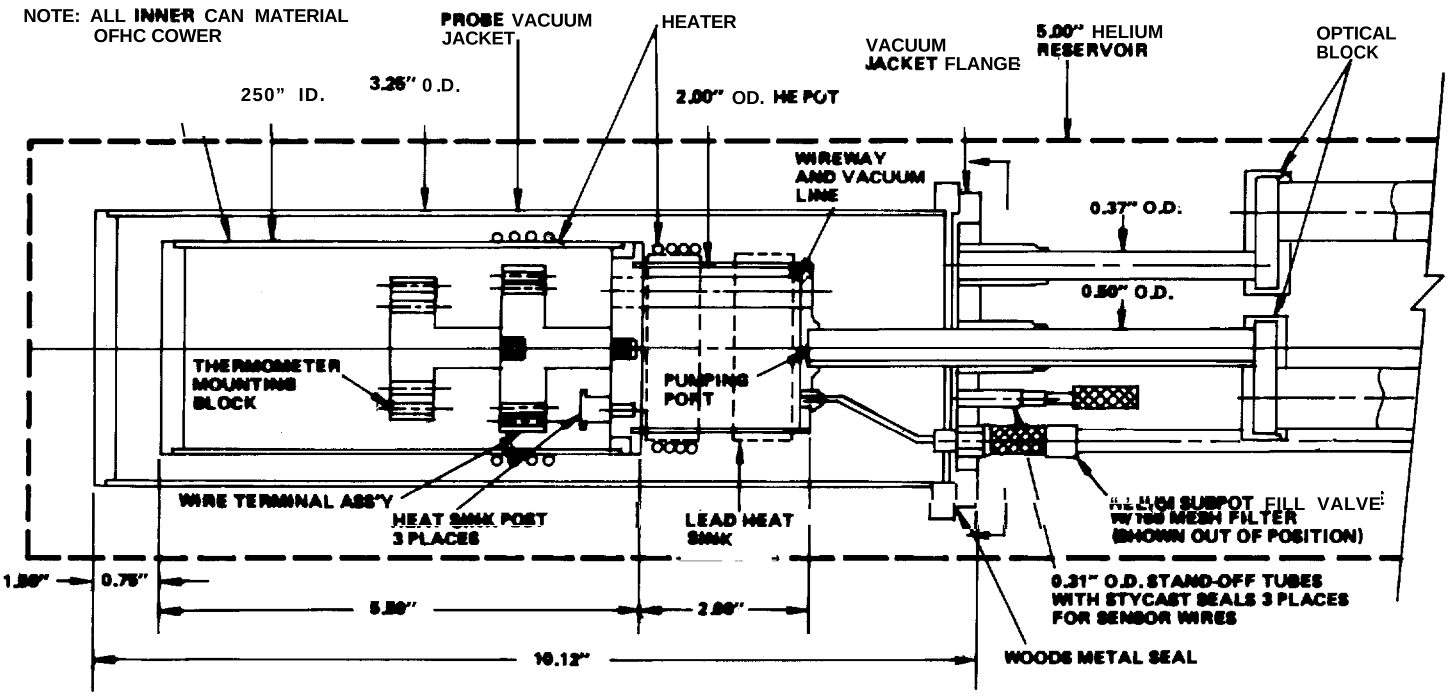


Figure 5. Calibration Probe

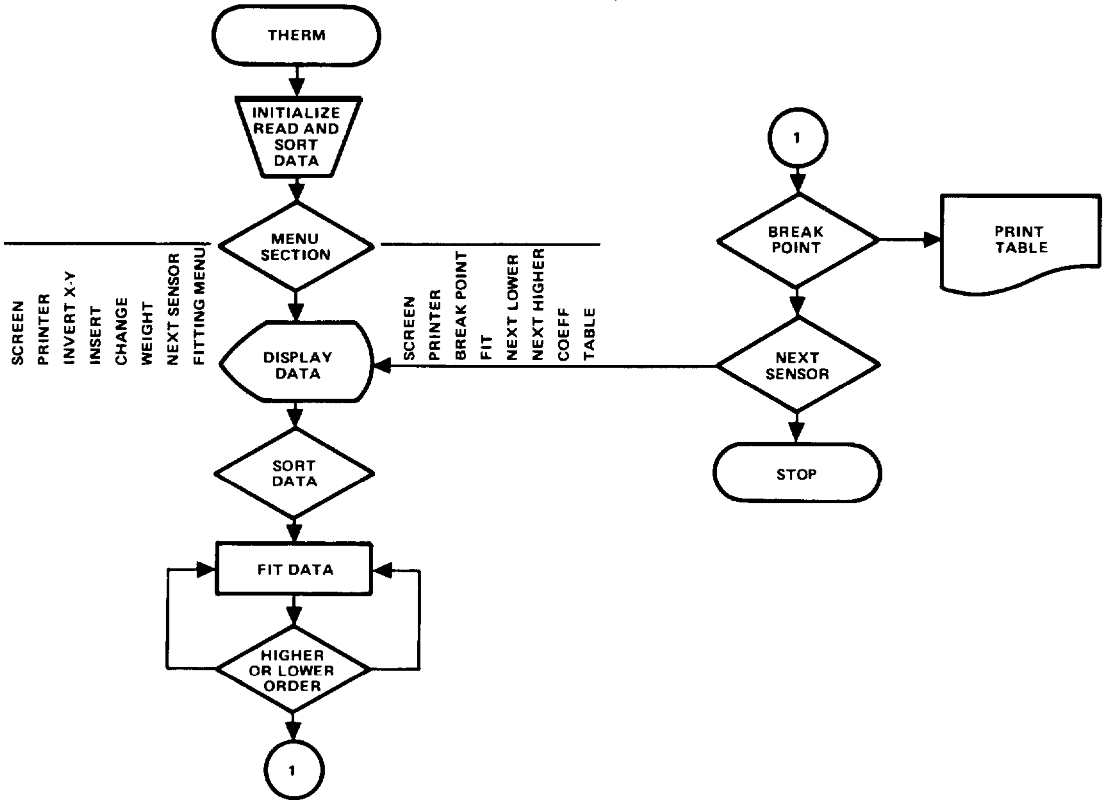
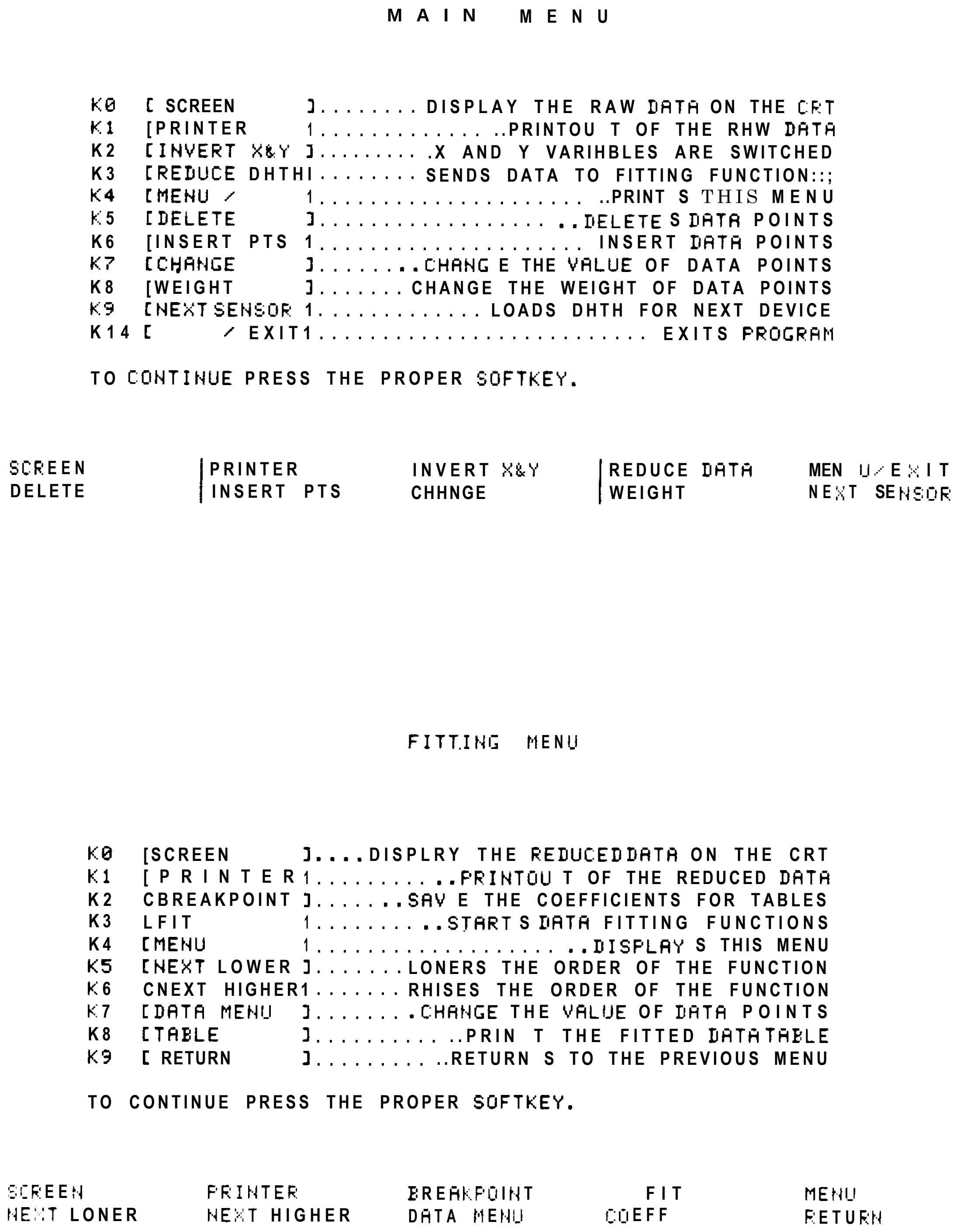


Figure 6. Block Diagram — THERM



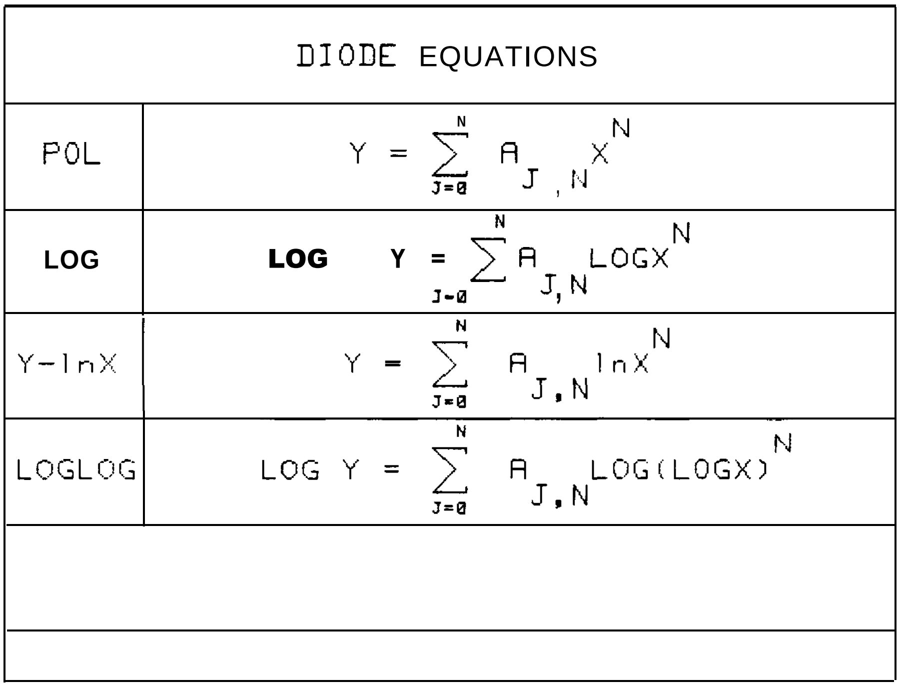
```
                         M A I N   M E N U

K0   [ SCREEN      ]........DISPLAY THE RAW DATA ON THE CRT
K1   [PRINTER      1...............PRINTOU T OF THE RHW DATA
K2   [INVERT X&Y   ].........X AND Y VARIHBLES ARE SWITCHED
K3   [REDUCE DHTHI........SENDS DATA TO FITTING FUNCTION::;
K4   [MENU /       1.......................PRINT S THIS MENU
K5   [DELETE       ]...................DELETE S DATA POINTS
K6   [INSERT PTS   1...................... INSERT DATA POINTS
K7   [CHANGE       ]........CHANG E THE VALUE OF DATA POINTS
K8   [WEIGHT       ].......CHANGE THE WEIGHT OF DATA POINTS
K9   [NEXT SENSOR  1..............LOADS DHTH FOR NEXT DEVICE
K14  [      / EXIT1.......................... EXITS PROGRAM

TO CONTINUE PRESS THE PROPER SOFTKEY.


SCREEN        |PRINTER       INVERT X&Y   |REDUCE DATA    MEN U/E X I T
DELETE        |INSERT PTS    CHHNGE       |WEIGHT         NEXT SENSOR




                          FITTING  MENU


K0   [SCREEN     ]....DISPLRY THE REDUCEDDATA ON THE CRT
K1   [PRINTER    1..........PRINTOU T OF THE REDUCED DATA
K2   CBREAKPOINT ].......SAV E THE COEFFICIENTS FOR TABLES
K3   LFIT        1.........START S DATA FITTING FUNCTIONS
K4   [MENU       1...................DISPLAY S THIS MENU
K5   [NEXT LOWER ].......LONERS THE ORDER OF THE FUNCTION
K6   CNEXT HIGHER1.......RHISES THE ORDER OF THE FUNCTION
K7   [DATA MENU  ]........CHANGE THE VALUE OF DATA POINTS
K8   [TABLE      ]...........PRIN T THE FITTED DATATABLE
K9   [ RETURN    ]..........RETURN S TO THE PREVIOUS MENU

TO CONTINUE PRESS THE PROPER SOFTKEY.


SCREEN        PRINTER        BREAKPOINT      FIT         MENU
NEXT LONER    NEXT HIGHER    DATA MENU      COEFF        RETURN
```

Figure 7. Main and Fitting Menu

POL	$Y = \sum_{J=0}^{N} A_{J,N} X^{N}$
LOG	$\mathrm{LOG}\ Y = \sum_{J=0}^{N} A_{J,N} \mathrm{LOG} X^{N}$
LOGY-X	$\mathrm{LOG}\ Y = \sum_{J=0}^{N} A_{J,N} X^{N}$
Y-LOGX	$Y = \sum_{J=0}^{N} A_{J,N} \mathrm{LOG} X^{N}$
Y-lnX	$Y = \sum_{J=0}^{N} A_{J,N} \ln X^{N}$
YEXP-X	$Ye^{-B/X} = \sum_{J=0}^{N} A_{J,N} X^{N}$

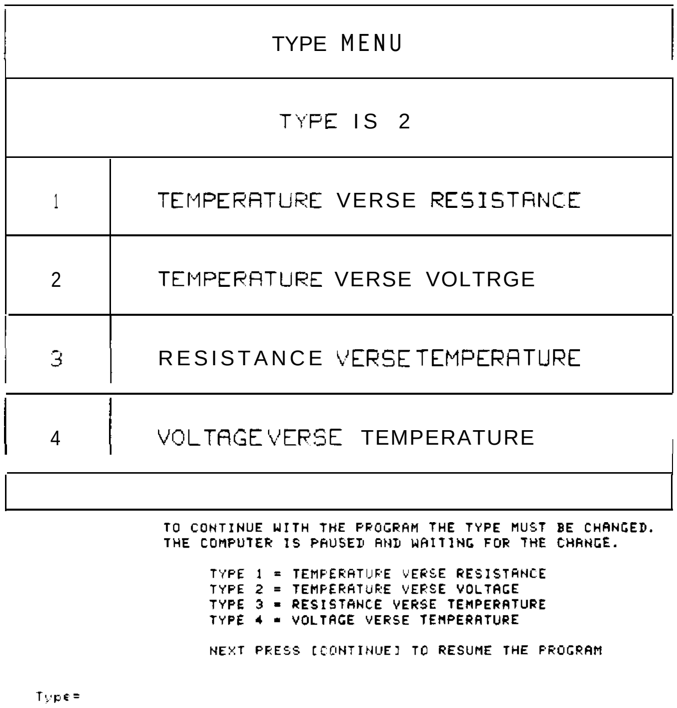
OPTIONS MENU	
CONT	PROGRAM RESUMES **WITH NO OPTIONS**
INV POL	$\dfrac{1}{Y = \sum_{J=0}^{N} A_{J,N} X^{N}}$
FERR	FRACTIONAL ERROR WITH WEIGHTING

Figure 8. Fitting Functions



DIODE EQUATIONS	
POL	$Y = \sum_{J=0}^{N} A_{J,N} X^{N}$
LOG	$\log Y = \sum_{J=0}^{N} A_{J,N} \log X^{N}$
Y-lnX	$Y = \sum_{J=0}^{N} A_{J,N} \ln X^{N}$
LOGLOG	$\log Y = \sum_{J=0}^{N} A_{J,N} \log(\log X)^{N}$

Figure 9. Functions for Diodes



TYPE MENU	
TYPE IS 2	
1	TEMPERATURE VERSE RESISTANCE
2	TEMPERATURE VERSE VOLTAGE
3	RESISTANCE VERSE TEMPERATURE
4	VOLTAGE VERSE TEMPERATURE

```
TO CONTINUE WITH THE PROGRAM THE TYPE MUST BE CHANGED.
THE COMPUTER IS PAUSED AND WAITING FOR THE CHANGE.

     TYPE 1 = TEMPERATURE VERSE RESISTANCE
     TYPE 2 = TEMPERATURE VERSE VOLTAGE
     TYPE 3 = RESISTANCE VERSE TEMPERATURE
     TYPE 4 = VOLTAGE VERSE TEMPERATURE

     NEXT PRESS [CONTINUE] TO RESUME THE PROGRAM

Type=
```

Figure 10. Options

PRT OMEGA F2105-300 S/N 40514-1 1mA

TEMPERATURE	RESISTANCE	INV DIFF	TEMPERATURE	RESISTANCE	INV DIFF
12.0000	.813020	42.3064	52.0000	9.301530	2.6509
13.0000	.842225	34.2405	53.0000	9.683331	2.6192
14.0000	.877557	28.3036	54.0000	10.069398	2.5902
15.0000	.919579	23.7966	55.0000	10.459449	2.5638
16.0000	.968856	20.2937	56.0000	10.853216	2.5396
17.0000	1.025934	17.5198	57.0000	11.250446	2.5174
18.0000	1.091341	15.2890	58.0000	11.650898	2.4972
19.0000	1.165573	13.4713	59.0000	12.054348	2.4786
20.0000	1.249092	11.9733	60.0000	12.460584	2.4616
21.0000	1.342319	10.7264	61.0000	12.869405	2.4461
22.0000	1.445633	9.6793	62.0000	13.280625	2.4318
23.0000	1.559363	8.7928	63.0000	13.694067	2.4187
24.0000	1.683790	8.0368	64.0000	14.109562	2.4068
25.0000	1.819146	7.3879	65.0000	14.526953	2.3958
26.0000	1.965611	6.8276	66.0000	14.946087	2.3859
27.0000	2.123314	6.3410	67.0000	15.366819	2.3768
28.0000	2.292334	5.9165	68.0000	15.789009	2.3686
29.0000	2.472702	5.5442	69.0000	16.212519	2.3612
30.0000	2.664402	5.2165	70.0000	16.637217	2.3546
31.0000	2.867371	4.9268	71.0000	17.062971	2.3488
32.0000	3.081506	4.6700	72.0000	17.489652	2.3437
33.0000	3.306662	4.4414	73.0000	17.917131	2.3393
34.0000	3.542659	4.2374	74.0000	18.345283	2.3356
35.0000	3.789280	4.0548	75.0000	18.773984	2.3326
36.0000	4.046281	3.8910	76.0000	19.203114	2.3303
37.0000	4.313388	3.7438	77.0000	19.632555	2.3286
38.0000	4.590303	3.6112	78.0000	20.062199	2.3275
39.0000	4.876710	3.4915	79.0000	20.491947	2.3269
40.0000	5.172274	3.3834	80.0000	20.921710	2.3269
41.0000	5.476647	3.2855	81.0000	21.351420	2.3272
42.0000	5.789468	3.1967	82.0000	21.781028	2.3277
43.0000	6.110372	3.1162	83.0000	22.210514	2.3284
44.0000	6.438987	3.0431	84.0000	22.639895	2.3289
45.0000	6.774940	2.9766	85.0000	23.069229	2.3292
46.0000	7.117860	2.9161	86.0000	23.498628	2.3288
47.0000	7.467379	2.8611	87.0000	23.928267	2.3275
48.0000	7.823132	2.8109	88.0000	24.358396	2.3249
49.0000	8.184764	2.7652	89.0000	24.789355	2.3204
50.0000	8.551930	2.7236	90.0000	25.221587	2.3136

Figure 11. Typical Data Reduction

PLATINUM RESISTANCE THERMOMETER

OMEGA
TESTOATA: **MAY 15, 1984**
REPORTNO.: **84-120-RT-050**

TABLE 1. FROM 12 TO 90K

PRT SERIAL NO.	POLYNOMINAL COEFFICIENTS FOR INDIVIDUAL PRT										
	A_0	$A_1 \times 10^{-1}$	$A_2 \times 10^{-2}$	$A_3 \times 10^{-3}$	$A_4 \times 10^{-5}$	$A_5 \times 10^{-7}$	$A_6 \times 10^{-8}$	$A_7 \times 10^{10}$	$A_8 \times 10^{-13}$	$A_9 \times 10^{-15}$	$A_{10} \times 10^{-17}$
40514-1	**0.792 989**	**-0.224 633**	**0.302 610**	**-0.209 922**	**1.406 400**	**- 3.492 992**	**0.428 079**	**-0.264 374**	**0.660 486**		
40514-2	**1.077 635**	**-1.063 670**	**1.334 604**	**-0.889 136**	**4.063 174**	**- 9.975 024**	**1.422 959**	**-1.196 942**	**5.533 471**	**- 1.087 093**	
40514-3	**1.078 376**	**-1.205 188**	**1.514 313**	**-1.011 007**	**4.544 968**	**-11.125 081**	**1.591 654**	**-1.345 711**	**6.259 250**	**- 1.237 836**	
40514-4	**0.951 495**	**-1.020 977**	**1.281 679**	**-0.854 558**	**3.965 035**	**- 9.835 511**	**1.413 195**	**-1.194 688**	**5.541 237**	**- 1.090 712**	
40514.5	0.817 490	-0.725 838	0.981 380	-0.709 050	3.530 475	- 8.978 269	1.302 971	-1.107 400	5.160 459	- 1.021 651	
40514-7	0.756 811	-0.624 733	0.851 965	-0.619 426	3.160 799	- 8.049 840	1.159 550	-0.973 994	4.473 818	- 0.871 275	
40514-a	0.929 405	-1.052 448	1.391 528	-0.970 386	4.489 **768**	-11.189 026	1.628 687	-1.404 186	6.678 271	- 1.353 742	
40514-g	1.621 257	-2.969 854	3.939 823	-2.821 434	12.706 030	-34.666 037	6.033 370	-6.795 814	48.110 073	-19.488 040	3.447 150
40514.11	1.696 080	-2.342 259	3.022 430	-2.111 614	9.606 229	-25.679 **055**	4.352 029	-4.769 858	32.778 699	-12.870 082	2.204 625

$$R = A_0 + \sum_{i=1}^{11} A_i T^i$$

WHERE: T = **TEMPERATURE (KELVIN)**
R = RESISTANCE **(OHMS)**

Figure 12. Matrix for Polynominals

Cryogenic Temperature Calibrations

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ABSTRACT

The Lockheed Missiles & Space Co. has acquired a closed cycle helium refrigeration system for calibration of high precision standard thermometers between 15 and 90 degrees Kelvin. A total of five triple point cells of high purity gases will be utilized to realize intrinsic temperature points for Argon, Nitrogen, Oxygen, Neon, and Deuterium. Calibrations will be done for Rhodium-Iron and Platinum resistor thermometers as well as for Germanium diodes.

INTRODUCTION

A closed cycle helium refrigerator system has been purchased from Cryosystems, Inc.. By the use of high pressure helium gas, temperatures below 10 degrees Kelvin will be attainable. It is planned to utilize five (5) triple point cells of high purity gases in order to realize primary and secondary fixed points as defined by the International Practical Temperature Scale of 1968 (IPTS-68). We are planning to measure resistance via the 4-wire method for rhodium-iron and platinum wire wound resistor thermometers using the intrinsic temperature points of argon, nitrogen, oxygen, neon, deuterium points only.

With these calibration points, the polynomials defined by IPTS-68 can be fitted between ~18. to 273.16 degrees Kelvin, i.e. regions 2, 3, and 4. The thermometers so calibrated will then serve as reference standards in a second cryogenic calibration station which performs comparison calibrations of sensors with unknown values versus the standards.

I. HARDWARE

The refrigerator was manufactured by CTI-Cryogenics and consists essentially of a compressor unit connected to a cold head via interconnecting flexible stainless steel piping. The cold head operates in two (2) stages thereby reaching temperatures below 10K. The heat loads are estimated at 250 mW at 10K, 1.4 W at 15K, and 2.0 W at 20K. (Fig. 1).

Fig. 2 shows schematically the 2 stage cycle of the refrigeration taken place inside the cold head with a single displacer. The He gas is supplied by the compressor at 240-260 psig to the top of displacer (piston). When he displacer rises, the gas streams to the center of the displacer (top end) which contains regeneration material that behaves like a good heat exchanger. The gas, somewhat cooled but still near the inlet pressure, enters the space near the first stage thermal load cooling it to the gas temperature. It then continues from the first stage to the center of the displacer (bottom end) once again containing a regenerator. The gas is heat exchanged more and then enters the bottom space of the cylinder, i.e. the second stage space where it heat exchanges with the second stage thermal load. Once all gas space is filled, the inlet valve closes and the outlet valve opens causing a rapid pressure drop and hence also a rapid decrease in temperature. Heat continues to flow from the thermal loads through the cylinder walls to the gas streaming upwards through the regenerators. It picks up more heat from the regenerators which therefore cool. Next the displacer is pushed down forcing the remaining gas through the regenerators. The outlet, low pressure gas, returns to the compressor slightly cooled. The cycle is now repeated at a rate of ~200rpm yielding low temperatures in a very short time, ~30 to 60 minutes.

The cryostat, itself, starts with the vacuum can which seals to the bottom end of the cold head. A highly polished can is screwed to the refrigerator at the first stage. This can serves as the initial heat intercept especially for radiation. At the second stage, the isothermal can is bolted. Inside this can, we have the adiabatic can which is attached to the isothermal can at the bottom and at the second stage interface. Inside the adiabatic can, we support the triple point cell via a weak mechanical link. The sensor to be calibrated is inserted into the bottom end of the cell.

Four (4) lead wires from the cell are then soldered to four (4) copper strips glued to the cell. This ensures good thermal contact of the sensor and its wires with the cell. From the top end of the copper strips, the wires feed to the outside world. Temperature sensing diodes are attached to the first and second stage interfaces to allow rough temperature monitoring. A heater wrapped around the top end of the cell allows fine temperature control (Fig. 3).

The cool-down is preceeded by an initial pump down (Fig. 1) to about 10^{-1} or 10^{-2} Torr. The compressor and refrigerator are then turned on and cool down commences. Cryopumping will decrease the vacuum to the 10^{-3} or 10^{-4} Torr level. During the cool-down, the entire subassembly consisting of the cold head and cryostat is turned by about 30 degrees. Since the triple point cell is only supported by a weak mechanical link with poor thermal conductivity, it will follow the direction of the gravitational field and thereby touch the adiabatic can with the bottom edge. This contact point is sufficient to cool the cell down via thermal conduction. Furthermore, since this is the only effective contact with the adiabatic can, it ensures temperature uniformity during the measurement.

II. INTERNATIONAL TEMPERATURE SCALE

The International Practical Temperatue Scale from 1968 (IPTS-68), amended in 1975, covers the range of 13.81 K, the triple point of hydrogen, to above 1064.43 K, the freezing point of gold. For the cryogenic calibration systems, we are interested in IPTS-68 devides this temperature domain into four (4) regions:

Region 1:	13.81 K to 20.28 K (Boiling point of hydrogen.)
Region 2:	20.28 K to 54.361 K (Triple point of oxygen.)
Region 3:	54.361 K to 91.188 K (Boiling point of oxygen.)
Region 4:	91.188 K to 273.15 K (Ice point of water.)

The lowest point (13.81 K) was chosen as the limiting value for the platinum resistance thermometers (PRT).

For our station, we will first cover Region 3, followed by Region 4, and finally a modified Region 2. We will not consider PRT calibrations for Region 1.

1.) Region 3

The region is bounded by 54.361 and 91.188 K. The update of 1975 for the IPTS-68 allowed the substitution of the argon triple point t 83.798 K instead of the oxygen boiling point at 91.188 K. We are therefore, defining Region 3 between the argon and oxygen triple points.

The formulism established by IPTS-68 is as follows: Temperature T is defined as (we will use T for degrees Kelvin and t for degrees Celsius)

$$T = 273.15 + \sum_{i=1}^{20} a_i \, [\ln W^*(T)]^i \qquad (1)$$

where the a_i's have been determined by fitting databf many PRT's over many years. The $W^*(T)$ is defined with

$$W(T) = W^*(T) + \Delta W(T) \qquad (2)$$

and also

$$W(T) = \frac{R(T)}{R(T_0)} = \frac{\text{Resistance value at temperature T}}{\text{Resistance value at ice point of water}} \qquad (3)$$

and $\Delta W(T)$ is called the deviation function and is given as a polynomial for each region. For Region 3 the deviation function is given as

$$\Delta W(T) = A_3 + B_3 T t C_3 T^2 \qquad (4)$$

which indicates three (3) unknowns; A_3, B_3, C_3. Hence, we require three (3) equations to solve for the coefficients. We will make use of three (3) fixed points, namely

$T_3 = 83.798$ K

$T_3' = 63.146$ K (Triple point of nitrogen.)

$T_4 = 54.361$ K.

Only T_3 and T_4 are recognized as primary fixed points. T_3' is only considered a secondary point. Nevertheless, we will make use of it in our system.

Using these three (3) fixed temperatures, we can turn equ. 1 inside out to obtain the corresponding W^* as

$W^*(T_3) = 0.2160570$

$W^*(T_3') = 0.12754708$

$W^*(T_4) = 0.09197255.$

By measuring the resistances at T_3, T_3', T_4, we have the ratios $R(T_3)/R(T_0)$, $R(T_3')/R(T_0)$, $R(T_4)/R(T_0)$ where $R(T_0)$ can be calculated from (derivation is involved and not shown here)

$$R(T_0) = \frac{R(TP)}{W^*(TP)} \qquad (5)$$

with TP = triple point of water = 273.16 K. Once again W* (TP) can be determined from equ. 1 as equal to 1.0000398651 so that R(TP) is required only. Equ. 4 can now be written as

$$\frac{R(T_3)}{R(T_0)} - W^*(T_3) = A_3 + B_3T_3 + C_3T_3^2$$

$$\frac{R(T_3')}{R(T_0)} - W^*(T_3') = A_3 + B_3T_3' + C_3T_3'^2 \quad (4')$$

$$\frac{R(T_4)}{R(T_0)} - W^*(T_4) = A_3 + B_3T_4 \text{ t } C_3T_4^2$$

so that solutions for A_3, B_3, C_3 can be found.

To find a particular temperature in Region 3 given R(T), one then uses

$$W(T) = \frac{R(T)}{R(T_0)}$$

in equ. 1 by first setting $\Delta W = 0$. The initial T so found is then used in equ. 4 to yield a new ΔW. By further iterations one can then obtain T to the required accuracy.

A word of caution is in order at this point. Solutions for Region 3 are found according to IPTS-68 with T_3, T_4 and the continuation of the derivatives of the deviation functions at point T_3, where Regions 3 and 4 meet. Region 4 in turn is fed a constant for the PRT's determined over many years from Region 5. The solution proposed with our system makes use of a third triple point cell thereby eliminating any need for a PRT constant from Region 5. However, as mentioned earlier, we had to make use of the nitrogen cell which (for whatever reason) has never been accepted by the International Temperature Commission. This automatically means that our results are not traceable to the high accuracy levels available internationally. On the other hand we will be quite content with accuracies on the 1 to 5 mK level.

2. Region 4

The deviation function for Region 4 is defined as

$$\Delta W(t) = A_4 + C_4 t^3 \ (t-100). \qquad (6)$$

Note in particular that for ease of computation, we will work in degrees C, i.e. t. We also note that only two (2) constants have to be determined (A_4 and C_4) so that two (2) equations are required. Since there are no accepted triple points between T_3 and 273.15 K, we use the point at T_3, namely

$$t_3 = T_3 - 273.15$$

and write

$$\Delta W(t_3) = A_4t_3 + C_4t_3^3\,(t_3 - 100). \qquad (7)$$

In addition, we make use of the fact that the derivatives of the deviation functions of Regions 3 and 4 have to be continuous at t_3. From equ. 6, we have

$$\frac{d[\ W(t_3)]}{dt_3} = A_4 + 4t_3^3\ C_4 - 300t_3^2C_4. \qquad (8)$$

From equ. 4, we have

$$\frac{d[\ W(T_3)]}{dT_3} = B_3 + 2C_3T_3. \qquad (9)$$

Equating both derivatives yields

$$B_3 \text{ t } 2C_3\ T_3 = A_4(4t_3^3 - 300t_3^2)C_4. \qquad (10)$$

Recall that B_3, C_3, T_3, and t_3 are known from Region 3. Equations 7 and 10 can be solved for A_4 and C_4 in terms of $\Delta W(t_3)$ where

$$\Delta W(t_3) = W(t_3) - W^*(t_3) \quad \text{(from equ. 2)}$$

and

$$W^*(t_3) = W^*(T_3).$$

We also recall that

$$W(t_3) = \frac{R(t_3)}{R(t_0)}$$

with $R(t_3)$ already measured for Region 3 and $R(t_0)$ given (measured) via equ. 5. (Note that $t_0 = T_0 - 273.15$). (The reader should be aware that these solutions are different from those defined by IPTS-68.)

3. Region 2

The deviation function in Region 2 is defined as

$$A\ W(T) = A_2 + B_2T + C_2T^2 + D_2\ T^3 \qquad (11)$$

requiring four (4) equations for a solution. The IPTS-68 utilizes the triple point of oxygen (T), the boiling point of neon (27.102K), ?he boiling point of hydrogen (20.28K), and the continuation of the derivatives of the deviation functions at T_4.

For our station, we will use T_4, the triple point of neon (24.561K), the triple point of deuterium (18.678K), and the continuation of the deviation functions at T_4. Once again, we have to caution the reader that only the triple point of oxygen (T_4) has been accepted as a primary fixed point. The triple point of neon is under question by as much as 2 mK and the triple point of deuterium is really not well accepted yet. Nevertheless, we will make use of these points since we will be able to double check the deuterium point with standards calibrated at national laboratories.

We now have

$$W^*(T_4 = 54.361) = 0.09197255$$

$$W^*(T_5 = 24.561) = 0.00870388$$

$$W^*(T_6 = 18.678) = 0.00340139.$$

We write equ. 11 three (3) times in the form

$$\frac{R(T_4)}{R(T_0)} - W^*(T_4) = A_2 + B_2T_4 + C_2T_4^2 + D_2T_4^3$$

$$\frac{R(T_5)}{R(T_0)} - W^*(T_5) = A_2 + B_2T_5 + C_2T_5^2 + D_2T_5^3$$

$$\frac{R(T_6)}{R(T_0)} - W^*(T_6) = A_2 + B_2T_6 + C_2T_6^2 + D_2T_6^3$$

Equating the derivatives of the deviation functions at T_4 yields

$$B_3 + 2C_3T_4 = B_2 + 2C_2T_4 + 3D_2T_4^2 \qquad (12)$$

where B_3 and C_3 are already known from Region 3. The constants A_2, B_2, C_2, D_2 can be determined in terms of

$$\Delta W(T_4) = \frac{R(T_4)}{R(T_0)} - W^*(T_4)$$

$$\Delta W(T_5) = \frac{R(T_5)}{R(T_0)} - W^*(T_5)$$

$$\Delta W(T_6) = \frac{R(T_6)}{R(T_0)} - W^*(T_6)$$

with $R(T_0)$ known from equ. 5.

III. CONCLUSIONS

We have shown with the above derivation that intrinsic point calibrations for the temperature range from 18. to 273.16 Kelvin can be performed according to IPTS-68. It still remains to cover the lower temperature range. In our case, we are attempting to reach somewhat less than 2 degrees K. As mentioned earlier, no triple point cells exists below the hydrogen triple point and because of practical reasons of manufacture, we will not attempt it. Instead, we will switch over to another, the provisional scale of 1976, called Echelle Provisoire de Temperature 1976 entre 0,5K et 30K or EPT-76. This scale covers the range from 0.5 to 30K and has been defined by agreeing with the IPTS-68 at 27.1K, the boiling point of neon.

Since our closed cycle refrigerator cannot reach temperatures below 10K, we will for EPT-76 calibrations use another calibration system utilizing liquid helium. With this system, we will be able to once again measure the triple points Of neon and deuterium. Since these points were already determined with the triple point cell system, we will use the sensors at these points to reference the system. Furthermore, we will utilize superconducting transition points of lead (7.1999K), and of indium (3.4145K). The lower temperature is reached by pumping on the liquid helium. This procedure will allow intrinsic point measurements below 10.K to be tied to the scale above 10.K (i.e. 18. and 25.K).

A word of caution should be aired here. The IPTS-68 and EPT-76 agree only at the boiling point of neon, 27.102K. At the triple point of hydrogen, IPTS-68 is quoted as 13.81K whereas EPT-76 lists 13.8044K, so that the EPT-76 is lower by 0.0056K; i.e. over 5mK. We have to keep this discrepancy in mind during our experiments and realize that traceability of temperatures in this region cannot be better than the 6mK by definition.

Data for our two (2) systems will be available within the next few months. It is hoped that the calculations can be realized as outlined above and that the system can then be used on a routine basis.

REFERENCES

(1) Supplementary Information for the IPTS-68 and the EPT-76, 1983.

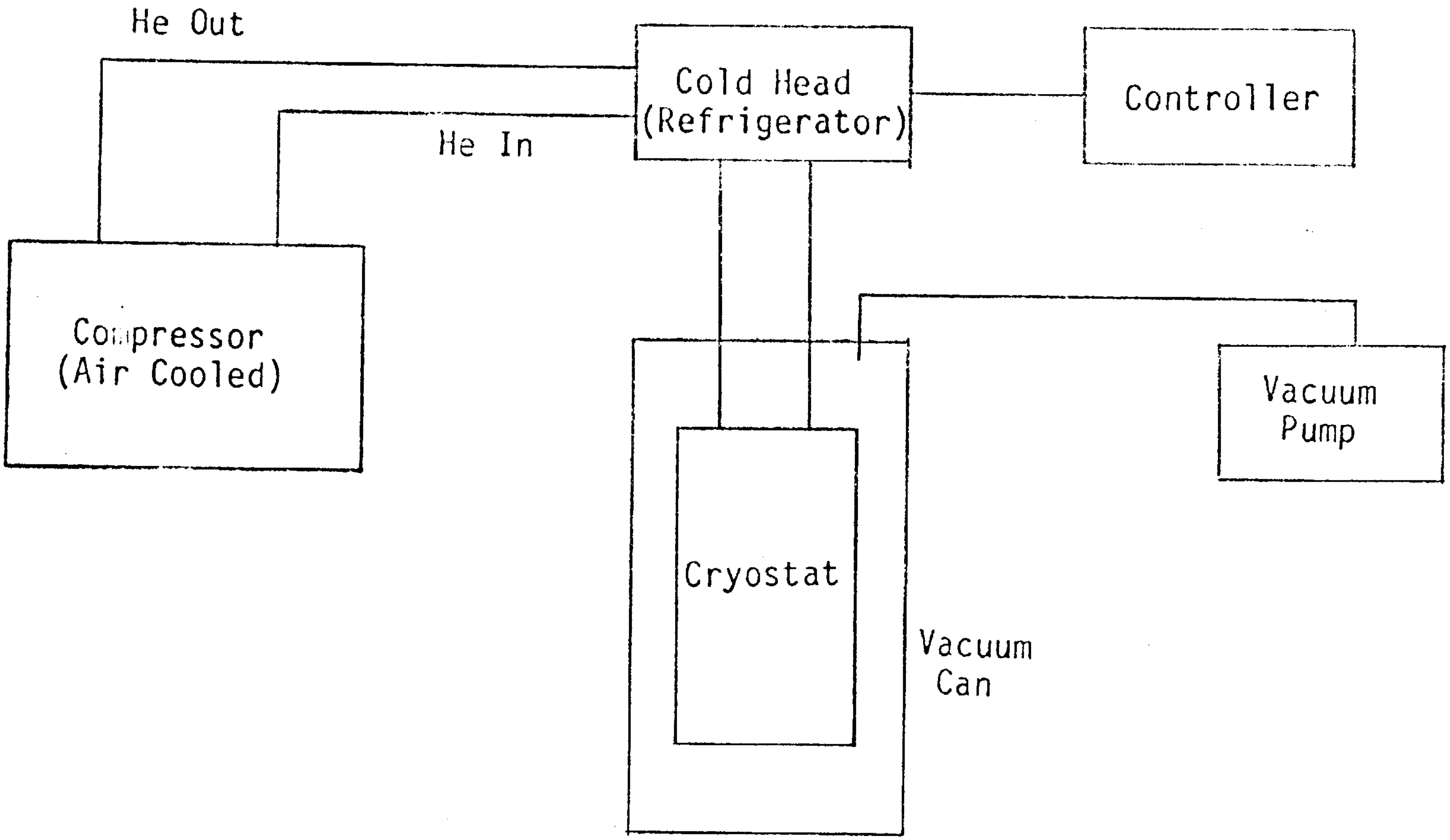


Fig. 1

Schematic of Refrigeration System

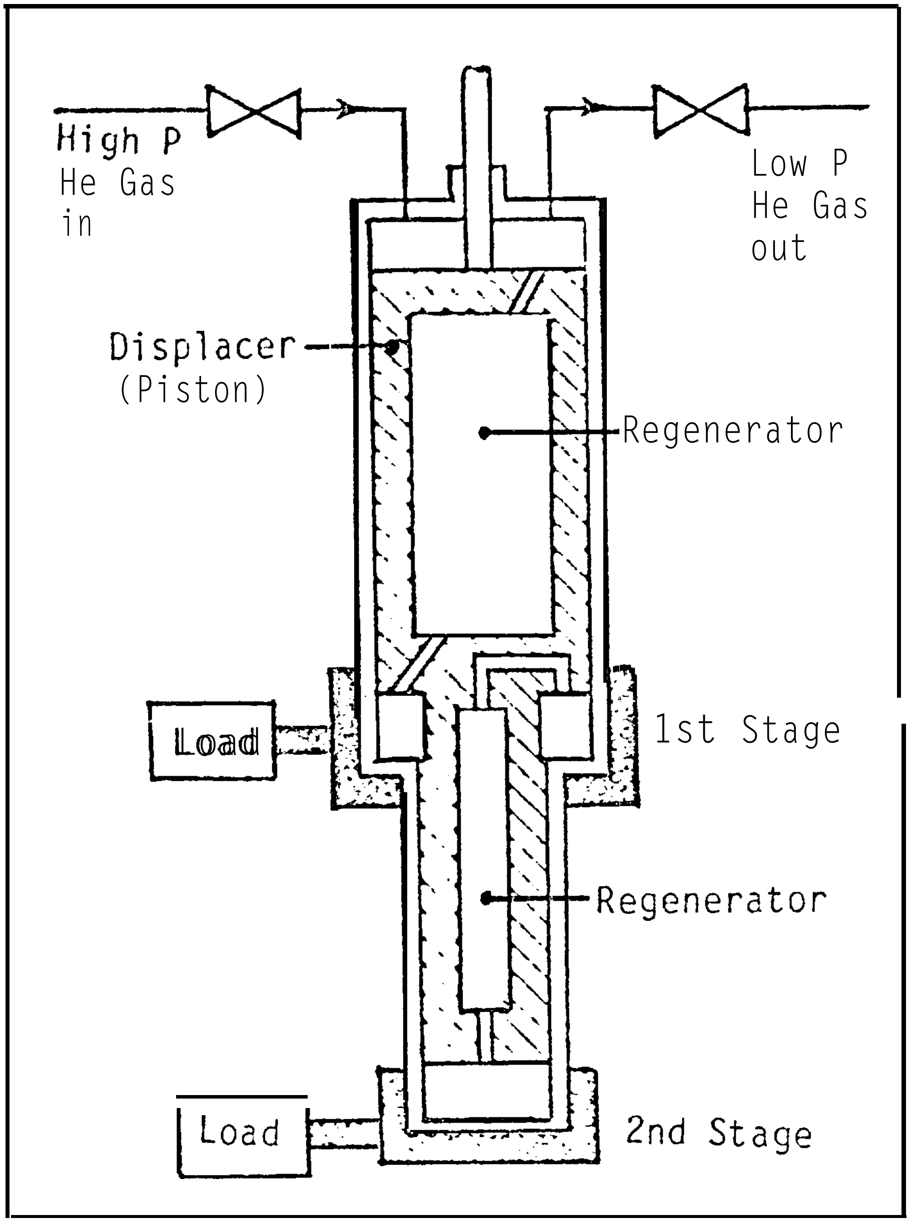
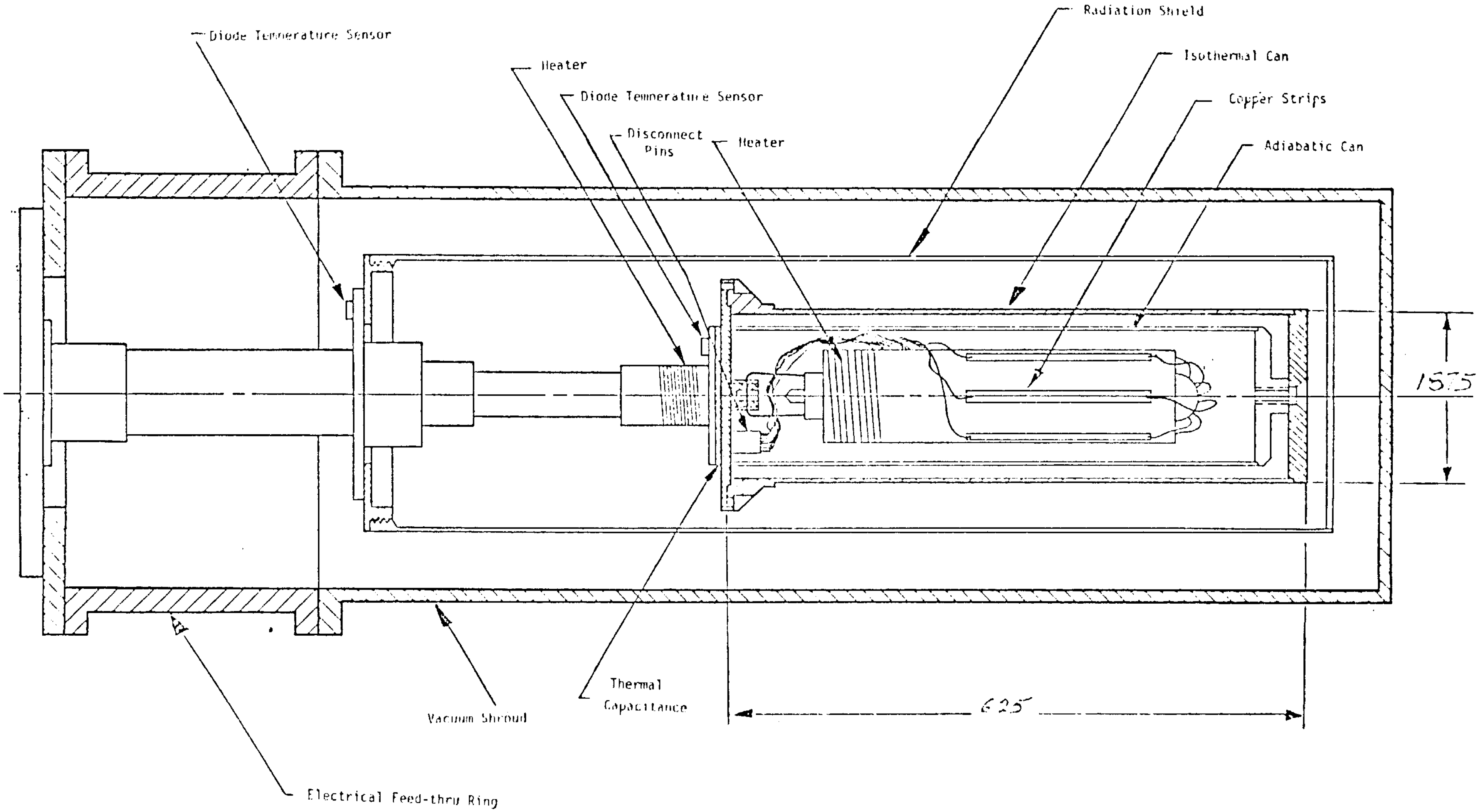


Fig. 2

Schematic of Refriqeration Cycle

Fig. 3



Details of Cryostat

SESSION III-C

STATISTICAL MEASUREMENT PROCESS UNCERTAINTY ANALYSIS

Patsy Oea
TRW Operations & Support Group

DEVELOPMENT OF UNCERTAINTIES FOR 14mm IMPEDANCE STANDARDS

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ABSTRACT

The development of the uncertainty statements for a wide range of SWR values became necessary when this laboratory received impedance standards whose values exceeded a SWR of 1.50. Normal calibration support at that time was 1.0 to 1.5 SWR. Standard impedances whose SWR values ranged from 2.0 to 4.0 had to be analyzed for errors since the past analysis had only been used to evaluate SWR values to 1.5. A complete error analysis review was put into action. The methods used to measure SWR were high directivity bridges (200-400MHz) and standard airlines (1.0-8.5GHz). A systematic and short-term error analysis was performed using propagation of error techniques and a long-term error model was derived from past historical customer data, as well as, from a newly created data base from in-house standards data. This paper addresses these systematic, short-term and long-term errors in the measurement of 14mm impedance standards.

INTRODUCTION

The availability of the desk-top computer has allowed evaluation of large amounts of historical data. This data previously had been maintained by manual systems (history folders) and in some instances evaluation of that data occurred only once as to demonstrate a "general" response or characteristic of a standard. Today, evaluation of coaxial impedance standards has taken on a new look. Instead of fixed uncertainty limits based upon a one time evaluation of errors the uncertainty limits are being computed for each and every unit based upon its own characteristics. Both short and long-term errors are being evaluated at the time of measurement. It is with this new computer power that the errors for the 14mm coaxial impedance standards are now being evaluated.

MEASUREMENT SYSTEMS

Current techniques and measurement systems used are high directivity bridges used from 10MHz to 1.0GHz whose measured values are in terms of return loss (dB) and standard airlines used from 1.0 to 8.5GHz whose measured values are in terms of SWR (dB). Even though a 6-Port ANA is in-house only after its evaluation will the above mentioned systems be replaced. The bridges are used in a fixed frequency system with a precision attenuation receiver, synthesized source and are padded by two low SWR 10dB attenuators (SWR<1.05).

The airlines are used in a fixed frequency 1KHz modulated system with a tuned slotted line measurement port and a 1KHz detection system. The bridges are calibrated using precision airlines and the airlines are calibrated dimensionally. (see figures 1 and 2)

SHORT-TERM ERROR ANALYSIS

Note, the following discussion of errors for coaxial impedance is in terms of SWR. Return loss values (dB) and SWR (dB) meter readings and terms of reflection coefficient are all converted to SWR values.

Bridge measurement errors: The systematic and random errors are computed in the following manner. (1) The bridge systematic error[1] ($\Delta\Gamma$) is computed from the relationship $\Delta\Gamma = .001 \pm 0.1\ \Gamma\mu^2$. The term .001 refers to directivity (60dB) and the term 0.1 $\Gamma\mu^2$ refers to the output connector mismatch with the test unit ($\Gamma\mu$) connected to it. Table 1 displays results for various values of SWR for 200 and 400MHz.

(2) Instrumentation systematic errors are contributed by the precision measurement attenuation' receiver which has a error of 0.02dB/10dB. To be conservative, all measurements below 20dB return loss are given 0.04dB error all other values are determined by the aforementioned relationship. Table 2 depicts errors associated with various values of return loss (dB) based upon mismatch SWR values. Propagation of error techniques[3] were used to transform the error in terms of return loss (dB) to values of SWR. The following describes the terms used in table 2.

R_L(dB) = return loss (dB) based upon mismatch SWR value.

AR,_ (dB) = error in terms return loss (dB) for a particular measured value.

ASWR = error in terms of SWR due to error in ΔR_L(dB).

The propagation of error technique is used for the transformation. $A\,SWR \cong 2\,[(.115)(10^{-R_L(dB)/20})*\Delta R_L(dB)]$ is the relationship used to transform return loss (dB) to SWR.

(3) Random error in making return loss measurements of the reflectometer bridges includes operator, connector, source and instrument error. Again, propagation of error techniques are employed to transform return loss variations to SWR values.

example: $\overline{R}_L(dB) = 21.0$ dB
$\sigma(R_L(dB)) = 0.05$ dB
then $\sigma(SWR) = 2\,[(.115)(10^{-21.0/20}).05]$
$= 0.0010$

$\overline{R}_L(dB)$ = average of "N" return loss measurements.
$\sigma(R_L(dB))$ = variation (variance) of "N" return loss measurements.
$\sigma(SWR)$ = variation of SWR transformed from return loss measurements.
$\sigma(SWR) \cong 2\;[(.115)(10^{-R_L(dB)/20})\,\sigma(R\,(dB)]$ this is the transfer function that relates the variance in return loss (dB) to variance in SWR.

Standard Airline Measurement Errors: The systematic and random errors are computed in the following manner.
(1) Systematic errors due to mismatch of the test port (Γ_{tp}), unit under test (Γ_{uut}) and the airline (Γ_{al}) are discussed. The test port mismatch was measured by looking from the measurement plane on the output port of the slotted line back toward the generator. The airline mismatch was computed from manufactures specifications using the following formula $SWR = 1.0013 + (.0013)\,F(GHz)$. The following relationship gives the total mismatch error due to the airline, test port and unit under test. $\Delta SWR = SWR_{uut} * [(1+\Gamma_{tp}\,\Gamma_{uut})^2 + (1+\Gamma_{al}\,\Gamma_{uut})^2-2]$. Using measured values for Γ_{tp} and computed values for Γ_{al} and nominal values for Γ_{uut} table 3 is constructed.

(2) Airline length errors evolve due to imperfect line lengths. Error analysis performed on the airlines maximize the effects of length errors by observing the change in voltage at a minimum on the standing wave.. As the SWR increases the sharper the minimum gets and the slope angle increases such that small changes in length give rise to large errors in SWR. Standard airlines have been measured to be within $\pm$ 0.02cm of their specified length. These airlines are of the beadless type.
(Note: It was found that by keeping the frequency to 0.01% produces negligible effects in SWR.) The following formula describes the voltage level of the standing wave at specific distances (d) along the wave at various values of SWR.[4]

$$E = E_1[1+\Gamma_{uut}-2\Gamma_{uut}\cos(\tfrac{4\pi d}{\lambda_g})]^{1/2}$$

where:
E = voltage of standing wave at a distance from minimum.
E_1 = incident voltage
Γ_{uut} = reflection coeff cient of unit under test
d = distance from minimum in centimeters
λg = wavelength in slotted line

Note the following relationships:
$E_{max} = E_1(1+\Gamma_{uut}+2\Gamma_{uut})^{1/2}$, when $d=\lambda/4$ from minimum
$E_{min} = E_1(1+\Gamma_{uut}-2\Gamma_{uut})^{1/2}$, when $d=0$ (at minimum)
$E_{error} = E_1[1+\Gamma_{uut}-2\Gamma_{uut}\cos(\tfrac{4\pi d}{\lambda_g})]^{1/2}$, when $0>d>\lambda/4$

therefore: $SWR = E_{max}/E_{min}$, but $SWR_{error} = E_{max}/E_{error}$ (near min) so that A SWR is equal to the error due to airline length in terms of SWR. Table 4 demonstrates the errors associated with different values of SWR at different frequencies with an airline length error of 0.02cm.
(3) Systematic instrument errors associated with the SWR (dB) measurements include errors generated by the ratiometer, SWR meter and the crystal detector on the slotted line. The ratiometer and the SWR meter are calibrated as one unit with a uncertainty of ± 0.02 dB for the range of use. The crystal error is ± 0.01 dB for non-linear response. To convert the errors in the instrumentation to errors in terms of SWR once again applies the propagation of errors technique. The following relation performs this transformation.

$A\,SWR = (.115)(10^{\frac{SWR(dB)}{20}})(A\,SWR\,(dB))$
A SWR = error in terms of SWR due to instrument errors
SWR (dB) = SWR values in terms of SWR (dB)
A SWR (dB) = ± 0.03 dB error due to instrumentation

Table 5 demonstrates the error in terms of SWR due to instrumentation error at a given value of SWR.
(4) Random errors associated with the standard airline method include the following: (1) connector repeatability, (2) operator performance, (3) instrument instability with time and (4) source fluctuations. These random components again are transformed from SWR (dB) readings to values of SWR. The following relationship describes the transform.

$\sigma(SWR) = (.115)(10^{\frac{SWR(dB)}{20}})(\sigma SWR(dB))$
$\sigma(SWR)$ = variance in terms of SWR
$\sigma(SWR\,(dB))$ = variance in terms of SWR (dB) readings
SWR (dB) = average of SWR (dB) readings

Table 6 demonstrates the relationship between the variance of SWR (dB) to the variance of SWR with different values of SWR.

In summary of the short term error analysis (covering both systematic and random errors) table 7 displays a typical data worksheet for a mismatch standard with a SWR value of 4.0. 200 and 400 MHz are evaluated by bridge error analysis while 1.0 to 8.5 GHz are evaluated by standard airline error analysis.

Table 8 is a comparison of the compilation of errors between the old method to the new method in terms of SWR for 1.00 to 4.0 SWR standards. The new method is a nominal value.

LONG TERM ERROR ANALYSIS

The preceding sections have discussed the short-term systematic and random errors. Those errors relate to the short-term component of the total error analysis. Now, let's turn to the long-term error component. The first attempt to characterize the long-term error was to make a general model to represent "types" of mismatch standards. Historical data was gathered over 11 years and a long-term variance was computed for each frequency measured. From this data a regression analysis was performed and a best fit to the data derived. This general model helped indicate the amount of variability based upon frequency. This evaluation gave a fixed value associated with a generic mismatch standard. In other words, the long-term error component was based upon a family of "like items" evaluation and was not based upon the item being measured. This approach was implemented because an automated data base for each item had not been created. This evaluation has been abandoned. The second approach involves the use of desk-top computers which now allows the creation of data bases. Individual historical evaluation of the long-term component is now feasible. Means and standard deviations are now readily available. (see table 9).

QUALITY CONTROL

Once the creation of the computer data bases had taken place quality control procedures were implemented. This program has the ability to display eight control charts, one for each frequency measured. At the completion of each measurement session the current data point is compared with past historical data. At this point the current data point is plotted on displayed control charts (see figure 3a and 3b). This would be the time for acceptance or rejection of the newly measured data point. If accepted, the new data point is stored on the data file; if not accepted, action is taken to correct the out-of-tolerance condition. Possible reasons for the out-of-tolerance condition could be operator error, instrumentation error, measurement technique, the standard changed or computer error! This evaluation allows us to review the new data and take corrective action before new data points are stored on data files. Once all data points are accepted only then are the data points stored on file.

TOTAL ERROR

A final error analysis will be performed in a report generation program that combines short-term systematic and random error and the long-term historical data variations. Now, each-standard will be evaluated on its own merit at each frequency measured. Currently, an effort to combine the data gathering program, the historical data and quality control program and the report generator program is in progress. Completion of this effort is expected soon.

SUMMARY AND CONCLUSION

The use of the propagation of error techniques has allowed the transformation of systematic and random errors of measured and computed values to units of SWR. Computers have allowed individual error evaluation for each frequency measured and creation of computer data bases has allowed automation of long-term error analysis and historical data file formation.

The ultimate goal of this laboratory is to transfer all historical data on folders to disk storage files. This will be a three to five year project. The quality control features are in a prototype state, new additions to the basic statistical calculations are being discussed. New testing of the means and variances will help evaluate historical data with current data.

Extensions of calibration cycles with realistic uncertainties limits will be addressed after completion of computer data bases.

ACKNOWLEDGMENT

The author wishes to thank Mr. W. H. DeBussey for creating the program that generates the history data files and quality control analysis.

REFERENCES

(1) Wiltron Catalog, 1978, p. 44

(2) Weinschel Engr. Catalog, 1978-79, pp. 58-61

(3) Zapf, Thomas L., Treatment of Errors and Uncertainties In Radio Frequency Measurements, NBS Report 9731, June 1969, pp. 44-45, 71-75

(4) Cross, A. W., Experimental Microwaves, Marconi Instruments Ltd., 1977, pp. 89-90

TABLE 1. ASWR: ERROR DUE TO BRIDGE

SWR	Γ_u	$\Delta\Gamma$	ASWR
1.005	.00249	.0010	.0020
1.100	.04762	.0010	.0020
1.200	.09091	.0018	.0036
1.500	.2000	.0050	.0100
2.00	.3333	.0121	.0234
4.0	.6000	.0370	.0768

TABLE 2. ASWR: ERROR DUE TO INSTRUMENTATION

SWR	R_i (dB)	ΔR_L (dB)	ASWR
1.005	52.1	0.12	.00007
1.100	26.4	0.06	.00066
1.200	20.8	0.04	.00084
1.500	14.0	0.04	.0018
2.00	9.7	0.04	.003
4.0	4.4	0.04	.005

TABLE 3. ASWR: ERROR DUE TO MISMATCH

FREQ (GHz)	.00249 (1.005)	.04762 (1.100)	.09091 (1.200)	.200 (1.500)	.333 (2.00)	.60 (4.0)
1.0	0	0	.0019	.0052	.0117	.042
2.25	0	.0010	.0021	.0057	.0127	.046
3.0	0	.0010	.0021	.0057	.0127	.046
5.0	0	.0011	.0024	.0065	.0144	.052
7.0	.0001	.0026	.0054	.0149	.033	.120
8.5	.0001	.0029	.0061	.0169	.037	.136

0 = denotes error is less than 10^{-4}

TABLE 4. ASWR: DUE TO AIRLINE LENGTH ERROR

	SWR					
F(GHz)	1.005	1.100	1.200	1.500	2.00	4.0
1.0	0	0	0	0	0	.0005
2.25	0	0	0	0	.0003	.0027
3.0	0	0	0	.00015	.0005	.0047
5.0	0	0	.0001	.00041	.0013	.031
7.0	0	.00010	.0002	.00081	.0026	.026
8.5	0	.00014	.0003	.0012	.0038	.037

0 = denotes error is less than 10^{-4}

TABLE 5. ASWR: ERROR DUE TO INSTRUMENTATION

SWR	SWR(dB)	ASWR(dB)	ASWR
1.005	.043	.03	.0035
1.100	.827	.03	.0038
1.200	1.584	.03	.0041
1.500	3.522	.03	.0052
2.00	6.020	.03	.0069
4.0	12.041	.03	.0138

TABLE 6. ASWR: ERROR DUE TO RANDOM COMPONENT

SWR	.005dB	.01dB	.02dB	.03dB	.04dB	.05dB
1.005	.0006	.0012	.0023	.0034	.0046	.0058
1.100	.0006	.0013	.0025	.0038	.0051	.006
1.200	.0007	.0014	.0028	.0042	.0055	.007
1.500	.0009	.0017	.0035	.0052	.007	.009
2.00	.0012	.0023	.0046	.0069	.009	.012
4.0	.0023	.0046	.0092	.014	.018	.023

TABLE 8.

OLD METHOD

SWR

FREQ(GHz)	1.00	1.10	1.20	1.50
0.2	.008	.008	.008	.010
0.4	.008	.008	.008	.010
1.0	.008	.008	.008	.010
2.25	.008	.008	.010	.012
3.0	.008	.008	.012	.014
5.0	.010	.010	.015	.018
7.0	.016	.016	.018	.020
8.5	.018	.018	.020	.022

NEW METHOD

SWR

FREQ(GHz)	1.00	1.10	1.20	1.50	2.00	4.0
0.2	.002	.003	.005	.014	.030	.084
0.4	.002	.003	.005	.014	.030	.084
1.0	.007	.009	.010	.016	.026	.070
2.25	.007	.009	.010	.016	.027	.076
3.0	.007	.009	.010	.016	.027	.078
5.0	.007	.009	.011	.017	.030	.093
7.0	.007	.010	.014	.026	.050	.12
8.5	.007	.011	.015	.028	.055	.15

IMPEDANCE MEASUREMENT SYSTEM USING REFLECTOMETER BRIDGES

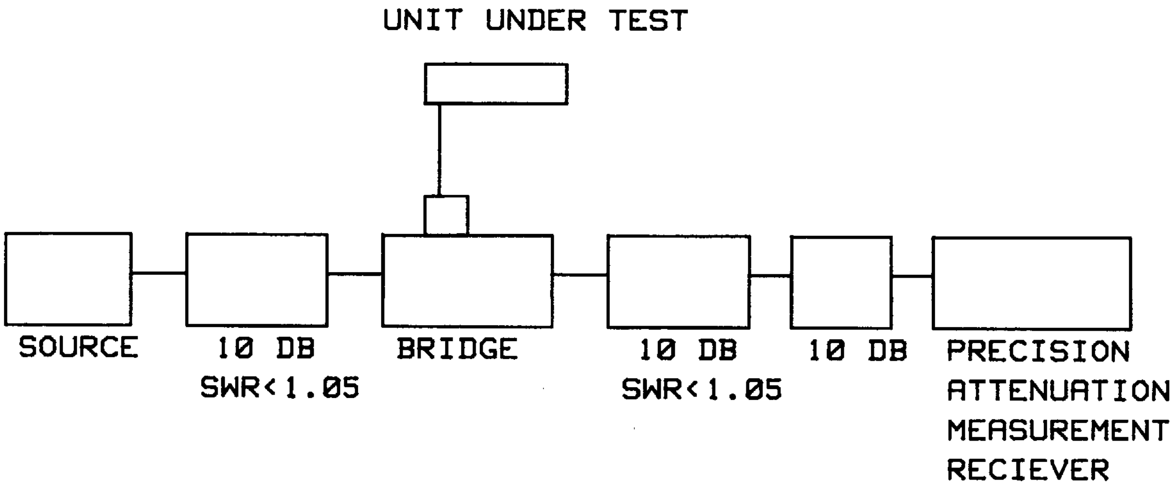

FIGURE 1

IMPEDANCE MEASUREMENT SYSTEM USING AIRLINES

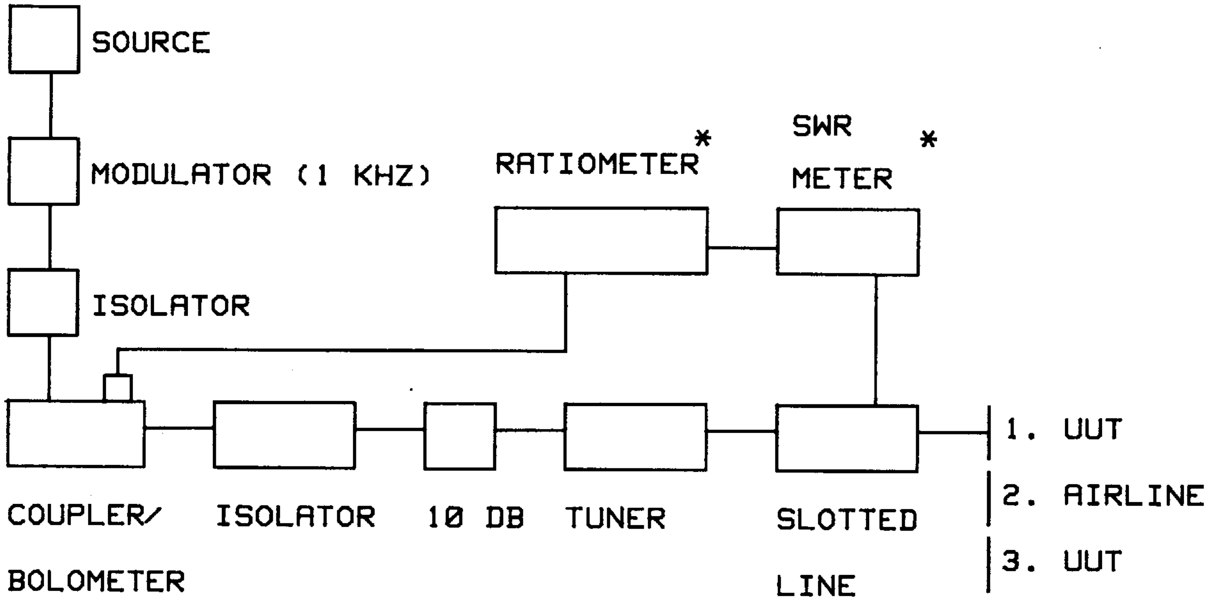

FIGURE 2

* CALIBRATED AS ONE UNIT

FIGURE 3(a)

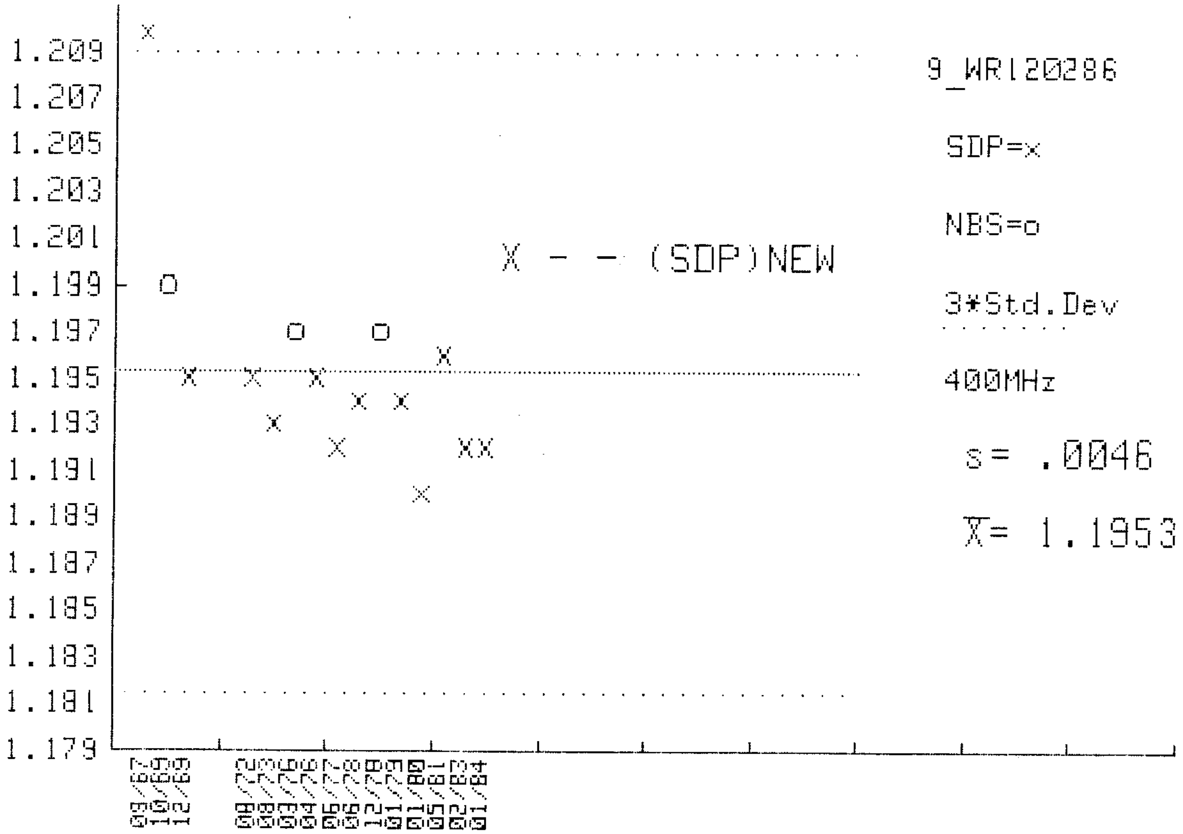

FIGURE 3(b)

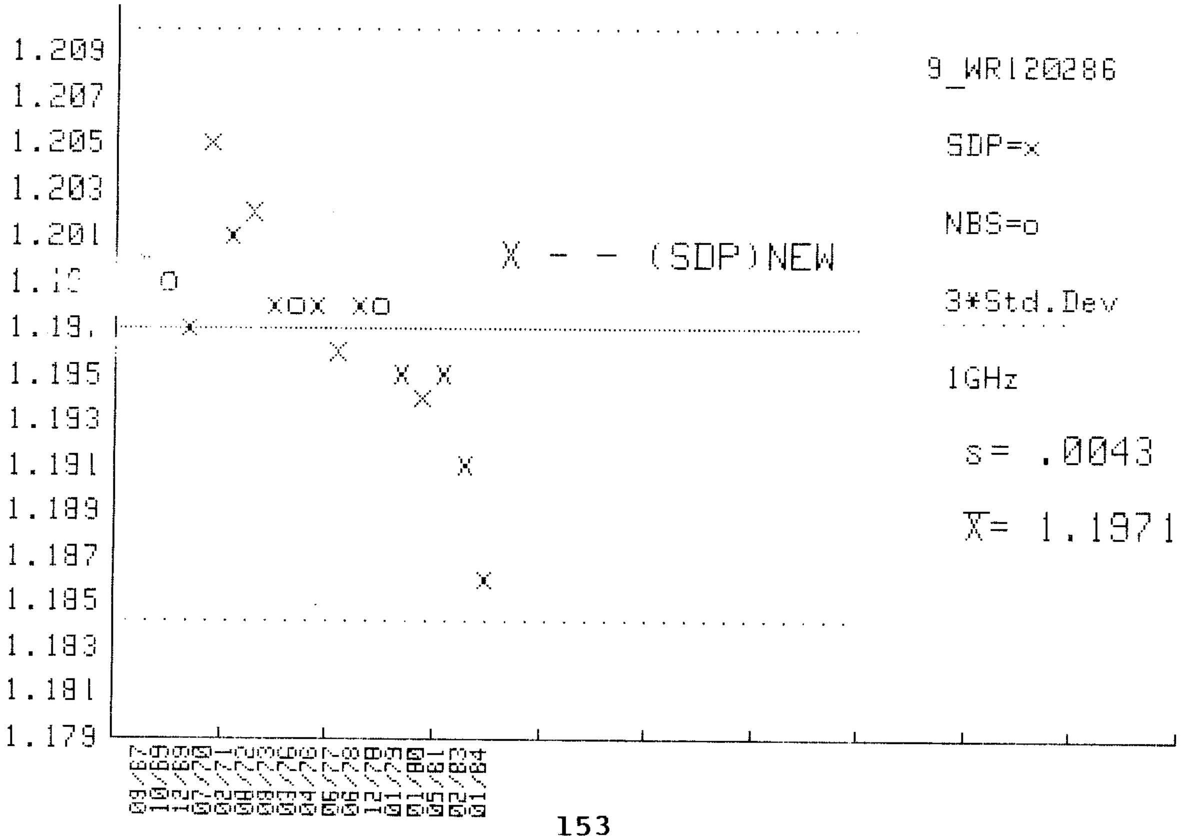

TABLE 7. WORKSHEET

MODEL: 900W200 SERIAL: 216

DATE: 15 MAR 1984

FREQ (GHz)	MEAS VALUE	VSWR	GENERATOR VSWR	SIGMA	SHORT VALUE	OPEN VALUE
0.20	4.013	4.199	0.000	0.0021	0.00	-0.41
0.40	3.914	4.212	0.000	0.0015	0.00	-0.58
1.00	11.814	3.897	1.020	0.0078		
2.25	11.654	3.826	1.020	0.0073		
3.00	11.920	3.944	1.020	0.0156		
5.00	11.962	3.964	1.020	0.0149		
7.00	11.625	3.813	1.020	0.0264		
8.50	11.381	3.707	1.020	0.0158		
9.00	0.000	1.000	0.000	0.0000		
[illegible]	0.000	1.000	0.000	0.0000		

ERROR ANALYSIS

FREQ (GHz)	BRIDGE ERROR	INSTRUMENT ERROR	RANDOM ERROR	T. ERROR
0.20	0.0777	0.0029	0.0004	0.081
0.40	0.0780	0.0029	0.0003	0.081

FREQ (GHz)	MISMATCH ERROR	AIRLINE ERROR	INSTRUMENT ERROR	RANDOM ERROR	TOTAL ERROR
1.00	0.0474	0.0005	0.0134	0.0043	0.066
2.25	0.0466	0.0023	0.0132	0.0039	0.066
3.00	0.0492	0.0045	0.0136	0.0087	0.076
5.00	0.0505	0.0127	0.0137	0.0083	0.085
7.00	0.0485	0.0220	0.0132	0.0142	0.098
8.50	0.0470	0.0296	0.0128	0.0082	0.098
9.00	0.0000	0.0000	0.0035	0.0000	0.003
11.00	0.0000	0.0000	0.0035	0.0000	0.003

TABLE 9.

HISTORICAL DATA SHEET FOR COAXIAL MISMATCH
MODEL-SERIAL 9_WR120286

LAB	DATE	INIT	200MHz	400MHz	1GHz	2.25GHz	3GHz	5GHz
SDP	09/67	DDE	1.210	1.210	1.200	1.205	1.205	1.200
NBS	10/69	N/A	1.197	1.199	1.199	1.196	1.197	1.196
SDP	12/69	WCS	1.198	1.195	1.197	0.000	1.188	1.203
SDP	07/70	WCS	0.000	0.000	1.205	0.000	1.203	1.198
SDP	02/71	WCS	0.000	0.000	1.201	0.000	1.196	1.199
SDP	08/72	WCS	1.198	1.195	1.202	1.200	1.195	1.202
SDP	08/73	WCS	1.195	1.193	1.198	1.203	1.197	1.199
NBS	03/76	N/A	0.000	1.197	1.198	1.198	1.196	1.195
SDP	04/76	RL	1.195	1.195	1.198	1.197	1.197	1.197
SDP	06/77	N/A	1.194	1.192	1.196	1.195	1.197	1.197
SDP	06/78	N/A	1.195	1.194	1.198	1.196	1.193	1.197
NBS	12/78	N/A	0.000	1.197	1.198	0.000	1.197	1.195
SDP	01/79	N/A	1.198	1.194	1.195	1.191	1.195	1.195
SDP	01/80	N/A	1.196	1.190	1.194	1.191	1.192	1.187
SDP	05/81	N/A	1.186	1.196	1.195	1.192	1.193	1.196
SDP	02/83	JWM	1.198	1.192	1.191	1.195	1.194	1.189
SDP	01/84	PLB	1.198	1.192	1.186	1.193	1.187	1.183
STANDARD DEVIATIONS - -			.0051	.0046	.0043	.0043	.0044	.0051
MEAN VALUES - - - - -			1.197	1.195	1.197	1.196	1.195	1.196

LAB	DATE	INIT	7GHz	8.5GHZ	9GHz	11GHz	15GHz	17GHz
SDP	09/67	DDE	1.190	0.000	0.000	0.000	0.000	0.000
NBS	10/69	N/A	1.192	0.000	0.000	0.000	0.000	0.000
SDP	12/69	WCS	1.194	1.187	0.000	0.000	0.000	0.000
SDP	07/70	WCS	1.190	1.180	0.000	0.000	0.000	0.000
SDP	02/71	WCS	1.188	1.184	0.000	0.000	0.000	0.000
SDP	08/72	WCS	1.199	1.188	0.000	0.000	0.000	0.000
SDP	08/73	WCS	1.185	1.183	0.000	0.000	0.000	0.000
NBS	03/76	N/A	0.000	0.000	0.000	0.000	0.000	0.000
SDP	04/76	RL	1.190	1.189	0.000	0.000	0.000	0.000
SDP	06/77	N/A	1.185	1.182	0.000	0.000	0.000	0.000
SDP	06/78	N/A	1.185	1.180	0.000	0.000	0.000	0.000
NBS	12/78	N/A	1.208	0.000	0.000	0.000	0.000	0.000
SDP	01/79	N/A	1.186	1.181	0.000	0.000	0.000	0.000
SDP	01/80	N/A	1.185	1.181	0.000	0.000	0.000	0.000
SDP	05/81	N/A	1.186	1.181	0.000	0.000	0.000	0.000
SDP	02/83	JWM	1.186	1.180	0.000	0.000	0.000	0.000
SDP	01/84	PLB	1.168	1.182	0.000	0.000	0.000	0.000
STANDARD DEVIATIONS - -			.0082	.0031	.0000	.0000	.0000	.0000
MEAN VALUES - - - - -			1.188	1.183	0.000	0.000	0.000	0.000

SESSION III-D

LOCAL AREA NETWORKS - A COMPARATIVE ANALYSIS

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LOCAL AREA NETWORKS

A COMPARATIVE ANALYSIS

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ABSTRACT

There has been alot of activity in the computer industry over the last several years centering around the concept of local area networks. Many computer manufacturers have announced their own versions of Local Area Networks. Specialized companies have released their own Local Area Networks, tying together various computer vendors' gear. Also, several standards organizations have looked closely at local area networks. The most prominent of these standards organizations is IEEE with its 802 series of Local Area Network specifications. This article will discuss the characteristics of these specifications in more detail.

INTRODUCTION

First, we must be sure we agree on our expectations for- a Local Area Network (often referred to as LAN). A LAN is designed to provide a simple, consistant, low-cost scheme for wiring a limited area, and facilitating the high-speed flow of information within that wired area. No restrictions are placed on the type of information flowing in the LAN. The information may be destined for a single receiver, or for many receivers. The information may be computer data, but could just as easily be voice data for things like telephone equipment, intercoms, and public address systems, or the information may be video data, for use with security monitors, information displays, and video-conferencing. In fact, the LAN does not concern itself at all with the kind of information flowing in it. The LAN leaves it up to the sending and receiving stations as to how to interpret the data. This is why multiple computer vendors may all claim to support file transfer on a particular LAN, but cannot send files back and forth to each other -- each vendor may use their own information format to send files, and might not understand the other vendors' formats. The LAN does not take notice of these discrepancies, it merely delivers packets of information, as requested by the sender.

WHY DIFFERENT LANS?

There are alot of different LANs on the market. The reason for this is that LANs, just like everything else, have trade-offs; speed vs cost, availability vs bandwidth, access time vs throughput. Different LANs strike different balances between the trade-offs, thereby having different characteristics, and appealing to different segments of the marketplace.

ETHERNET

Ethernet, also known by its more technical name of Carrier Sense Multiple Access with Collision Detect (CSMA/CD) is the basis for the IEEE 802.3 specification. It works by having a potential sender first listen to see if any other station is sending infomation on the cable. If the cable is in use, our sender must wait for the other sender to finish. Once, the cable is free, our sender can then send its message. While it is sending, it also listens to the cable to make sure no other station sent a message at the same time. Two stations sending at the same time is called a collision. If that happens; each sender interrupts their message, waits a random amount of time, and then tries again Eventually, the message will get through uninterrupted. Note that since sending stations first listen to see if anyone else is using the cable, collisions only occur if two or more stations try to send at the same time. Once the sender gets the first few bytes of the message off, no other stations will attempt to send until the message is completed.

There are quite a few advantages to this scheme. The algorithm is easy to implement, providing a low cost for connection. Stations do not have to keep track of other stations on the LAN, so it is easy to add and remove stations, simplifying installation, expansion, and reconfiguration of the LAN. The time an individual station must wait to use the LAN is based entirely on traffic load. It makes no difference whether the LAN has many low-traffic stations or just a few high-traffic stations.

Ethernet has disadvantages, too. The time it takes a sending station to get access to the LAN is based on the probability that no other stations are sending, or need to send. Some critical applications cannot accept only probability that a certain sender will get to use the LAN within a given time frame. They must have a guaranteed maximum access time. Also, Ethernet works best under light load conditions. Heavy usage of an Ethernet LAN could cause station access time to become unacceptable.

Ethernet lends itself best to applications that provide a large number of stations sending random sized information packets at random intervals, and that don't require guaranteed split-millisecond access to the LAN. An example of this would be an office automation environment. Ethernet's characteristics make it a good general purpose network.

TOKEN BUS

The Token Bus is the LAN architecture specified by the IEEE 802.4 committee. It works by having participating stations take turns controlling the LAN. After a station is done transmitting, it sends a token on to the next station in the chain, notifying the next station that it is its turn to control the LAN. During the time a station has control of the LAN, it can send messages, request responses, and poll other stations to see if they have messages to send. A timer controls just how long a station may hold the token. When the last station in the chain is finished with its turn controlling the LAN, the token is returned to the first station in the chain. Provisions exist within the protocol for adding and removing stations, and for recovering when the token is lost. There are also provisions for higher priority messages to have better chances ofgetting on the LAN than lower priority messages.

The advantages to this method lie in the ability to configure the LAN to exactly meet the needs of the application. Note that not all stations on the LAN need be in the token chain. Stations not in the chain may be polled by controlling stations within the chain. Also, when traffic gets heavy, the Token Bus LAN can depend on its stations taking turns controlling the LAN to ensure all stations have equal opportunity to send messages. Ethernet cannot guarantee this.

However, there are many disadvantages to this technique. To pass on the token, stations must keep track of the next station in the chain. For error recovery, stations most also keep track of the previous station in the chain. A significant piece of the LAN bandwidth is given over to keeping these pointers accurate. The complexity of this algorithm drives up the cost per connection. If too many stations are added to the chain, response time may become unacceptable.

Token bus LANs are best suited for manufacturing and laboratory applications. A small number of stations in the chain can control and collect data from specialized instruments. Should a station in charge of polling a group of instruments fail, a second station can pick up the responsibility without requiring any re-wiring. Also process control messages can be given priority over other less time dependent messages.

TOKEN RING

The Token Ring architecture, basis of the IEEE 802.5 proposal, works on a similar principle to the Token Bus. However, the Token Ring LAN takes advantages of the physical design of the LAN being in a ring. In the Token Ring, a free token is passed from station to station around the cable. When a station wants to transmit, it modifies the token going by, marking it busy. The station then appends its outgoing message behind the busy token. The busy token and message propagate around the ring, each station checking the destination address as the message goes by. As the message goes by the intended receiver', the message is marked as received, and continues around the ring. When the sender receives the busy token, he changes it back to a free token for the next station on the ring. The sender can then check the sent message for the flags set by the receiver, and verify that the message was received correctly. Like the Token Bus, special consideration had to be taken to allow recovery from Token loss. However, unlike the Token Bus, no special considerations are needed for adding and removing stations--in the Token Ring, stations merely break into or disconnect from the ring. The next physically adjacent station will be the one to next receive the token.

There are two main advantages to this method. The first is its easy reconfiguration--whole sections may be brought in or out of the LAN merely by reshaping the ring. The second is that, like the Token Bus, it behaves predictably in saturation conditions.

The disadvantages are that even in low utilization conditions, a station must still wait for the free token before sending, and the cost per connection is usually higher than Ethernet. Because of the delay caused by waiting for the token, a smaller number of stations is recommended.

The Token Ring performs well in the general case, where offered load approaches the actual bandwidth of the LAN.

SO WHICH IS BEST?

Which LAN is best usually is based on just who you are talking to. The labs and manufacturing areas may prefer the Token Bus LAN, providing them with distributed control over test gear, process monitoring, and process control equipment. The individual office departments may prefer Ethernet for its low cost and easy reconfiguration. MIS departments may prefer a Token Ring to handle the load of all the data traffic in the company.

The IEEE 802 project is addressing this problem as well. The 802.7 committee is looking at specifications for bridges--devices that will translate messages from one LAN format to another, making all inter-connected LAN types behave as one giant Local Area Network. Using bridges, the Lab can have one Token Bus LAN, and manufacturing another, each tuned for that specific application. The office departments can have their own, inexpensive Ethernets. And MIS can tie them all together with a Token Ring.

This set-up provides specialized LANs where they are needed, and simple inexpensive LANs where specialization is unnecessary. Also, this means a single station per department on the more expensive high availability company backbone network, where the bridge connects the departmental LAN into the company-wide network,

SUMMARY

Various LANs meet various requirements. There is no one best LAN architecture. By using bridges between the various LANs, a network can be created that gives the best possible fit to every application. Also, departments need not put off networking just because other technologies will be available in a few years. Departmental LANs based on IEEE 802 standards will be able to connect to future standards via a bridge device. Bridges will provide the means for dissimilar LANs to function together as a unified network.

SESSION IV-A

AUTOMATED TEST EQUIPMENT (ATE) CALIBRATION

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AUTOMATIC CALIBRATION NEW TECHNOLOGY*

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Abstract

Automatic calibration and computer data base management system technology has advanced to enable completely automatic generation of calibration procedures, performance of the procedure, and autoreporting of instrument tolerances/corrections to users.

An application of this new technology at Arnold Engineering Development Center, using a network of automatic calibration systems, relational data base management systems and remote user-controlled terminals, is described. Likely, future developments of these fields into the area of expert systems is explored.

Introduction

Automatic calibration has two critical information requirements - internal and external. Internal information includes specifications, IEEE 488 address, unique bus codes to activate functions, selection of a finite set of calibration data points, and a choice of calibration techniques. These internal information requirements are data needed to perform the classical calibration process. External information requirements include

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*The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Systems Command. Work and analysis for this research were done by personnel of Computer Sciences Corporation, subcontractor to Pan Am World Services, Inc., MSSP, operating contractor for the AEDC base services. Further reproduction is authorized to satisfy needs of the U. S. Government.

parameters required to select an instrument for a specified task, information required by users to correct or analyze data taken by a particular instrument, and management of an instrument inventory - instrument location, service interval, cost accounting, and laboratory work flow scheduling. The following discussion presents solutions to these calibration requirements.

Definition of the Requirements

Internal information requirements are typically satisfied by a calibration procedure written uniquely for a particular manufacturer/model instrument. For automatic calibration, this solution generally requires a custom computer program for each model instrument.

Were it possible to standardize models within an organization, the custom procedure would work well, However, in an engineering environment or under competitive procurement policies, the norm is a wide variety of instrument models. Few calibration organizations have the luxury of a staff sufficient to develop custom procedures.

External information requirements have historically been the weakest link of the calibration chain. Instrument users typically have only a basic understanding of performance tolerances and no knowledge of an instrument's corrections.. Where corrections are required,, a typed report of calibration often accompanies the instrument.

Most large instrument inventory management functions are still handled by batch-oriented computer programs with a multitude of thick listings containing out-of-date information. The listing may have been correct when run, but frequent changes can take place in thirty days.

A more general solution to both the internal and external information requirement is desirable. This perspective changes the original problem to the question - can data be processed in such a manner that they

1. are current:
2. provide users with a means of rational instrument selection;
3. enable users to manually or automatically correct and/or analyze uncertainties associated with a particular instrument;

4. provide calibrators with ranges, functions and tolerances necessary to automatically calibrate an instrument; and
5. enable ad-hoc query of the data in an unpredictable format?

Solution to the Requirements

Data base management systems (DBMS) offer numerous advantages over the older custom application programs. Physical data organizations are isolated from'the logical data organization.' This permits a change in the manner in which the data are viewed without affecting the actual data. A DBMS also manages efficient storage and retrieval of data, data security, and permits apparently simultaneous data access by multiple users. The ability to retrieve and manipulate information precludes the requirement for extensive reports, listings, and specifications.

A primary benefit to users of a DBMS lies in its ability to work in real time. Batch-oriented calibration recall/ data systems are often poorly used because of doubts about their accuracy. In a dynamic organization, i.e., high instrument turnover, new tasks and techniques often make thirty-day-old data useless. We need to know where an instrument is today, not where it was two weeks ago.

The ability to formulate and immediately obtain answers to new questions (ad hoc query) regarding instrument management or data system is highly desired. If one could preconceive all possible questions to query a data base, these questions could be coded into the original system. However, all future questions cannot be anticipated. Most managers have experienced the frustration of asking the computer center for a seemingly simple report only to wait weeks while a programmer learns someone else's "elegant" undocumented code.

The relational DMBS offers the additional advantages of very easy design of new applications, simple structural modification, and some English-like ad hoc query languages.

A relational DBMS can easily handle ad hoc queries such as:

- Find a meter that will measure 100 VDC within 0.002% and 20 VAC at 30 kHz within 0.03% in location X, Y, or Z.
- How many instruments did technician "A" calibrate on the day following an absence?
- Of the instruments with no activity for two or more years, print the ones belonging to organization G.

AEDC Instrument Management System

The Arnold Engineering Development Center (AEDC), an Air Force Systems Command Laboratory, is installing a system called IMIS (Instrument Management Information System). IMIS does all the things conventional calibration recall systems do, but interactively, in real time. The system also integrates instrumentation technical data, both specifications and actual calibration results. Instrument users are thus able to obtain computer-aided selection of instruments based on technical criteria and to correct measurements automatically after completing tests.

The calibrating laboratory's procedures are automatically generated to calibrate ranges and tolerances specified in the data base. Figure 1 shows the logic for a multimeter calibration procedure selection. A single generalized procedure is programmed for each major calibration system. The data base is queried for ranges, limitations, and tolerances. If the unit under test (UUT) is itself automatic, its addresses and a unique hardware handler are called to customize the calibrator to that particular UUT. This allows a single high-level BASIC statement to be used for any UUT to read the digital multimeter (DMM), for example, such as READ DMM (R1). This avoids an incoherent stream of ASCII characters which are typically used.

IMIS Data Structure

Data are logically arranged into a group of tables in a form called "third normal". Figure 2 shows an example data base. The ease with which the structure can be modified or new relations added is a source of the system's strength.

User display screens are developed for routine manipulation of the data. For example, referring to Figure 2, if a user wanted the address of item ID Number I-12345, the system would match Mfr. 28480 in the ID file and Mfg. ID file, yielding Hewlett-Packard's address. Further inquiry may lead to the fact that Spec No. A1, B1.1, A2 and B2.1 apply to I-12345.

Uniform maintenance of instrument results and specifications is another key contribution of the system. Using principles developed for the ATLAS programming language, a specification structure is developed.

Referring to Figure 3, the specification file is a two-tier system. "A" level specifications refer to the physical quantity with which the unit is concerned. "B" level specifications refer to a function that the "A" level is dependent upon. "A" specifications are sources, sensors, or loads.

Calibration results, where necessary, are linked back to their specification file for reference. The results are given in equation form where the attribute "form" describes the equation. The most common form is an nth-degree polynomial (form nP) to which the data have been fit. Other common forms are "POW" for power curve, y = axb, "LOG" for logarithmic curve, y = a + b ln x, "EXP" for exponential curve, y = aebx.

The example in Figure 3 shows a first-degree polynomial (FORM is 1P) with equation, y = 0.985 + 3.75E-5 X, with X in Hz. Solving this equation at 400 Hz, 800 Hz, and 1200 Hz, we can obtain a correction at these points of 1.000, 1.015, and 1.03, respectively, as a multiplier for the 100-mV scale for any frequency within its range.

These corrections result in more accurate measurements than would be realized in a conventional system. A side benefit is realized where the item is known to be used only in its autocorrecting mode. Under this condition, it is not necessary for laboratory technicians to physically readjust the instruments. This in turn leads to greater stability since the UUT is not subjected to mechanical disturbances during recalibration.

Acquisition of calibration data for this data base is being rapidly automated at AEDC. Automatic measurement systems are currently in use for multimeters, pressure transducers, fuel flowmeters, and temperature transducers. Additional systems are in various planning stages for frequency instruments, accelerometers, load cells, and signal sources. Figure 4 shows the communication system between the laboratory, central computer facility, and user facilities.

Artificial Intelligence Systems

The calibration/instrument maintenance field is a clear candidate for future artificial intelligence systems. Although not planned for immediate application, CAD/CAM systems contain the knowledge base of circuit schematics, components, and their specifications. This base is a necessary prerequisite to an EXPERT system. Systems capable of using such a knowledge base to diagnose circuits and malfunctions are inevitable.

An EXPERT system for troubleshooting electronic systems was developed in 1975. SOPHIE (Brown and Burton) uses circuit rules such as Kirchoff's laws, interacting with students to complete a repair.

Digital Equipment Corporation uses an EXPERT system, R1, to aid in the difficult task of configuring VAX computer systems.

These modest beginnings will likely grow, becoming essential as an aid to technicians faced with ever-increasing circuit complexity. EXPERT systems which understand common English language are rapidly growing. These systems will allow non-computer-trained experts to easily put their expertise in the computer.

References

1. Principles of Data Base Systems. Ullman, Jeffrey D., Computer Science Press, 1980.

2. Building Expert Systems. Hayes-Roth .Waterman Lenat (eds.), Addison Wesley, 1983.

3. Criteria for Selection of an Automatic. Calibration System Computer. Carrington, Ken, NCSL Newsletter, Vol. 23, No. 2, June 1983.

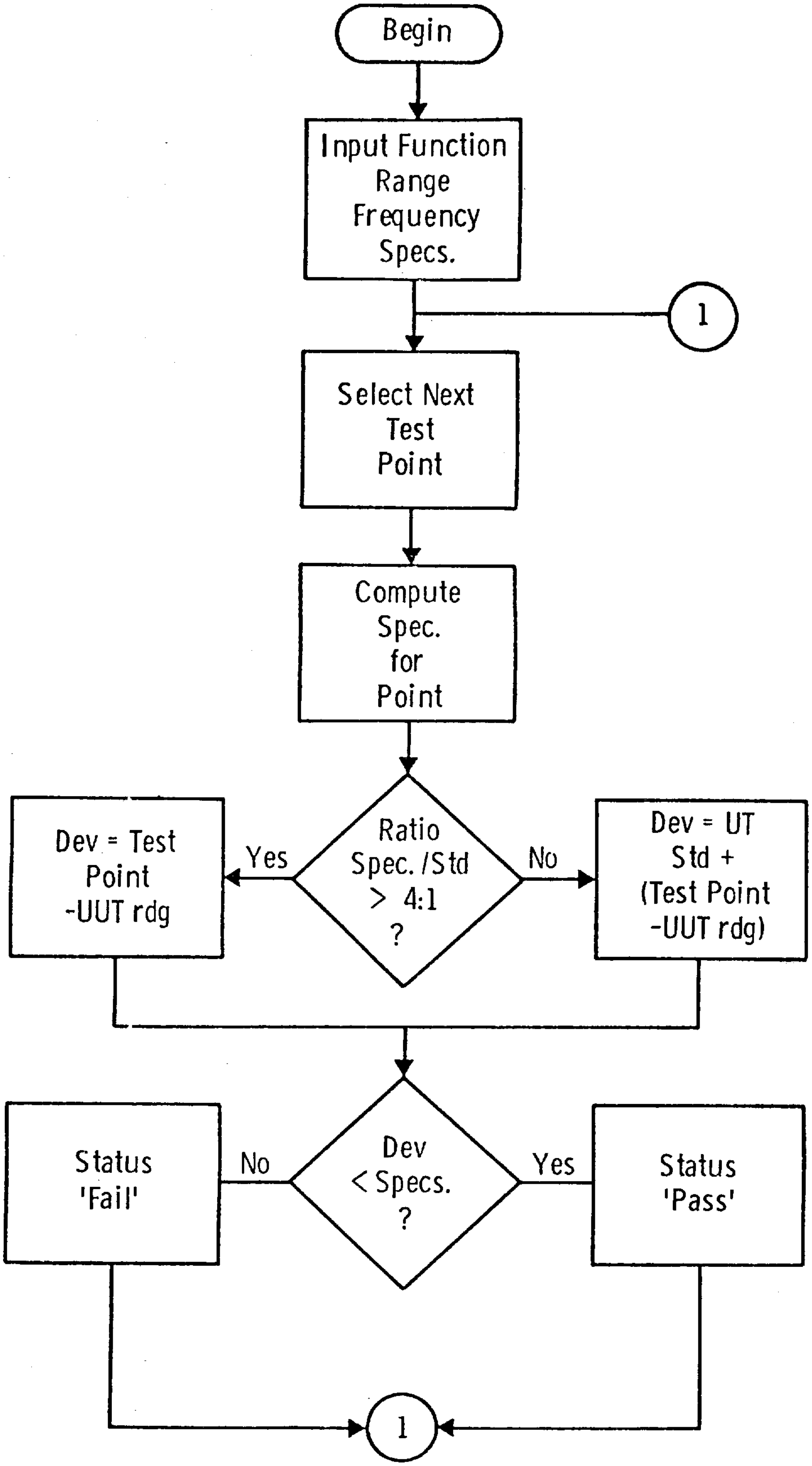

Figure 1. Multimeter Calibration

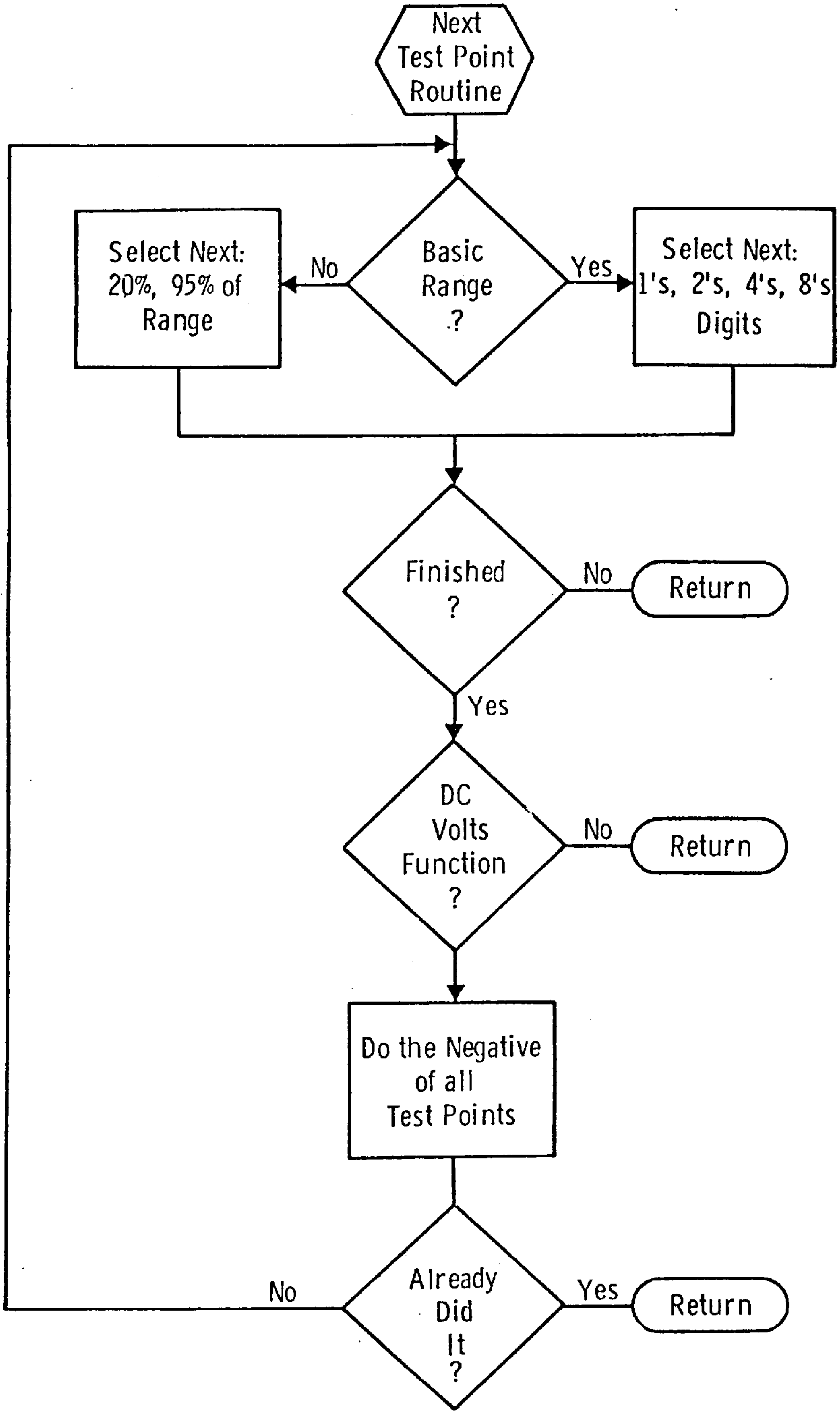

Figure 1. Continued

ID FILE

Item	MFR	Model	Serial	Cost
l-12345	28480	3581A	123-4567	4900
l-23456	80009	7854	4AB123	14230

MFG. ID FILE

MFR	Name	Address
28480	Hewlett Packard Co,	1820 Embarcadero Rd., Palo Alto, CA 94303
80009	Tektronix, Inc.	P.O. Box 500, Beaverton, OR 97077

MFR, MODEL FILE

MFR	Model	Spec. No.	TO	Interval	WUC
28480	3581A	A1 B1.1 A2 B2.1	3-4-595-l	6	XBQGG
80009	7854	A16 B16.1 A17 B17.1	3-4-94-l	6	XCDMA

Figure 2. Sample Data Structure

SPEC FILE

Spec. No.	Function	SO/SE	R-Min	R-Max	Unit	TOL-PC-RNG	TOLPC RDG	TOL-Offset
A.1	Volts-AC	SE		300	mV	4		
B1.1	Freq. Resp.		15	50000	Hz			
A2	Volts-AC	SE	0	1000	mV			
B2.1	Freq. Resp.		400	1200	Hz	4		

CAL-RESULT FILE

I-No.	Spec.-Ref.	CP	Degree	Form	Constant	Remarks
1-12345	B2.1	C	A	1P	0.985	X in Hz
1-12345	B-2.1	C	B		3.75E-5	

Figure 3. Specifications and Results Example

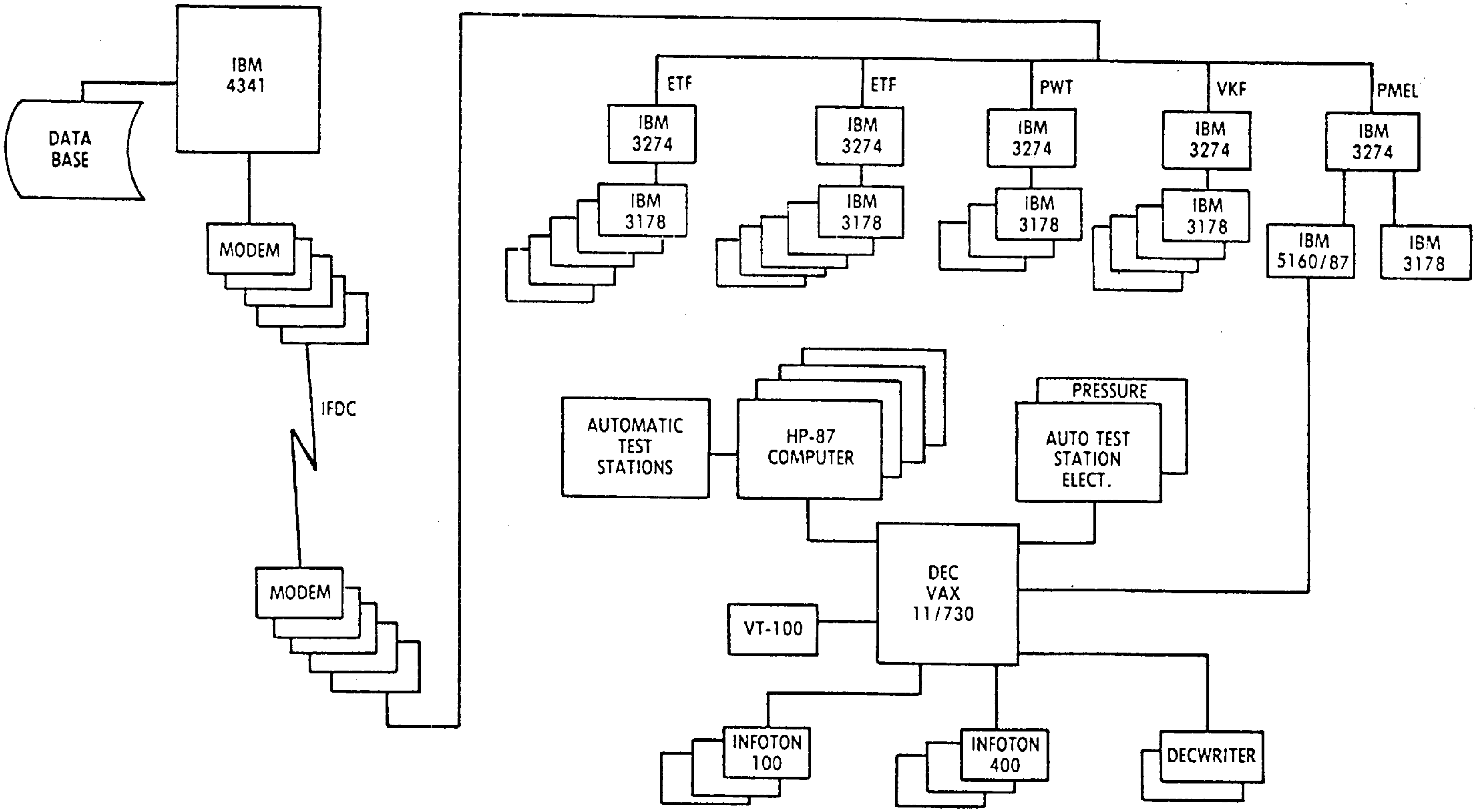

Figure 4. Communications

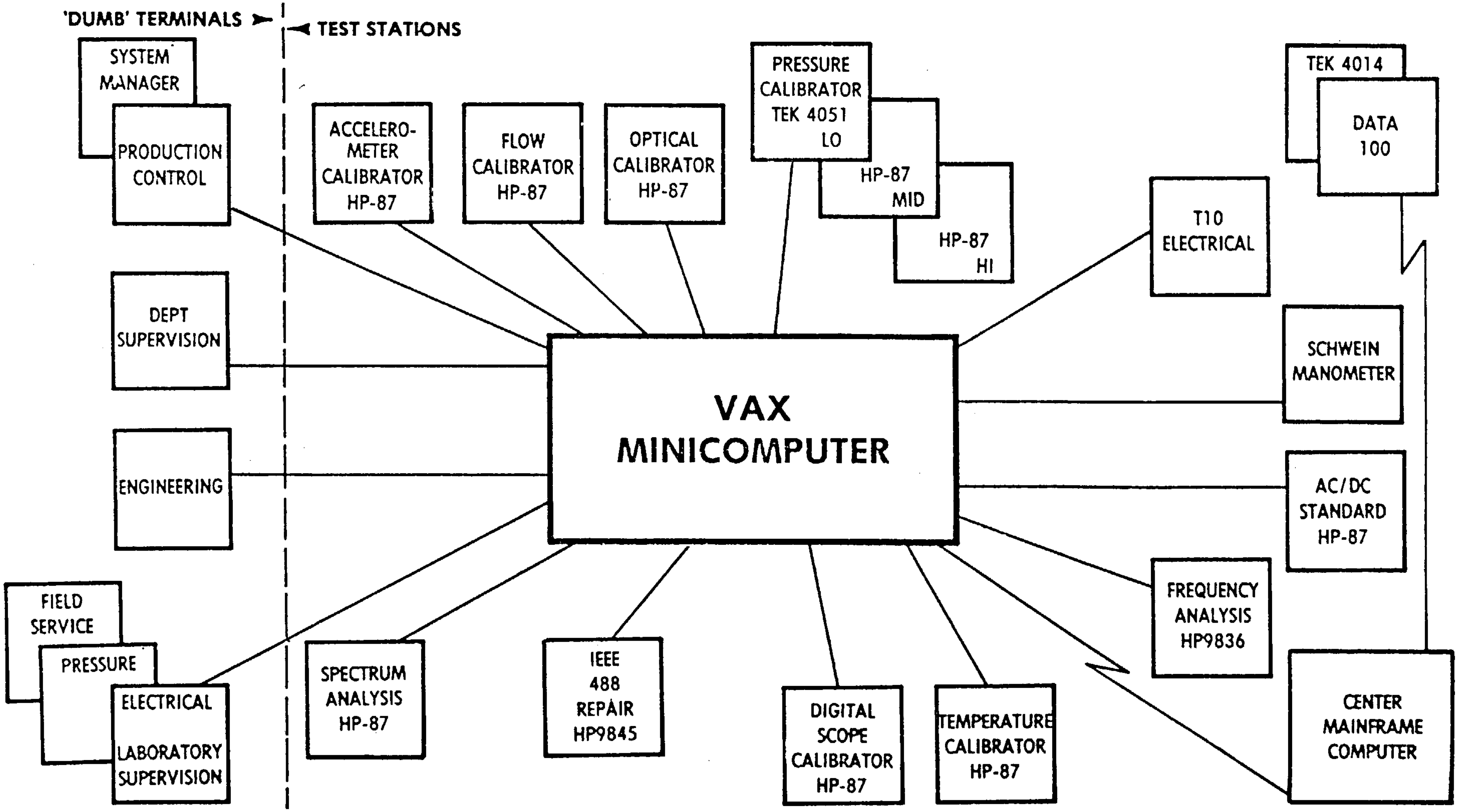

Figure 5. Calibration Systems

SESSION IV-B

LASER AND OPTICAL FIBER METROLOGY

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TEST RESULTS ON THE MODULAR LASER CALIBRATOR

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ABSTRACT

A prototype modular laser calibrator has been constructed consisting of laser transmitter modules together with associated modular optics. The modular laser calibrator is capable of generating and measuring pulsed laser stimuli for calibration of a variety of laser related components, test equipment, and fixtures. All electro optical and mechanical components and fixtures are housed inside an enclosure consisting of an optical bench and cover. All components and assemblies are mounted so that no alignment or adjustment is required by the user or calibration technician. All settings required in a calibration procedure can be selected by externally accessible controls. Units or components to be calibrated can be inserted into the calibrator or attached to mating ports with eye-safe light-tight adapters coupled to safety interlocks. The system, together with the units under test, is a Class I laser system that can be used in any laboratory or shop environment outside specially prepared laser-safe facilities.

Tests have demonstrated that the system is compact, easy to use, and provides a capability for quickly calibrating a variety of equipment and test sets in support of laser rangefinder-target designators (LRTD's).

INTRODUCTION

The concept and preliminary design of the Modular Laser Calibrator (MLC) has been reported by Schweizer, Miller, and Schumann (1). A prototype MLC has been constructed and delivered to the Navy Metrology Engineering Center (MEC). Tests have been conducted to determine the performance characteristics of the system and to evaluate its usefulness in the field. Preliminary calibrations have been performed. Final calibrations have been initiated at the Navy Primary Standards Department, West (NPSD). Development of detailed procurement specifications has been initiated.

BACKGROUND

Test equipment and test sets have been, and will be deployed in the field in support of laser rangefinders and target designators. Some systems operate at the 1.064 micron Nd:YAG wavelength. Systems employing other wavelengths are contemplated.

The test equipment requires calibration support. Parameters presently requiring support are laser energy, pulse width, attenuation, and receiver sensitivity. It is planned to provide the calibration support at the Type III level either at the Type III laboratories or by on-site teams stationed at the Type III laboratories. The equipment under consideration for the Type III laboratories is the Modular Laser Calibrator. The purpose of the MLC is to provide a compact portable eye-safe calibration system to the Type III's either at home or on-site in the field. A prototype MLC has been delivered to MEC. Most of the evaluation tests have been completed. The system is at NPSD awaiting final calibration.

GENERAL REQUIREMENTS

The MLC is designed to be modular, portable, and eye-safe. It consists of a platform on which the various modular components are mounted. Also mounted on the platform is a light-tight cover with interlocks to ensure eye-safe operation unless the interlocks are specifically defeated. Also provided are special adapters to couple the MLC to test instruments in an eye-safe manner. In fact, the MLC cannot be operated unless all interlocks are actuated by test instruments and appropriately keyed adapters, or when specially designed covers are mounted over the exit ports.

PRESENT REQUIREMENTS

The MLC prototype as presently configured is capable of calibrating the following equipment:

1. AN/AAM-75 Range Simulator, which consists of a fiber optic attenuation system.
2. EG&G 580 Radiometer, pulse mode.
3. EG&G 581 Laser Energy Meter.
4. EG&G 550 Radiometer, pulse mode.

5. Scientech 38-0101 Laser Calorimeter with Isoperibol Enclosure.
6. TS-3942/AAM-60(v) calorimeter.
7. TS-3886/PAR Laser Safety Evaluator (LASE).
8. Laser Precision Rj-7100 Laser Energy Meter (with silicon probe).

Note: Adapters for items 6 and 8 have not been constructed. These items can be calibrated by defeating the interlock system, provided Class IV laser safety conditions are met. Similarly, most other equipment for measuring 1.064 micron Nd:YAG laser pulses can be calibrated by the present MLC provided pulse width and energy equipments are met.

CONFIGURATION

The prototype MLC consists of an optical head, a microprocessor control unit, and a number of special adapters, and cover plates. The prototype MLC consists of an optical *source system,* and *a* radiometer mounted in a configuration similar to that in laser rangefinder/target designators the source system emits pulses of laser energy through a variable attenuator followed by two beam splitters. One of the two lateral branches of the laser beam enters an energy monitor; the other enters a fixed attenuator-diffuser system to generate a low level fluence having a magnitude of the order of 0.01 to 1.0 microjoule/cm^2 for calibrating the LASE. The main beam passes through the high energy exit port of the MLC, either raw or expanded depending on the position of the internal laser beam expander. The low level radiometer head is also inside the MLC. It is capable of detecting received pulses in the range from 5 to 100 pJ/cm^2. The MLC has a microprocessor readout and control unit separate from the optical head capable of collecting data in two integrate and hold circuits, either of which may be displayed upon command. For peak power, the output of the MLC radiometer may be photographed on a conventional 1 GHz oscilloscope with camera, or the data may be acquired with a transient digitizer for analysis by computer. For energy, the output of the low-level radiometer can be fed into the second integrate and hold circuit of the control unit. Mechanical controls for thevariable attenuator, the beam expander, and for azimuth and elevation of the low level radiometer are accessible on the sides of the instrument.

SPECIFICATION

The performance specifications of the MLC prototype are listed in Table I.

TABLE I. SPECIFICATIONS OF PROTOTYPE MLC

Wavelength:	1.064 uM
Pulse Width:	17 +/- 4 ns
Range of output energy (high level port):	10 uJ to 100 mJ
Range of output fluence (low level port):	0.01 to 10 uJ/cm^2
Pulse-to-pulse amplitude stability:	+/- 3%
Beam divergence:	< 3 mrad
Beam attenuator:	0 to 30 dB continuously variable
Radiometer range:	100 pJ/cm^2 to 10 mJ/cm^2 with S/N better than 100:1
Weight:	<100 lb. including laser head
Dimensions:	< 14in H x 12in W x 36in L

COMPONENTS

The laser *is* a KEI LD-82 capable of delivering 150 millijoules per pulse at internally controlled repetition rates of 5 and 10 pps. It is also capable of being fired by external pulses as in the case of the MLC. Control of the firing pulses is provided by the microprocessor control box which can fire the laser single shot, ten shots, or continously at 1 pps.

The monitor photodiode is an EG&G FND-100.

The low-level radiometer consists of a 2 inch diameter f/2 collecting lens and a Judson J16-18A germanium photodiode.

The attenuator consists of a CVI AAT-50-106H which consists of a rotatable halfwave plate and polarizer.

MEASUREMENTS

Eye safety measurements were performed using a Laser Precision Rj 7100 laser energy meter with silicon probe. With all screws removed from the cover, leaving open screw holes, the maximum leakage fluence detected was 25 nJ.cm^2. Thus, Class I operation capability was demonstrated. Additional tests with all screws in place and test instruments inserted into the exit ports of the MLC, showed a maximum leakage of 11.6 pJ/cm^2 near the radiometer positioning controls.

The short term stability of the Rj 7100 was measured using a Power Technology CS-100 LED operating at 1.064 urn. The stability of the LED emission was first checked using an EG&G FND-100 silicon photodiode and a Tektronix 7104 oscilloscope with 7A22 plug-in amplifier. The instability of a *system where* the LED output pulses were measured by the Rj 7100 was +/- 0.85%. By using the Rj 7100 to measure the output of the low level MLC port, the pulse-to-pulse instability of the laser was found to be +/- 10%, a problem that requires correction since measurements on other lasers showed an instability of less than +/- 3%.

Further measurements were conducted with an

Rj 7100 at the low energy port and a Scientech 38-0101 calorimeter at the high energy port. The calorimeter was read out by means of the Scientech Model 362 Power and Energy Meter connected to a strip chart recorder.

Measurements showed a standard deviation of the laser output of the order of 10%, which indicated that the laser had deteriorated further.

Measurements performed by the contractor prior to delivery using the laboratory at MEC showed that when the output of the main port was about 100 mJ, the output of the low energy port was about 1 uJ/cm^2. The useful range of the attenuator was about 1000 to 1. The receiver radiometer had a noise level of 5 pJ/cm^2, and a saturation level of 100 pJ/cm^2, that is a dynamic range of about 20.

CONCLUSIONS

Test have demonstrated that the MLC prototype is portable by two men, compact, very easy to use, and eye-safe. Due to the monitor, it was possible to perform trial calibrations of test instruments despite large fluctuations in the energy of the laser pulses. The prototype has successfully demonstrated the usefulness of the MLC concept.

PLANS

A specification has been developed for procurement of a quantity of MLC's during this fiscal year.

REFERENCES

(1) F. Schweizer, R. G. Miller, and L. W. Schumann, "A Modular Laser Calibrator", Proceedings of the Measurement Science Conference, 1984., pp. 20-26.

SESSION IV-C

TIME AND FREQUENCY MEASUREMENTS-CONCEPTS

Frank Koide
Rockwell International

SESSION IV-D

PRECISION DIMENSIONAL MEASUREMENTS OUTSIDE THE LABORATORY

Harry Haymes
Sanders Associates

FLEXIBLE METROLOGY FOR FLEXIBLE MANUFACTURING THE PROCESS CONTROL ROBOT
AS PRESENTED TO 1985 MEASUREMENT SCIENCE CONFEREENCE
JANUARY 17-18, 1985
BY DAVID H. GENEST

The concept of Flexible Manufacturing started in the United States many years ago and moved to Japan and Europe, who pioneered the basic principles. Now these concepts are being put into practice in the United States. This paper deals with an aspect of FMS which is now becoming quite popular, and that is the concept of AUTOMATED FLEXIBLE METROLOGY. We are now starting to understand that an "INDEPENDENT PROCESS VERIFIER" is a key element in the success of an FMS.

This is an area that Brown & Sharpe its board of directors and senior executive staff have recognized as a strength and an emphasis for our future business. The main emphasis of Brown & Sharpe is metrology. With the onset of FMS, metrology requires a different group of applications engineers, different measurement techniques, and a different overall philosophy. Let us begin to understand what FLEXIBLE MANUFACTURING is all about, what FMS offers the customer, and how The INDEPENDENT PROCESS VERIFIER AIDS in the success of flexible manufacturing.

WHAT DOES FLEXIBLE MANUFACTURING OFFER A COMPANY?

AUTOMATED MANUFACTURING; this simple concept relates to the automation of your present processes and parts handling as well as streamlining the flow of parts through your shop. COMPACT UNIFIED, CONTROLLED MANUFACTURING; a better organization of machine tools, again a better flow of your manufacturing process. LOWER LABOR INTENSITY; with the cost of labor and manufactured goods increasing daily, controlling labor costs is a critical element of any process. BATCH PROCESS-ABILITY; the "key" element of FMS. The ability to respond quickly and efficiently to rapid changes in the marketplace and run smaller batches of a wider variety of parts through the same manufacturing system, are critical to business success. REDUCED SETUP; which in conjunction with batch process-ability reduces the costly changeover when market demands differ from original forecast, and REDUCED SCRAP; obviously a goal of every manufacturer in the world today.

The seventh key element of an FMS is direct feedback for process control. The key element in this area is the Independent Process Verifier or the metrology element of the FMS. Let's look a little closer into the Direct Process Feedback (DPF) in order to accurately specify a dimensional gage that can be effectively intergrated into a FMS, so that accurate and timely machine tool offsets can be made.

1. The gage must be LINKED to an FMS Host; there has to be a two-way conversation with the Host that is providing guidance for the overall FMS.

2. The gage must be as FLEXIBLE as the FMS in which it resided. This means that as parts and/or designs vary, the metrology process must be able to handle those changes in tooling, fixtures, stylii, probes, etc. without a change in structure. In addition, being a flexible gage cannotes the ability to handle a wide variety of fixtures and palletts again, without having to employ a wide variety of gage types.

3. The gage must be FAST enough to keep up with the FMS part output. Not only are people demanding to measure the critical features, but they require more features per part thus increasing the amount of features that a gage can measure in a given time frame, more process information will be made available and the ability to accurately control the overall process improves.

4. The gage, if it is to be included in an FMS, must be ACCURATE enough to provide valuable, concise feedback to the FMS host so the proper machine tool offsets may be added. This is a key element of the Independent Process Verifier. The ability to provide accurate, timely information to the FMS Host ensures that the process remains in control at all times.

5. SELF-SUFFICIENCY in an FMS environment is an area that must be fully understood prior to selecting the proper gage for the FMS. The gage has to be self-sufficient in that it must operate automatically and without operator intergration, i.e., the common task of cleaning bearing ways is prohibited, since an FMS must run continuously 24 hours a day.

6. STABILITY is an area that must be understood in the design of the gage. It must also be understood in the cleaning of parts prior to measurement, the positioning

of the gage within the MS, the controlling of the gages environment and the required gaging accuracies.

The major areas that we have covered are LINKABILITY, FLEXIBILITY, SPEED, ACCURACY, SELF SUFFICIENCY and STABILITY. These six areas have to be seriously considered in the design statement before a gage is designed. These are the areas that must be addressed in any market research in the area of FLEXIBLE METROLOGY; and the bottom line, when a gage goes into an FMS, it must fulfill all of the requirements of each of these areas to ensure a successful FMS.

There has been discussion in the past of measurement being made on the machine tool via machine tool-touch trigger probes. There will always be this need and it will. expand to some extent in the future; but the main emphasis of the machine tool is to cut chips, not to make measurements. Due to the limitations of time and the expanding requirement of full geometric software, measurements critical to the process cannot be made on the machine tool due to the accuracy required, the complexity of the features, and the philosophy of not verifying a part by the machine that produced it. The information for offsets and the state of the actual process must come from an Independent Process Verifier.

Another area that requires a brief comment and that we have alluded to, is the level of attention and planning giving the overall FMS and, in particular, the metrology aspect of the FMS. This area must be given a place of prominence in the planning stage of any FMS because it is this area which will ensure a successful FMS!

Now, let's turn our attention to a comprehensive survey performed by Brown & Sharpe aimed at specific customer and OEM FMS needs. This relates not only to the gage, but supporting elements such as accuracy, repeatability, software, electronics and CAD/CAM interfaces.

Today's manufacturing process requires vertical, horizontal arm and high speed measuring robot configurations. A wide variety of parts will be automated; thus, a wide variety of machine configurations are required. Second, common software for all configurations is essential so that operators are not required to utilize a wide variety of software packages. Third, common electronics for configurations are manadatory. Again, to keep elements common throughout the FMS, if more than one machine configuration is used, only one "kit" of repair electronics is required.

Common language for machining and measurement is another important area. This could be APT, COMPACT-2, the IBM AML (A Manufacturing Language) or it could be as simple as a CAD/CAM system which provides the common source of language for machining, design, and measurment. This brings up the importance of linking to CAD/CAM data bases. This area has been quite vague for years and is now becoming a reality in many plants today. The ability to write gaging part programs offline with the sophistication of a CAD/CAM work station frees the gage to execute programs only, greatly increasing its efficiency.

Networking to dissimilar controllers, e.g., AGV, rotary table, machine tool controller hosts, etc., must be accomplished smoothly in order to communicate properly. Communications via DECNET, ETHERNET and/or MAP is essential. A point that has come out of our in depth market survey of customer requirements for an FMS, is that people will be automating very closely toleranced parts; thus, the need to repeat to tenths and hold tenths accuracy is as important in the FMS as it is today with conventional CMM's. The stability of the measuring machine arises again with the addition of the hostile FMS plant environment. This must be studied very early in the product marketing, research, and specification, so that the proper design can be made; again, the environment must be understood fully when the machine is installed. The environment must also be understood by the end user and the machine tool builder, as well as the conventional gage manufacturer.

A substantial increase in measurement speed is the last consideration and one of the key areas of the flexible metrology issue. The speed of automated parts manufacturing will increase with the FMS, and gage speeds must increase similarly.

These are the nine areas that we have found from our marketing survey, together with the understanding of the FMS in the earlier portion of the program, that forms the Brown & Sharpe philosophy relative to Dimensional Metrology in Flexible Manufacturing Systems. It is with this philosophy that Brown & Sharpe has developed a complete line of Process Control Robots PCR's (see

Fig.1.) The distinction of the PCR from the conventional CMM is primarily because the PCR is a new class of machine required for this very different form of metrology. Process control in its name refers to the fact that we are not doing measurement or inspection per se; we are: in fact, providing information to help control the process, Robot refers directly to manufacturing, to flexibility and high speed motion, which are required for the Independent Process Verifier. The PCR must be a very fast device that has flexibility and provides timely and accurate data for the proper control of the manufacturing process.

This paper is not devoted to expounding upon the benefits of the Brown & Sharpe PCR, but a quick glance at the machine's mechanical structure will give you an idea of what features are required on a PCR in order to satisfy the FMS needs and desires.

Any type of Process Control Robot that will go into an FMS must take full advantage of state-of-the-art multi-tasking operating systems, such as UNIX and DEC's RSX-11M and VMS. For multiple arm configurations of the PCR the multi-tasking operating system, allows both arms to be operated through a single microprocessor. This capability is quite important as it significantly reduces cycle time. The design of the PCR must be flexible and modular in concept so it can be easily customized to adapt to each FMS OEM's rotary table, pallet exchange system, and/or transferline. Single and dual arm configurations (primarily for conveyor/transferline applications) are also reqnired (See Fig.2.) with the dual arm further reducing the measurement cycle times. With the single micro, full part measurement results are made available through one processor, saving time and required. networking.

An automatic probe changer is essential in FMS applications so as to further reduce cycle times. Requalification between probe changes is eliminated for a further increase in measurement speeds. The robot controller is an essential part of the PCR in that it provides the high speeds (20 in/sec velocityand .3 G acceleration required to get the necessary feature measurements in the short time frames demanded in FMS. applications.

The PCR must be designed to operate in a machine tool environment and thus must be as stable as possible during temperature changes. Therefore, it makes sense that it be built like a machine tool. For this reason, the PCR is composed of components such as high-speed rack and pinion drive systems essential for positive high-speed motion with high accuracy. The market survey also specifies the size of parts that will be automated and the size of the required PCR. The PCR measuring ranges are 500mm x 300mm x 300mm or 1000mm x 500mm x 700mm, which will accomodate approximately 80% to 90% of the FMS user requirements. This also supports the marketing done by machine tool manufacturers in the smaller machine tools (500mm x 500mm x 500mm) are also becoming more popular.

Again alluding to the machine tool nature of the PCR, solid roller and ball bearings are essential in order to get high speed and high accuracy in a hostile production environment. Thus wraparound type, reciprocating, permanently lubricated roller and ball bearing packs are key elements of the PCR design. Both a 4 position index, full-contouring and slide rotary tables are options that need to be included on the PCR to accomodate a wide variety of FMS applications. Of course, the fact that it will be operating in a machine tool environment means that full way covers are required. Optional positively pressurized way covers would be desirable to protect the drive and measuring systems from foreign matter. This again supports the philosophy of the PCR's self-sufficiency, allowing for a high degree of accuracy and stability in the hostile production environment. The controller, computer: and readouts also must be protected from the environment. This requires full air conditioning of those elements.

Another important aspect that supports the FMS market's requirements is that the Process Control Robot provides a high degree of volumetric accuracy (up to +/- .010mm). The PCR, being the Independent Process Verifier, can take full advantage of improved environments. In addition, through the state-of-the-art robot controller, temperature compensation firmware or software can be easily utilized to further increase measurement accuracies in hostile environments.

Looking into the market requirements of the machine tool controller, we find 3m/sec velocity and .3G acceleration with the acceleration and deceleration being customizable. Using different machines in different environments with varied probe configurations, users need the ability to customize the "excel"/"decel" to optomize speed. Up to seven axes of machine motion are needed, with the more axes being moved simultaneously the higher the speed of the system. With this controller, on-the-fly non-contact measurements can be performed for contouring applications. Along with this capability a very high degree of straight line motion is required again for high accuracy contouring such as mold making aircraft parts, machine parts, etc.

One further area that is having a major impact in the metrology market is vision. The PCR accomodates the Brown & Sharpe/AISI vision probe. Thus, a PCR installed in an FMS can use Renishaw touch trigger probes, the Brown & Sharpe/Diffracto LaserProbe and the vision probe to measure both features and/or contours, further expanding the level of flexibility of the PCR (See Fig.3.).

Looking into all of the special needs of both the OEM and end user, and at available technology, one comes to the conclusion that:

(a) The PCR must be a horizontal design. The majority of machining done on an FMS will be done horizontally, thus, fixtures are made for horizontal access.

(b) The PCR must be flexible in its ability to accept a wide variety of pallet sizes and fixture types. It must measure a wide variety of parts and accomodate changes in part designs without machine restructuring.

(c) It is desirable for the user to have built in vabration damping so that again the machine is self-sufficient. The PCR has its own elastomeric and optional air/oil vibration damping system built into its structure.

(d) The design of the PCR should be modular and customizable to accomodate various rotary table/pallet exchange systems so that large pallets and fixtures do not reduce the available measuring space.

(e) A high speed changer that does not require requalification between probe changes must be available so that valuable time is not lost on non-measurement tasks.

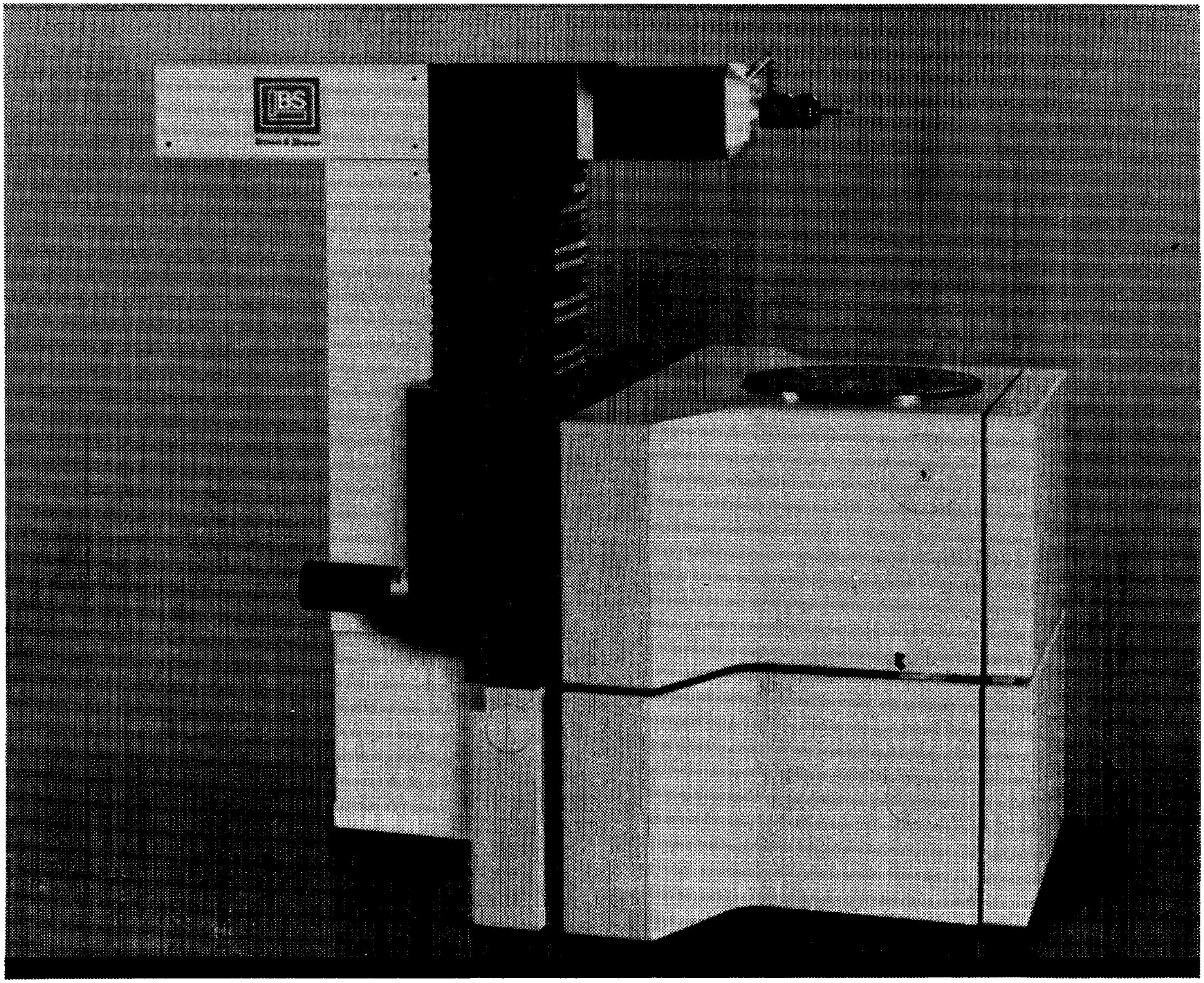
All of these characters add up to high speed metrology essential to FMS.

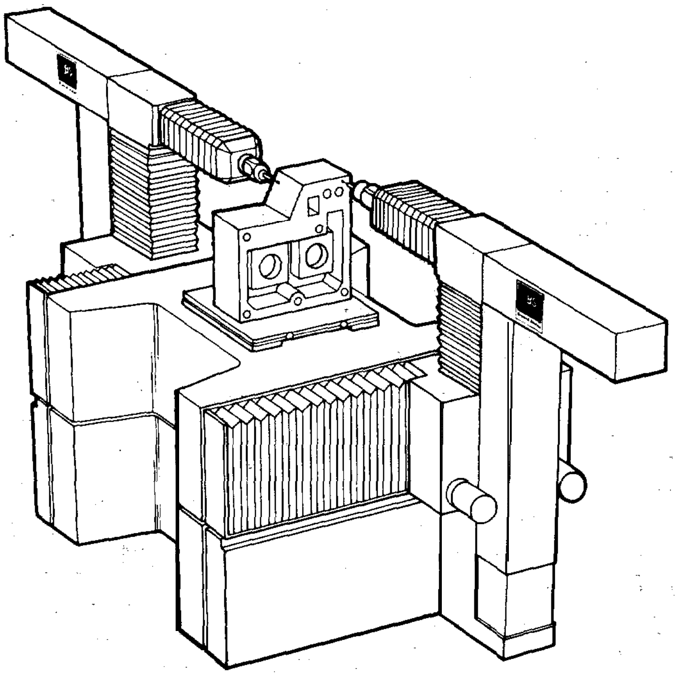
We have now looked at the needs of the FMS manufacturers and studied the extensive FLEXIBLE METROLOGY market survey of the end users that evaluated the required elements of the Independent Process Verifier. Finally, we have looked at the mechanical structure of a PCR. Another key area is system support for the PCR. A deep understanding of what is required by the FMS customer and a close working relationship with major technical groups of the world to keep abreast of the changes in FMS is necessary.

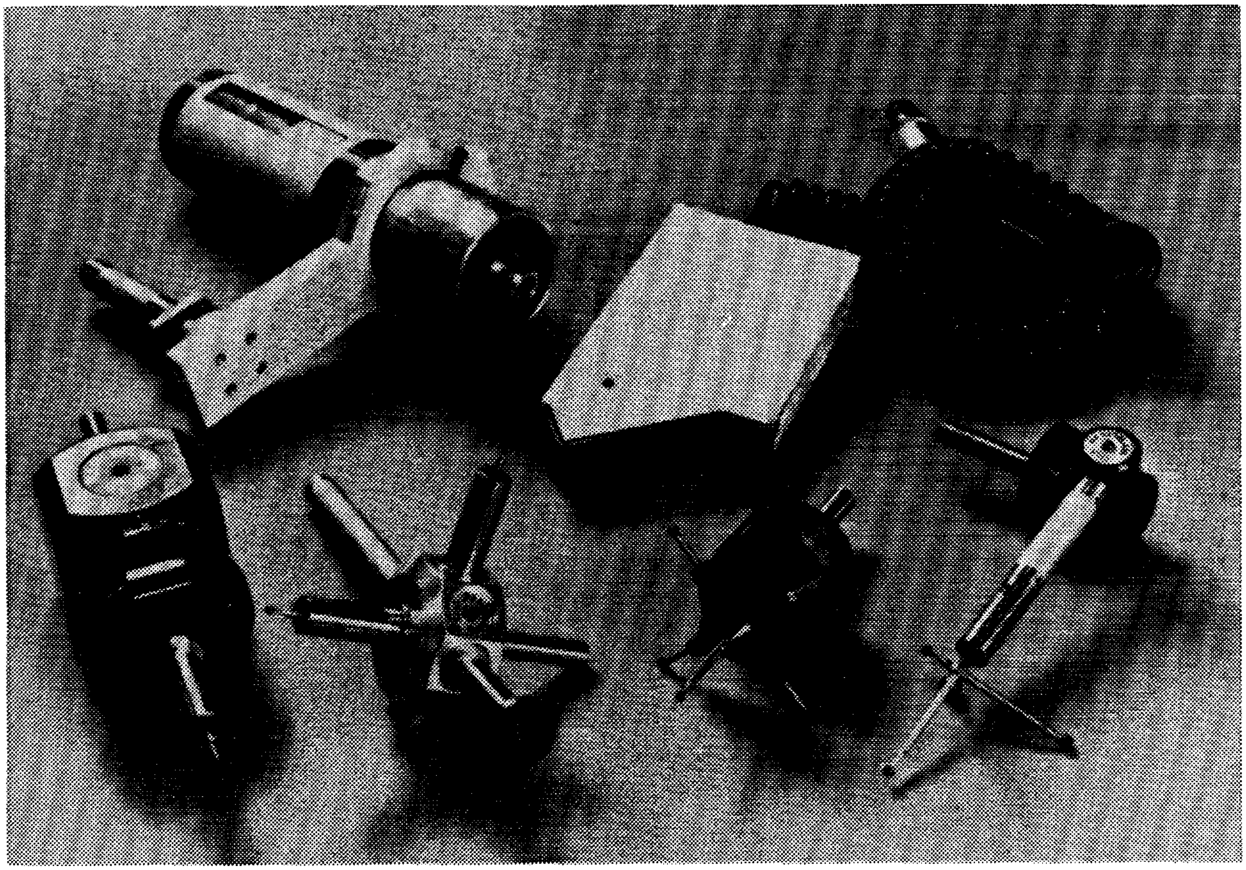
CAM-I is an organization that allows this to happen. It has a very strong technical committee studying the design of a Universal CMM Interface which will help define future metrology software packages throughout the world. Understanding and participation in CAM-I, APT, IGES and ASME committees, and a good working relationship with all the CAD/CAM manufacturers of the world, are key areas of customer support for the PCR's In depth knowledge in state-of-the-art manufaccuring areas such as APT, AML, UNIX, MAP, geometric modelers and sculptured surface packages helps broaden the scope of the PCR supplier's quality control package. In addition, Brown & Sharpe has developed a good working relationship with major CAD/CAM manufacturers such as Calma, McAuto, Prime, CADAM, CGS of General Motors, Computer Vision and Applicon to provide a strong base of support for the customer.

Included in the discussion of support is the PCR's statistical Process Control (SPC) package. This is a package that provides valuable history for Quality Information Systems (QIS) and FMS hosts. It is the key system element of the PCR that will help productivity and eliminate rework. Two of the key SPC routines that are essential in understanding and controlling the process are; Normal Inference Plots, which provide a quick evaluation of how the mean relates to the process limits; and X Bar/R and X Bar/S trend plots which offer quick evaluation of the process relative to trending toward out of tolerance, and tracking the numbers of parts that can be made at the current trend prior to going out of tolerence. With the transmittal of this information to the FMS Host, corrections can be made in the process so that the process "never" goes out of control. Again, this information originates from the Process Control Robot.

It should be apparent that the PCR is in fact THE Independent Process Verifier. As you can see from this discussion, we believe that the PCR is a key element in the success of the FMS. In fact, it is an element that deserves a place of prominence in the overall planning of every FMS.







SESSION V-A

AUTOMATED TEST SYSTEMS (ATS) CALIBRATION

Joseph Santo
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PATEC: PAST - PRESENT - FUTURE
An Air Force Approach to ATS Calibration

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ABSTRACT

PATEC was first developed to perform a system level calibration of an Air Force developed automatic calibration system. The concept has since been applied to Automatic Test Systems and proved successful. From a modest beginning of one system in 1977, it has grown to over 25 systems. PATEC is included in the Modular Automatic Test Equipment guides, which are now mandatory for use in the Air Force when buying or modifying any ATS. PATEC consists of three essential parts; a set of portable standards, a Calibration Test Program Set, and the necessary documentation. PATEC solves most of the problems found in the traditional, pull, calibrate, and replace method of ATS calibration.

INTRODUCTION

During the development of an automatic calibration system (ACS), for use in Air force Precision Measurement Equipment Laboratories (PMELs), it was desired to calibrate the ACS in a manner which would compensate for any switching or cable length errors which were present. A technique was developed to calibrate at the system interface and to use software algorithms to compensate for cable losses. This process was successful and an attempt was made to apply this principle of total system calibration to an intermediate level Automatic Test System (ATS).

THE TRADITIONAL APPROACH

The traditional approach to ATS calibration is to remove certain instruments from the system and then send them, on a periodic basis, to a local calibration facility. The instruments are then calibrated as bench type instruments to full manufacturer's specifications, returned to the ATS, re-installed, and hopefully all works well. Unfortunately, this is not always satisfactory for the following reasons:

ATS downtime is aggravated by numerous calibration intervals for the removed equipment.

Each instrument needs to be removed from the ATS with the attendant problems of connector damage, This is especially true when dealing with RF instruments.

Calibration effort is wasted on unused functions and accuracies. The entire ATS is down if an unused function fails calibration.

Remote and programmable features of the instruments are not exercised.

System performance features of the instruments are not exercised.

System performance, including cabling, loads, and switching, is not checked.

Many ATS functions are now at the printed board level, integral to the ATS, and cannot be calibrated away from the ATS without designing dedicated test equipment.

All calibration is done manually.

THE PATEC APPROACH

PATEC was designed to eliminate all of the problems associated with the traditional approach. In order to do this, one must look at a total system approach to calibration rather than the traditional piece-meal approach. PATEC is, therefore, composed of three main parts:

1. A definition of the calibration requirements.
2. A set of portable standards.
3. A Calibration Test Program Set (CTPS).

A discussion of these three areas will reveal some of the basic principles of a PATEC application.

REQUIREMENTS

It has been our experience that this portion of a PATEC application is, by far, the most difficult. Figure (1) graphically depicts the ATS specification dilemma. In order to bring some perspective to the problem of calibrating complex ATS systems, one must remember that any ATS has three attributes (from a calibration viewpoint).

1. The sole purpose of the ATS is to supply stimuli and measure signals from some unit under

tests (UUT)
2. The accuracy requirements decrease the closer you get to the UUT.
3. The number of ranges and functions of the ATS instrumentation used is minimized at the UUT.

The Air Force uses a standard data item, the Calibration Measurement Requirement Summary (CMRS) (DI-S-6177B) to gather the requirements data from the system contractor.

This brings us to the first three principles of a PATEC application:

* Calibrate as close to the UUT interface as possible.
* Calibrate only those ranges and functions actually used during UUT testing, self testing, and system diagnostics of the ATS.
* Calibrate to the accuracies specified in the CMRS, not manufacturer's specifications.

PORTABLE STANDARDS

An analysis of the CMRS will reveal what ATS instruments require external standards for calibration. It is important to note that PATEC dictates a maximum use of ATS assets in order to minimize the number of external standards required. Those instruments which do require external standards are commonly called "core" instruments. In order to automate the calibration process as much as possible, the use of IEEE-488 programmable instrumentation is encouraged. The subject of portable standards will be discussed again later in this paper. The important points to remember are these additional PATEC principles:

* Minimize the number of external standards required.
* Use IEEE-488 programmable instrumentation wherever possible.

As with all calibration schemes there are exceptions to the rule. There are some instruments which simply cannot economically be calibrated on site. PATEC handles these devices on an exchange basis.

THE CALIBRATION TEST PROGRAM SET (CTPS)

The CTPS is composed of all those other things peculiar to an ATS. In essence they are broken down into three major efforts:

1. A software calibration program
2. A calibration interface test adaptor (CITA)
3. The necessary documentation.

SOFTWARE: Most PATEC application programs are prepared by a contractor following guidelines supplied by the Air Force. All PATEC application programs run on the host ATS computer using the available display and print devices for communicating to the operator. At this time, the guidance is informal and tailored to each application, however, there are some general rules that we attempt to follow. The software is divided between an Executive segment and Task segments. At the Executive level, the operator has at least the following selections:

1. Operator control of the calibration sequence.
2. Report generation.
3. Termination of the program.

The calibration sequence is table driven. Tables are set up for pass/fail/incomplete, and for valid/invalid tasks. The pass/fail/incomplete is self explanatory. The valid/invalid is used because of the boot-strap nature of a PATEC calibration scheme where most tasks depend on a previous task being successfully completed.

At the completion of each calibration task the operator is given the options to:

1. Repeat the previous task.
2. Continue to the next task.
3: Return to the Executive,

When a calibration is completed, a calibration report is generated. The calibration report must contain at least the following information:

1. The parameter under calibration.
2. The nominal or cardinal value.
3. The actual value read,
4. The error.
5. A pass/fail indication.
6. The tolerance.

There are many additional features of PATEC calibration software and they are detailed in an Air Force publication, AGMCP 66-60, available from The Aerospace Guidance and Metrology Center, Directorate of Metrology, Systems Engineering Branch, MLSE, Newark AFS OH 43057-5475.

CALIBRATION INTERFACE TEST ADAPTOR (CITA): The CITA is a physical device used to connect the portable PATEC standards to the ATS at the point selected to perform the calibration. The CITA must contain only passive devices with no internal switching. In some applications, it has been possible to use the self test adaptor with the necessary modifications. The CITA must include the cable set required to connect the portable standards to the CITA.

DOCUMENTATION: Most documentation is covered by Data Items. These include documentation on the software in the form of product specifications, Source listings, and all other data required to organically maintain the software. The CITA is covered by a Type 1 specification and detailed parts breakdowns. In addition, a calibration Technical Order (TO), written in accordance with MIL-M-38793, is required. The TO provides the operator instructions on how to begin the calibration process, and a list of functions and accuracies which the ATS is required to meet. In addition, a list of equipment required to calibrate the ATS, a table of performance limits, and a set of signal flow diagrams to aid the calibrator in case of difficulty is provided.

This brings us to some additional PATEC principles:

* The calibration program resides on the host ATS computer and uses the available display and print devices.
* The CITA contains no active components or switching and includes the cable set to connect the portable standards to the CITA.

Before we leave this portion of the PATEC story and talk about some logistics and application matters, it would be appropriate to talk a bit about the Air Force Modular Automatic Test Equipment (MATE) program and how PATEC interfaces with it.

THE MATE SYSTEM

MATE is a comprehensive ATS acquisition process which has been mandated for use in the Air Force, It consists of a series of guides on Testability, Hardware Modules, and Software Modules. Also included are Software tools for automatic test program generation, verification, and validation, along with tools for predicting life cycle costs and test program set costs. Some of the more important aspects of MATE are the manner in which it handles the interface language to the MATE modules, the MATE modules themselves, and the requirement for passive interface test adaptors. Most of these standards have a direct impact on the calibration of a MATE ATS system. The basic structure of an ATS built to MATE standards is shown in Figure (2). The Control Interface Intermediate Language (CIIL) is MATE's method of making the system independent of a particular manufacturer's module. For instance, when MATE wants to talk to a DVM it sends out a standard CIIL sequence, no matter who's DVM is used. It then becomes the job of the module supplier to deliver a MATE module with a Test Module Adaptor (TMA) to decipher the standard CIIL message and reformat it into something his instrument understands. In addition to the reformating the TMA also takes care of all the handshake protocols. For most applications, TMAs are hardware devices. A major goal of the MATE program is that TMAs will be offered by manufacturers as an optional interface just as IEEE-488 interfaces are common today.

MATE AND PATEC

The MATE guides require the ATS developer to calibrate the ATS as a system and, at least, to consider using the PATEC approach. At present new guidance is being generated to require PATEC on MATE systems unless a waiver is granted by AGMC.

When applying PATEC to a MATE system the portable standards are also required to interface to the MATE CIIL buss through the use of a TMA (refer to Figure (3)). The PATEC TMA is a micro-computer with all the decoding and protocol taken care of via software. The PATEC instrumentation uses standard IEEE-488 interfaces. This has proved to be quite beneficial to us in that, through the use of software drivers we are able to reconfigure the group of portable standards for the particular ATS being calibrated. In addition, we are able to substitute equipment, if that becomes necessary, by simply re-configuring the PATEC TMA. At present, we have MATE compatible communication handlers and drivers for all MATE systems and for all the IEEE-488 based instruments used as external calibration standards on MATE systems. The PATEC TMA is described in detail in the AGMCP 66-60 publication mentioned earlier.

HOW IS A PATEC APPLICATION NORMALLY ACCOMPLISHED?

PATEC, or any other calibration scheme, should not be an after-thought in a systems development. When Program Offices develop a new or replacement ATS they normally have a series of "wickets" they must pass through to reach their final goal of a working, supportable system. It is our job, for the Air Force, to insure that one of those "wickets" is called calibration. These program steps are contained in the Statement of Work (SOW) for the development of the ATS. When PATEC is included in the SOW things progress suprisingly smoothly. When an ATS is developed according to the MATE guides, PATEC is automatically included in the SOW. Once the contractor has been selected the next step is usually a Preliminary Design Review (PDR) where the details of PATEC are explained, with an emphasis placed on determining the calibration requirements as soon as possible. Once the calibration requirements are firm, a set of external standards is selected and furnished to the contractor for Calibration Test Program Set development. If all goes well, at the time of the Critical Design Review (CDR), the contractor is ready to begin calibration program development. During this period, numerous exchanges are made between the contractor and Air Force metrologists. This process continues until the job is finished and approved by the Air Force.

It is interesting to note that prior to PATEC the Air Force accepted ATS systems on the basis of successful completion of the Self-Test program. This is no longer true. The contractor must now demonstrate a successful calibration of the ATS before the system is accepted by the Air Force.

PATEC APPLICATIONS

PATEC started modestly in 1977 with a single application to an ATS used to provide support to MM-II, III launch facilities. This was essentially a manual calibration with the ATS host computer merely prompting the operator through the calibration process. No attempt was made to automatically control the calibration standards. This mode of operation was used in the next several applications of PATEC. The Pave Paws application, in 1979, was the first ATS to automatically control the external standards through the IEEE-488 bus. Since that time, all applications of PATEC automate the calibration process as much as possible. Table 1 presents a summary of PATEC applications, past, present, and in process.

A typical calibration scenario would look like this: At an appointed calibration interval the

PMEL technician brings his portable PATEC standards to the ATS location. In co-operation with the system operator, the CTPS is loaded and calibration of the "core" items is accomplished. The remainder of the ATS is calibrated automatically using the "core" instruments as secondary standards. When the calibration is completed, a single calibration label is placed on the ATS. The PMEL packs up its standards and returns at the next calibration interval, usually 6 months, If interim failures occur, the failed item is replaced and re-calibrated with PMEL assistance for "core" items or by the user for non-"core" items. Interim failures do not change the calibration interval for the ATS.

Three additional PATEC principles are:

* Include the requirement for PATEC calibration in the Statement of Work.
* Calibration of ATS should be performed by trained metrologists.
* Since the ATS is calibrated as a system, only one calibration label and one calibration interval is required.

THE FUTURE:

THE CORE PATEC: After applying PATEC to over 25 different automatic test systems, two things became quite apparent. First, if we continued to develop a set of PATEC standards for each ATS using PATEC we would, by 1985, have some Air Force installations which would have over 8 sets of PATEC standards. Secondly, if you were to line up these 8 sets of PATEC standards side by side, you would be hard pressed to discern any difference in them. As it turns out, there is little difference in the types of external standards required for any given ATS. The truly unique item is the Calibration Test Program Set and interface adaptors. This led to the concept of a CORE PATEC. The CORE PATEC is a collection of standards, common to all PATEC applications. These CORE standards are then augmented, if necessary, for peculiar requirements of an ATS. The present distribution plan is to supply a set of CORE standards to every PMEL on the basis of at least one per PMEL with additional quantities predicated on total workload and not on the number of different model numbered ATS being supported.

Augmentation packages, as required, would be distributed on an ATS model number basis. At present, we are about 50% complete in distributing these CORE PATECs and by the end of FY 85 we should have at least one CORE PATEC per PMEL. Another degree of freedom is introduced when PATEC is used on a MATE system. Because of our programmable TMA we are able to re-configure the set of portable standards and substitute items without affecting the calibration test program.

USER CALIBRATION: An interesting phenomenon has occurred in the past two years. With the advent of fully automated calibration, the users have suddenly awoken and said "Hey, there's nothing to this calibration business. You just hook-up the PATEC, push the button, and sit back and relax. We can do this just as well, or better, than a trained metrologist, so --- why do we need them? Give us the standards and we'll do our own calibration." Once this notion has taken root, it is amazing how many other arguments can be generated to support this user calibration philosophy. The bottom line is, as long as everything goes well, anyone can run a calibration program, It's when things go wrong that a skilled metrologist is required. This is a very difficult area and there may indeed be legitimate cases where user calibration is warranted. This is especially true of ATS that must deploy with the weapon system. In these cases the prudent system developer will design the ATS, from the beginning, to be supportable by a limited set of built in standards. In the Air Force, the Directorate of Metrology has taken the firm position that it is the responsibility of the PMEL to calibrate Automatic Test Systems.

SOFTWARE ADJUSTMENTS: The first PATEC application included a set of alignment routines that the calibrator could elect if a calibration segment failed. We have attempted to include these types of instructions in other applications with limited success. There have also been some outright failures. The problem arises in internal configuration control of commercial instruments. An adjustment control may be in one location through serial number 1000 and may be moved or eliminated in newer serial numbered devices. This has a disastrous effect on any alignment program. With the advent of newer instrumentation, where these mechanical adjustments are being replaced with software adjustments, a new era is upon us and we can now seriously consider requiring complete alignment routines in the calibration test program sets. This is one of the more exciting developments in ATS calibration.

TWO LEVELS OF MAINTENANCE: The Air Force is seriously looking at it's present three levels of maintenance with the goal of eliminating the intermediate level. What effect would this have on the PATEC concept? To eliminate the intermediate level requires extensive built in test (BIT) capabilities in the prime mission equipment. This reliance on BIT must be tempered with sound metrology practices. Somehow, every BIT scheme must be traced to an external standard. The challenge will be to develop small, environmentally immune standards which will be taken to the prime weapon system to provide the required traceability. This is in complete agreement with PATEC principles. In essence, this merely brings PATEC to the flight line rather than the maintenance shop.

SUMMARY

PATEC is viable concept for ATS calibration. It has been successfully applied to over 25 different Automatic Test Systems and has been adopted as the preferred calibration approach for Air Force systems being developed under the MATE guides. The basic principles of the PATEC concept are given below:

- * Calibrate as close to the UUT interface as possible.
- * Calibrate only those ranges and functions actually used during UUT testing and self testing of the ATS.
- * Calibrate to the accuracies specified in the CMRS, not manufacturer's specifications.
- * Minimize the number of external standards required.
- * Use IEEE-488 programmable instrumentation wherever possible.
- * The calibration program resides on the host ATS computer and uses the available display and print devices.
- * The CITA contains no active components or switching and includes the cable set to connect the portable standards to the CITA.
- * Include the requirement for PATEC calibration in the Statement of Work.
- * Calibration of ATS should be performed by trained metrologists.
- * Since the ATS is calibrated as a system, only one calibration label and one calibration interval is required.

ACKNOWLEDGMENTS

In a project as extensive as PATEC it is always dangerous to begin acknowledging people for fear of overlooking someone. There are, however some key players in the PATEC game who deserve plaudits. Mr Charles Gambill and his group of skilled logistics are our primary contact points with the program offices. All of our standards laboratories perform yeoman services in acceptance testing literally hundereds of items per year in support of the program. Mr James Orecchio bears the burden of receiving and shipping all of the PATEC standards. Those people who are responsible for the technical application of PATEC have my unending gratitude for a job well done. They are Messrs Terry Green, James Coffey, Gene Pishner, and Frank Brewer. A special thanks to Alan Terwilliger and DeWitt Howard who perform herculean tasks to insure delivery schedules are met. Finally, this program would not be the success it is without the support and encouragement of Mr Selden McKni ht, his staff, and the Air Force PMEL personne3 who utimately make PATEC work.

BIOGRAPHICAL SKETCH

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Mr. Santo graduated from the University of Dayton in 1961 with a BSEE degree, and from George Washington University in 1963 with an MSE degree with a speciality in Metrology. He has been employeed by the Air Force since 1961 in various metrology engineering positions. Some of his major accomplishments were the development of several versions of automatic calibration systems used in Air Force calibration laboratories, and the development of the PATEC concept for the on-site calibration of automatic test systems. Mr. Santo is presently Chief of the Systems Enginnering Branch in the Directorate of Metrology.

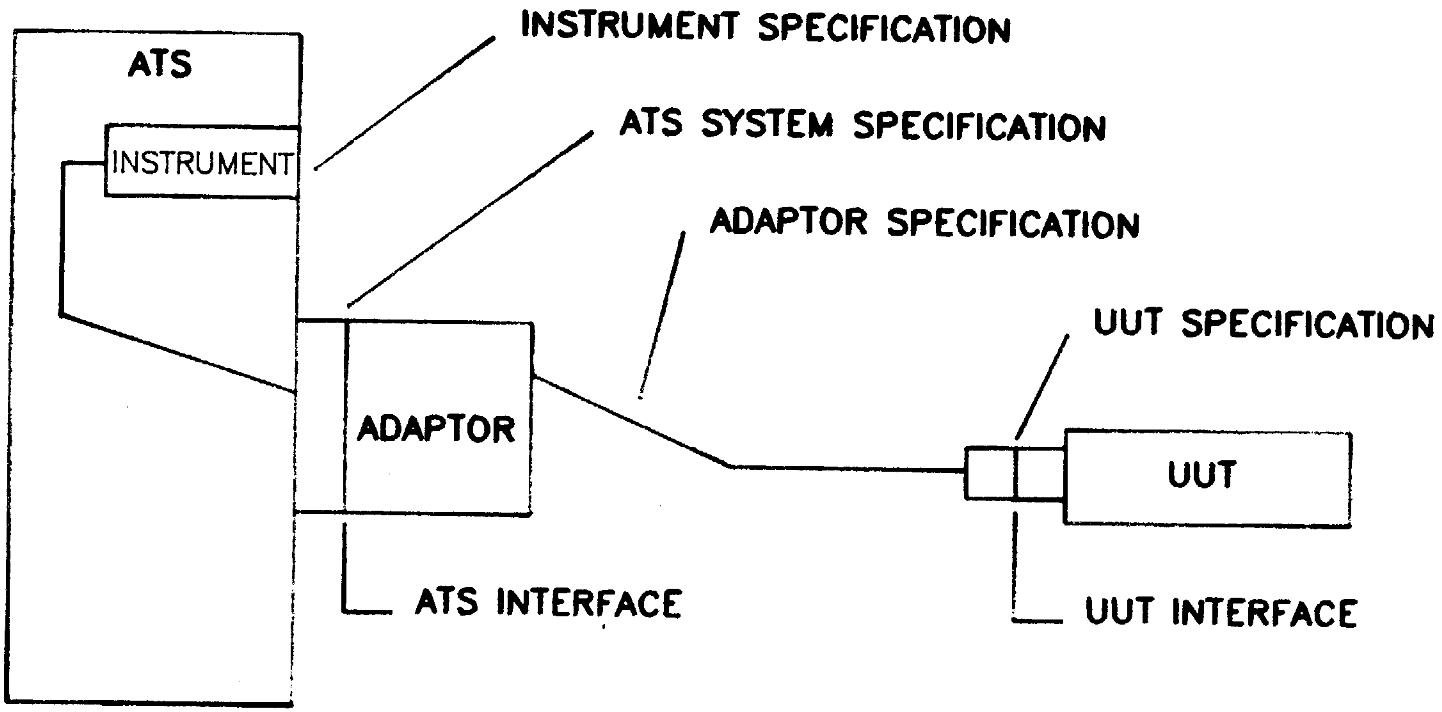

Figure (1) The ATS Specification Dilemma

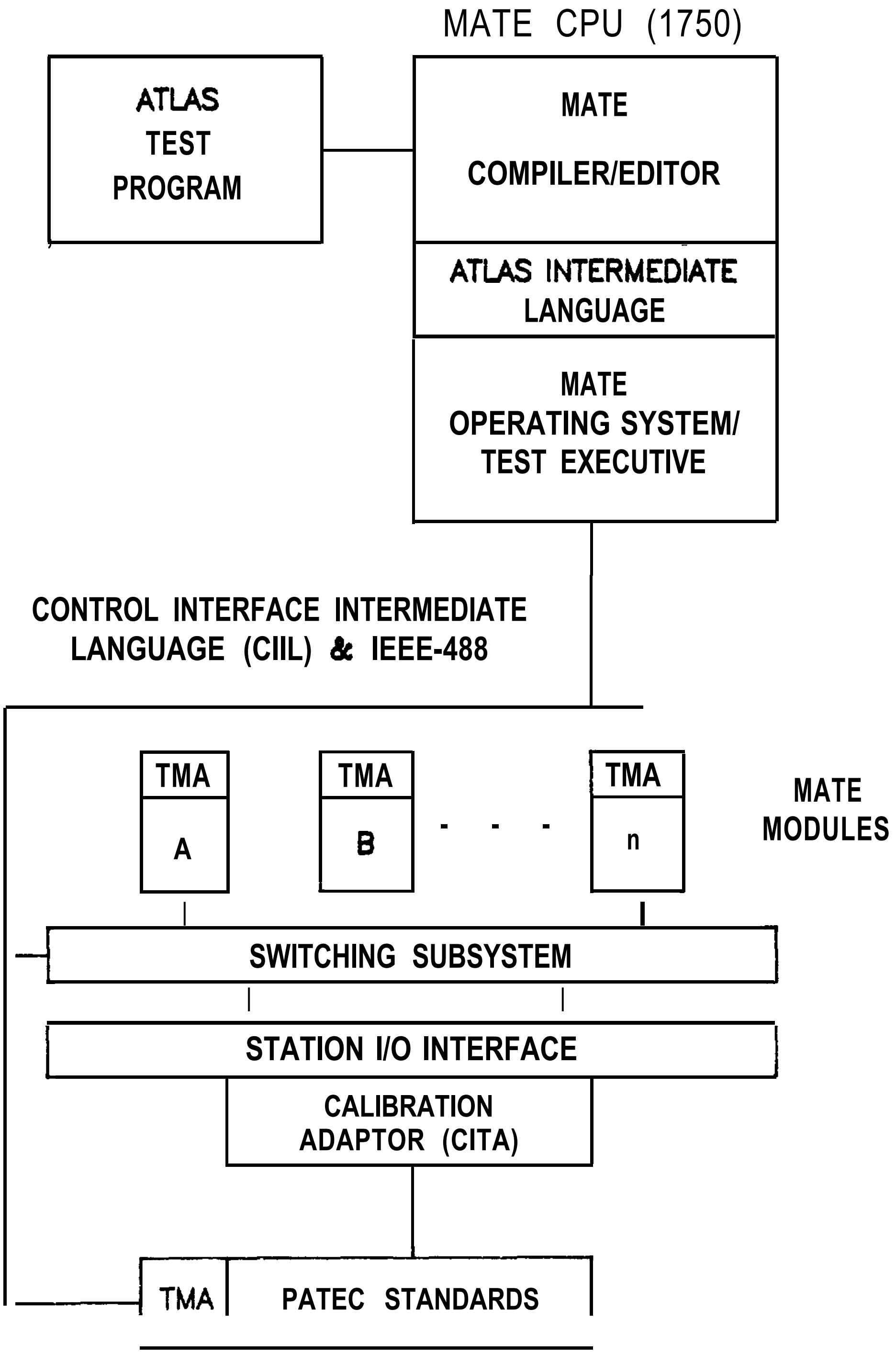

Figure (2) MATE and PATEC interfaces

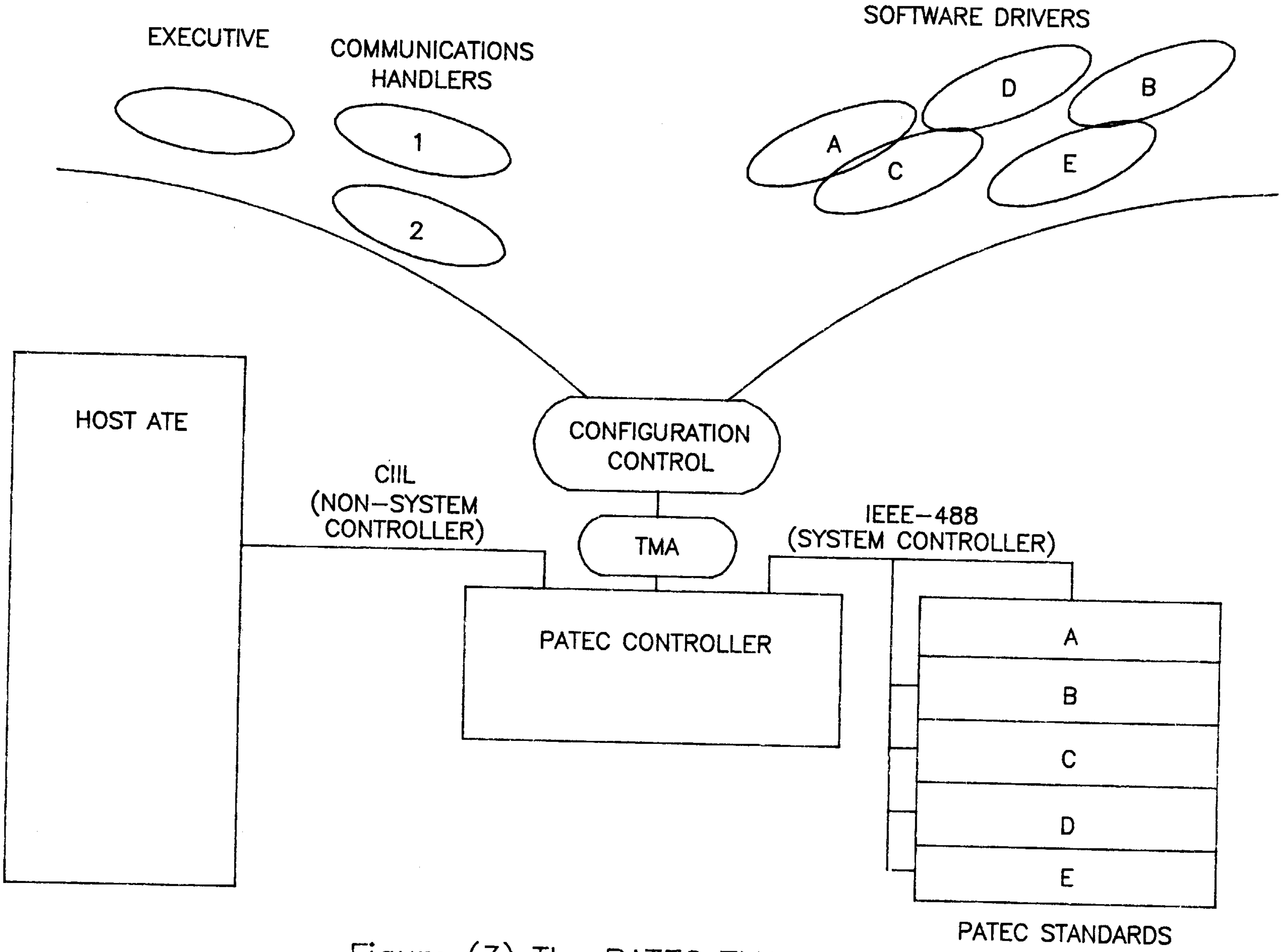

Figure (3) The PATEC TMA

TABLE 1. PATEC APPLICATIONS

ATS SYSTEM	OPERATIONAL DATE	INTERFACE CALIBRATED AT	MATE COMPATIBLE?	CALIBRATION TIME (Hrs)	AUTOMATED PATEC STANDARDS
MINUTEMAN II,III	1977	ATS	NO	3	NO
TITAN	1979	ATS	NO	3	NO
PAVE PAWS	1979	UUT	NO	3	YES
ECM TEST SET	1980	UUT	NO	8	YES
ESTS (ALCM)	1981	ATS	NO	8	NO
B–52 DFCS	1983	ATS	NO	8	YES
A–10 IATS	1984	ATS	YES	10	YES
KMT–1	1982	UUT	NO	3	YES
KPST	1982	UUT	NO	3	YES
EHR	1983	UUT	NO	2	YES
WRATE	1984	ATS	YES	8	YES
DATSA	1985	ATS	YES	15	YES
AWLS	1985	ATS	YES	12	YES
EF–111	1985	ATS	NO	8	YES
PEACEKEEPER	1986	UUT	NO	10	YES
MM–II,III REP.	1986	ATS	NO	3	YES
LANTIRN	1986	ATS	YES	15	YES
B–1B LIATE	1986	ATS	NO	8	YES
B–1B DATSA	1986	ATS	YES	16	YES
ETS (ECM)	1985	ATS	NO	12	YES
BMEWS	1986	UUT	NO	3	YES
F–15 TISS	1986	ATS	YES	12	YES
FB–111	1985	ATS	NO	12	YES
WILD WEASEL	1986	ATS	NO	10	YES
RAPIDS	1985	ATS	YES	8	YES
GATE	1986	ATS	YES	8	YES

AN APPROACH TO ATE CALIBRATION
VIA PERFORMANCE VERIFICATION
AT THE SYSTEM INTERFACE

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ABSTRACT

A method of verifying the performance of automatic test equipment (ATE) in its normal operating environment and configuration is presented as the best approach to achieving an overall system calibration. The method consists of the transport of well-characterized signal sources to the ATE station and the application of these electrical stimuli directly to a well-defined electrical interface on the test station. Data is presented on typical accuracies that have been obtained on limited parameters and ranges during the testing process, using calibrated commercial equipment.

INTRODUCTION

Several approaches have been used to assure that ATE systems perform properly. The traditional approach is the calibration of each "drawer" or instrument of the system. Typically, instruments such as a digital voltmeters, precision voltage or waveform sources, and frequency counters, are removed from the ATE station and sent to a calibration laboratory where their performance is evaluated and any necessary calibration adjustments are made. Such an approach has several shortcomings. For example, the test system often cannot be used during the time the instruments are removed for calibration unless replacements can be found. A more serious deficiency of this approach, from a metrology point of view, is the fact that instruments are not characterized in the same environment as they are used. For example, the accuracy of a digital voltmeter may exhibit sensitivity to temperature changes. Its normal operating temperature range in the ATE system may be quite different than that encountered in the calibration laboratory. In addition, interferences, such as high frequency signals produced by other instrumentation and computers in the ATE system may degrade the performance of such precision measurement equipment. These effects are usually not present when the performance of the measurement equipment is evaluated in the calibration laboratory. A further shortcoming of the practice of removal, calibration, and replacement of measurement equipment is that such procedures result in a calibration that does not account for losses and offsets in the signal path between the interface connector, where the unit under test UUT is connected, and the instrument terminals, where the instrument was calibrated. Since signals from the UUT are typically switched through relays and have relatively long path lengths, signal losses and offsets may affect the measurement accuracy, especially for low-level signals. In view of the shortcomings listed above, the user of ATE which has had instruments removed and calibrated outside the ATE system itself may have greater confidence in the equipment performance than is warranted.

Another calibration approach employed with ATE systems in order to increase the confidence in the resulting measurements is the use of various types of built-in test or self-testing schemes. If properly implemented, such schemes may be valuable towards assuring that measurements made by an ATE system are consistent. However, such techniques alone cannot perform a calibration function to determine the difference between values of physical quantities, such as voltage and frequency, measured by the ATE system and those measured quantities that have traceability to national standards. Measurements have traceability to a designated set of standards if and only if scientifically rigorous evidence is produced on a continuing basis to show that the measurement process is producing measurement results for which the total measurement uncertainty relative to national or other designated standards is quantified [1].

To assure verification of the performance of test equipment, and achieve meaningful traceability, well-characterized standards must be applied to the ATE station while it is operating in its normal environment. An example of such an "in-situ" station calibration is the Portable Automatic Test Equipment Calibration Concept (PATEC) used by the Air Force Guidance and Metrology Center. The PATEC concept consists of verifying the performance and calibrating certain critical or "core" instruments used by the ATE system using portable programmable calibrators connected via the system interface. After such direct calibration, the remainder of the instrumentation contained in the station are then calibrated by using the core instruments as standards, together with "wrap around" interface adapters. The Navy implements a similar concept using the .Modularly Equipped and Configured Calibrators and Analyzers (MECCA). Both of these programs utilize portable calibration systems that assure the performance of ATE on site via a system calibration.

THE USE OF TRANSPORT STANDARDS

The National Bureau of Standards (NBS) has had a program, in cooperation with the Department of Defense (DoD) to determine the feasibility of using transport standards to verify the performance and calibration of ATE systems [2]. The approach employs the use of portable transport standards with sufficient accuracy and long-term stability to properly characterize the ATE station under investigation. It was essential that these transport standards were sufficiently versatile so as to permit the application of a range of well-calibrated stimuli directly to the UUT interface connector. A realistic evaluation of the accuracy of the ATE system could then be made when the system was operating in essentially the same conditions as when testing a UUT.

Portable transport standards offer an advantage over alternative methods of characterizing an ATE station since the effects of losses and offsets occuring in the cabling and switching networks can be also properly characterized. In addition, it is desirable to be able to program the transport standards by means of a computer or instrument controller since statistically meaningful tests require that lengthy sequences of stimuli be applied to the ATE system under test. For example, to adequately characterize ac voltage measurements made by an ATE system, many combinations of voltage amplitudes and frequencies must be applied. Portable transport standards, in conjunction with portable "desk-top" controllers, offer a powerful way to generate such sequences, with the flexibility of making possible program changes on site.

IMPLEMENTATION OF THE TRANSPORT STANDARDS FOR AC, DC, PHASE, AND PULSE PARAMETERS

Based on a knowledge of the key measurement capabilities of an ATE system to be characterized, the parameters and ranges of the required stimuli can be selected. For example, in this particular project ac and dc voltages, electrical phase angle, and pulse duration were the quantities used to characterize one particular "third-generation" ATE system initially studied by NBS. DC voltages from +/- 100 mV to +/- 195 V, and ac voltages from 300 mV to 140 V (rms) at various frequencies from 50 Hz to 10 MHz were applied to the ATE system at the UUT interface connector in order to investigate its dc and ac measurement performance. Additionally, it was desired to verify the performance of the ATE station in measuring pulse duration over a range of 50 nS to 1000 ns.

Two transport packages consisting of test equipment were assembled; one for the dc and low-frequency ac voltage source, and the second for a pulse voltage source. The dc and low-frquency ac voltage source package contained a commercial meter calibrator, a digital voltmeter, and a desk-top computer/controller. The pulse source package contained a high resolution time synthesizer for generating pulses of precise time duration, and a pulse generator that was used to generate the output repetition rate of the pulses. In addition, an NBS Phase Angle Calibration Standard was used as a source of phase angle signals [3]. The NBS Phase Angle Calibration Standard produces a pair of digitally synthesized sine waves. All parameters, with the exception of the pulse repetition rate, were capable of being controlled by the computer/controller via an IEEE-488 bus. Thus, sequences of various voltages or pulse widths could be applied to the ATE system with a minimum of operator intervention.

Prior to applying these sources to an ATE system, the transport packages were carefully characterized to measure their accuracy, their stability with time, and the effects of temperature, line voltage, and other environmental factors that may affect their performance. In all cases, the characterization of the transport standards package was performed at the termination of the cable and adapters that were necessary to interconnect the standards with the ATE system under investigation. Furthermore, the input impedance of the ATE system was simulated with resistance-capacitance networks at the interconnection interface. Thus, the electrical environment during the characterization tests performed on the transport standards approximated that encountered during the connection of the transport standards to the ATE system.

For example, the output of the dc transport source was intercompared periodically with the U.S. Legal Volt maintained by NBS. Over a period of five months, the dc source exhibited a 3 sigma uncertainty of less than 0.004 percent over a voltage range of +/-0.1 to +/-200 V dc. Likewise, over a three month period, the pulse source exhibited changes in pulse duration of less than +/-0.6 percent over the range of 50 to 1000 ns.

The voltage of the ac output from the source was measured as a function of rms amplitude and frequency by means of a thermal voltage converter. The ac and dc voltages of the source were available at the same output terminals by programming the source over the IEEE-488 bus. The output of the thermal converter was measured by the digital voltmeter, also controlled by the bus. In this manner, full control was exercised over the generation and application of ac and dc voltages to the converter and over the recording of the resultant thermocouple emf voltages. A multiplier (current scaling resistor), inserted between the source and the thermoelement allowed the thermal converter to be used over a voltage range of 2 to 600 V ac (rms).

The observed 3 sigma uncertainty in the voltage of the ac source over the frequency range of 50 Hz to 50 kHz was less than +/-0.01 percent during a three month period. The combined effects of temperature and line voltage changes along with additional uncertainties contributed by the thermal converters, voltmeter non-linearities, and effects due to movement of the source from the calibration laboratory at NBS to the remote ATE site gave conservative estimates of total uncertainties of +/-0.02 percent and +/-0.12 percent for dc and ac voltages, respectively.

AC voltages at frequencies between 50 kHz and 10 MHz are more difficult to measure accurately than those at lower frequencies. At the higher frequencies, small inductances and capacitances associated with the connection of the calibration source to the ATE system become important. If not properly accounted for, the losses in the cable between the wideband output of the source and the interface of the ATE system introduce a source of systematic uncertainty. To connect the source to the ATE system, a 1.5-m cable is required. Typically, this additional cable length provides an attenuation of the signal of approximately 0.6 percent at 10 MHz. Thus, all measurements were made using a 1.5 m length of RG-58/U cable connected to the wideband output unless otherwise specified.

The ac voltage output at the interface adapter pins, as a function of frequency, was determined by the use of a thermal voltage converter which has a specified input impedance of 50 ohms (+/- 0.3 percent) and a voltage range of approximately 0.2 to 0.45 V ac (rms). To measure voltages in excess of 0.45 V ac, a set of two precision 50-ohm coaxial attenuators was used that had power attenuations of 6 and 10 dB respectively. By means of the attenuators, either individually or in series, the voltage measurement range could be extended to 2.8 V ac. The overall uncertainty of the output voltage of the wideband source at the interface adapter pins was calculated to be +/-0.7 percent. This value was deemed to be more than adequate for verifying the performance of an ATE station with a +3- 3 percent accuracy specification.

APPLICATION OF TRANSPORT STANDARDS TO AN ATE SYSTEM

The transport standards were applied to several third-generation ATE systems used by DoD. Measurement programs were written in ATLAS to permit the ATE station to measure dc voltages, low frequency ac voltages in the frequency range of 50 Hz to 50 kHz, and high frequency ac voltages in the range of 50 kHz to 10 MHz. Additional programs measured pulse duration and phase angle. The transport standards were interconnected to the ATE system by means of the cables and the interface adapter that had been used in the characterization of the standards. This overall package permitted the application of the ac and dc voltages, pulses, and phase angles to the ATE system under the same conditions in which they were calibrated. In addition, a means was provided for the ATE station to generate a "test complete" pulse to the controller. The controller then instructed the transport standards to provide the next stimuli in a preprogrammed sequence. The measurements from the ATE station were printed and recorded on the system disk file. In this manner, an extensive set of measurement data could be obtained to analyze the errors of the ATE system being characterized since all the data was in "machine compatible" form.

CONCLUSION

The use of accurate transport standards has been demonstrated to be a useful concept for the characterization and calibration of ATE systems. In order to meaningfully characterize the performance of an ATE system, the signals must be accurately determined at a defined measurement interface over the range of environmental conditions that typically would be encountered.

REFERENCES

1. B. C. Belanger, "Traceability: An Evolving Concept," ASTM Std. News, Vol. 8, No. 1, Jan. 1980, pp. 22-28.

2. T. F. Leedy, W. L. Gans, B. A. Bell, P. S. Lederer, and R. E. Nelson, "Automatic Test Equipment Calibration/Performance Verification Evaluation and Research Program," NBSIR 82-2601, Parts I and II (Dec. 1982). [Limited distribution; not available from NTIS]

3. R. S. Turgel and N. M. Oldham, "NBS Phase Angle Calibration Standard", NBS Technical Note 1144, U.S. Department of Commerce, National Bureau of Standards, July 1981.

CALIBRATION TEST PROGRAM SETS

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ABSTRACT

The calibration of Automatic Test Equipment (ATE) used to support Navy weapons systems is a difficult technical requirement. Ensuring that calibration support is delivered with an ATE system as one of the Integrated Logistics Support (ILS) elements is a challenge. The evolution and status of Navy Calibration Test Program Set implementation will be reviewed.

INTRODUCTION

Fellow Metrologists - Computers are everywhere! Automation of test equipment is commonplace and this is changing the nature of our profession. We have a problem! The integration of software, hardware, and system configuration has increased the complexity of metrology.

Let me tell you of one approach to make your job easier. This approach can be applied to any automated test system.

The calibration of ATE is a complex task that must be included in the ILS Planning and become one of the considerations from the conceptual design phase through the deployment phase.

BACKGROUND INFORMATION

The calibration of ATE has undergone many changes over the years. Up until recently, because of the complexities involved, a common method of calibration consisted of system components or building blocks. Time has indicated that this piecemeal approach is not sufficient in most cases. The parts, when assembled into a system, do not necessarily indicate the overall performance of the system. There is a logistic problem of sending the BB to the calibration laboratory which causes excessive system downtime. In addition, the wear and tear on the BB's appear excessive. The calibration of the ATE on-site as a system evolved as the better technical approach.

TECHNICAL CONSIDERATIONS

An ATE system can be considered as one test instrument with input/output (I/O) specifications. However, it is a very complex instrument because of the number of calibration standards required to perform a calibration. The number of calibration standards required to perform the calibration is usually eight or ten items or more. In addition, the connection to the ATE I/O interface usually presents a challenge. Because of these requirements, it was difficult for the metrology personnel at MEC to communicate to sponsors concerning exactly what was needed to perform an ATE system calibration. I am sure there was confusion on the part of the metrology personnel concerning exactly what constraints existed on the sponsors. In any event it took a considerable period of time before the concept of a Test Program Set (TPS) was linked to the calibration requirements of ATE. In part, I feel it was the idea that something "special" was needed. Also, a TPS is used to allow an ATE system to test another item, whereas we were concerned in testing the ATE system itself. Eventually, a close look at MIL-STD-2077A for TPS revealed that all the parts of a TPS were needed for calibration i.e., software, printed information, and an interface device (ID). However, these components needed to be developed to calibrate the ATE system. This reversed the application in that the ATE became the unit under test (UUT). Hence, MIL-STD-2077A was rewritten to reflect that reversal in application and named Calibration Test Program Set (CTPS). The managerial aspect of describing to the sponsors what we wanted was simplified. We need a special TPS; the sponsors know how to handle TPS's; and the existing management and procurement systems can be used to provide what is needed. Sometimes using the appropriate terminology can greatly reduce the problems and aid in arriving at a solution.

Now the sponsors could fund the various ATE manufacturers to provide CTPS, but how does a CTPS fit into the Integrated Logistics Support Plan (ILSP)? The ILSP is the overall project management scheme used to deploy a weapon system. One fact had become very evident during our earlier efforts - the calibration requirements must be considered during the conceptual phase of the ATE development project. By early involvement, the calibration requirements are made evident to the ATE manufacturer. Usually this becomes an educational process for the ATE personnel. A guidance document was developed to specify the various phases of development of the CTPS. It has been found that this early-on involvement is crucial to adequate calibration support.

At that time, the Center published two technical requirement documents to provide a mechanism for defining CTPS preparation requirements. However, our sponsors looked at our efforts and although they agreed that it was a giant step in the right direction, questions still remained as to how the requirements could be implemented in the actual contractual schema to obtain CTPS's. We thought a simple reference in the contract to our documents would be sufficient. The sponsors disagreed. After several discussions, the approach decided upon was to add an Appendix to MIL-STD-2077A for TPS's that is essentially our previously developed technical documents, written into military standard format.

WHAT IS A CTPS?

The CTPS consists of those items necessary to calibrate ATE at the system I/O interface(s). These include the electrical, mechanical, instructional, and logical decision elements. The CTPS excludes the actual calibration standards in a physical form, but specifies what calibration standards are to be used in the calibration process. These calibration standards consist of items normally designated standards within the Navy.

A CTPS is composed of a Calibration Strategy report, a Calibration Test Program (CTP), an ID, a Calibration Procedure Instruction (CPI), and supplementary data. The requirements for each of the above CTPS elements will now be discussed.

CALIBRATION STRATEGY REPORT

A test strategy report shall be prepared for each CTPS. The calibration strategy report shall be prepared in a format suitable for review and analysis by the technical reviewing agent prior to detailed CTPS design. The purpose of the Calibration Strategy Report shall be to outline all calibration requirements, to delineate problems or constraints anticipated in implementing a calibration design, and to provide a detailed overview of the calibration approach. The contents of the calibration strategy report shall include, but are not limited to:

(a) ATE Function Description. Describes the major functions of the ATE.

(b) Calibration Concept. Describes the calibration approach by which the ATE parameters will be calibrated using calibration standards. This narrative description shall provide sufficient information about the calibration of each parameter to ensure that an adequate technical analysis has been performed. Block diagrams showing proposed configurations are usually helpful.

(c) Calibration Constraints. Describes problems and/or incompatibilities between the ATE requirements and calibration standards capabilities. These will include the type, purpose, and function of signal conditioners required in the interface in order to overcome the constraints identified, as well as other supplementary calibration aids such as loads or special-purpose cables recommended to solve mechanical or electrical problems that have been identified.

(d) ATE System I/O Interface Specifications. The detailed ATE system I/O interface specifications shall be stated in tabular format for all measurement and stimuli parameters.

(e) Operator Interaction. The type of man/machine interface required to calibrate the ATE, and planned in the calibration concept, must be identified and described.

(f) Run-Time Prediction. The estimated run-time to calibrate an in-tolerance ATE, including setup time, and manual intervention times must be provided individually and cumulatively.

CALIBRATION TEST PROGRAM

The CTP shall, as a minimum, consist of program identification date, identity checks, calibration routines, and calibration data recording.

In order to assure sufficient CTP accuracy in respect to ATE tolerance as well as reliability and repeatability of test results, CTP's are required to be designed to meet minimum Test Accuracy Ratios (TAR's) (typically ≥4:1) in test design. The technical reviewing agent will generally impose blanket TAR's for specific functions where deemed appropriate. Unless otherwise specified, the TAR required shall be equal to or greater than 4:1 unless specific deviation has been approved.

INTERFACE DEVICE

The ID shall be as simple as possible. The ID is intended to be a connection device only. Both electrical and mechanical design shall be simple. No signal generation, synchronization, or shaping shall be involved.

It is a requirement to minimize the complexity of the ID subject to the following:

(a) Only one ID shall be required for calibration, if possible. The ID shall be designed with a 20% expansion capability. That is, provisions shall be'made in the design of the ID to accommodate unanticipated ID requirements including number of wires, added functions, and/or subassemblies 20% greater than the defined requirements.

(b) The ID shall be small enough to permit the ID to be physically supported by the intended ATE work surface.

(c) The ID's shall be designed in conformance with the requirements of MIL-T-28800, Type III, Class 4, equipment.

CALIBRATION PROCEDURE INSTRUCITON

The CPI shall contain that information which cannot be communicated by the ATE and is required to accomplish calibration. Content and format of the CPI shall be as specified by MIL-M-38793.

CURRENT STATUS

Presently, MEC personnel are being invited to meetings during the conceptual design stage of ATE development. This is essential to ensure that adequate calibration support is considered during the ATE design, factory testing, first article test phases, and subsequent to delivery to the fleet. Adequate calibration support is essential to ensure weapon systems support equipment reliability.

The CTPS offers a systematic approach to automated test systems calibration and should make the task easier to accomplish, Use it and make your job easier.

REFERENCES

(1) Metrology Engineering Center, "Technical Requirements for Calibration of Test and Monitoring Systems (TAMS)", NAVAIR 17-35TR-1.

(2) Metrology Engineering Center, "Automated Test Equipment (ATE) Calibration Requirements Analysis (CRA)", NAVAIR 17-35TR-2.

(3) Metrology Engineering Center, "Technical Requirements for Calibration Test Program Sets (CTPS) for Automatic Test Equipment (ATE)", NAVAIR 17-35TR-3.

(4) Metrology Engineering Center, "Calibration Requirements for Automatic Test Equipment", NAVAIR 17-35CR-ATE-1.

(5) MIL-STD-2077 (AS), "Test Program Sets, General Requirements for"

Session V-B

LASER AND OPTICAL FIBER METROLOGY

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SESSION V-C

TIME AND FREQUENCY MEASUREMENTS-APPLICATIONS
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PHASE NOISE MEASUREMENTS - METHODS, SOLUTIONS, AND TRENDS

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Abstract

In the past, phase noise measurements have required complex, dedicated instrumentation operated by highly specialized phase noise experts. As system requirements have changed, testing has become more widespread, and commercial measurement solutions are now available. This paper compares the four most common methods of measuring phase noise: 1) direct spectrum; 2) heterodyne/counter; 3) frequency discriminator; and 4) phase detector. The advantages and disadvantages of each method are outlined, including the most important parameter-for each method -- noise floor sensitivity. Knowing which method is optimum for a particular type of oscillator is useful in selecting a measurement system and differentiating between the noise floor of the measurement system versus the noise of the oscillator under test.

Introduction

The frequency stability of the oscillators used in today's communications and radar/DE systems is critical. Errors caused by short-term frequency instabilities have haunted most engineers who have tried to meet sensitivity specifications in a radar or communications system. Thus, the level of phase noise on oscillators is no longer a supplemental characteristic, but a significant specification.

Phase noise is a complex quantity to control, and has been difficult to measure. In the past, phase noise measurements were done by a select group who inherently understood the measurement. Today all functional areas involved with the design, testing and manufacturing of oscillators need a method to measure phase noise. Fortunately, the knowledge of phase noise has increased considerably in the past few years, and improving test methods reflect these advances.

Phase Noise and its Importance

If we could design a perfect oscillator, all signals could be represented by:

$$V(t) = A, \sin 2\pi f_o t.$$

But in the real world, every signal has some unwanted amplitude and frequency fluctuations, which can be described by:

$$V(t) = (A,+ \varepsilon(t)) \sin (2\pi f_o t + b(t)).$$

The amplitude fluctuations &(t) are commonly called AM noise and are usually less critical in modern communications systems. The frequency fluctuation, or phase noise, is the more important and more difficult quantity to measure.

In the time domain (Figure 1), phase noise can be seen as changes in the zero crossings of a signal. The noise perturbations repeat on each cycle with a statistical characteristic. In fact, a significant amount of power occurs in other signal frequencies. Thus, in the frequency domain (Figure 1), there will be a noticeable amount of power in the spectrum at the frequency corresponding to the perturbation. Another way to think about phase noise is as a continuous spectrum of infinitely close phase modulation sidebands, arising from a composite of low frequency noise.

Phase noise is critical in frequency conversion applications where signals span a wide dynamic range. Unwanted sideband phase noise converts into the information passband and limits the overall system sensitivity. For example, in a Doppler radar system as shown in Figure

2, phase noise on the transmitter and receiver LO's translates directly to the system IF, and then to the demodulated information passband. If a large clutter signal and a small signal from a moving object are both system inputs, the phase noise translated from the receiver LO to the larger signal masks the smaller desired signal.

Measurement Methods

There are many methods to measure phase noise, depending on the level of noise to be measured, and the availability of time, equipment and money. This paper discusses the four most common techniques.

1. Direct Spectrum Method

The simplest, easiest, and perhaps oldest method for phase noise analysis of sources is the direct spectrum technique. Here, the device under test (DUT) inputs directly into a spectrum analyzer tuned to the carrier frequency, as shown in Figure 3. Displayed on the spectrum analyzer is the power spectral density of the oscillator in terms of $\mathcal{L}(f)$, or single sideband phase noise to carrier ratio, in units of watts/Hz/watt, or dBc/Hz.

The direct spectrum method, given a state-of-the-art synthesized analyzer, has fair noise floor sensitivity at offsets of 1kHz to 100 kHz from the carrier. It is generally not useful for close-in analysis, nor can it be used to measure the broadband noise floor (offsets >100 kHz) of most sources because of the inherent high broadband noise floor of the spectrum analyzer itself.

The direct spectrum method is simple to use, displays $\mathcal{L}(f)$ directly, and also accurately displays discrete signals simultaneously. Unfortunately, it cannot be used to measure sources with high AM noise, nor sources with low close-in noise or low broadband noise, nor can it measure close-in to a non-phase -locked source. The direct spectrum method is optimimum for measuring a source with low drift and relatively high noise, such as a multiplied crystal.

2. Heterodyne/counter Method

The heterodynelcounter method is a time domain technique where the DUT is downconverted with a mixer and a low-noise reference to a low IF frequency, or beat frequency ν_b, as shown in Figure 4. A high resolution counter then repeatedly counts the IF signal, with the time period between each measurement held constant. This allows several calculations of the fractional frequency difference, y, over the time period used. The Allen variance of these differences can then be calculated. The square root of this variance is called $\sigma_y(\tau)$, where τ is the time period used in the measurement. This process is generally repeated for several different time periods, and $\sigma_y(\tau)$ is plotted vs. τ as a measure of the signals' short-term instability in the time domain.

The heterodynelcounter method yields excellent close-in noise floor sensitivity, depending on the beat frequency used. This method is generally preferred for low-noise measurements at offsets less than 1 kHz, such as measurements on crystal oscillators and frequency standards.

Because two signals are actually downconverted to a low IF frequency (the DUT and the reference LO), the heterodynelcounter method can be used for a wide range of input frequencies. This method has very good sensitivity close-to-the-carrier. However, it requires two sources (including the low noise LO reference), the sources must be offsettable from each other (or a third oscillator introduced), and the physical implementations of counters limit the measurements to offsets less than several tens of kHz. The heterodyne/counter method is ideal for stable sources used in navigation systems, where a description of the oscillator stability in the time domain is the most applicable unit.

3. Frequency Discriminator Method

In the frequency discriminator method, often called the one oscillator method, the short-term frequency fluctuations of the source are translated to baseband voltage fluctuations, as shown in Figure 5. A baseband analyzer measures the output voltage fluctuations, which can be interpreted in terms of $S_{\Delta f}(f)$, or the spectral density of frequency fluctuations, in units of Hz^2/Hz, or dBHz^2/Hz.

There are several common implementations of frequency discriminators, each with its own advantages and disadvantages. A convenient discriminator is the delay line/mixer implementation. Because of the inherent relationship between frequency and phase, the sensitivity of the discriminator method degrades as $1/f^{-2}$ as the carrier under test is approached. Therefore, the frequency discriminator method yields a high close-in noise floor (poor sensitivity) and extremely low broadband noise floor (good sensitivity). This is similiar to the noise characteristic of free-running sources, as shown in Figure 6.

The frequency discriminator method is an attractive test method for free-running sources because it requires only one source and has a low broadband noise floor. Also, in the delay line/mixer implementation, the AM noise is suppressed 15 to 30 dB depending on the frequency range of the mixer. Unfortunately, though this method is simple, it has poor close-in sensitivity. The delay line/mixer disciminator may be difficult to implement at microwave frequencies due to the loss in the delay line. Other sensitive implementations at microwave (such as a cavity discriminator) are usually narrow-band.

One of the trends in phase noise measurements is the need for a low-cost, broadband phase noise measurement system. The HP 11729C Carrier Noise Test Set, as shown in Figure 7, can be used in the frequency discriminator method as a low-cost solution for measurement of free-running sources. A 10 MHz to 18 GHz test signal is applied to the Carrier Noise Test Set, where it is downconverted to an IF frequency with a low-noise microwave reference signal. (This low-noise microwave reference signal is internally generated from a 640 MHz SAW resonator multiplied to within 1280 MHz of the test source.)

The actual discriminator then operates at the IF frequency. The IF output is split into two sides. One side is input directly to the LO port of a phase detector. The other side is delayed thru a simple external delay line (such as a length of RG 223/U cable), and is applied to the other port of the phase detector. When the two signals at the phase detector are adjusted for phase quadrature (90 degrees out of phase), the baseband voltage fluctuations at the output of the phase detector are proportional to the frequency fluctuations of the test source (provided that the noise of the test source is greater than the sensitivity of the discriminator with the length of line used.)

The HP 11729C, in this discriminator mode, needs only an external spectrum analyzer for low-cost phase noise measurements. Discriminating at the IF means that increased sensitivity can be obtained by using a long line without the problem of loss incurred at microwave frequencies. To measure a 10 GHz source with a 100 ns (68 ft) discriminator made of RG 214 cable directly at the test frequency, for example, would require >+40 dBm of input power! With the HP 11729C discriminator method with a 100 ns delay, a 10 GHz source at +7 dBm can be measured with typical sensitivity of -80 dBc/Hz at a 1 kHz offset, and -142 dBc/Hz a 1 MHz offset.

The HP 11729C, furthermore, needs only the same inexpensive piece of coaxial cable to make measurements on sources from 10 MHz to 18 GHz. There is a built-in quadrature monitor, and any convenient microwave or RF source (set to the test frequency or the IF frequency) can be used for calibration by substitution. Measurements with the HP 11729C are limited only by the noise floor of the multiplied SAW oscillator, which has a broadband noise floor of <-142 dBc/Hz at a 10 MHz offset from a 10 GHz carrier.

4. Phase Detector Method

The final method of phase noise mesurement is the phase detector method, sometimes called the two-source or quadrature technique. In this method, the DUT and a low-noise reference source are input to a phase detector at the same frequency and 90 degrees out of phase (phase quadrature) as shown in Figure 8. The output of the phase detector, proportional to the combined phase noise of the two input sources, can then be measured on a baseband spectrum analyzer. The output of the phase detector is $S_\phi(f)$, the spectral density of phase fluctuations, in units of rad^2/Hz or dB rad^2/Hz.

The phase detector method provides good sensitivity over the entire offset frequency range; it can be used to measure high quality standards (good close-in noise) or state-of-the-art free-running oscillators (low broadband noise). The lower limit of system sensitivity is dependent on the two-port noise of the phase detector and low noise amplifier. In actual usage, however, the real limit to system sensitivity is the noise of the reference source used (because the output of the phase detector is proportional to the combined noise of the two input sources).

The phase detector method provides the lowest overall system noise floor. It can be used at any frequency where a suitable reference and a mixer/phase detector can operate at that frequency. Because of the low noise floor, many types of sources can be measured with one measurement system. The difficulty of this method lies in finding a reference source that has lower noise than the test source. It also may be difficult to phase lock to a source with high drift. To take advantage of the good close-in sensitivity, additional corrections inside the phase lock loop are necessary.

Because the phase detector method provides the most powerful and versatile of the measurement methods, a variety of commercial solutions are available. To understand how these solutions compare, it is useful to break the phase detector method into three essential pieces -- the reference source, the phase detector and quadrature circuitry, and the baseband analysis (Figure 9).

As phase noise measurements must often be made at the routine technician level, the need for an automatic solution increases. As phase noise becomes more critical as a specification, the need for fully-specified measurement solutions also increases. The HP 3047A Phase Noise Measurement System provides the phase detection and quadrature circuitry and the baseband analysis (to 40 MHz offsets) in a fully-specified automatic system.

As. the level of phase noise for modern communications systems necessarily becomes lower, and as the number of frequencies where phase noise must be measured increases, the need for a broadband, low-noise reference source becomes a critical path. The HP 11729C, combined with the HP 8662A RF Synthesized Signal Generator, provides a low-noise microwave reference signal with phase noise as much as 30 dB lower than typical microwave synthesized signal sources. (The HP 8673B has typical phase noise of -93 dBc/Hz at a 10 kHz offset from a 10 GHz carrier; the HP 11729C/8662A has typical noise of -123 dBc/Hz at the same offset.)

Hewlett-Packard has combined the low noise floor of th.e HP 11729C/8662A with the automatic detection and analysis of the HP 3047A into the HP 11740A -- a complete, fully automatic phase noise measurement system specified for sources from 5 MHz to 18 GHz (Figure 10). The HP 11740A Microwave Phase Noise Measurement System implements both the phase detector and frequency discriminator methods for measurement versatility. With a built-in microwave reference source and VCO, the user simply inputs his test signal and the user-friendly software will lead him through the measurement.

As well as a need for a fully specified solution, there is also a need for an automatic solution that leverages off existing equipment for lower cost. The HP 11729C/8662A combined with commonly available spectrum analyzers (such as the HP 8566A/B and HP 8568A/B) provides this low cost solution. With the flexibility for both phase detector and frequency discriminator methods, an automated system using the HP 11729C/8662A provides improved productivity and accuracy and hard copy output, with the software optimized for the specific application.

Summary

The first and most important criterion in choosing a phase noise measurement method is system noise floor sensitivity. The typical noise floor sensitivity of the four measurement methods is shown in Figure 11. The direct spectrum method is the easiest technique if the source is stable and the noise is fairly high. The heterodyne/counter method has limited usefulness for microwave sources. The noise floor sensitivity of the frequency discriminator follows the spectra of free-running sources. The phase detector method can have the best overall sensitivity depending on the reference source used. Figure 11 also shows the typical phase noise of four types of sources to indicate the applicability of the different measurement techniques. Finally, Figure 11 shows the typical noise floor of the HP 11729C/8662A, the lowest commercially available broadband reference source.

Table 1 summarizes the most likely measurement method for several types of sources, or for several different applications. The simplest method for measuring a Gunn-diode free-running oscillator, for example, is the frequency discriminator method, which has a low broadband noise floor and can track the drift in the source. Note that this table does not give the only choice for a measurement; for example, this same Gunn-diode oscillator could also be measured with the phase detector method, given a reference VCO with low enough phase noise and sufficient tuning range to track the drift of the DUT. The optimum measurement method is dependent upon the DUT oscillator performance and the measurement data desired.

In summary, there are a number of techniques for measuring phase noise, each with its own set of advantages and disadvantages. Most of these measurement techniques are implemented in currently available commercial equipment. The requirement to measure phase noise no longer needs to be a terrifying experience. Today, there is a measurement solution for the most demanding requirements for phase noise testing.

Conclusion

The phase noise measurement field continues to grow and develop. For example, one of the most important new frontiers in the phase noise measurement area is the need to make phase noise measurements on pulsed carriers. (Note that phase noise measurements can only be made to offsets less than 1/2 the PRF (pulse repetition frequency), since the noise spectrum is repeated on each spectral line.) Measurements on pulsed carriers with high duty cycles (> 20%) can be made fairly easily using the phase detector method. This solution can be implemented with the HP 3047A and HP 11740A Phase Noise Measurement Systems.

Phase noise measurements on low duty cycle pulsed carriers becomes much trickier. A modified delay line technique has been successfully implemented by TRW. The phase detector method can also be used for making phase noise measurements on pulsed signals with low duty cycles. This method is implemented in a commercially available solution in the HP 11729C/8662A. Selecting pulse mode on the HP 11729C switches in a user-supplied external low-pass filter, designed to reject the PRF feed-through. Pulse mode also applies error current to help balance the diodes in the phase detector, minimizing the dc offset feeding through the feedback path. Pulsed phase noise measurements have successfully been made on pulsed carriers with < 2% duty cycles. However, the success of the measurement is highly dependent on the design of the source and its pulse modulator. Gating at the phase detector by using the HP 8663A in the pulsed mode can improve system sensitivity.

Another new growth area is the need to measure the phase noise on millimeter wave sources. AM noise and two-port noise measurements will also increase in importance. As the importance of phase noise in communications and radar/DE systems grows, the challenge will be to find better ways to make today's measurements and new ways to make the measurements of tomorrow.

References

1. HP RF and Microwave Phase Noise Measurement Seminar, Hewlett- Packard Company, 1984.

2. Scherer, D. (HP), "Generation of Low Phase Noise Microwave Signals", HP RF and Microwave Measurement Symposium, May, 1981.

3. Scherer, D. (HP), "The Art of Phase Noise", HP RF and Microwave Measurement Symposium, May, 1983.

4. Howe, D., "Frequency Domain Stability Measurements: A Tutorial Introduction", N.B.S. Technical Note 679, National Bureau of Standards, Boulder, CO, 1976.

5. Lance, Seal, Mendoza and Hudson, (TRW), "Automating Phase Noise Measurements in the Frequency Domain", 1977 Annual Frequency Control Symposium,

6. Shoaf, J.H., Halford, D., Risley, A.S., "Frequency Stability Specification and Measurement: High Frequency and Microwave Signals", N.B.S. Technical Note 632, January, 1973

7. Temple, R. (HP), "Choosing a Phase Noise Measurement Technique - Concepts and Implementation", HP RF and Microwave Measurement Symposium, February, 1983.

8. Fischer, M., "An Overview of Modern Techniques for Measuring Spectural Purity", Microwave, Vol.18, No.7, pp. 66-75, July, 1979.

9. Ondria, F.G., "A Microwave System for Measurements of AM and FM Noise Spectra", IEEE Transactions of Microwave Theory and Techniques, Vol. MTT-16, pp. 767-781, September, 1968.

10. Hewlett-Packard staff, "Phase Noise Characterization of Microwave Oscillators - Phase Detector Method", PN 11729B-1, August, 1983.

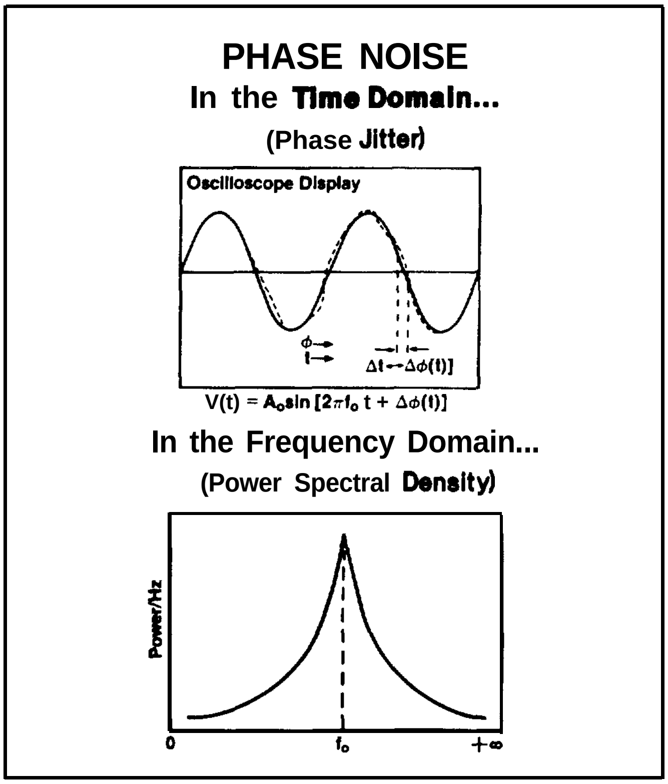


Figure 1. Phase noise in both the frequency and time domains.

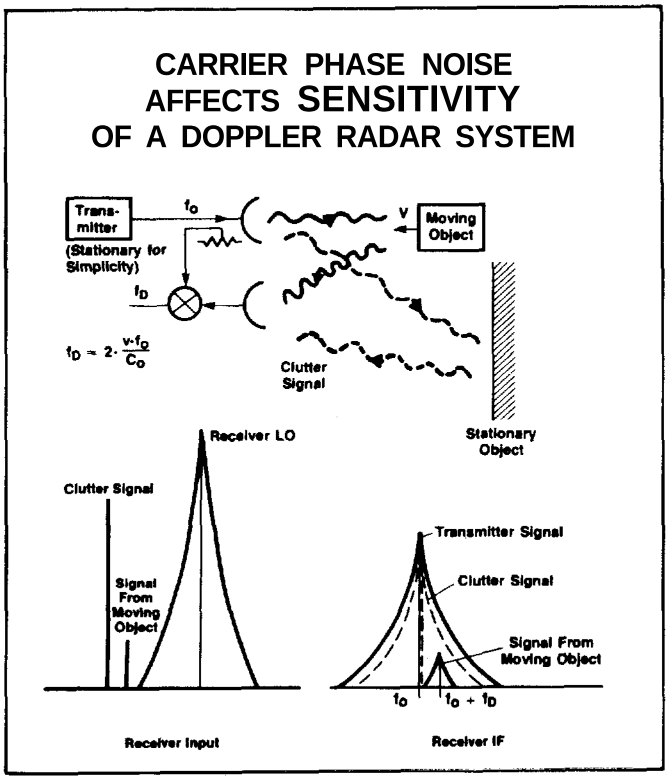
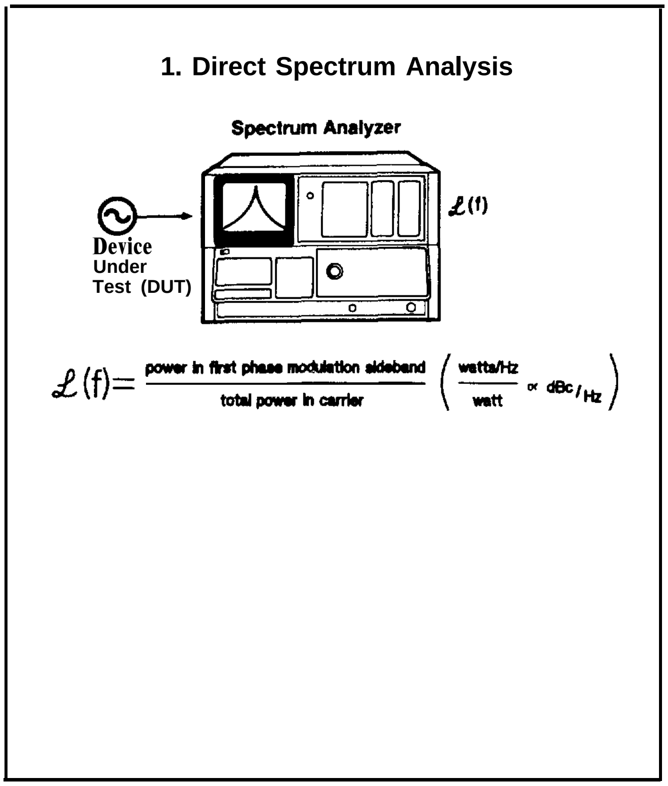


Figure 2. Phase noise on the local oscillator of the receiver can limit the sensitivity of a doppler radar.



1. Direct Spectrum Analysis

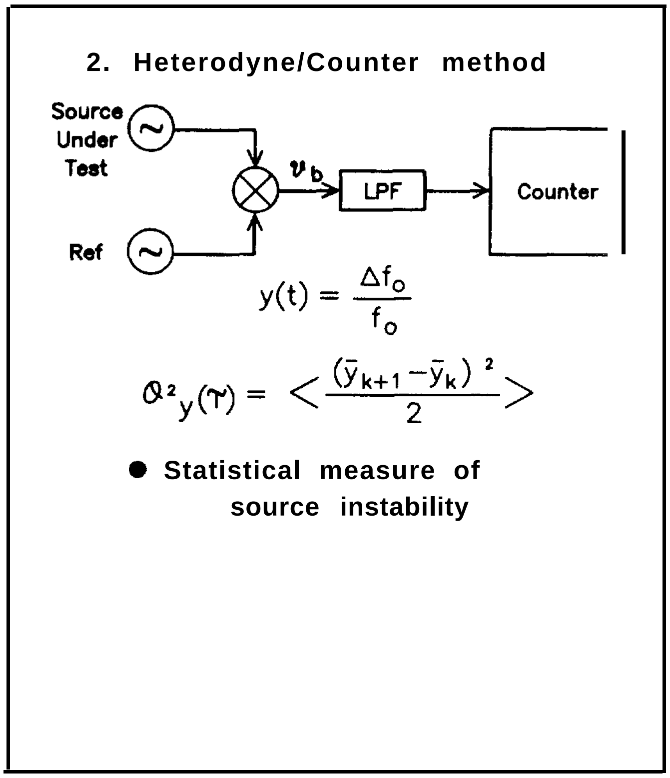
Spectrum Analyzer

Device
Under
Test (DUT)

$\mathcal{L}(f)$

$$\mathcal{L}(f) = \frac{\text{power in first phase modulation sideband}}{\text{total power in carrier}} \left(\frac{\text{watts/Hz}}{\text{watt}} \text{ or dBc/Hz} \right)$$

Figure 3. The direct spectrum method of phase noise measurement. The DUT is applied to the input of a spectrum analyzer, which directly displays the phase noise.



2. Heterodyne/Counter method

Source
Under
Test

Ref

v_b

LPF

Counter

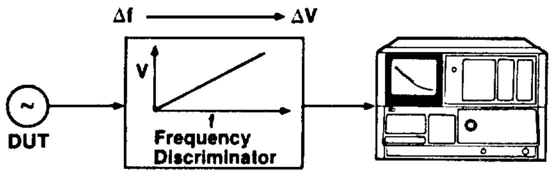
$$y(t) = \frac{\Delta f_o}{f_o}$$

$$\sigma^2_y(\tau) = \left\langle \frac{(\bar{y}_{k+1} - \bar{y}_k)^2}{2} \right\rangle$$

- Statistical measure of source instability

Figure 4. The heterodyne/counter method of phase noise measurement. The DUT is downconverted, and then the IF signal is repeatedly counted by a high-resolution counter.

3. Frequency Discriminator method



$$S_{\Delta f}(f) \text{ spectral density of frequency fluctuations} = \frac{\Delta f^2_{rms}(f)}{B} \left[\frac{Hz^2}{Hz}\right]$$

Figure 5. In the frequency discriminator method, the short-term frequency fluctuations of the DUT are converted to baseband voltage fluctuations which are measured by a baseband analyzer.

TYPICAL SENSITIVITIES OF FREQUENCY DISCRIMINATOR METHOD

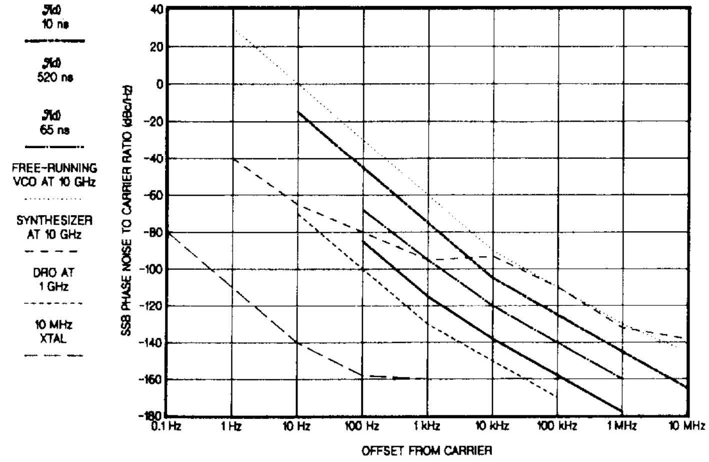


Figure 6. The system sensitivity of the frequency discriminator method follows the noise characteristic of free-running sources (low broadband noise floor, with the phase noise increasing as f^{-2} as the carrier under test is approached.)

Frequency **Discriminator** Method- HP **11729C Implementation**

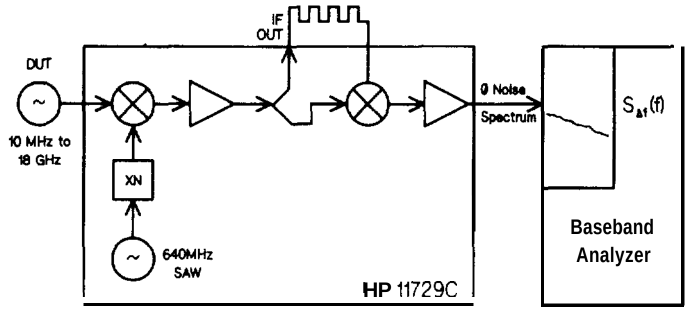
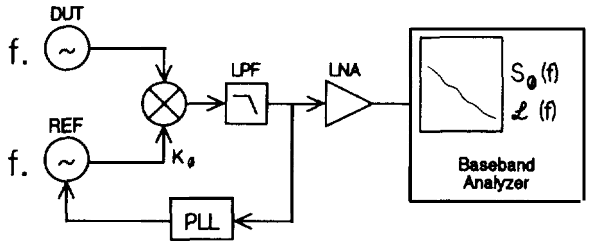


Figure 7. A low-cost, high performance phase noise measurement using the frequency discriminator method is implemented in the HP 11729C Carrier Noise Test Set. The DUT is downconverted to an IF with an internal low noise reference signal. The frequency discrimination actually takes place at the IF frequency.

4. Phase Detector Method

(two-source technique)

(quadrature technique!



$S_\phi(f)$ = spectral density of phase fluctuations

$$= \frac{\Delta\phi^{2}_{rms}(f)}{B} \quad \left(\frac{rad^2}{HZ} \text{ or dBr}^2/\text{Hz}\right)$$

Figure 6. The phase detector method of phase noise measurement. The short-term phase fluctuations of the DUT are converted to baseband voltage fluctuations which are measured by a baseband analyzer.

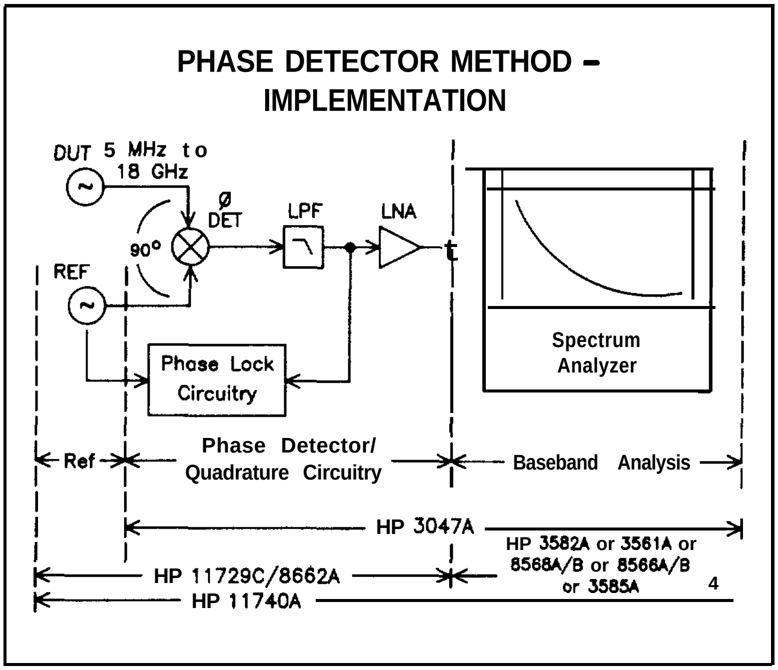

PHASE DETECTOR METHOD - IMPLEMENTATION

Figure 9. A complete phase noise measurement system using the phase detector method requires 3 essential pieces - the reference source, the detection and quadrature circuitry, and the baseband analysis section.

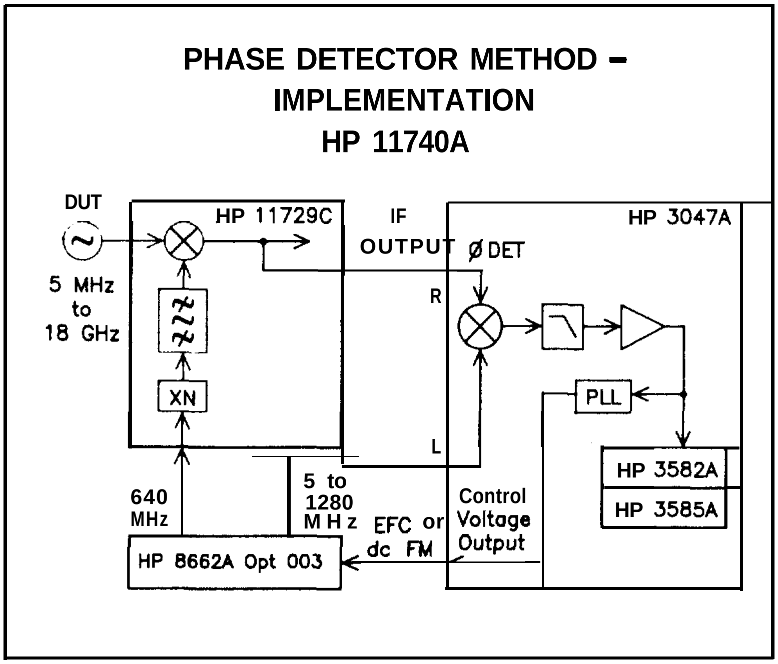
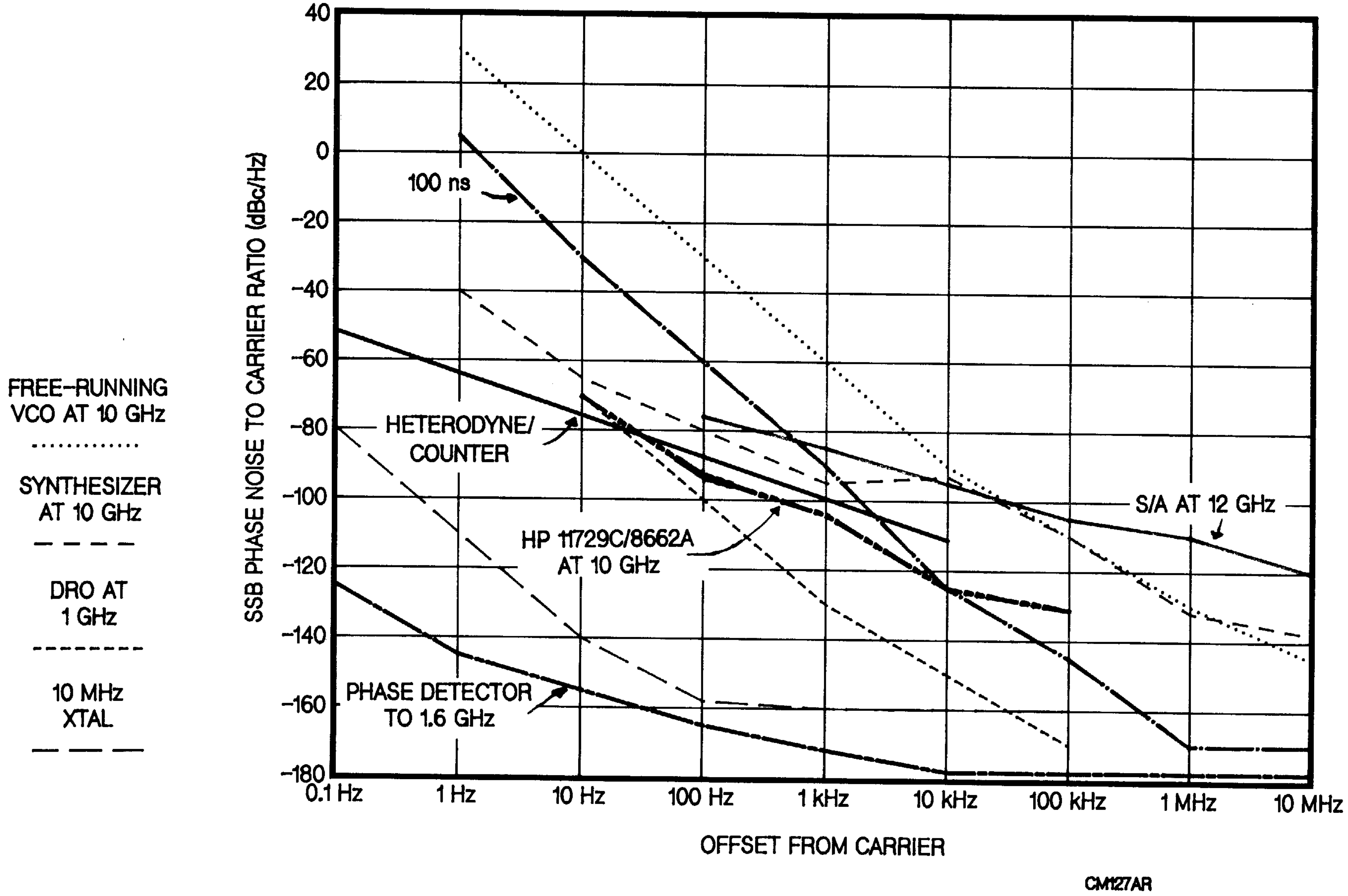

PHASE DETECTOR METHOD - IMPLEMENTATION HP 11740A

Figure 10. The HP 11740A Microwave Phase Noise Measurement System is a complete, fully automatic, specified system for accurate measurements on sources from 5 MHz to 18 GHz.

Figure 11. Comparison of the sensitivities of the four major methods of phase noise measurement. Also shown are the typical noise spectra of four different types of sources.

COMPARISON OF SYSTEM SENSITIVITY



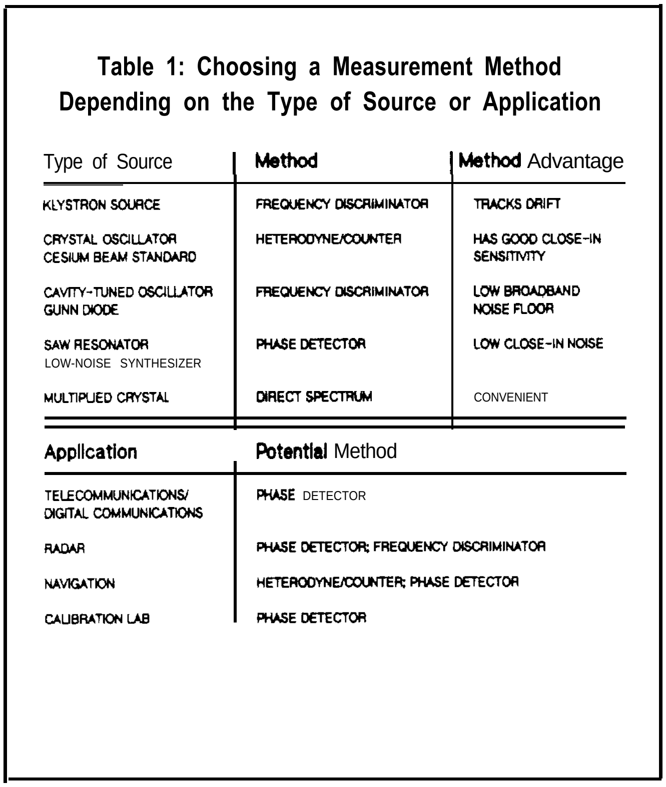


Table 1: Choosing a Measurement Method Depending on the Type of Source or Application

Type of Source	**Method**	**Method** Advantage
KLYSTRON SOURCE	FREQUENCY DISCRIMINATOR	TRACKS DRIFT
CRYSTAL OSCILLATOR CESIUM BEAM STANDARD	HETERODYNE/COUNTER	HAS GOOD CLOSE-IN SENSITIVITY
CAVITY-TUNED OSCILLATOR GUNN DIODE	FREQUENCY DISCRIMINATOR	LOW BROADBAND NOISE FLOOR
SAW RESONATOR LOW-NOISE SYNTHESIZER	PHASE DETECTOR	LOW CLOSE-IN NOISE
MULTIPLIED CRYSTAL	DIRECT SPECTRUM	CONVENIENT

Application	**Potential** Method
TELECOMMUNICATIONS/ DIGITAL COMMUNICATIONS	PHASE DETECTOR
RADAR	PHASE DETECTOR; FREQUENCY DISCRIMINATOR
NAVIGATION	HETERODYNE/COUNTER; PHASE DETECTOR
CALIBRATION LAB	PHASE DETECTOR

Table 1. Choosing a likely phase noise measurement method by knowing: 1) the type of source or 2) the final application. The optimum measurement method is dependent on the noise level of the oscillator and the measurement data desired.

TIME AND FREQUENCY DOMAIN
MEASUREMENTS FOR GPS RUBIDIUM FREQUENCY STANDARDS

JANUARY 18, 1985

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ABSTRACT

Space-Qualified Rubidium frequency Standard's (RFS) are being developed for the NAVSTAR Global Positioning System (GPS) by Rockwell International Corporation's Defense Electronics Operations. This paper presents the test data of the time and frequency domain measurements along with the automated test system as a essential element in the evaluation of RFS performance in a simulated spacecraft environment.

Typical production test data for stabilities from 1 to 100,000 seconds averaging time and Power Spectral Density/Phase Noise Test with offset from the carrier as close as 4 millihertz will be discussed along with Life Tests to 1 ,000,000-seconds averaging time.

INTRODUCTION

The Rockwell International, Defense Electronics Operations in Anaheim, California has been involved in the development and production of space-qualified Rubidium Frequency Standards (RFS) for the GPS NAVSTAR Program since the initial inception in 1974. To date, a total of 37 flight units were produced for Satellites 1 through 12.

The first series of nine satellites are in orbit and has been declared operational. NAVSTAR 1 through 3 carries three redundant RFS and NAVSTAR 4-10 has three RFS and one Cesium Beam Frequency Standard.

Rockwell is currently in the process of producing 56 flight units on the Phase II Production program for GPS 13 through 40 satellites. The GPS validation phase has demonstrated navigational accuracies of a few meters in three dimensions.

The RFS test cycle covers two major phases, the pre-production and the acceptance level testing. The pre-production testing covers the board and system assembly, where tests are made of the components, absolute frequency, temperature coefficient, and frequency stability. The acceptance-level testing includes the environmental and certification tests. All of the certification tests and part of the pre-production and environmental tests are performed on six test systems located within the Rockwell Anaheim Facility.

SPACE-QUALIFIED RFS TEST PROGRAM

Automated Test System

Rockwell's Rubidium Frequency Standard has been developed from a commercial EFRATOM Rubidium Physics Package[1]. Extensive modification and repackaging have been performed to meet spacecraft requirements and to improve reliability and stability. Acceptance testing of the production RFS is required to assure compliance with the design goals and conformance to the Phase I specification. Computer automation of the RFS is utilized because of the large amount of data to be gathered over an extended time period and the need to extensively process this data.

A central or a time share-computer concept was selected to allow for greater versatility of utilization and to allow implementation of additional test stations. The computer system utilizes a sophisticated version of basic as the programming language available to users and can be extended to service up to 16 terminals. It is essentially a minimum system requirement to support the storage and processing requirements.

In the existing configuration, a total of six Automated Rubidium Frequency Standard Stations are available for test. Two stations are used for engineering and the remaining four stations are for production test. All six stations are equipped with microcomputer systems that provide redundant data collection and storage capabilities if the time shared computer should fail. At the end of the test, these data would than be transferred to the Central Computer for analysis.

System redundance prevents the loss of test time without interruption. A functional block diagram of the RFS test station and a photograph of three of the four production automated test stations are shown in Figures 1 and 2, respectively [5].

A valuable feature of the time share concept utilized is the ability to access data being stored in disc from one program using one I/O port by executing an independent program from a second port. This feature allows data analysis without interrupting data collection while using a number of different programs. Fail safe features are incorporated into all test stations to protect the RFS from power-line voltage transients, supply over-voltage, and current, over-temperature, and water flow-rate restrictions in the vacuum pumps.

The RFS supply current and telemetry-monitored test point levels are recorded throughout the test cycle. The RFS frequency is measured using the “Time Mark System” [2]. This system, developed by Rockwell’s Metrology Laboratory, is similar in principle to the NBS chronograph. The heterodyned beat period is measured without dead time (the loss of time required to re-arm the counter). In this system, the beat-frequency zero crossings load the value of a free running counter into an output buffer. This system was implemented by simple modification of an electronic counter.

Figure 3 shows the RFS mounted in the vacuum chamber which simulates the spacecraft pressure. Cooling is provided through the RFS baseplate to the mounting block which simulates the spacecraft mounting. Coolant from a temperature-stabilized bath is circulated through a maze within the block.

Test Specifications

The testing of Rockwell’s RFS is controlled by two specifications, one an assembly and alignment procedure and the second an Acceptance Test Procedure (ATP). These test procedures have been witnessed and certified by Quality Engineering. There are approximately 76 inspection points where a Quality Assurance Inspector must approve and stamp off the work before additional testing can proceed. All these steps are planned and recorded in a FAIR book system. FAIR is an acronym for Fabrication-Assembly-Inspection-Record.

This system also keeps track of all parts installed into the RFS. If a failure occurs during assembly, the retest must start over per the retest matrix listed in the assembly procedure. If a failure occurs during the ATP, the failure must be documented by Reliability Engineering, who also notifies the prime contractor, and generates a failure analysis report.

At the completion of a successful ATP the test data is assembled into a data package by Quality Engineering and a formal data review is conducted with the prime contractor, Air Force Space Division, and the technical consultants for the Air Force.

After the data review, the RFS is packaged and shipped to the prime contractor. The data is impounded in the Data Submittal department where it is available for review at a later date. This data includes all acceptance test record cards, “FAIR” books, computer printouts and strip charts.

Figure 4 shows the Product Acceptance test flow for the RFS from the Module Assembly level to the point of shipment, the space vehicle factory test. A typical calendar time for product acceptance test is approximately three months.

Performance Test

An overview of the RFS performance tests in the Time and Frequency Domain are shown in Figure 5. The tests are basically categorized in: (1) The Two Sample Allan Variance, Sigma y (Tau) vs. Tau in Seconds; (2) Phase Noise, $S\phi$ (f) vs. Fourier Frequency; (3) Power Spectral Density, Sy(f) vs. Fourier Frequency; and (4) Frequency Spectrum Analysis for Harmonics and Spurious Response. The tests frequencies span over 12 orders of magnitude from 4 Millihertz to 20-MHz offset from the carrier frequency of 10.23 MHz.

The tests are not only performed to control the quality of the product but also to detect trends and provide diagnostic aids in trouble shooting out-of-tolerance conditions.

Time Domain Data

Figure 6 is a two-sample Allan Variance Computer printout [3,4]. Section 1 is for l-second fundamental beat period with adjacent data pairs averaged to obtain the 2-second Allan Variance, and so on for the 4 and 8 second results. The second section fundamental beat is for 10 seconds. The third and fourth section results are calculated from stored data that is the average of 10 (100-seconds) and 80 (800-seconds) lo-second beat periods. This method is a reasonable alternative to storing large amounts of data, and still retaining acceptable confidence limits. The calculated drift per day is based on the last five days of testing. The Allan Variance results presented in Figure 6 reflect the removal of a first-order curve (drift).

Figure 7 is a graphical computer printout of the 800-second data used to calculate the Allan Variance of Figure 6. The graphs are the average of 10, 20 and 50, 800-second data resulting in 8,000, 10,000, and 40,000 seconds per bar with each asterisk representing two **parts** in 10^{13} in the fractional frequency change. The graph readily demonstrates the exponential warmup characteristic present in the RFS frequency.

Figure 8 is a Allan Variance plot of the printout in Figure 6. The vertical bars at each data point represent the range of confidence limits. The insert in the top right corner is the graph of Figure 7 for the average of 50, 800-second data points. It is apparent, that the warmup characteristic displayed by the insert is a predominant cause of the Allan Variance flattening or turning upward for longer sample times. In Figure 9 where the insert shows essentially flat data, or in Figure 10 where removal of the drift results in a relatively flat plot, the Allan Variance values continue a downward trend. These latter plots are typical of Rockwell’s production units.

Frequency Domain

Two methods are used to determine the Phase Noise and the Power Spectral Density (PSD) performance of the RFS. In the first method, a conventional Phase-Lock Detection System measures the phase noise components from 1 Hz to 5 kHz offset from the 10.23 MHz RFS output frequency. A typical phase noise plot is shown in Figure 11. It is noted that the average measured data is about 20 dB below the acceptable performance requirements of -83 dB and -123 dB at 1 Hz and 5 KHz respectively.

A Fast Fourier Transform (FFT) Power Spectral Density Measurement System is used to characterize the close-in noise components for offset frequencies between 4 Millihertz to 0.5 Hz of the RFS output frequency.

This technique is performed by processing the Allan Variance time domain data (nominal l-second sample times) and transforming it into the frequency domain by a FFT program to produce a Power Spectral Density Plot. A total of 1024 one-second data points are normally taken with the Time Mark

System and processed in four groups of 256 data points to provide a PSD plot with a minimum of four samples at 4 millihertz. A typical or normal PSD plots are shown for both the Atomic Mode (closed loop) and Crystal Oscillator Mode (Open loop) in Figures 12 and 13 respectively. An Allan Variance limit line is drawn on the PSD Plots to represent the specification for an acceptable RFS.

Note that the atomic mode is essentially flat and the Crystal mode has a downward slope toward the 0.5 Hz frequency as expected. Any abnormal conditions of the RFS will be shown as discontinuities (large upward or downward slopes) exceeding the specification limit line.

A abnormal PSD plot is shown in Figure 14 for the Crystal Oscillator Mode while Figure 15 shows the Allan Variance data to produce the PSD plot. It can be seen that there is a large upward slope at about 0.03 Hz on the PSD Plot, exceeding the 1×10^{-11} limit. This condition was caused by having two 10.23 MHz Oscillators on the same Test System with close-in frequencies. It is noted that the Allan Variance plot (Figure 15) shows a broad peak at about the 16-second sample time (0.06 Hz) instead of 0.03 Hz as produced by the PSD plot.

False peaks can be generated by using a FFT program due to its sampling rate. These false peaks can be isolated by using another set of data (1024 points) at a slightly different sample time, i.e., 1.1 seconds instead of 1.005 seconds. These false peaks are caused by the foldover of spurs outside the frequency range of interest. The new sample rate will cause the false peaks to move to a different frequency and the peak of interest will remain at the same frequency.

RUBIDIUM FREQUENCY STANDARD LIFE TESTS

The life tests were initiated to characterize the RFS developed for the GPS autonomous operational goals. Especially, the 14-day, 131 -meter error requirement. This requirement allows an error of 437 nanoseconds after 14 days without a time correction or upload. The first life test was performed in 1978 for 100 days. During the 100-day test there was one power interruption. The second test was performed in the first half of 1983 for 140 days [6]. Both life tests have demonstrated that the GPS autonomous operational goals can readily be achieved.

In order to predict time error for autonomous operation, David Allan of the National Bureau of Standards (NBS) has published a model for the prediction of time error based on previous performance of the RFS in terms of the Allan Variance, $\sigma y(\tau)$ and the data length. This model has set GPS autonomous operation standards and prediction of available navigational accuracy versus time from upload. This model was compared to the actual time prediction error. In addition, the relation of characterization data length to the time prediction error was explored using the NBS formula and the long term test data. Figure 16 shows a comparison of the NBS computation to one of the actual 14-day time error segments. The time error shows it is well within one of the most critical GPS autonomous operational goals (437 nanoseconds).

The Allan Variance, $\sigma y(\tau)$ can be calculated both with and without the warm up period data. it can be seen from Figure 17 that the main effect of this behavior is on the long term values or the “random walk”. the total data represents the usual RFS Allan Variance signature. The Allan Variance plot shows that the $\sigma y(\tau)$ is well under the RFS GPS Phase II goal of 5×10^{-13} for τ between 10^5 to 1^6 seconds.

Figure 18 is a plot of the Allan Variance from the data collected in a RFS Life Test conducted in early 1978. The calculations reflect removal of the first-order drift characteristic. The test term was 100 days (8600) data of approximately 1 000-seconds averaging time). The plot revealed two distinct drift characteristics separated near the midpoint of the test. Both are very linear. The plot identified by the o symbol is the Allan Variance calculated from data points 1 to 8600, and the plot using the X symbol is calculated from the data points 4300 to 8600. These data indicate that the Rockwell’s RFS is capable of meeting the GPS Phase II specification.

CONCLUSIONS

It has been shown that the application of Allan Variance and Phase Noise measurements in conjunction with the FFT transformation technique is essential in the development of a Space-Qualified RFS Test Program. Use of Time and Frequency measurement techniques has been a key factor in the success of the Test Program to date.

Expertise in the field of precision frequency and time measurements as well as the capability to interface special test equipment with computer technology are essential in meeting test requirements for Space-Qualified Rubidium Frequency Standards.

By employing a fast fourier transform power spectral density measurement technique, it has shown that the test uncover problems which otherwise may have gone undetected.

The Test Program has also demonstrated GPS autonomous operational goals based on the 100 and 140-day Life Tests. The Life Test has shown that the time prediction error is some what influenced by the apparent aging of the Rubidium lamp. However, once the RFS has been operating for 50-60 days, the Rubidium lamp ages and the “Random Walk” values decrease dramatically.

REFERENCES

1. F. K. Koide and E. M. Hicks, “Atomic Clock Test Program for NAVSTAR,’ Fifth Cal-Poly Measurement Science Conference, December 1975.
2. E. M. Hicks, “An Innovative Method for Measuring Frequency Stability without Deadtime,” Sixth Cal-Poly Measurement Science Conference, December 1976.
3. J. A. Barnes et al, “Characterization of Frequency Stability,” IEEE Transactions on Instr. & Meas., IM-22, June 1975
4. P. Lesage and C. Audoin, “Characterization of Frequency Stability,” IEEE Transaction on Instr. & Meas., IM-22, June, 1975
5. F. K. Koide, D. E. Ringer, C. E. Earl, “Contractor Point of View for System Development & Test Program,” Twelfth Annual PTTI Application and Planning Conference, December, 1980.
6. H. Bethke, D. Ringer, M. Van Melle, “Rubidium and Cesuim Frequency Standard Status and Performance on GPS Program”, Precise Time & Time Interval Meeting, November, 1984.

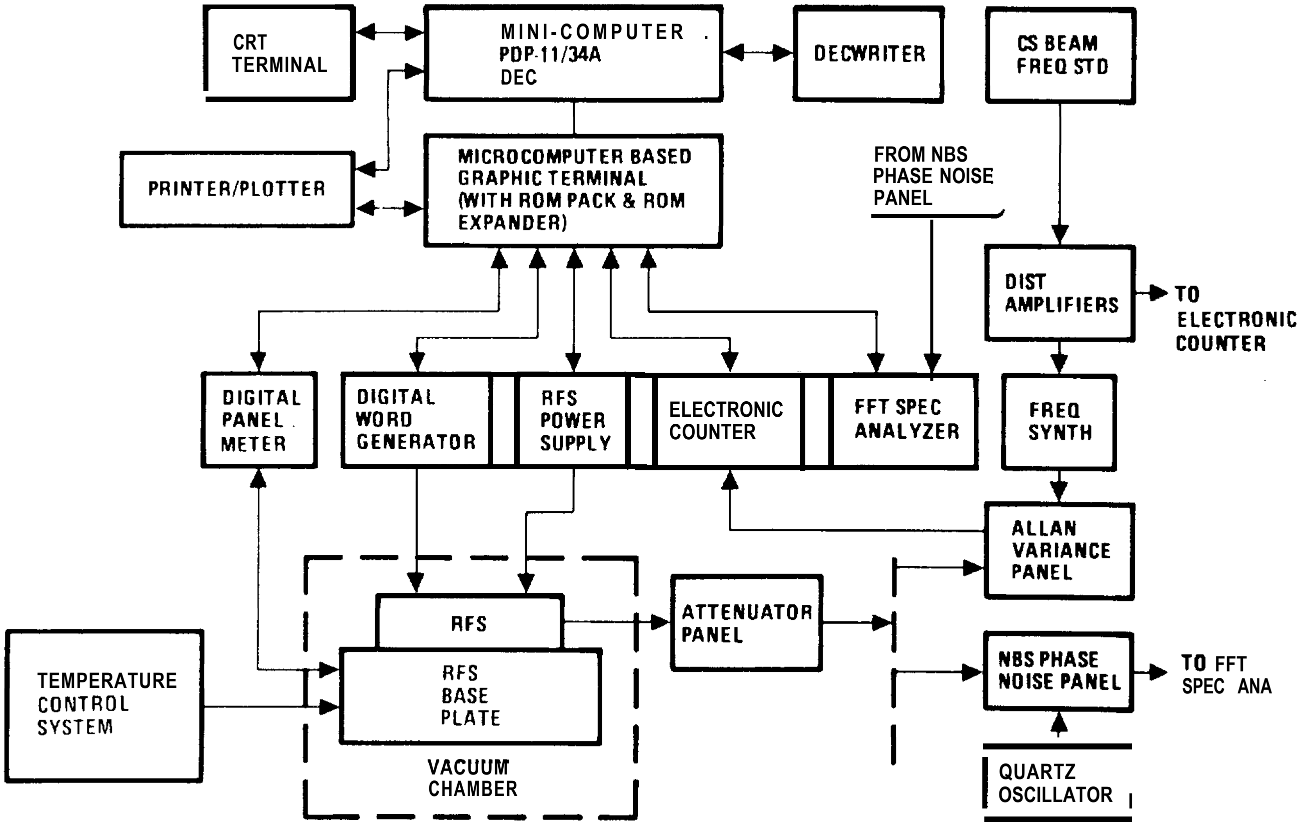


Figure 1. Block Diagram of Automated Rubidium Frequency Standard Test Station

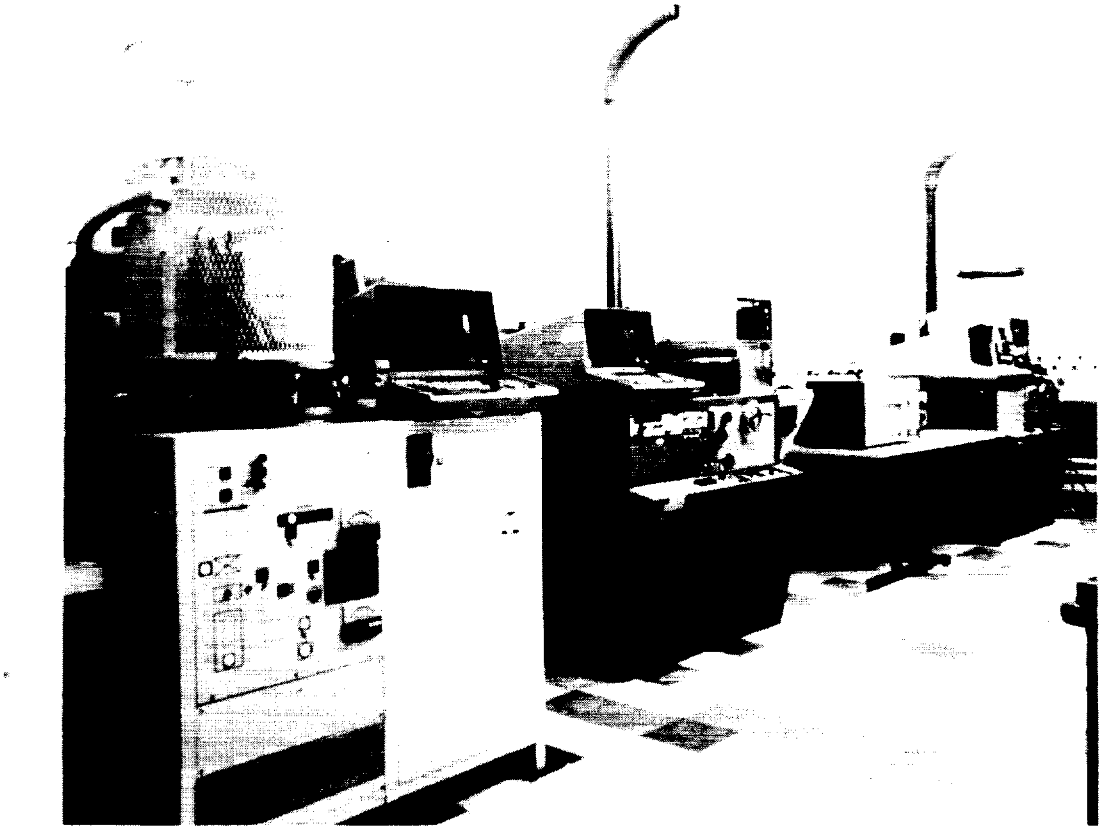


Figure 2. Photo of Automated Rubidium Frequency Standard Test Stations

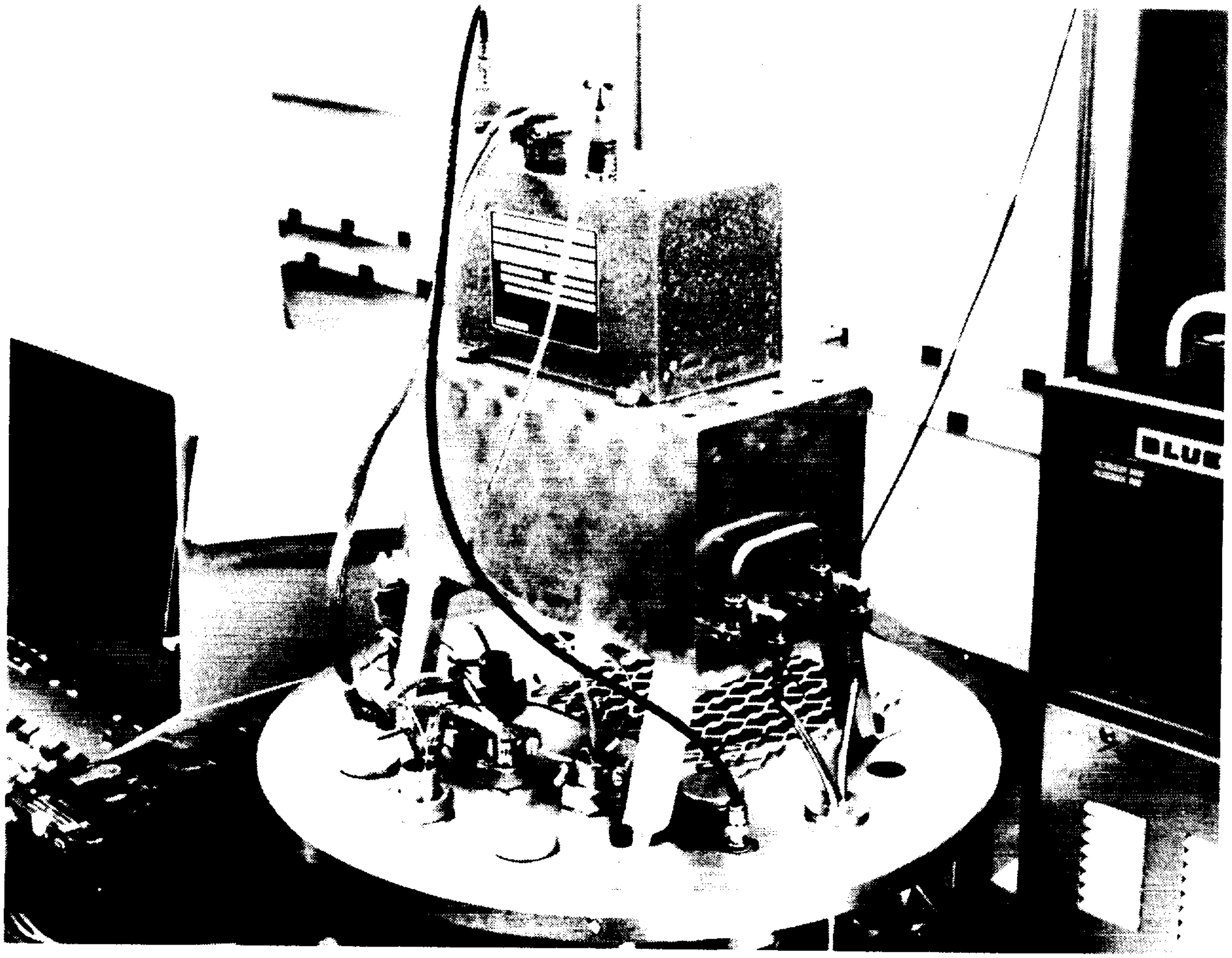


Figure 3. Rubidium Frequency Standard

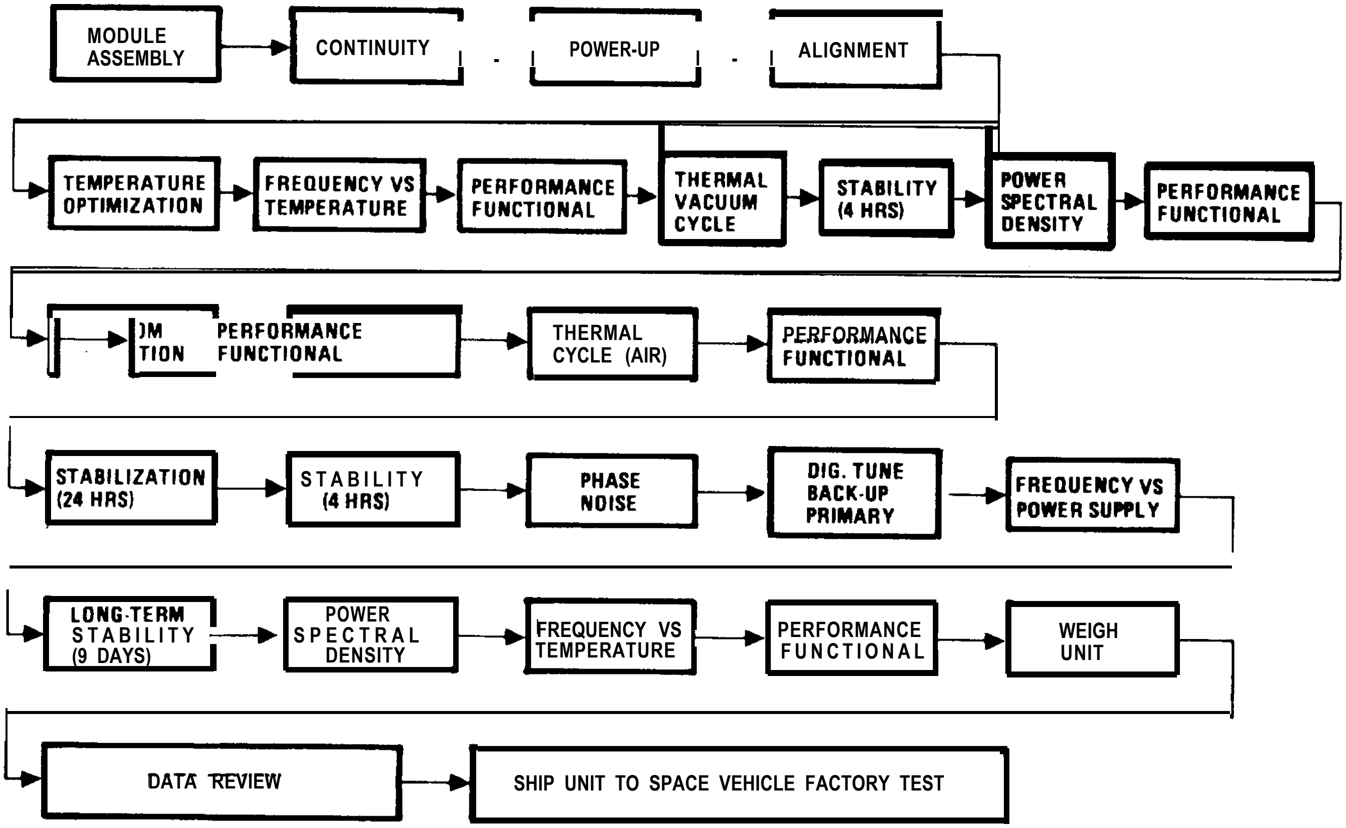


Figure 4. Rubidium Frequency Standard Test Flow

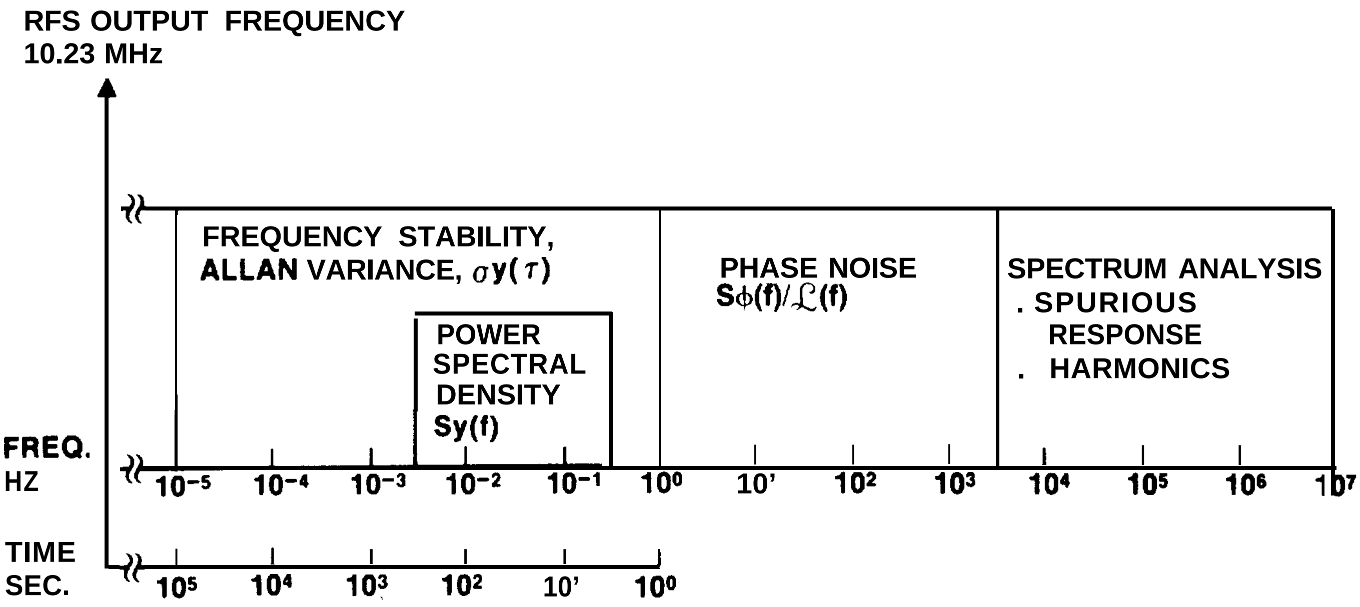
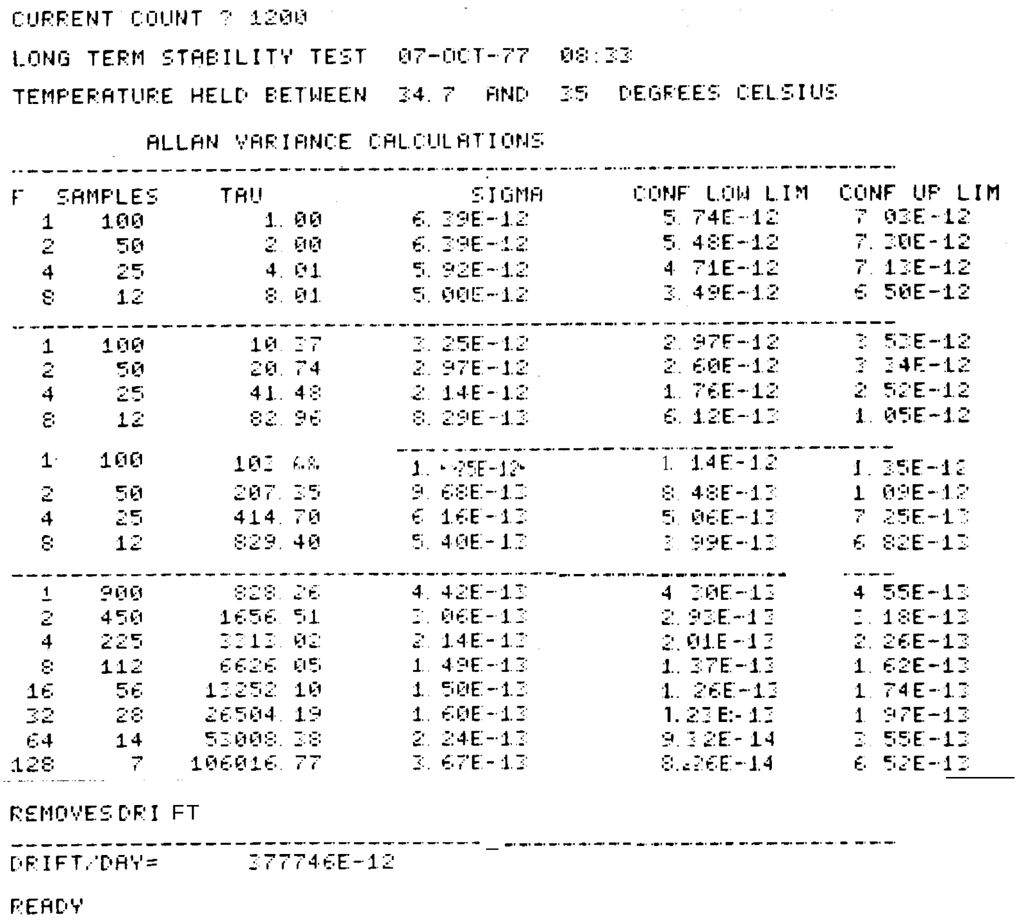
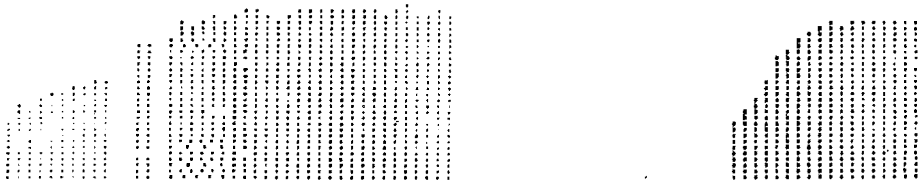


Figure 5. Overview of Rubidium Frequency Standard Performance Tests



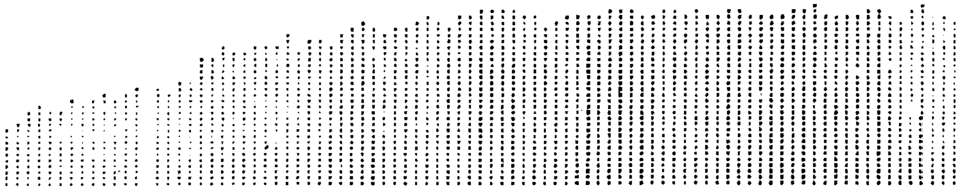
```
CURRENT COUNT ? 1200

LONG TERM STABILITY TEST  07-OCT-77  08:33

TEMPERATURE HELD BETWEEN  34.7  AND  35  DEGREES CELSIUS

          ALLAN VARIANCE CALCULATIONS
-----------------------------------------------------------------
F  SAMPLES    TAU              SIGMA        CONF LOW LIM  CONF UP LIM
  1   100         1.00       6.39E-12         5.74E-12      7.03E-12
  2    50         2.00       6.39E-12         5.48E-12      7.30E-12
  4    25         4.01       5.92E-12         4.71E-12      7.13E-12
  8    12         8.01       5.00E-12         3.49E-12      6.50E-12
-----------------------------------------------------------------
  1   100        10.37       3.25E-12         2.97E-12      3.53E-12
  2    50        20.74       2.97E-12         2.60E-12      3.34E-12
  4    25        41.48       2.14E-12         1.76E-12      2.52E-12
  8    12        82.96       8.29E-13         6.12E-13      1.05E-12
                          --------------------------------------
  1   100       103.68       1.25E-12         1.14E-12      1.35E-12
  2    50       207.35       9.68E-13         8.48E-13      1.09E-12
  4    25       414.70       6.16E-13         5.06E-13      7.25E-13
  8    12       829.40       5.40E-13         3.99E-13      6.82E-13
--------------------------------------------------------   ----
  1   900       828.26       4.42E-13         4.30E-13      4.55E-13
  2   450      1656.51       3.06E-13         2.93E-13      3.18E-13
  4   225      3313.02       2.14E-13         2.01E-13      2.26E-13
  8   112      6626.05       1.49E-13         1.37E-13      1.62E-13
 16    56     13252.10       1.50E-13         1.26E-13      1.74E-13
 32    28     26504.19       1.60E-13         1.23E-13      1.97E-13
 64    14     53008.38       2.24E-13         9.32E-14      3.55E-13
128     7    106016.77       3.67E-13         8.26E-14      6.52E-13

REMOVESDRI FT
-----------------------------------------------------------------
DRIFT/DAY=       377746E-12

READY
```

Figure 6. Computer Printout of Allan Variance Calculation



DISPLAY IS THE AVERAGE OF 20 DATA POINTS (16,000 SEC/ DATA) RESOLUTION = 2 PARTS IN 10 TO 13TH (900 DATA)

DISPLAY IS THE AVERAGE OF 50 DATA POINTS (40,000 SEC/ DATA) RESOLUTION = 2 PARTS IN 10 TO 13TH (900 DATA)



DISPLAY IS THE AVERAGE OF 10 DATA POINTS (8,000 SEC/ DATA) RESOLUTION = 2 PARTS IN 10 TO 13TH (900 DATA)

Figure 7. Graphical Plots

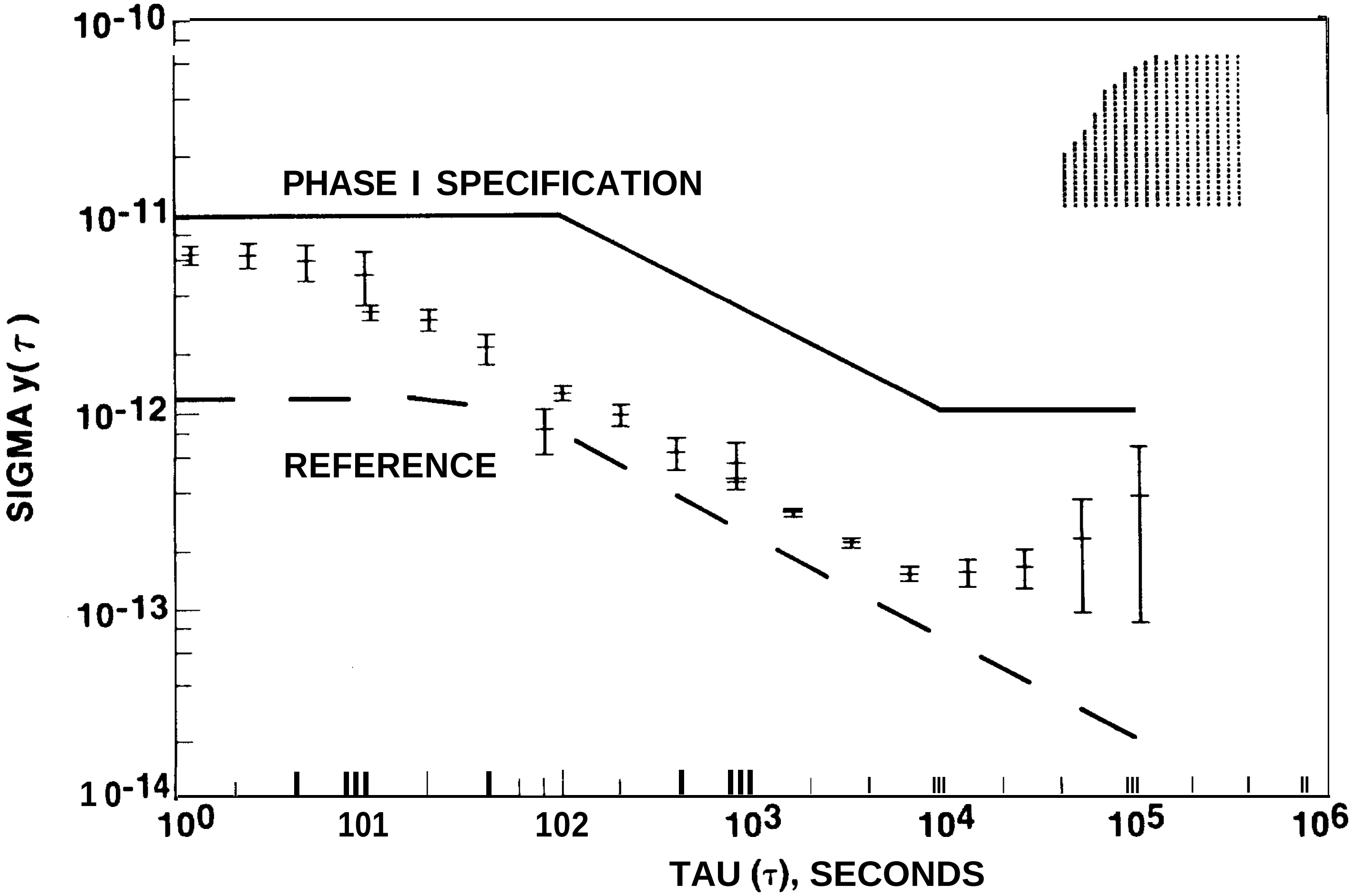


Figure 8. Computer Printout of Allan Variance Plot

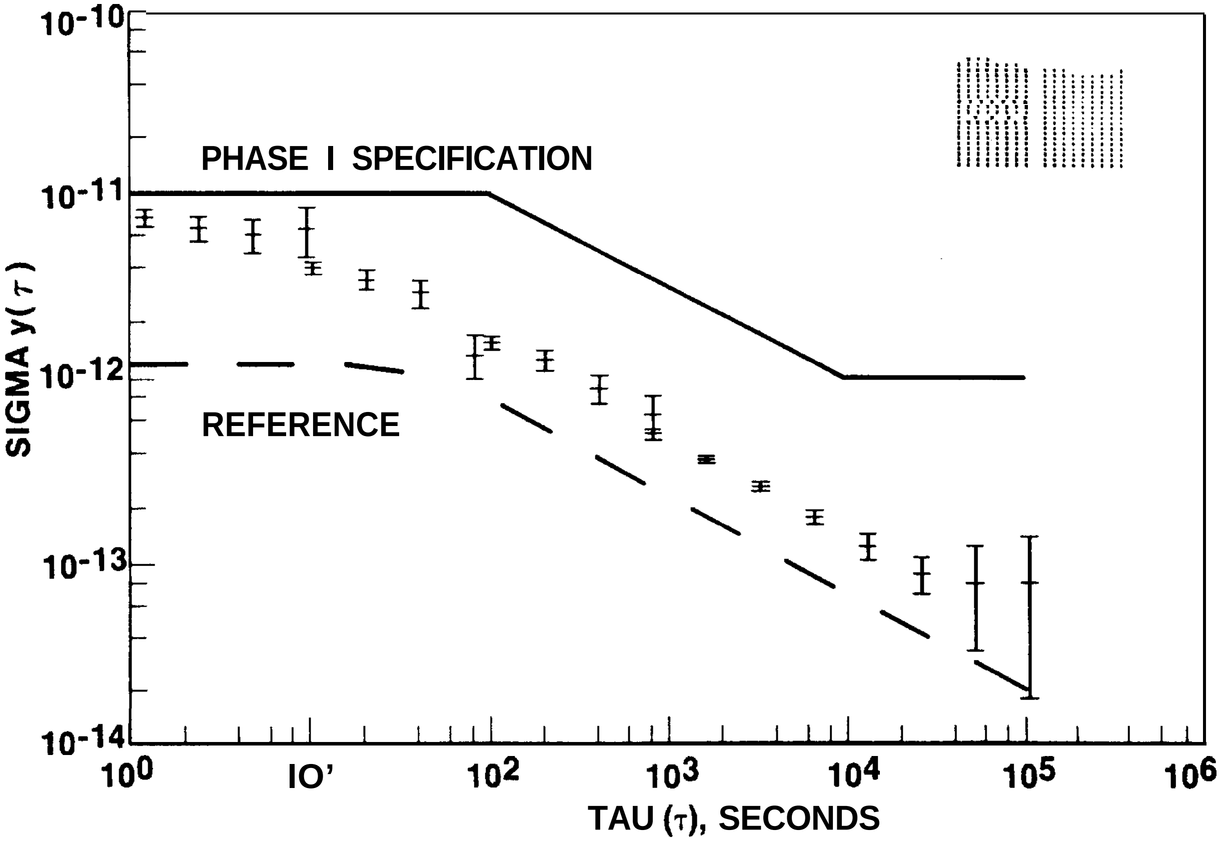


Figure 9. Computer Printout of Allan Variance Plot

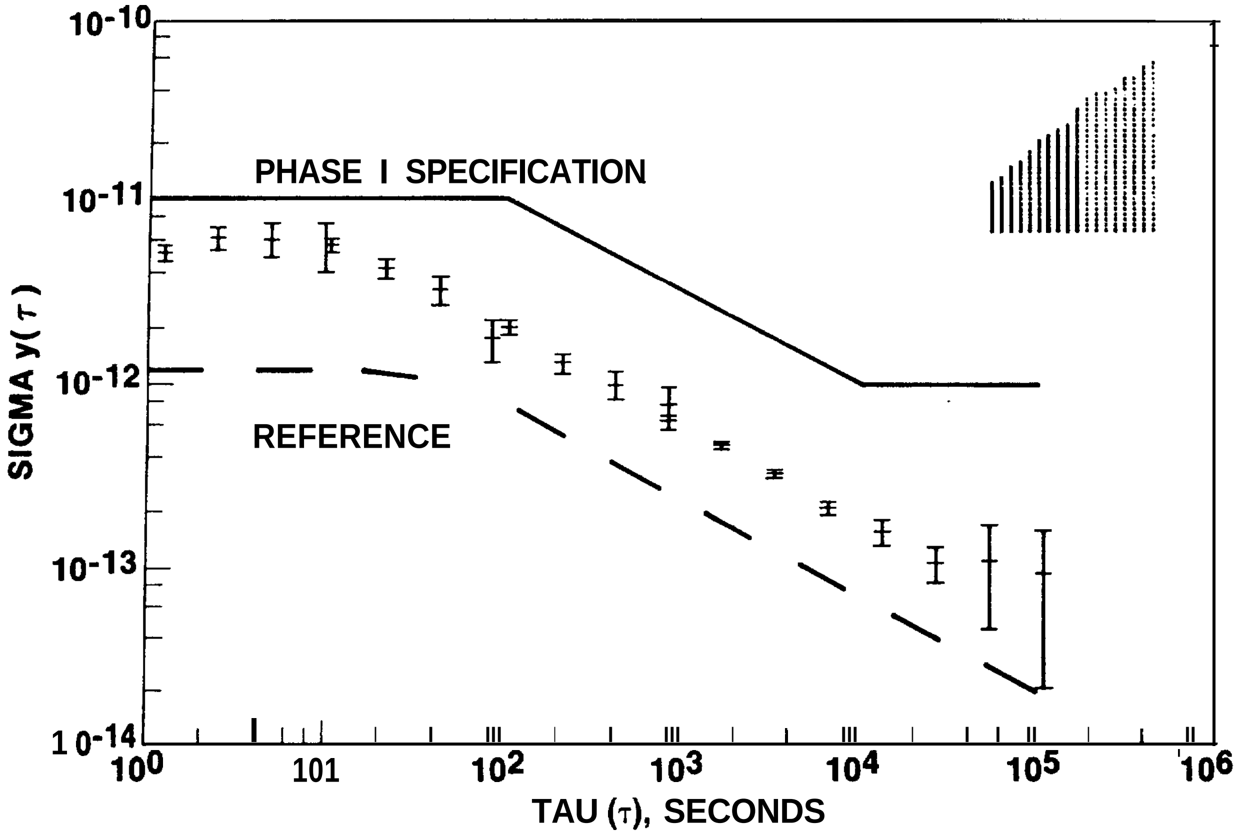


Figure 10. Computer Printout of Allan Variance Plot

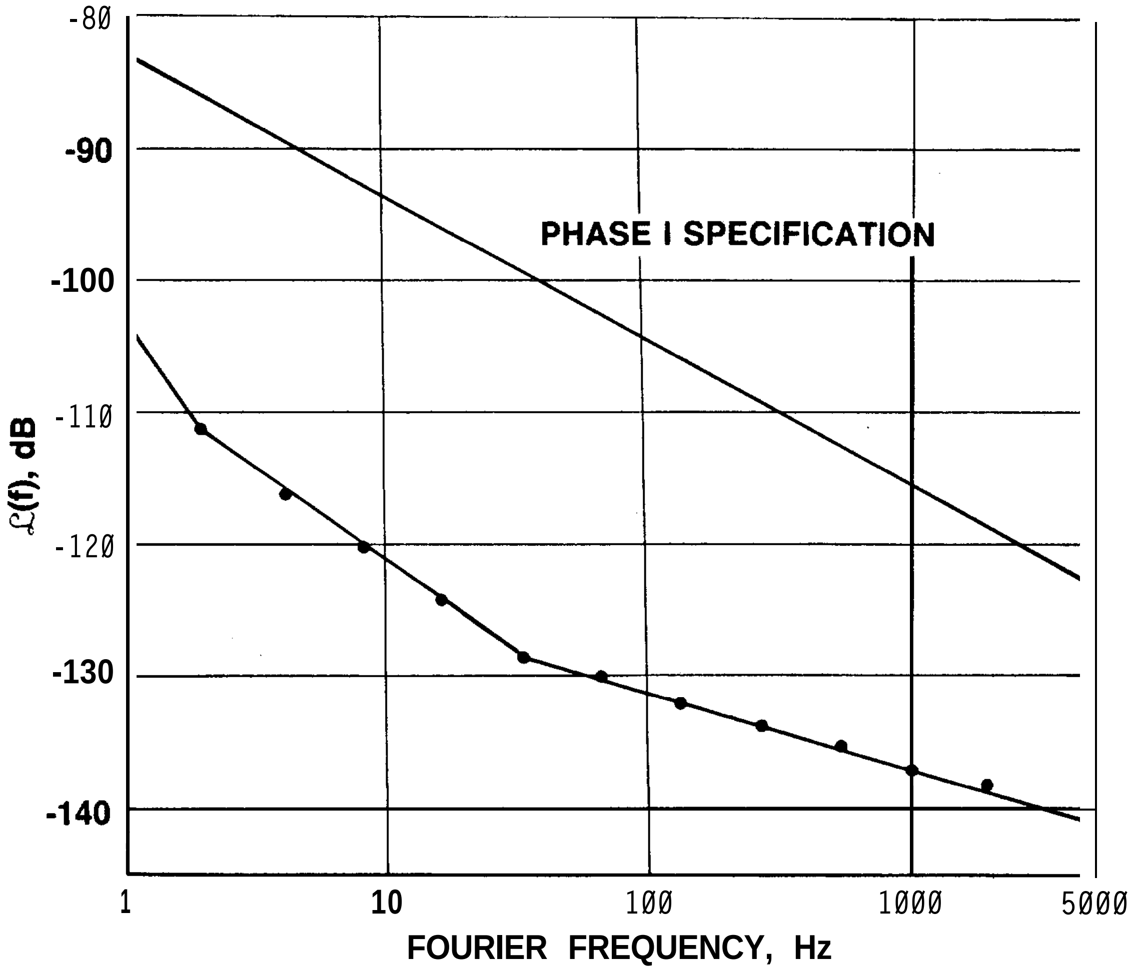


Figure 11. Typical Phase Noise Plot

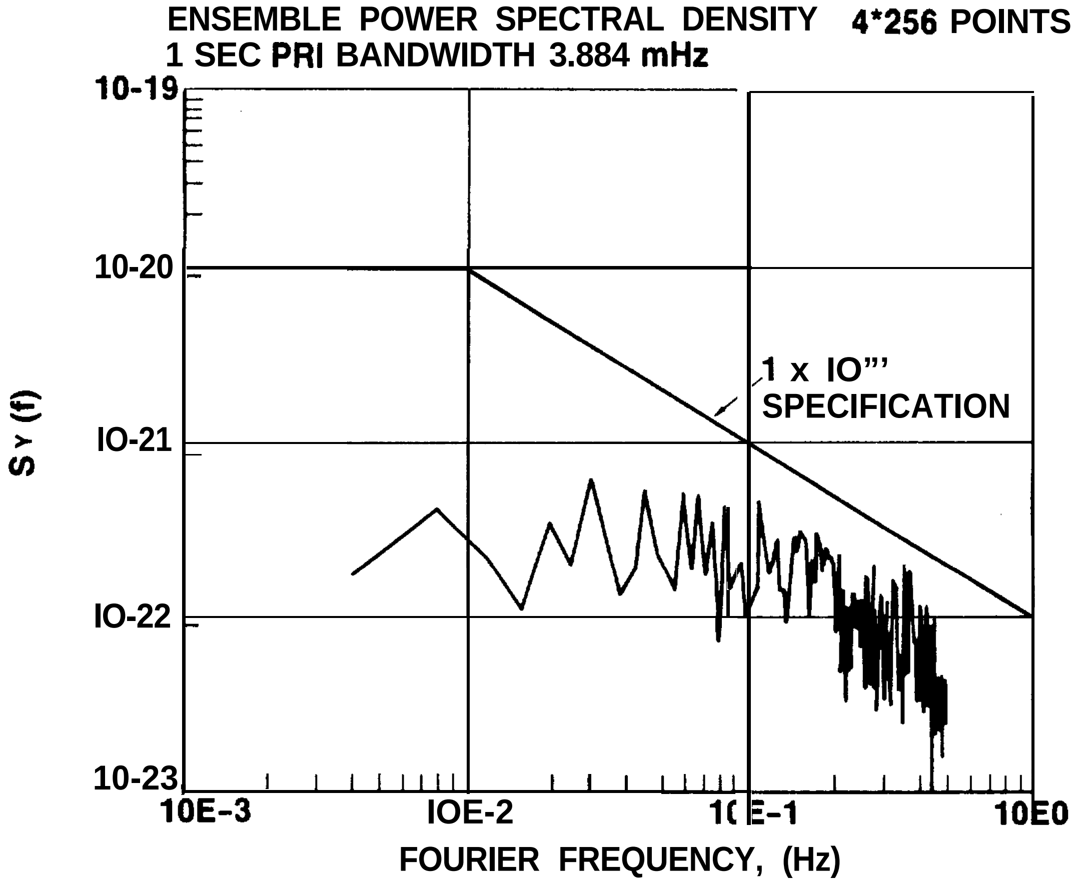


Figure 12. Computer Printout of Power Spectral Density Plot

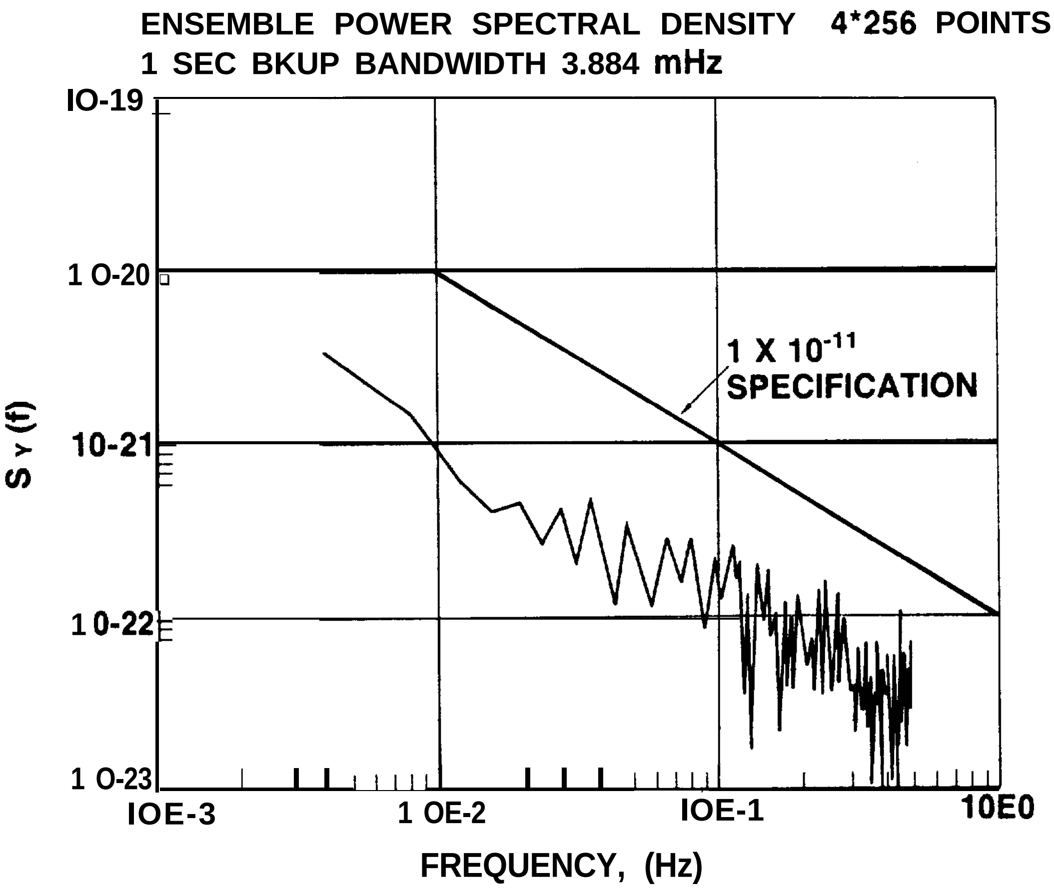


Figure 13. Computer Printout of Power Spectral Density Plot

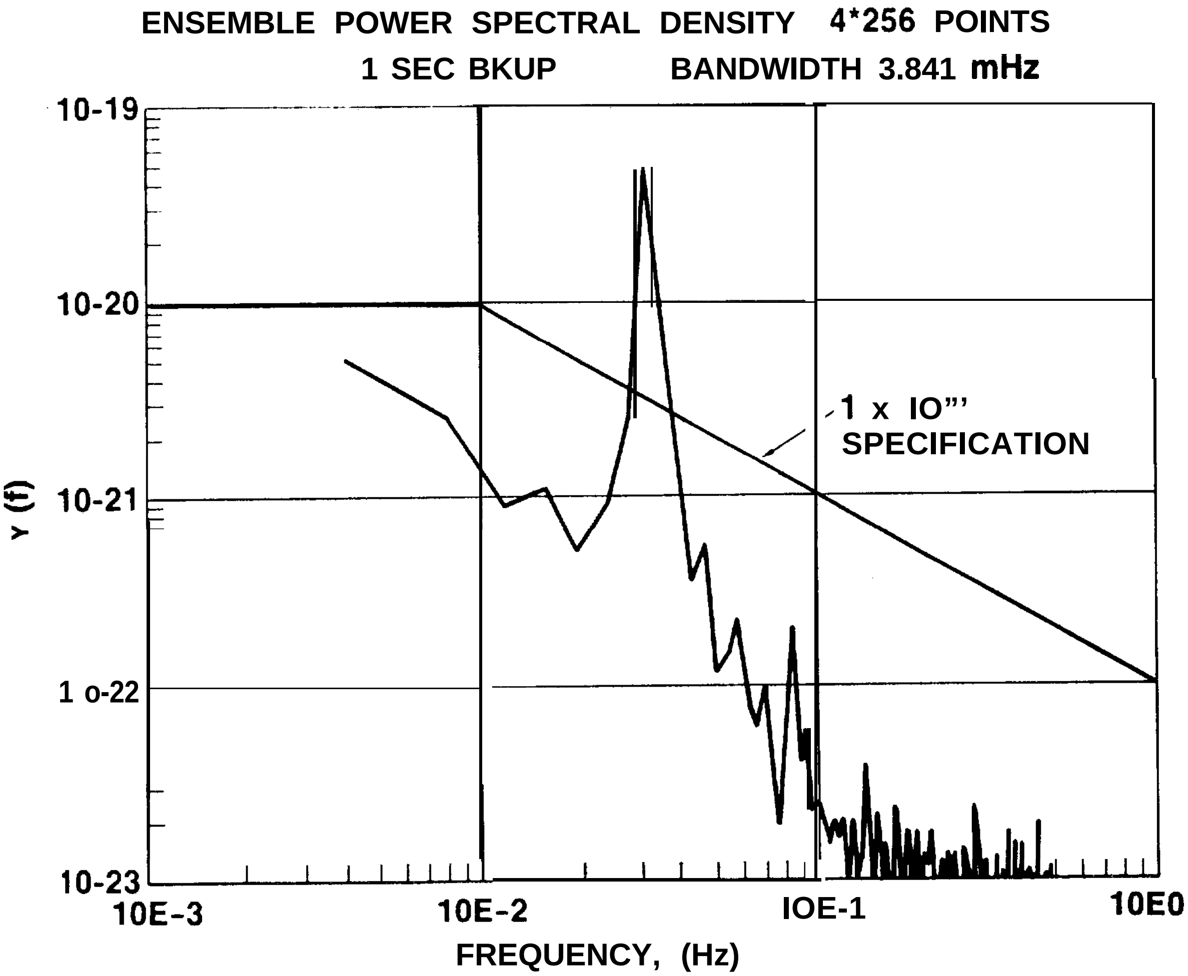


Figure 14. Computer Printout of Power Spectal Density Plot

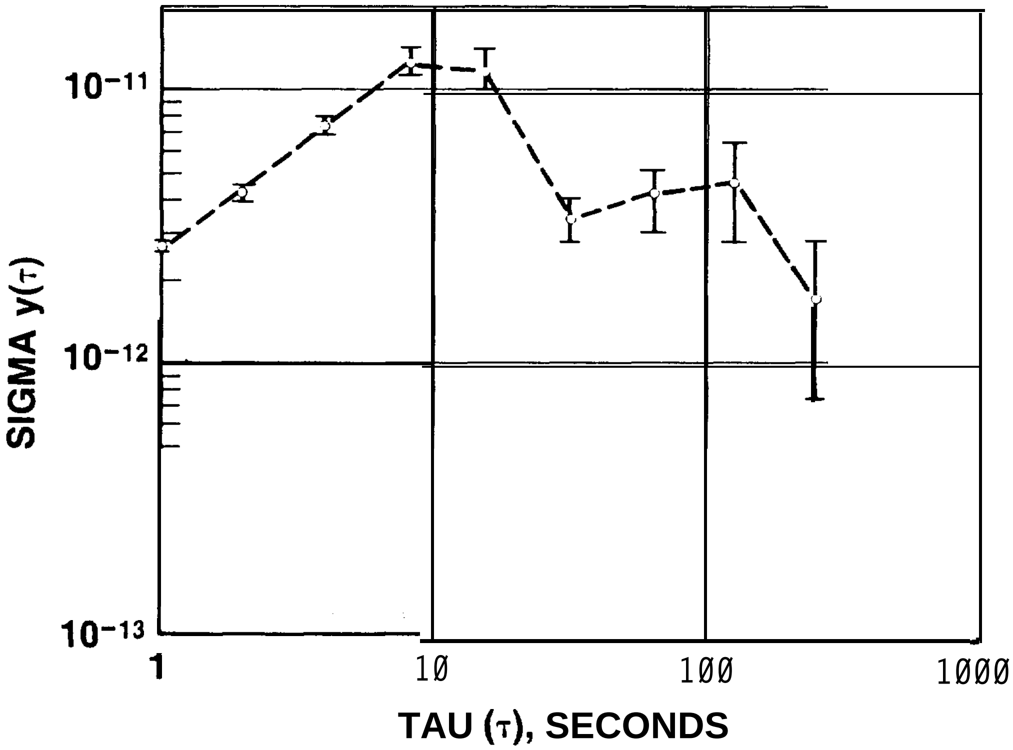


Figure 15. Allan Variance Plot (Crystal Mode)

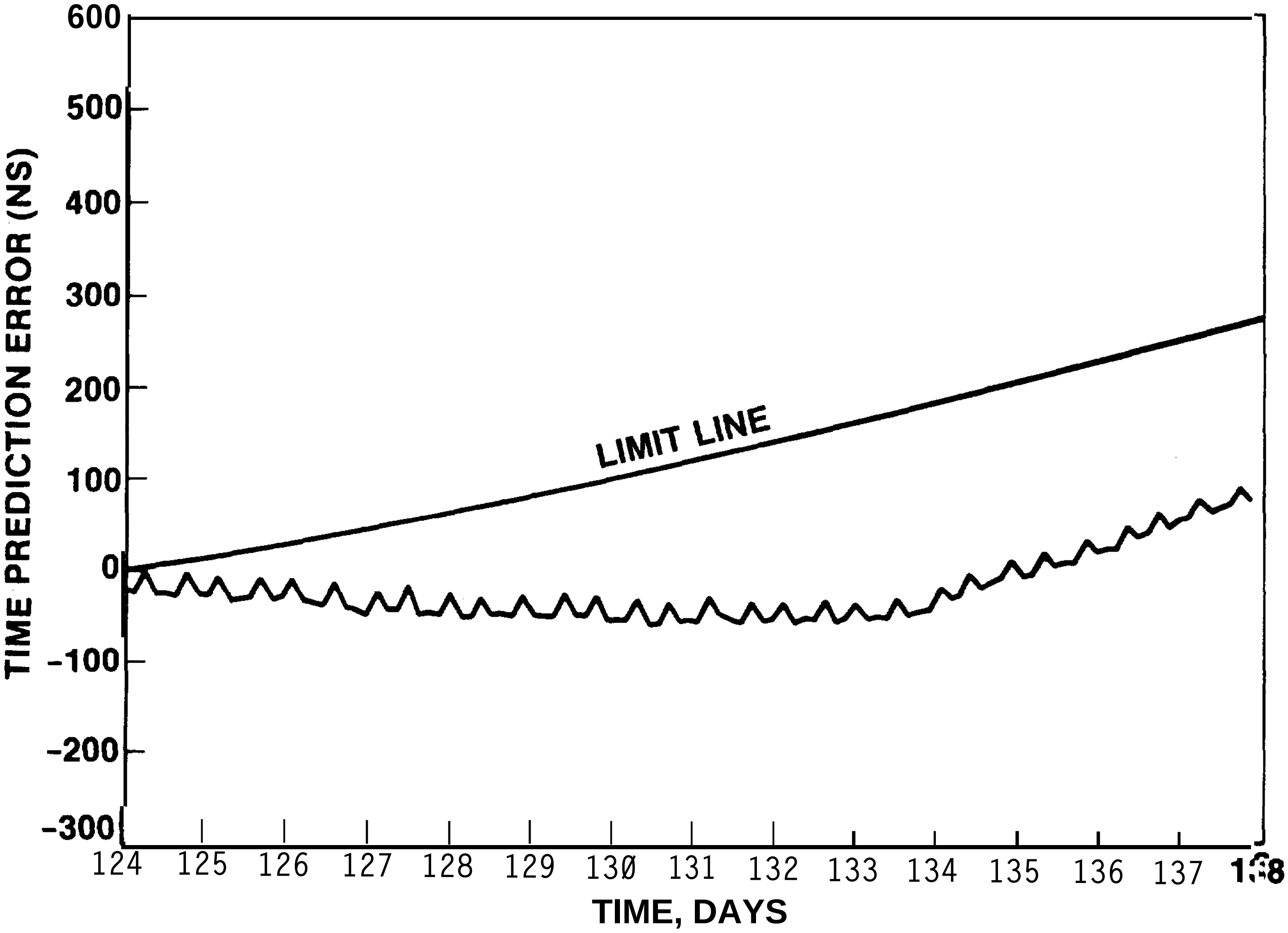


Figure 16. Representative 14 Day Time Error Segment

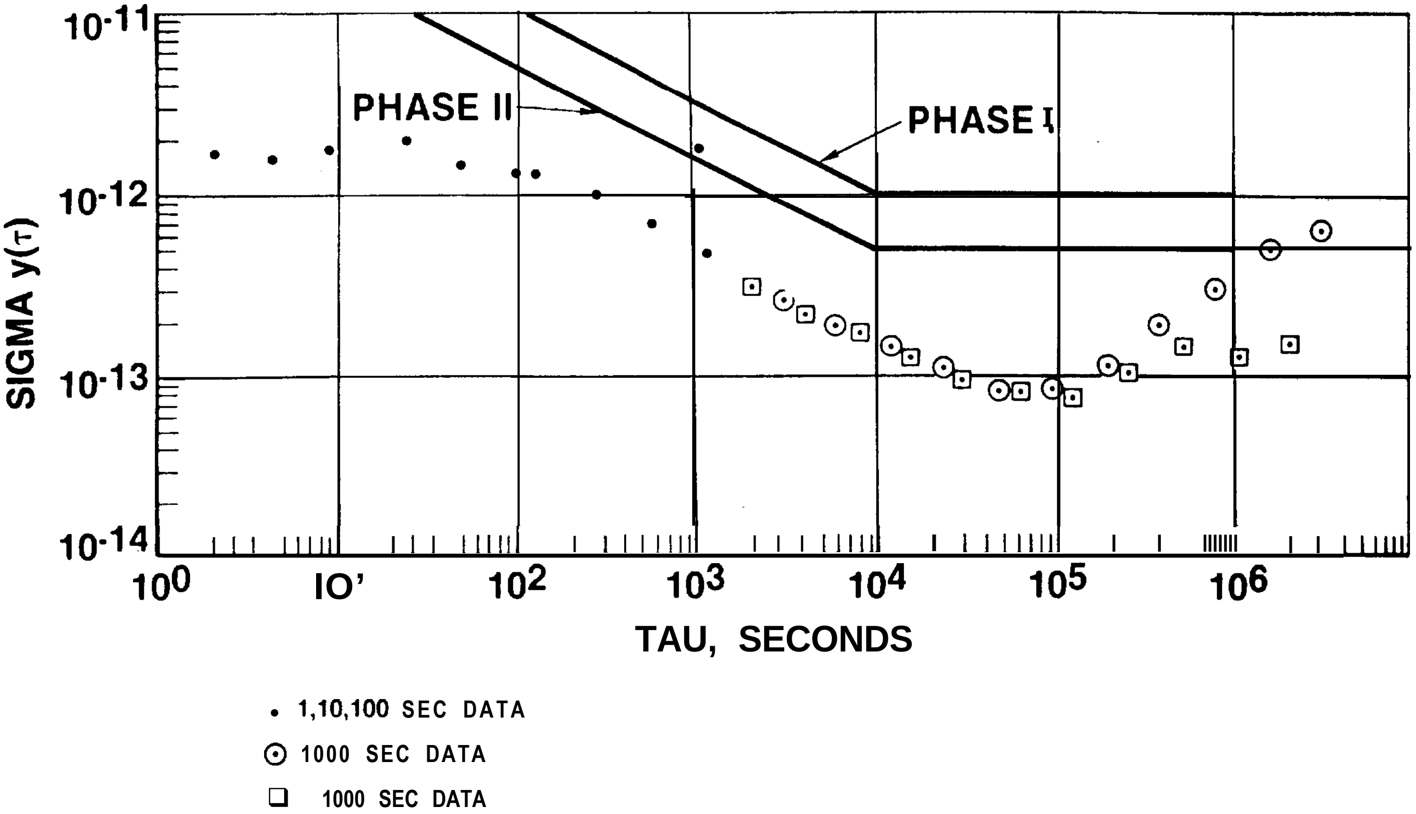


Figure 17. Allan Variance Life Test Plot

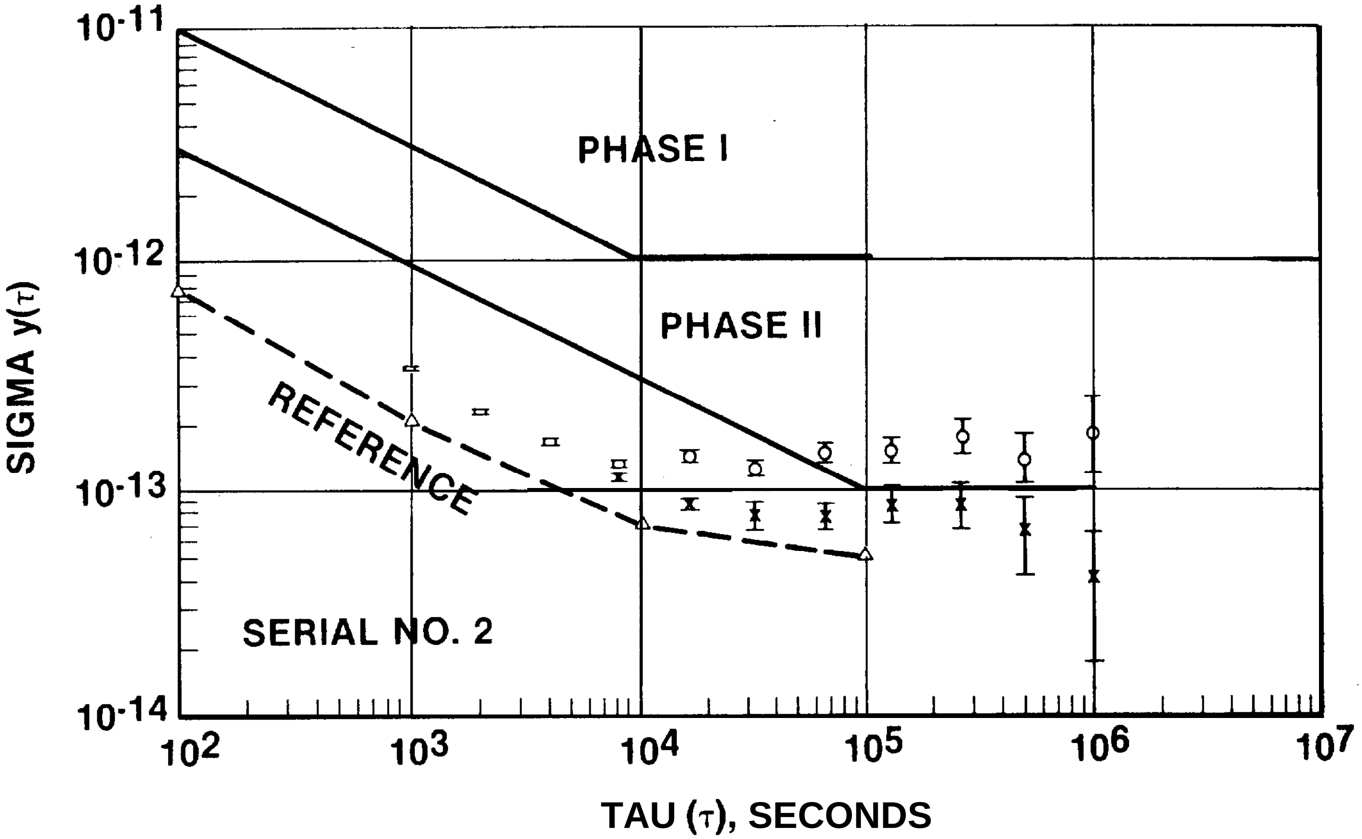


Figure 18. 100-Day Allan Variance Life Test Plot

ABSTRACT

"How & When to Perform Allan Variance Calculation or Phase Noise Measurements"

David Allan, National Bureau of Standards, Boulder, Colorado.

Managers are often required to make key program decisions based on the performance of some elements of a large system. This paper is intended to assist the manager in this important task in so far as it relates to the proper use of precise and accurate clocks. An intuitive approach will be used to show how a clock's stability is measured, why it is measured the way it is, and why it is described the way it is. An intuitive explanation of the meaning of time domain and frequency domain measures as well as why they are used will also be given.

ABSTRACT

"Precision Frequency Sources - A Status Report"

Dr. Sam Stein, Ball Corp., Efratom Division, Boulder, Colorado

This paper reviews precision frequency sources which are commercially available from U.S. manufacturers, It covers temperature compensated and oven controlled quartz crystal oscillators and rubidium, cesium and hydrogen atomic oscillators. Part one provides an overview of each technology and summarizes the principles of operation and the strengths and weaknesses of each technique. Part two of the paper reviews the commercially available devices covering and performance characteristics with comparisons based on data and specifications published by several manufacturers, Part three identifies factors which limit the performance of today's precision frequency sources. Several research areas are discussed which may enable significant future improvements in commercial frequency sources.

ABSTRACT

"NBS Time and Frequency MAP Program"

David **Allan**, National Bureau of Standards, Boulder, Colorado

The National Bureau of Standards (NBS) established two new time and frequency services in 1983. They permit the user to obtain time and frequency traceable to the NBS with greater precision and less effort than previously possible. The new services are for users who require time transfer accuracies in the three nanosecond to one microsecond range or frequency calibration capability in the 1 part in 10^{11} to one part in 10^{14} range. This paper will describe the NBS Time and Frequency Measurement Assurance Program (MAP) utilizing the Loran -C or the Global Positioning System (GPS) to achieve the users accuracy requirements.

TIME TRANSFER AND CLOCK ANALYSIS
VIA THE GLOBAL POSITIONING SYSTEM (GPS)

O. Jay Oaks, Jr., James A. Buisson, and Mark J. Lister
Space Applications Branch
Space Systems & Technology Division
Naval Research Laboratory
Washington, DC 20375

ABSTRACT

A GPS time transfer receiver developed by the Naval Research Laboratory has been provided by the GPS Program Office to Rockwell International in Anaheim, California, to perform clock measurements and analysis. The receiver performs time measurements between GPS satellite clocks and a ground clock. The measurements are referenced to the GPS Master Clock and also to the Naval Observatory Master Clock (UTC(USNO MC)) using data transmitted by the satellites. Measurements were made over a period of a year using the laboratory cesium standard at Rockwell as the ground station clock. A phase plot was kept relative to the Naval Observatory UTC and stability analysis of the clock was performed using the data. The measurement results of the time comparison had an RMS less than 100 ns and the frequency stability as compared against the USNO ensemble was on the order of parts in 10^{13} over a one day period.

INTRODUCTION

In September of 1983 the Naval Research Laboratory (NRL) installed a Global Positioning System (GPS) Time Transfer Receiver in the Metrology Laboratory of Rockwell International in Anaheim, California. The GPS Program Office sponsored this effort to provide a means to reference time and frequency measurements to the U.S. Naval Observatory atomic time standard. The U.S. Naval Observatory maintains the time standard for the Department of Defense and civilian users through an ensemble of atomic cesium clocks [1]. Daily measurements are made of the difference between GPS time and U.S. Naval Observatory (USNO) Master Clock time. These measurements are used by the GPS Control Segment to provide GPS satellite users with a reference to the USNO atomic time standard, UTC (USNO MC).

Time transfer users of GPS perform time interval measurements between their local reference and any GPS satellite. The data transmitted in the satellite message contains information required for the user to reference the time measurements to GPS or to the U.S. Naval Observatory. Measurements are normally made on a daily basis for a period of weeks or months to establish a time history difference between the user and U.S. Naval Observatory. This data may be further analyzed to determine frequency stability characteristics. The GPS receiver used at Rockwell International, Anaheim (RIA) was designed and built by NRL and contains a frequency stability analysis program which was first developed at the National Bureau of Standards and later implemented into the NRL receiver.

THE NAVSTAR GLOBAL POSITIONING SYSTEM

NAVSTAR GPS is a tri-service Department of Defense (DOD) program. The first GPS satellite flown was the Navigation Technology Satellite (NTS-II) which was designed and built by NRL [2,3]. GPS provides the capability of very precise instantaneous navigation and transfer of time from any point on the earth. There are three primary segments of GPS, the Space Segment, the Control Segment, and the User Segment. The final operational Space Segment will consist of a constellation of 18 satellites, three in each of six orbital planes with an additional three on-orbit spares. The satellite orbits are nearly circular at an altitude of 10,890 nautical miles and inclined 55° to the equator. The period is one half of a sideral day, resulting in a constant ground track, but with the satellite appearing 4 minutes earlier each day.

The control segment consists of a master control station (MCS) and monitor stations (MS) placed at various locations around the world [4]. The current MCS is located at Vandenberg Air Force Base with the support monitor tracking stations at Alaska, Guam, Hawaii, and Vandenberg, California. The monitor stations collect data from each satellite and transmit to the MCS. The data is processed to determine the orbital characteristics of each satellite and the trajectory information is then uploaded to each satellite, once every 24 hours as the spacecraft passes over the MCS.

The user segment consists of a variety of platforms containing GPS receivers, which track the satellite signals and process the data to determine position and/or time. Navigation is performed by simultaneous or sequential reception of at least four satellites, and time transfer is performed by reception of a single satellite. Coverage of the final GPS constellation is such that at least four satellites will always be in view from any point on the earth's surface.

Each GPS satellite transmits on two L-band frequencies, L1 at 1575.42 MHz and L2 at 1227.6 MHz [5]. The ground receiving system described here uses only the L1 frequency. The second frequency is transmitted for users to measure and correct for the ionospheric delay. Single frequency users may use an ionospheric correction model for which parameters are transmitted in the satellite navigation message. The L1 frequency consists of two carrier components in phase quadrature with each other. One component is biphase modulated with a 1.023 Megabit/sec (Mbps) coarse/acquistion (C/A) pseudorandom noise (PRN) code and the other is biphase modulated with a 10.23 Mbps precise (P) code. The C/A code repeats every millisecond allowing quick acquisition, and the P code is a long code sequence which is truncated to repeat every 7 days but whose higher rate allows more precision, primarily for military users. Each satellite transmits on the same L1 and L2 frequencies, but each has a unique C/A and P code which provides discrimination between satellites. Each L1 carrier component is also biphase modulated with 50 bit/sec (bps) data which contains the navigation message. The final modulated L1 frequency is of the form:

$$2A\, G_i(t)\, D_i(t) \cos\omega_{L1} t + A\, P_i(t)\, D_i(t) \sin\omega_{L1} t$$

where A is the amplitude, $G_i(t)$ is the C/A code sequence, $P_i(t)$ is the P code sequence, $D_i(t)$ is the data 'sequence, and ω_{L1} is the carrier frequency. The C/A code component is 3db higher in amplitude than the P code component. The NRL designed GPS time transfer receiver uses only the C/A code component of the L1 signal [6]. All modulating and carrier signals are derived from the onboard spacecraft atomic reference oscillator.

The general format of the 50 bps data is shown in Fig. 1. The navigation message is transmitted in five subframes [7]. Each subframe lasts six seconds and contains 300 bits of information. The primary information is contained in subframes 1,2, and 3 and requires a maximum of 30 seconds to receive after locking onto the data. Secondary information is contained in subframes 4 and 5 which commutate 25 different subframes of information each. Twelve and one half minutes may be required to receive the desired information in these subframes. Subframe 1 contains the information required for the user to compute the SV clock offset from GPS time. Subframes 2 and 3 contain the necessary information to compute the SV position. For time transfer, it is assumed that the user position is known, and along with the computed SV position, the range delay of the signal from the satellite can be determined. Subframe 4 contains the ionospheric correction model parameters and the USN0 MC time offset from GPS parameters. Subframe 5 contains a shortened version of the SV ephemeris and a health summary for each satellite in the GPS constellation. This data is referred to as the almanac and is used to compute satellite visibilities, satellite search frequency offsets due to doppler shift, and satellite tracking priorities according to satellite health and geometry with respect to the user.

GPS TIME TRANSFER

Each of the GPS satellites transmits signals that are derived from atomic standards. The NRL designed receiver determines time from the GPS satellite signals in the following manner. The six second repeating subframes in conjunction with the one millisecond repeating C/A code is viewed as a clock signal. The C/A code is tracked to a fraction (3%) of a one microsecond chip width, deriving a 1 kilopulse/sec (kpps) clock which counts time in milliseconds. The 1 kpps is divided by 1000 in a milliseconds counter to provide a satellite 1 pps. The milliseconds counter is synchronized to the proper count by using the epoch of the six second subframe. A time interval measurement is made between the satellite clock 1 pps and the station clock 1 pps to get a measured t. This basic measurement is refered to as pseudorange and must be corrected to obtain the actual difference between the ground clock and the satellite clock. These corrections are described later. First, consider the link of the satellite clock to GPS time and UTC (USNO MC) time.

The GPS Monitor Stations make measurements from each satellite and transmit them by ground link to the GPS Master Control Station. These measurements are used to determine the orbit of each satellite and the difference of each satellite clock from the GPS master clock. The U.S. Naval Observatory makes measurements from the GPS satellites and determines the difference between GPS time and UTC (USN0 MC) time. This difference is transmitted to the GPS Master Control Station. The Master Control Station models each satellite clock difference from GPS time with a second degree polynomial, and models the difference between GPS time and UTC (USNO MC) time with a first degree polynomial. The coefficients of these polynomials are uploaded into each respective satellite along with the ephemeris of the satellite. The satellites transmit this information to the user in the navigation message t-71.

The measured offset between the ground clock and the satellite clock is determined by correcting the pseudorange measurement (Δt (pseudorange)) for signal path propagation delay (Δt (range)), ionospheric and troposheric delay (Δt(iono+tropo)) and the propagation delay in the receiver itself (Δt (receiver)). The path delay is determined by computing the position of the satellite relative to the receiving station using the ephemeris transmitted in the navigation message. The ionospheric and tropospheric delays are computed from models, and the receiver delay is used as calibrated and provided with each unit. The satellite clock difference is then calculated as:

$$\text{At (user-SV)} = \Delta t\ \text{(pseudorange)} - \Delta t\ \text{(range)} - \text{At}\ \text{(iono+tropo)} - \Delta t\ \text{(receiver)}$$

The time relative to UTC (USNO MC) is then determined by first computing the satellite clock offset from GPS time (Δt (SV-GPS)) using the second degree polynomial coefficients and the offset of GPS time from UTC (USNO MC), (Δt (USNO-GPS)), using the first degree polynomial coefficients which are transmitted in the navigation message. The user clock offset from UTC (USNO MC) is then computed as:

$$\Delta t\ (\text{USER-USNO}) = \Delta t\ (\text{USER-SV}) + \Delta t\ (\text{SV-GPS}) - \Delta t\ (\text{USNO-GPS})$$

This final value is referred to as the predicted offset from UTC (USNO MC) because the Δt (USNO-GPS) term is predicted from a first degree polynomial. A more accurate value is referred to as the observed offset where Δt (USNO-GPS) is obtained from actual USNO measured values. When possible the user makes measurements simultaneously with USNO from the same satellite having common view to both ground sites. The user offset from UTC (USNO MC) is computed for the time of the measurement minimizing the errors caused by GPS predictions.

GPS TIME TRANSFER RECEIVER

The NRL built GPS time transfer receiver is a microcomputer based system which tracks GPS satellites on the single L-band frequency of 1575.42 MHz. The receiver uses only the C/A code of 1.023 MHz and tracks this code to within 3% of a chip (30 nsec). Any GPS satellite can be tracked by the operator providing the appropriate satellite code identification to the receiver. The receiver uses an omni-directional antenna and the bandwidth is sufficient that any satellite may be tracked from horizon to horizon without operator assistance. Figure 2 is a general block diagram of the receiver.- The receiver consists of-an RF subsystem, C/A code generator, time interval measurement unit', and a microprocessor with associated interfacing equipment.

The RF subsystem provides preamplification, down conversion, and baseband processing for the GPS signal. Figure 3 shows the primary functions of the RF subsystem. The GPS signal from the antenna is first preamplified, downconverted to an intermediate frequency (~100 MHz), and then downconverted to a baseband frequency (~20 MHz). Two phase lock processes are implemented at baseband. A delay lock loop provides code correlation for the spread spectrum signal and a doubling loop is used to phase lock to the carrier after code correlation is achieved. The code loop provides a satellite clock signal and the carrier loop provides the data which contains the navigation message.

In order to implement the delay lock loop, a half-bit early and a half-bit late replica of the C/A code are required for code lock. To get data from the carrier loop the on-time code is required. Figure 4 is a block diagram of the C/A code generator. The 1023 bit code for a satellite of interest is loaded into a 1023 x 1 bit random access memory (RAM) by the microprocessor. The microprocessor implements a linear feedback shift register algorithm to determine the code pattern for a particular satellite. The code VCXO frequency is divided by 20 to get the code chip rate of 1.023 MHz. The 1.023 MHz signal clocks a divide-by-1023 counter which is used to address the code RAM. The output of the RAM is the C/A code at the 1.023 MHz chip rate with a 1 msec period. The code is clocked into a shift register at twice the chip rate (2.046 MHz), and the proper phases of the half-bit early, half-bit late, and on-time codes are obtained on consecutive shift register bit outputs.

The time interval measurement unit, shown in Fig. 5, is used to measure pseudorange, calibrate the receiver internal 1 pps delay, and measure the code and carrier VCXO frequencies for tuning purposes. A 24 bit binary counter is provided with a gated 62.5 MHz clock which is synthesized from the reference 5 MHz and has a duration equal to the start to stop interval of the selected measurements. The frequency of 62.5 MHz was chosen for convenience because of the 16 nsec period which makes the measurement data output of the 24-bit counter a binary integer of nanoseconds times four.

The microprocessor subsystem provides receiver control functions such as tuning, C/A code generation, and time interval measurement control as well as operator interface functions. It performs data processing to determine the time transfer answers and stores the results on a floppy disc. The operator interface is a keyboard and CRT display. The receiver state and status are displayed on the CRT as well as the data from a satellite being tracked. Two types of data files are stored on the floppy disc. 4 complete data file contains all measurements made during a single satellite track taken at six second intervals, and a summary file contains a single average value of time transfer from each of many satellite tracks with statistics obtained from a linear fit to the individual data points. These summary values are used to plot the time offsets which are presented later.

The NRL time transfer system contains a frequency stability analysis program which provides the user with a means of performing on site analysis of the ground station clock. This program utilizes the GPS time transfer data obtained by the receiver and recorded in the summary file on the system's floppy disc. The program calculates daily time transfer estimates of the difference between the ground clock and GPS time valid at 1800 UT, and performs a frequency stability analysis of the clock. The frequency stability analysis program, usually executed on a weekly basis, may be used as often as necessary. The program is capable of maintaining a maximum of 400 data points after which the newest data replaces the oldest data.

A more rigorous data analysis may be performed by further processing of the time transfer data, contained in the receiver summary files. The data obtained at the Rockwell ground station (RIA) was transfered to a PDP-11/70 computer at NRL. The predicted time transfer between the RIA clock and UTC (USNO MC) was plotted and the linear and quadratic residuals analyzed by fitting a first and second degree polynomial to the data. More accurate results were obtained by using the observed data (RIA-GPS) also recorded in the receiver summary files. This observed data from the summary file was mathematically combined with the USNO-GPS time transfer results which are published on a daily basis by the U.S. Naval Observatory. The resulting time transfer of RIA-USNO was then analyzed via the same methods as the predicted data.

GPS TIME TRANSFER RESULTS

In September, 1983 the NRL GPS time transfer system was deployed at Rockwell International's Anaheim (RIA) site. Since that time the receiver has been gathering time transfer data by tracking each active GPS satellite once a day for a ten minute period, which yields enough data points to be statistically meaningful. Upon completion of a pass the time transfer results in the summary file, (RIA-USNO) and (RIA-GPS), are used in conjunction with USNO's published results, (USNO-GPS), to plot the predicted and observed data.

These predicted and observed time transfers are shown plotted in Figs. 6 and 7. In these figures each point represents the resultant time transfer of one satellite pass. Each plot shows a statistical summary containing the epoch and data span in Modified Julian Day (MJD), the filter tolerance in microseconds, the number of points filtered, the RMS in microseconds, the phase at the epoch time in microseconds, and the frequency in PP10(12). The filter tolerance is set to a large value (10 microseconds1 so that all data points are used.

The predicted time transfer between UTC (USNO MC) and RIA (Fig. 6) contains several discontinuities. These discontinuities occur when the prediction of GPS time relative to the UTC (USNO MC), computed from a first degree polynomial whose coefficients are transmitted in the navigation message, is not accurate. The inaccuracy may occur for two reasons. The UTC (USNO MC) prediction parameters are updated weekly by the GPS control segment. The measurements, made by USN0 and provided to the GPS control segment, are performed daily, however the weekly update by the control segment has been sufficient for the current GPS specification of maintaining GPS time relative to USN0 time to within 100 ns. Also, since the prediction parameters are updated only weekly, the receiver operation currently used reads these parameters daily during a special track. If for some reason this track is not performed, then the receiver uses the parameters obtained from the last special track. Conceivably, parameters that are a week or more old could cause large errors. It is these discontinuites that lead to the high RMS in the plot of Fig. 6. This RMS value is reduced by using the observed data (Fig. 7) which contains no discontinuities. While the RMS of the observed data, 90 nanoseconds, is significantly lower than that of the predicted data, it should be noted from Figs. 6 and 7 that the phase values calculated for the same epoch (day) agree to within four nanoseconds with a frequency agreement of 6 PP10(15).

The frequency offset between UTC (USNO MC) and the RIA clock was removed from the observed data of Fig. 7 and the resultant graph is shown in Fig. 8. This allows the scatter of the data to be examined with finer resolution.

Figure 9 shows the quadratic residuals resulting from removing both the frequency offset and aging offset between UTC (USNO MC) and the RI.4 clock from the observed data of Fig. 7. Note, in the statistical summary table, that the aging term is equal to zero. This is the expected result when the clock under analysis is a cesium beam atomic standard as is the case at RIA.

The frequency stability analysis program uses the time transfer data gathered by the NRL receiver to calculate daily time estimates at 1800 UT. These time transfers of RIA-USNO, valid at 1800 UT, are presented in Fig. 10. The frequency stability (sigma-tau) is then calculated for the clock driving the GPS receiver. These results are shown in Fig. 11.

The results of this operational data provided useful information in evaluating the GPS as a means of performing frequency stability and atomic clock analysis. The GPS time transfer data can be collected on a routine basis with minimum operator intervention. The time transfer data immediately available is useful to determine when a clock has failed and also can provide a good estimate of clock stability. The data, which is stored on floppy discs, can be transfered to a larger mainframe computer for more sophisticated analysis when necessary.

REFERENCES:

1. Klepcznski, W.J., and Hall, R.G., "Time Service," Naval Research Reviews, pp. 28-36, October 1976.
2. Easton, R.L., Buisson, J.A., and McCaskill, T.B., "Initial Results of the NAVSTAR GPS NTS-2 Satellite," NRL Report 8232, May 1978.
3. Easton, R.L., Buisson, J.A., McCaskill, T.B., Oaks, O.J., Stebbins, S., and Jeffries, M., "The Contribution of Navigation Technology Satellites to the Global Positioning System," NRL Report 8360, Dec. 1979.
4. Russell, S.S., and Schaibly, J.H., "Control Segment and User Performance," Journal of the Institute of Navigation, Vol. 25, No. 2, Summer 1978.
5. Spilker, Jr., J.J., "GPS Signal Structure and Performance Characteristics," Journal of the Institute of Navigation, Vol. 25, No. 2, Summer 1978.
6. Oaks, O.J., Frank, A., Falvey, S. Lister, M., Buisson, J., Wardrip, S., and Warren, H., "Prototype Design and Initial Test Evalutation of a GPS Time Transfer Receiver," NRL Report 8608, July 27, 1982.
7. Van Dierendonck, A.J., Russell, S.S., Kopitake, E.R., and Birnbaum, M., "The GPS Navigation Message," Journal of the Institute of Navigation, Vol. 25, No. 2, Sumner 1978.

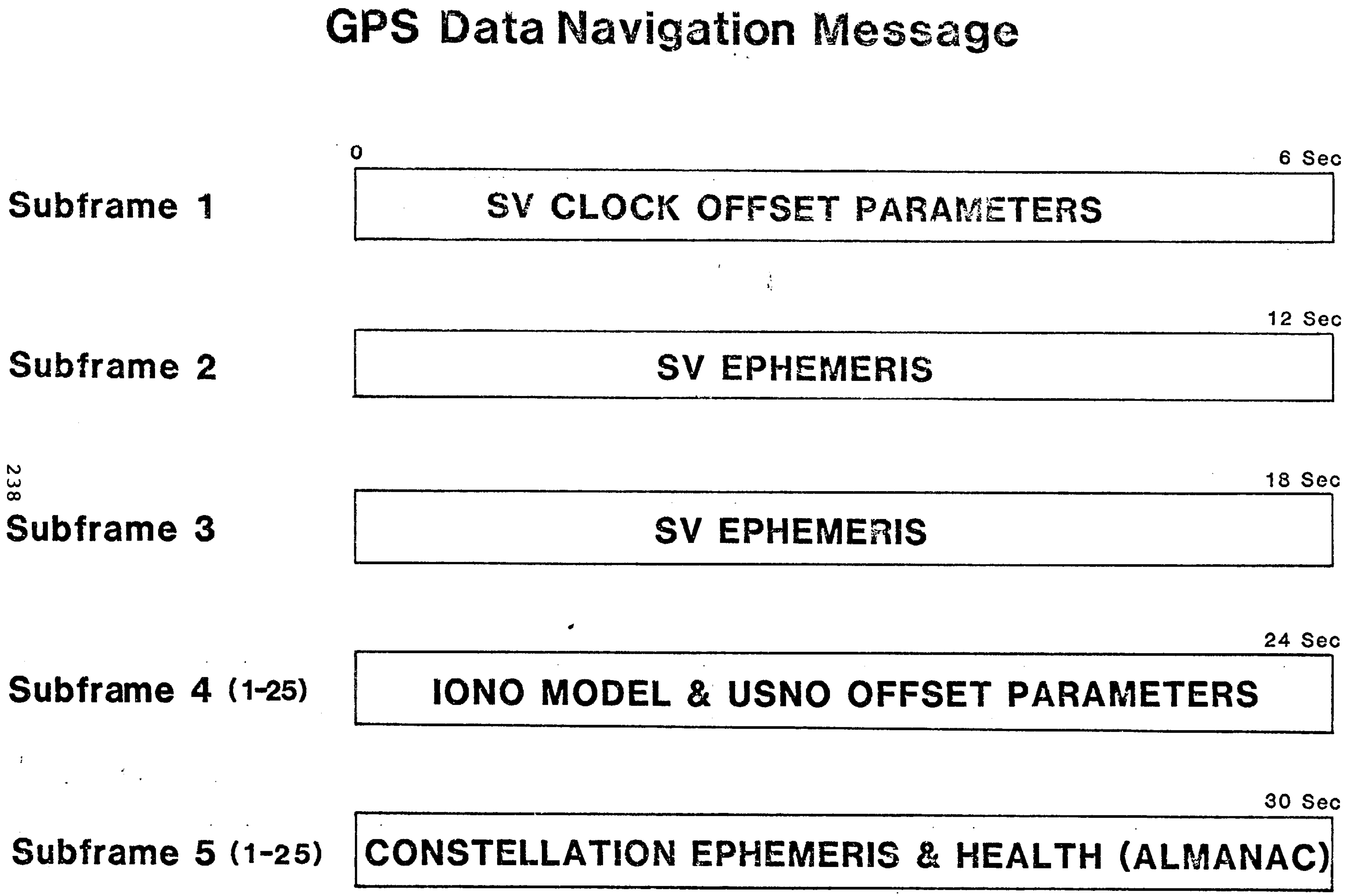

GPS Data Navigation Message
0
6 Sec
Subframe 1
SV CLOCK OFFSET PARAMETERS
12 Sec
Subframe 2
SV EPHEMERIS
18 Sec
Subframe 3
SV EPHEMERIS
24 Sec
Subframe 4 (1-25)
IONO MODEL & USNO OFFSET PARAMETERS
30 Sec
Subframe 5 (1-25)
CONSTELLATION EPHEMERIS & HEALTH (ALMANAC)

Figure 1

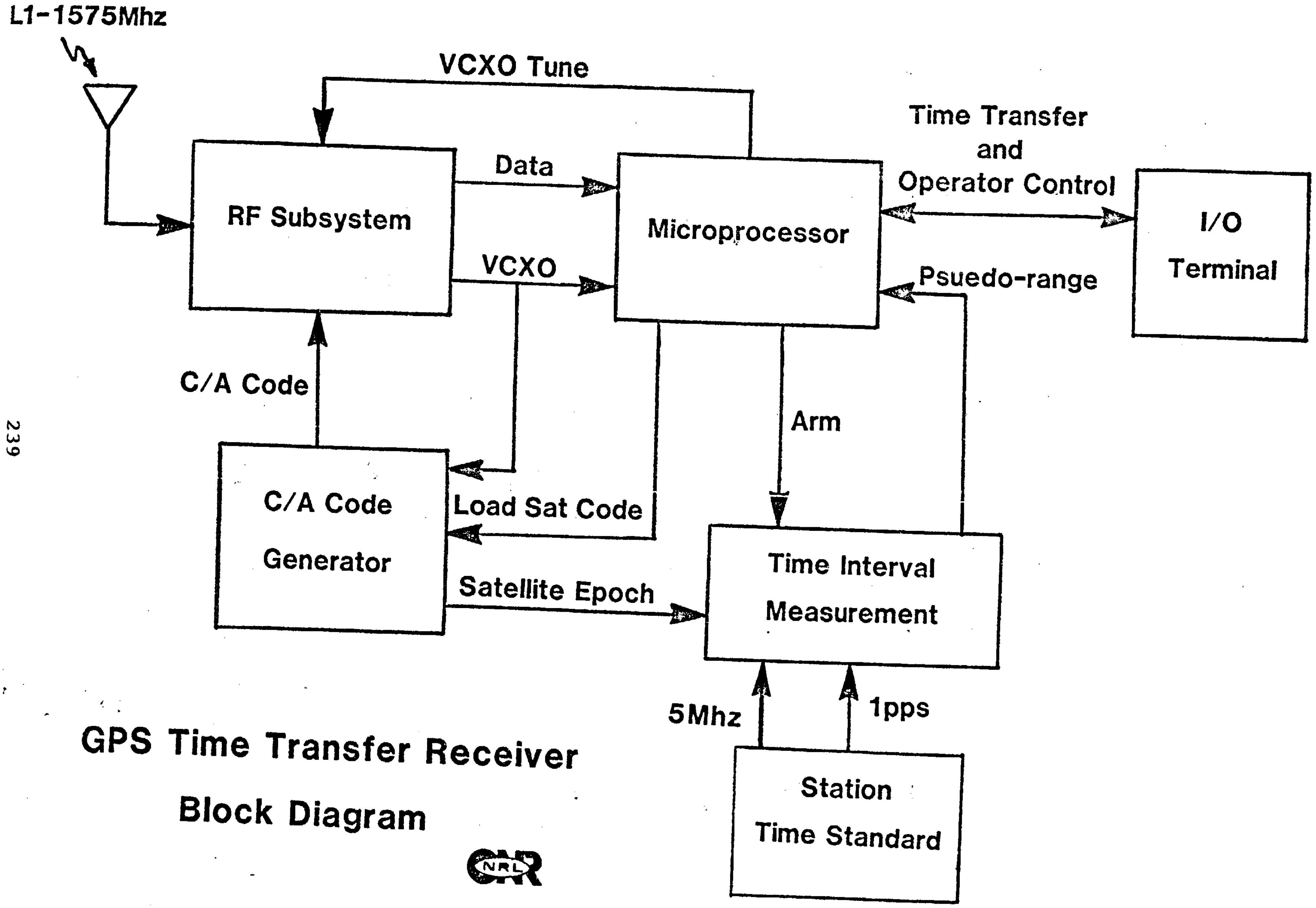

L1-1575Mhz
VCXO Tune
RF Subsystem
Data
VCXO
Microprocessor
Time Transfer and Operator Control
I/O Terminal
Psuedo-range
C/A Code
Arm
C/A Code Generator
Load Sat Code
Satellite Epoch
Time Interval Measurement
5Mhz
1pps
Station Time Standard
GPS Time Transfer Receiver Block Diagram
NRL

Figure 2

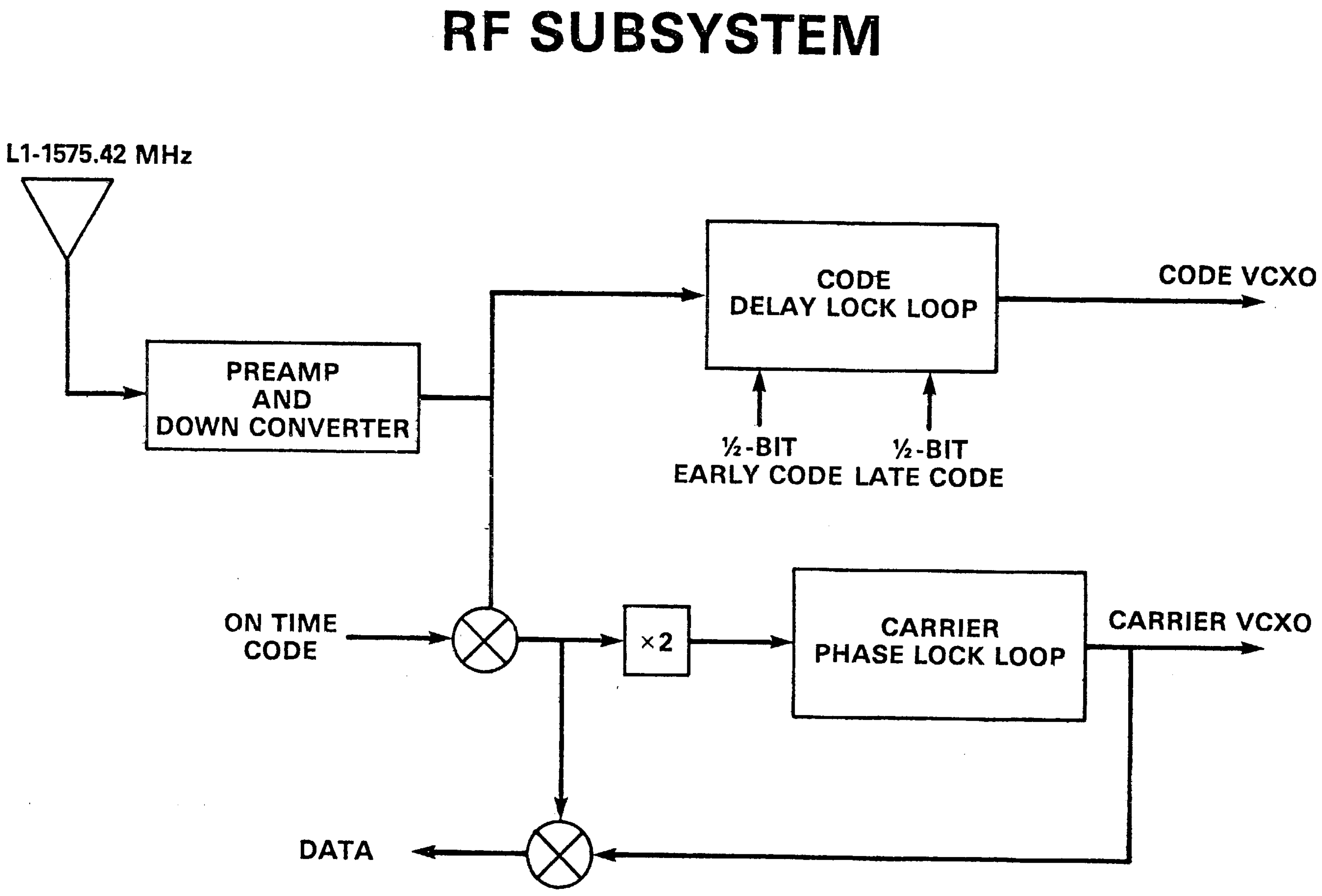

RF SUBSYSTEM
L1-1575.42 MHz
PREAMP AND DOWN CONVERTER
CODE DELAY LOCK LOOP
CODE VCXO
½-BIT EARLY CODE
½-BIT LATE CODE
ON TIME CODE
×2
CARRIER PHASE LOCK LOOP
CARRIER VCXO
DATA

Figure 3

C/A CODE GENERATOR

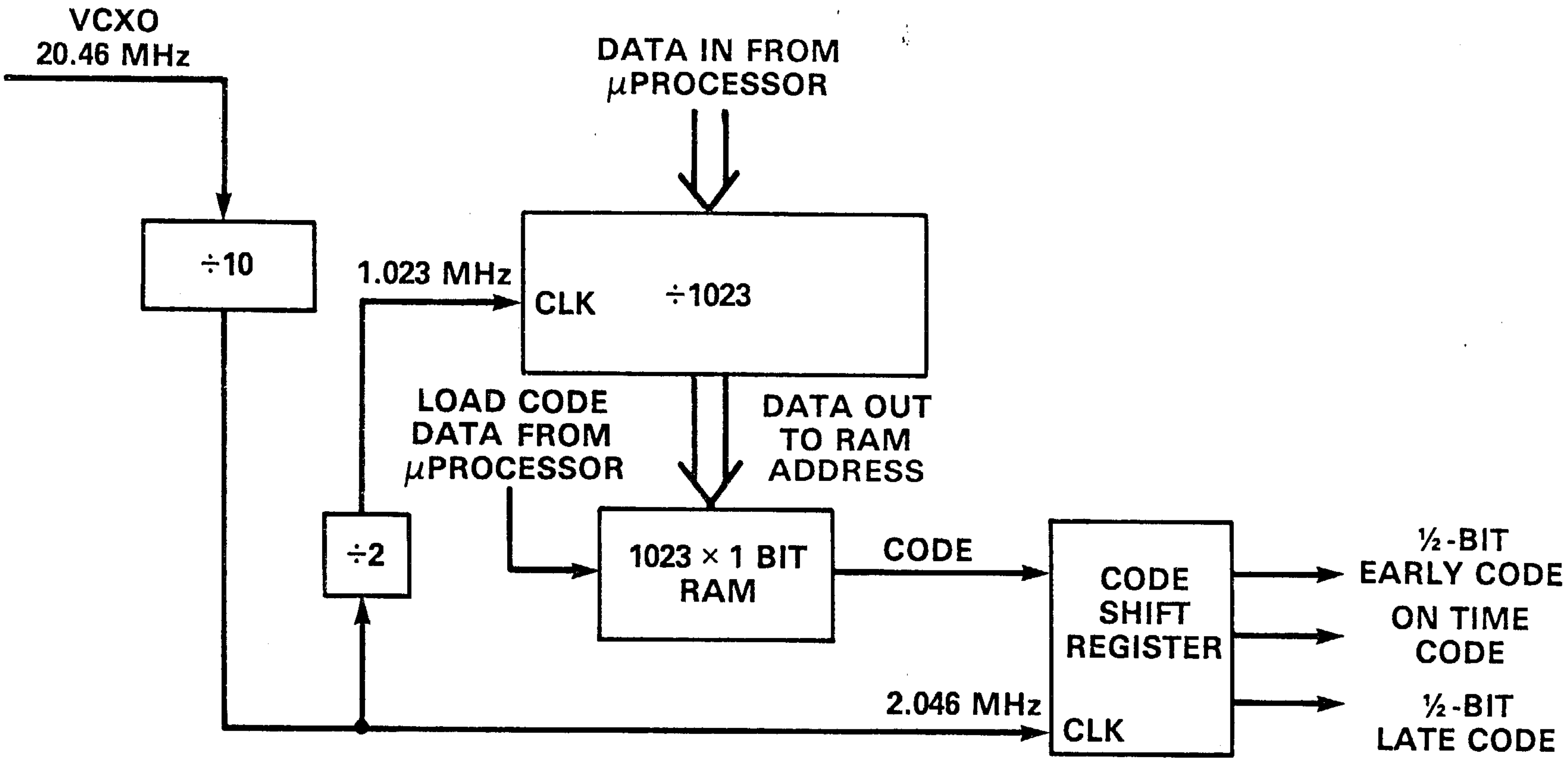
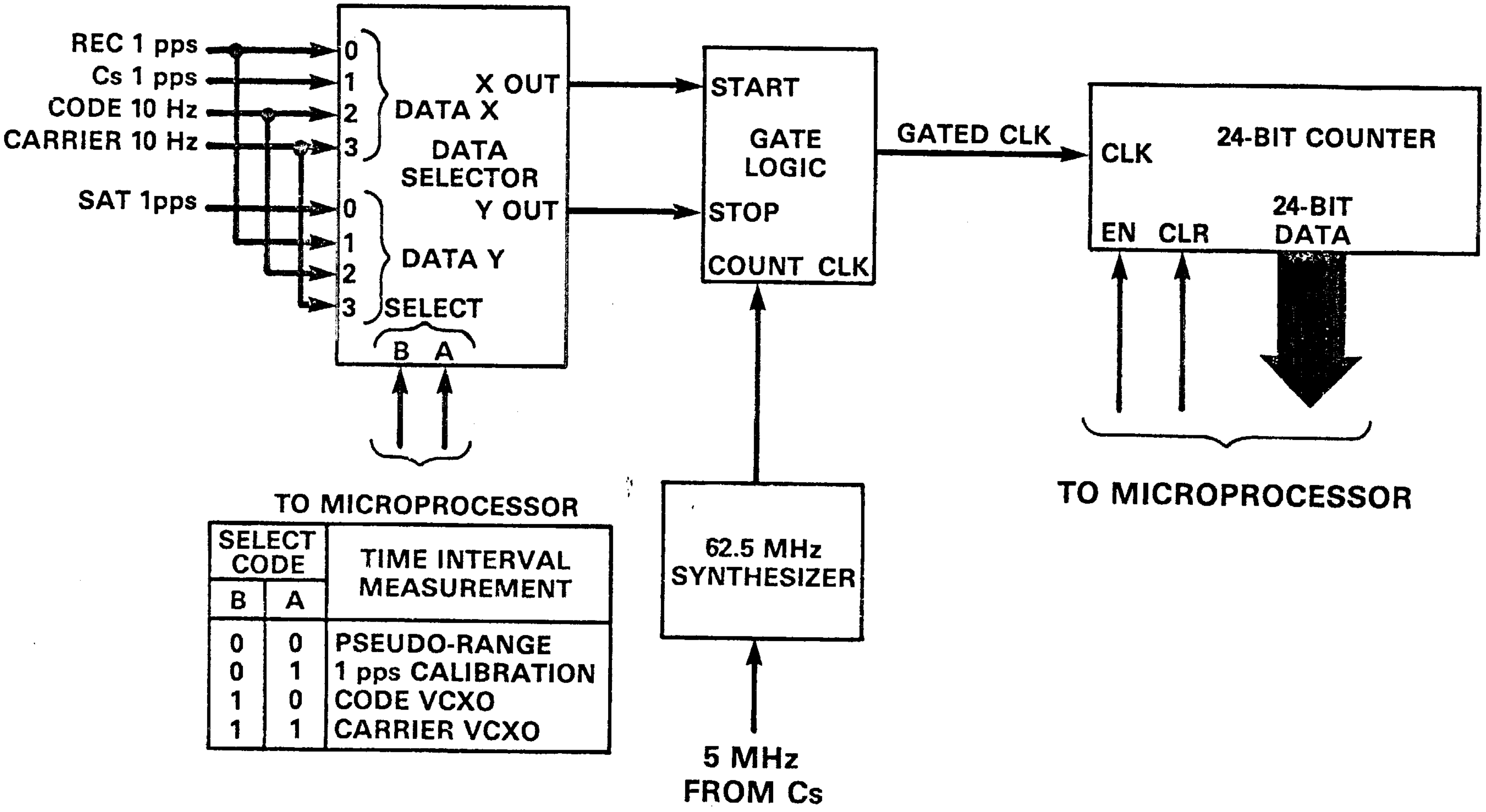


Figure 4

TIME INTERVAL MEASUREMENT



SELECT CODE		TIME INTERVAL MEASUREMENT
B	A	
0	0	PSEUDO-RANGE
0	1	1 pps CALIBRATION
1	0	CODE VCXO
1	1	CARRIER VCXO

Figure 5

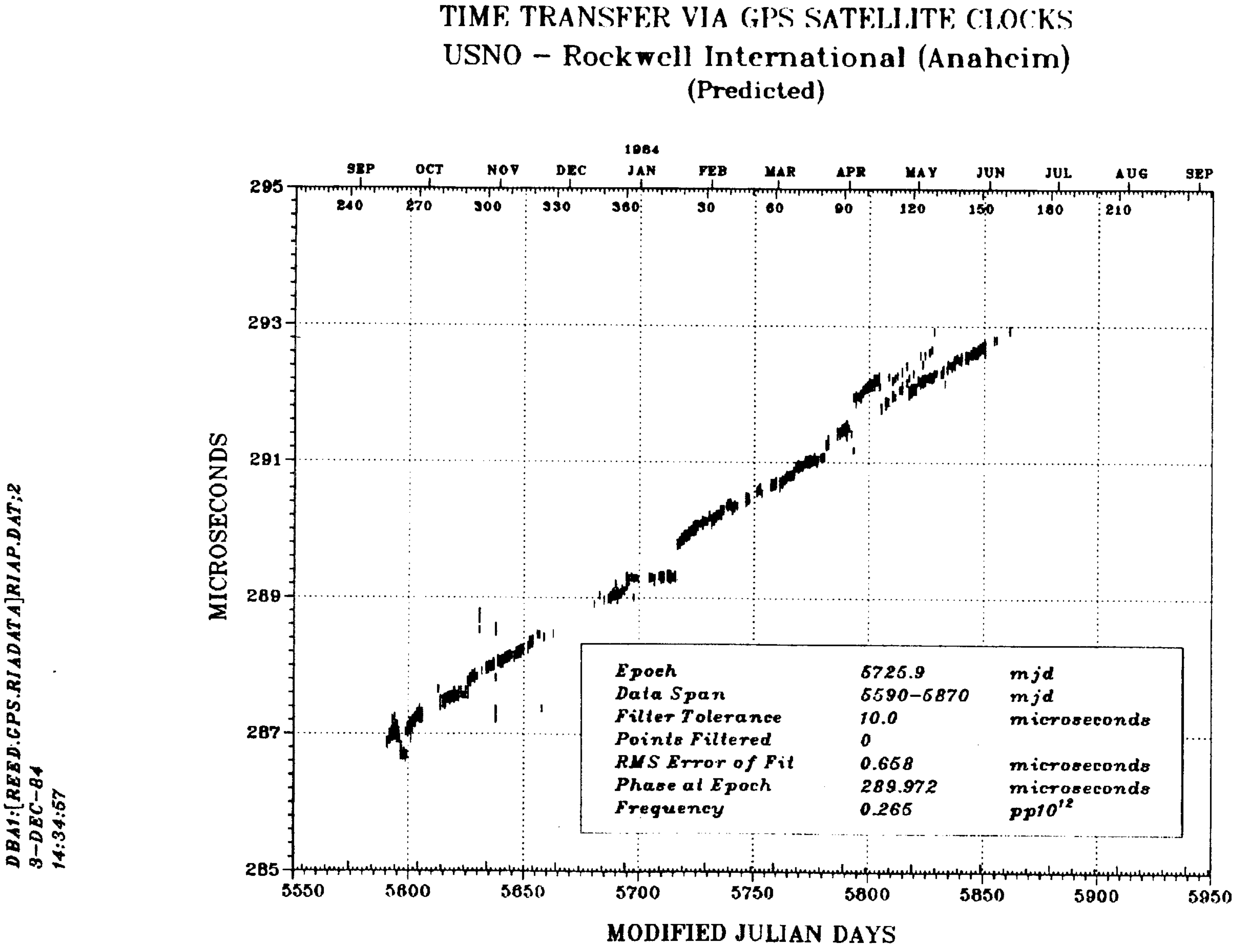

TIME TRANSFER VIA GPS SATELLITE CLOCKS
USNO – Rockwell International (Anaheim)
(Predicted)
1984
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
240
270
300
330
360
30
60
90
120
150
180
210
295
293
291
289
287
285
MICROSECONDS
5550
5600
5650
5700
5750
5800
5850
5900
5950
MODIFIED JULIAN DAYS
Epoch 5725.9 mjd
Data Span 5590-5870 mjd
Filter Tolerance 10.0 microseconds
Points Filtered 0
RMS Error of Fit 0.668 microseconds
Phase at Epoch 289.972 microseconds
Frequency 0.265 pp10^12
DBA1:[REED.GPS.RIADATA]RIAP.DAT;2
3-DEC-84
14:34:57

Figure 6

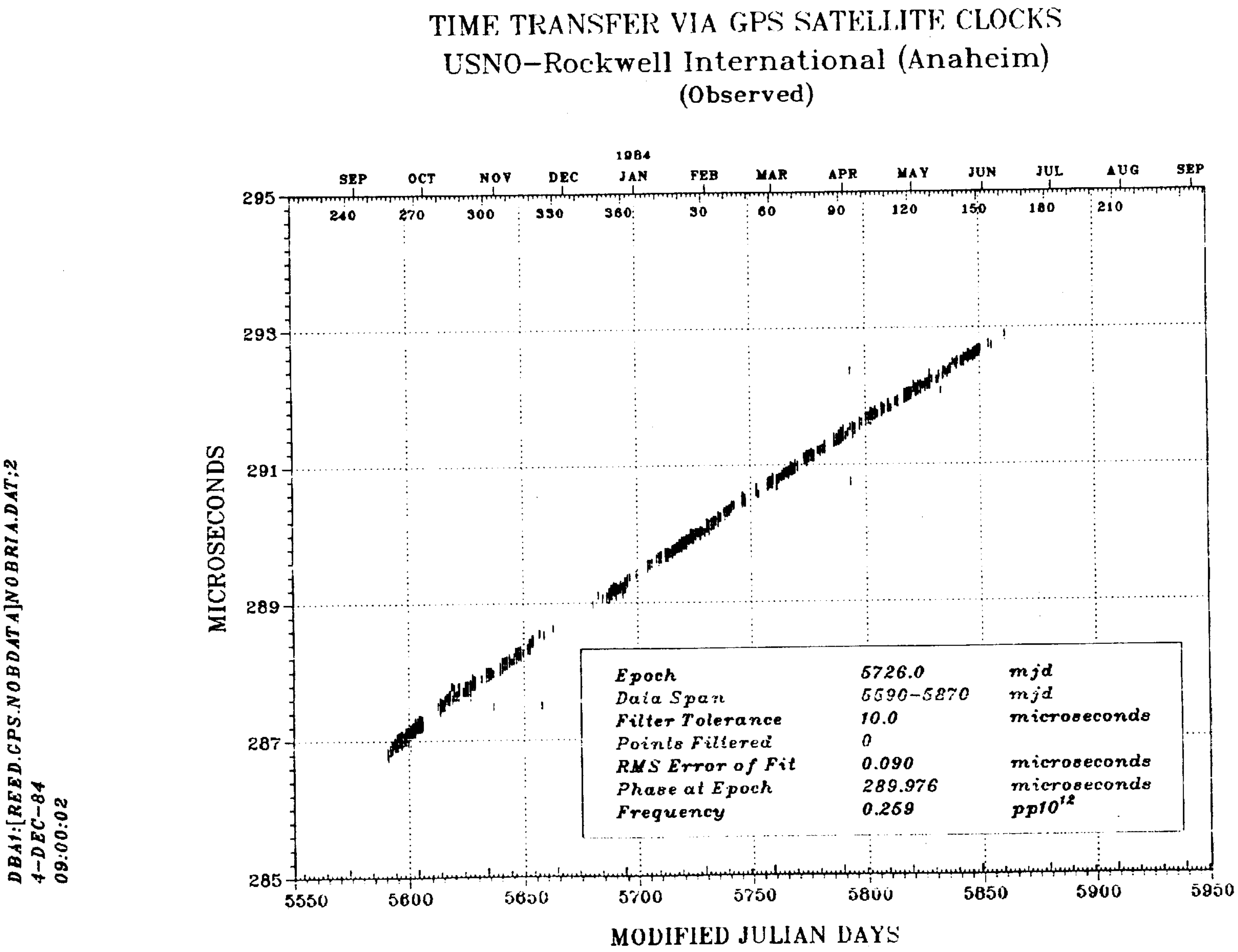

TIME TRANSFER VIA GPS SATELLITE CLOCKS
USNO–Rockwell International (Anaheim)
(Observed)
1984
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
240
270
300
330
360
30
60
90
120
150
180
210
295
293
291
289
287
285
MICROSECONDS
5550
5600
5650
5700
5750
5800
5850
5900
5950
MODIFIED JULIAN DAYS
Epoch 5726.0 mjd
Data Span 5590–5870 mjd
Filter Tolerance 10.0 microseconds
Points Filtered 0
RMS Error of Fit 0.090 microseconds
Phase at Epoch 289.976 microseconds
Frequency 0.259 pp10^12
DBA1:[REED.GPS.NOBDATA]NOBRIA.DAT:2
4-DEC-84
09:00:02

Figure 7

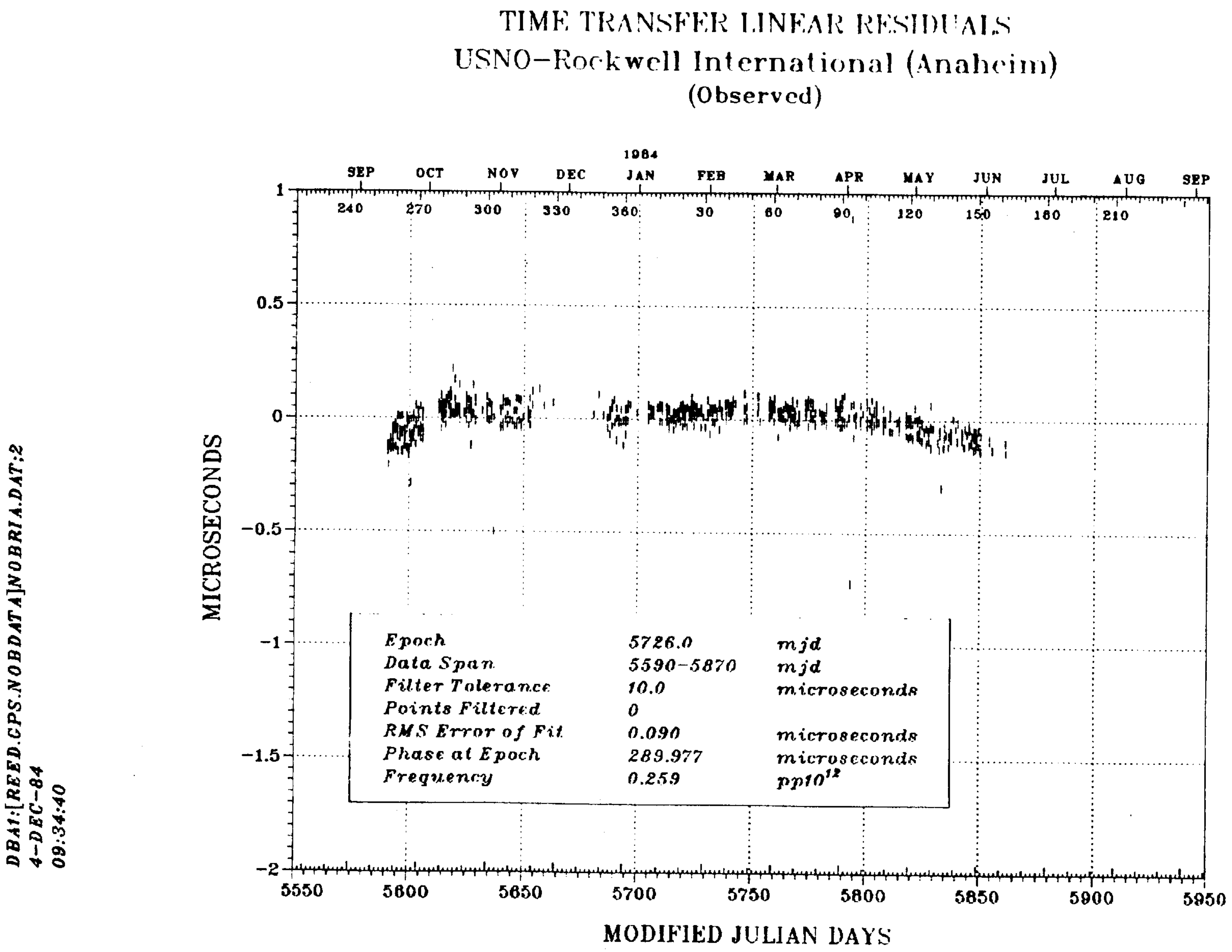

TIME TRANSFER LINEAR RESIDUALS
USNO–Rockwell International (Anaheim)
(Observed)
1984
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
240
270
300
330
360
30
60
90
120
150
180
210
1
0.5
0
−0.5
−1
−1.5
−2
MICROSECONDS
5550
5600
5650
5700
5750
5800
5850
5900
5950
MODIFIED JULIAN DAYS
Epoch 5726.0 mjd
Data Span 5590–5870 mjd
Filter Tolerance 10.0 microseconds
Points Filtered 0
RMS Error of Fit 0.090 microseconds
Phase at Epoch 289.977 microseconds
Frequency 0.259 pp10^12
DBA1:[REED.GPS.NOBDATA]NOBRIA.DAT;2
4-DEC-84
09:34:40

Figure 8

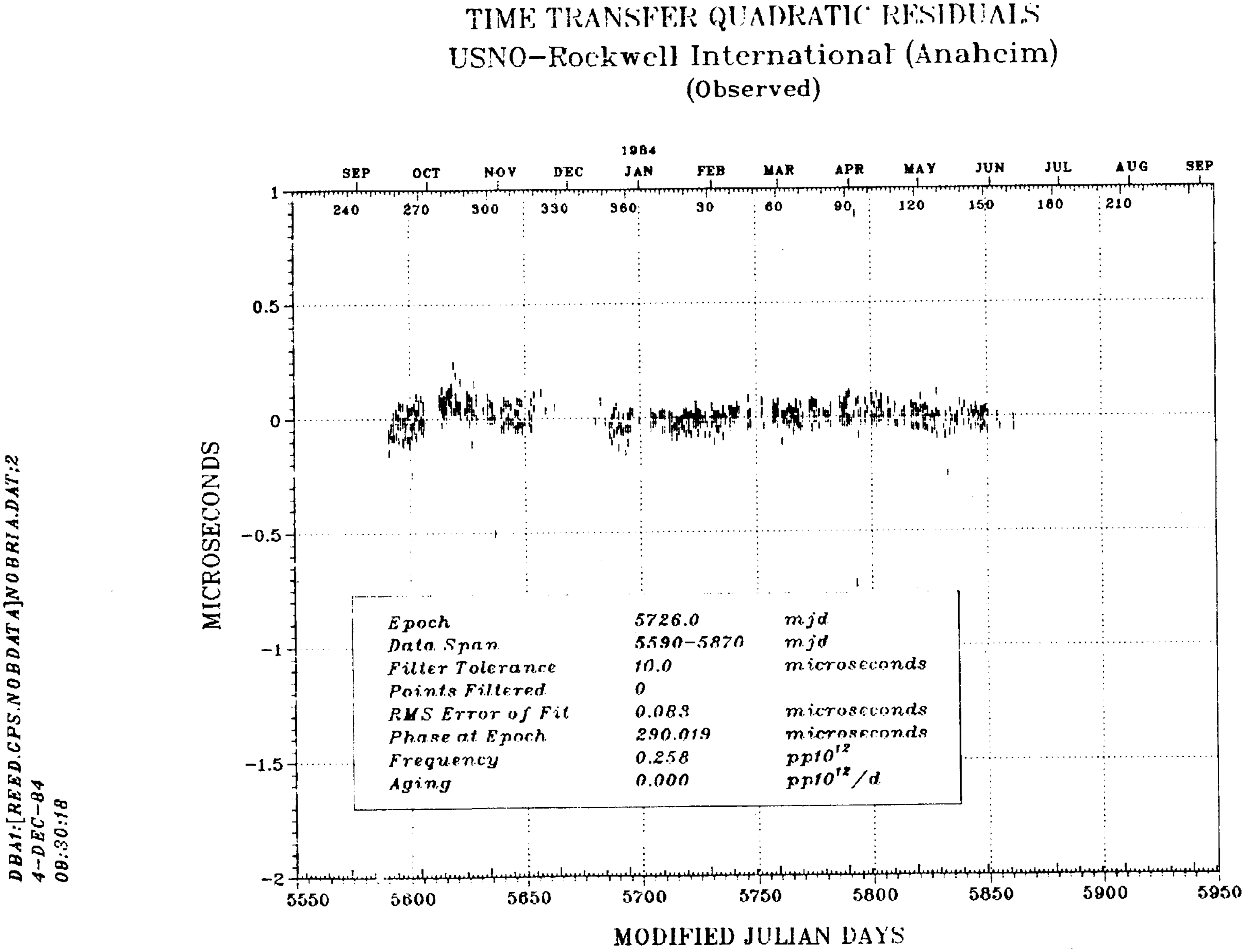
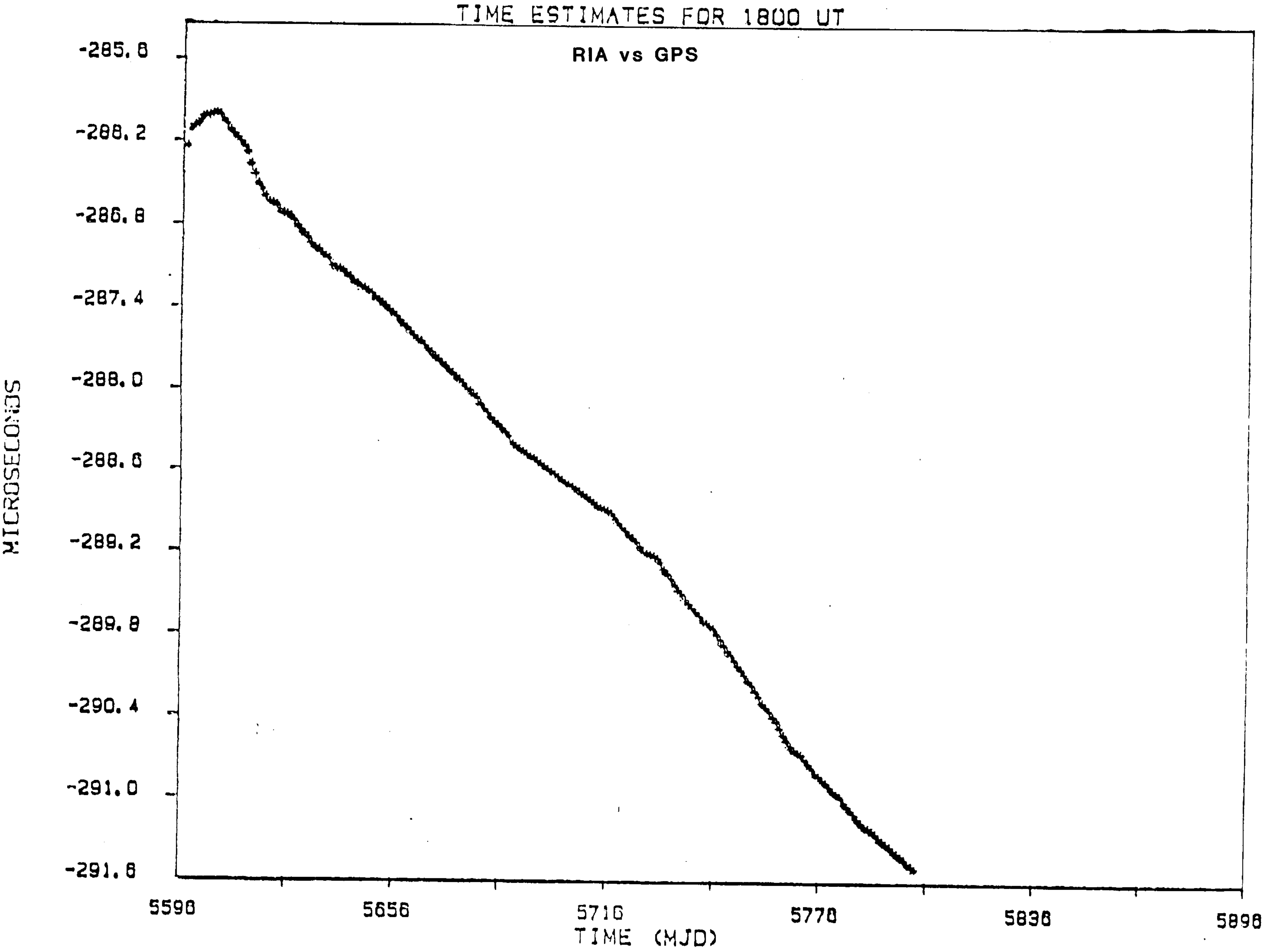

TIME TRANSFER QUADRATIC RESIDUALS
USNO–Rockwell International (Anaheim)
(Observed)
1984
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
240
270
300
330
360
30
60
90
120
150
180
210
1
0.5
0
−0.5
−1
−1.5
−2
MICROSECONDS
5550
5600
5650
5700
5750
5800
5850
5900
5950
MODIFIED JULIAN DAYS
Epoch 5726.0 mjd
Data Span 5590−5870 mjd
Filter Tolerance 10.0 microseconds
Points Filtered 0
RMS Error of Fit 0.083 microseconds
Phase at Epoch 290.019 microseconds
Frequency 0.258 pp10^12
Aging 0.000 pp10^12/d
DBA1:[REED.CPS.NOBDATA]NOBRIA.DAT;2
4-DEC-84
09:30:18

Figure 9


TIME ESTIMATES FOR 1800 UT
RIA vs GPS
MICROSECONDS
-285.6
-286.2
-286.8
-287.4
-288.0
-288.6
-289.2
-289.8
-290.4
-291.0
-291.6
5596
5656
5716
5776
5836
5896
TIME (MJD)

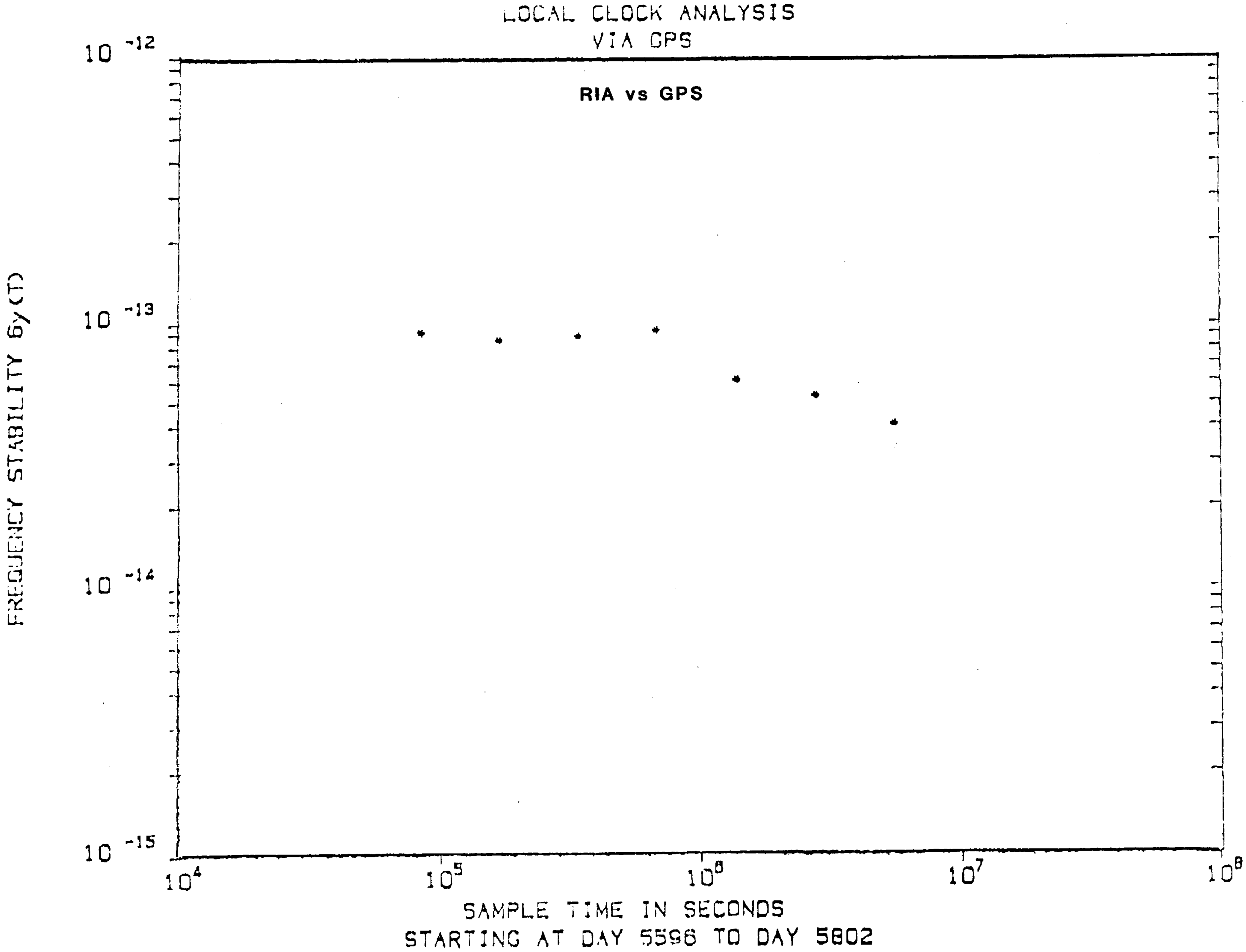

LOCAL CLOCK ANALYSIS
VIA GPS
RIA vs GPS
FREQUENCY STABILITY $\sigma_y(\tau)$
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
SAMPLE TIME IN SECONDS
STARTING AT DAY 5596 TO DAY 5802

Figure 11

CLOCK CHARACTERIZATION TUTORIAL

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National Bureau of Standards
Boulder, Colorado 30303

ABSTRACT

Managers are often required to make key program decisions based on the performance of some elements of a large system. This paper is intended to assist the manager in this important task in so far as it relates to the proper use of precise and accurate clocks. An intuitive approach will be used to show how a clock s stability is measured, why it is measured the way it is, and why it is described the way it is. An intuitive explanation of the meaning of time domain and frequency domain measures as well as why they are used will also be given.

Explanations of when an "Allan variance plot should be used and when it should not be used will also be given. The relationship of the rms time error of a clock to a $\sigma_y(\tau)$ diagram will also be given. The environmental sensitivities of a clock are often the most important effects determining its performance. Typical environmental parameters of concern and nominal sensitivity values for commonly used clocks will be reviewed.

SYSTEMATIC AND RANDOM DEVIATIONS IN CLOCKS

This paper is tutorial in nature with a minimum of mathematics -- the goal being to characterize clock behavior. First, time deviations or frequency deviations in clocks may be categorized into two types: systematic deviations and random deviations. The systematic deviations come in a variety of forms. Typical examples are frequency sidebands, diurnal or annual variations in a clock s behavior, time offset, frequency offset and frequency drift. Figure 1 illustrates some of these.

If a clock has a frequency offset, the time deviations will appear as a ramp function. On the other hand, if a clock has a frequency drift, then the resulting time deviations will appear as a quadratic time function --the time deviations will be proportional to the square of the running time. There are many other systematic effects that are very important to consider in understanding a clock s characteristics and Figure 1 is a very simplistic picture or nominal model of most precision oscillators. The random fluctuations or deviations in precision oscillators can often be characterized by power law spectra. In other words, if the time residuals are examined, after removing the systematic effects, one or more of the power law spectra shown in Figure 2 are typically observed. The meaning of power law spectra is that if a Fourier analysis or spectral density analysis is proportional to f^β; β designates the particular power law process ($\beta = 0, -1, -2, -3, -4$ and $\omega = 2\pi f$). The first process shown in Figure 2 is called white noise phase modulation (PM)., The noise is typically observed in the short term fluctuations, for example, of an active hydrogen maser for sample times of from one second to about 100 seconds. This noise is also observed In quartz crystal oscillators for sample times in the vicinity of a millisecond and shorter. The flicker noise PM, f^{-1}, is the second line in Figure 2. This kind of noise is often found for sample times of one millisecond to one second in quartz crystal oscillators. The f^{-2} or random walk PM indicated by the third line is what is observed for the time deviations of rubidium, cesium, or hydrogen frequency standards. If the first difference is taken of a series of discrete time readings from the third line, then the result is proportional to the frequency deviations, which will be an f^0 process or a white noise frequency modulation (FM) process. In other words the time and the frequency are related through a derivative or an integral depending upon which way one goes. The derivative of the time deviations yields the frequency deviations, and the integral of the frequency deviations yields the time deviations. So, random walk time deviations result from white noise FM. In general, the spectral density of the frequency fluctuations is ω^2 times the spectral density of the time fluctuations. The fourth line in Figure 2 is an f^{-3} process. If this were representative of the time fluctuations then the frequency would be an f^{-1} or a flicker noise FM process. This process is typical of the output of a quartz crystal oscillator for sample times longer than one second or the output of rubidium or cesium standards in the long term (on the order of a few hours, few days, or few weeks depending upon which standard). We find that in very long term, most atomic clocks have an f^{-4} type behavior for the time fluctuations -- making the frequency fluctuations an f^{-2} process or random walk FM. These five power law processes are very typical and one or more of them are appropriate models for essentially every precision oscillator. Characterizing the kind of power-law process thus becomes an important part of characterizing the performance of a. clock (1). Once a clock has been characterized in terms of its systematic and its random characteristics then a time deviation model can be developed. A very simple and useful model that is commonly used is given by the following equation (2):

$$x(t) = x_o + y_o \cdot t + 1/2D \cdot t^2 + \varepsilon(t) \qquad (1)$$

where x(t) is the time deviation of the clock at time t, xo is the synchronization error at t = o, and y_o is the syntonization error at t = o, which produces a linear ramp in the time deviations. D is the frequency drift term, which is almost always an applicable model element in commercial standards. This $1/2Dt^2$ term in the time deviation due to the frequency drift yields a quadratic time deviation. Lastly, the $\varepsilon(t)$ term contains all of the random fluctuations. It is this term which is typically characterized by one or more of the various power law processes. Once a clock has been fully characterized, then it is possible to do optimum time prediction. Shown in Figure 3 are some examples. The even power law spectra have simple algorithms for prediction. In the case of white noise PM, the optimum predictor is the simple mean. In the case of random walk PM, it is the last value. In the case of random walk FM, an f^{-4} process on the time, the optimum predictor is the last slope. In the case of flicker noise, the prediction algorithms are significantly more complicated but not intractable, and ARIMA techniques can be employed in order to develop optimum prediction algorithms (3).

THE CONCEPT OF AN ALLAN VARIANCE

Figure 4 illustrates a simulated random walk PM process. Suppose this process is the time difference between two clocks or the time of a clock with repsect to a perfect clock. Again this process is typical of the time deviations for rubidium, cesium, and passive hydrogen clocks. Choose a sample time τ, as indicated, and note the three time deviation readings (x_1, x_2, and x_3) indiaated by the circles and spaced by the interval τ. The frequency deviation y_1 is proportional to the slope between x_1 and x_2 ($y_1 = (x_2 - X,)/T$). Similarly y_2 is proportional to the slope between x_2 and x3 ($y_2 = (x_3 - x_2)/\tau$). The difference in slope, Ay, is a measure of the frequency change from the first τ sample interval to the next adjacent τ sample interval. With a fixed value of τ, imagine averaging through the entire data set for all possible readings of x_1, x_2, and x3 displaced by τ each yielding a Δy. The average squared value of Ay divided by 2 is called the "Allan variance . In theory, it is the average over all time. In practice, finite data sets yield rapidly converging estimates. The square root of the Allan variance is *denoted* $\sigma_y(\tau)$; $\sigma_y(\tau)$ is an efficient estimator of the power law spectra model for the data. How $\sigma_y(\tau)$ changes with τ indicates the exponent for the power law process. In fact, in the case of random walk FM, $\sigma_y(\tau)$ is statistically the most efficient estimator of this power law process. If power law processes are good models for a clocks random fluctuations, which they typically are, then the Allan variance analysis is faster and more accurate in estimating the process than the Fast Fourier Transform. Some virtues of the Allan variance are: It is theoretically and straightforwardly relatable to the power law spectral type ($\beta = -\mu - 3$, $-2 < \mu < 2$, where μ is the exponent of τ). Once a data set is stored in a computer it is simple to compute $\sigma(\tau)$ as a function of τ. The difference in frequency, Δy, is often closely related to the actual physical process of interest, e.g. frequency change after a radar return delayed by, τ, effects of oscillator instabilities in a servo with loop time constant τ, the change in frequency after a calibration over an interval τ, etc. Some drawbacks of the Allan variance are: it is transparent to periodic deviations where the period is equal to the sample time τ. It is ambiguous at $\mu = -2$, i.e. $\sigma_y(\tau) \sim \tau^{-1}$ may be either white noise PM or Flicker noise PM. Remembering from above the relationship between the spectral density of the frequency deviations and the spectral density of the time deviations, if S,(f) $\sim f^{\beta}$ and $_yS(f) \sim f^{\alpha}$, then $a = \beta + 2$ and $a = -\mu - 1$ $(-2 < \mu < 2)$, where $S_x(f)$ is the spectral density of the time deviations and $S_y(f)$ is the spectral density of the fractional frequency deviations. Figure 5 shows the noise type and the relationship between μ and α. There are some ways around the ambiguity problem at $\mu = -2$. For noise processes where $\alpha > 1$ there is a bandwidth dependence (4). A software trick can be employed to effectively vary the bandwidth rather than doing it with the hardware. Rather than calculating $\sigma_y(\tau)$ from individual phase points the phase can be averaged over an interval τ. Hence the x_1, x_2, and x_3 from Figure 4 become phase or time difference averages. As τ increases the effective measurement system bandwidth decreases. This technique removes the ambiguity problem. We have called this the modified Allan variance or modified $\sigma_y(\tau)$ analysis technique. Figure 6 shows the μ, a mapping for the modified Allan variance. For white noise PM, μ is equal to -3, and for flicker noise PM, μ is equal to -2.

TIME PREDICTION ERROR OF A CLOCK

Another -concept which has become useful is the computation of the time error of prediction. In the case of white noise FM and random walk noise FM, $\tau\sigma_y(\tau)$ is the optimum time error of prediction. For white *noise PM* the optimum value achievable is $\tau\ \sigma_y(\tau)/\sqrt{3}$, and for flicker noise FM it is $\tau\ \sigma_y(\tau)/\sqrt{\ln 2}$.

Applying some of the above concepts to state of the art frequency standards yields the frequency stability plot shown in Figure 7 (5), and the corresponding RMS time prediction error plot shown in Figure 8. The RMS time prediction error plot is based on reference (2) and is a function of the levels of noise in the clock and also the uncertainties associated with determining the systematic deviations due to a finite data length.

ENVIRONMENTAL EFFORTS ON CLOCKS

From a management point of view, the characteristics of the various clocks should be related to the needs of a particular program. It is important to keep in mind that, in practice, systematic and environmental effects often are the predominant influence on the time and frequency deviations of a clock. The reliability of a clock is often a basic issue, and the manager should assure himself that adequate reliability has been documented. The manager also needs to ask the following questions in each application that he may have. What are the environmental conditions, the rapidity of the temperature changes, the magnetic field conditions, the shock and vibration conditions, and the humidity conditions? How do these conditions affect the clock s performance? All clocks are affected at some level by changes in the above environmental parameters plus some others as well. Some clocks are affected by barometric pressure. Vibration can be extremely important. In some clocks the servos will unlock, for example, if a 1 kHz vibration is present. (6) Some clocks are accoustically sensitive. What is the gravitational or g sensitivity? What are the cost, size, weight and power requirements? Line voltage power fluctuations can affect clocks. Changes in the dc power can affect some clocks. We have found that a good clock environment can improve clock performance considerably, and we have provided a highly controlled environment for the NBS clock ensemble to improve the performance over that obtained in typical laboratory environments. Another very important question to ask is what is a clock s lifetime? Redundancy and/or multiple clocks are sometimes necessary to overcome lifetime and reliability problems. It is important to take a system s approach in establishing the best clock(s) and clock(s) configuration. In some cases the program needs are for synchroniztion to UTC, in other cases the needs are for syntonization, i.e. the frequencies within a system need to agree. Often the need is for time or frequency self consistency within a program, e.g. GPS requires time consistency. It seems many people are buying cesium standards as a panacea, when in fact they may not be solving the problem at hand. Buying a cesium standard does not guarantee synchronization. However, it does guarantee syntonization within some accuracy. All clocks will diverge and eventually depart from synchronization tolerance. It's just a matter of time! Knowing a clock s characteristics, the system requirements, and the environmental conditions will allow the manager to know the best clock or clocks to buy and the best way to implement them. For example, a rubidium clock coupled to a GPS receiver (used in the common-view mode with UTC(USNO MC) or with UTC(NBS) would have better short term and better long term stability than any commercial cesium clock available. The stability would be somewhat worse in the vicinity of τ equal to one day. In practice, there are some problems with this idea, but it illustrates the point.

Lastly, Figures 9 through 13 show nominal values for some important clock coefficients that managers and design engineers need to properly assess when evaluating which clock or clocks will best serve their needs. These are only nominal values and there will be exceptions. A band of values is listed for these coefficients ranging from nominal best performance available from laboratory-type standards through the range of typical values observed and specified for commercially available standards.

ACKNOWLEDGEMENTS

The author wishes to express appreciation to Mr. Roger Beehler and Dr. Richard Jones for their assistance in proofing the text and to Dr. Lindon Lewis and Dr. Fred Walls for assistance with the data in Figures 9-1 3.

REFERENCES

(1) Barnes, J. A., Chi, A., Cutler, L. L., Healey, D. J., Lesson, D. B., McGunigal, T., Mullen, J. Jr., Smith, W., Sydnor, R., Vessot, R., and Winkler, G. M. Characterization of Frequency Stability, Proc. IEEE Trans. on Instrumental and Measurement IM-20, 1971 p. 105. NBS Tech. Note 394 1971.

(2) Allan, D. W. and Hellwig, H., "Time Deviation and Time Prediction Error for Clock Specification, Characterization and Application, IEEE Position Location and Navigation Symposium Proceedings, 1978 pp. 29-35.

(3) Box, G. E. P. and Jenkins, G. M., Time Series Analysis Forcasting and Control, Holden-Day, 1970, Catalog No. 77-79534.

(4) Vessot, R., Mueller, L., and Vanier, J., "The Specification of Oscillator Characteristics from Measurements Made in tine Frequency Domain, Proc. of the IEEE, Vol. 54, 1966 pp. 199-207.

(5) Winkler, G.M. R., Improved Master Clock Reference System at USNO," PTTI 1983, to be published.

(6) Walls, F. L., Vibration and Acceleration Induced Timing Errors of Clocks and Clock Systems, " 36th Annual Symposium on Frequency Control , 1982 p. 37.

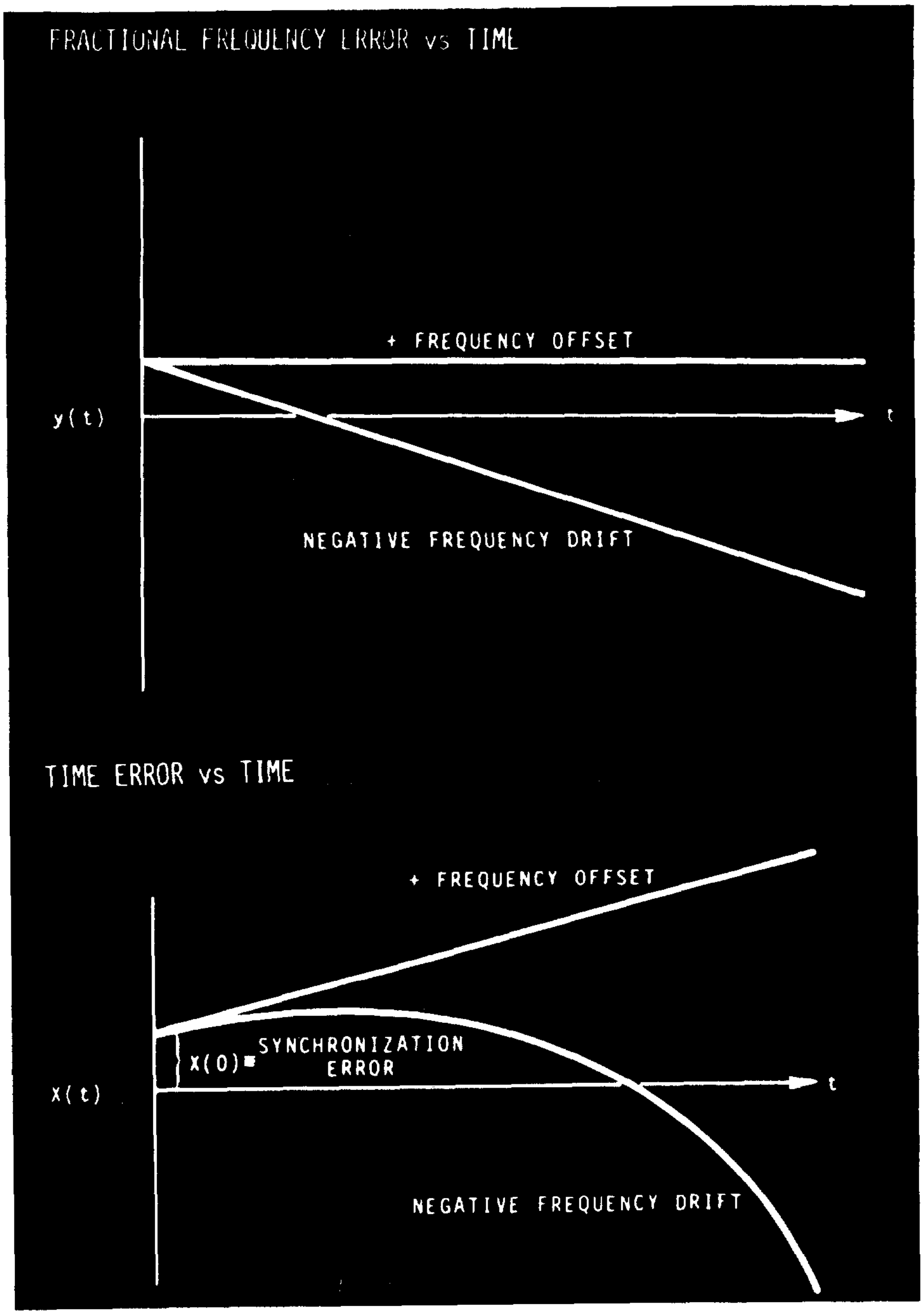

Figure 1. Frequency, y(t), and time, x(t) deviation due to frequency offset and to frequency drift in a clock.

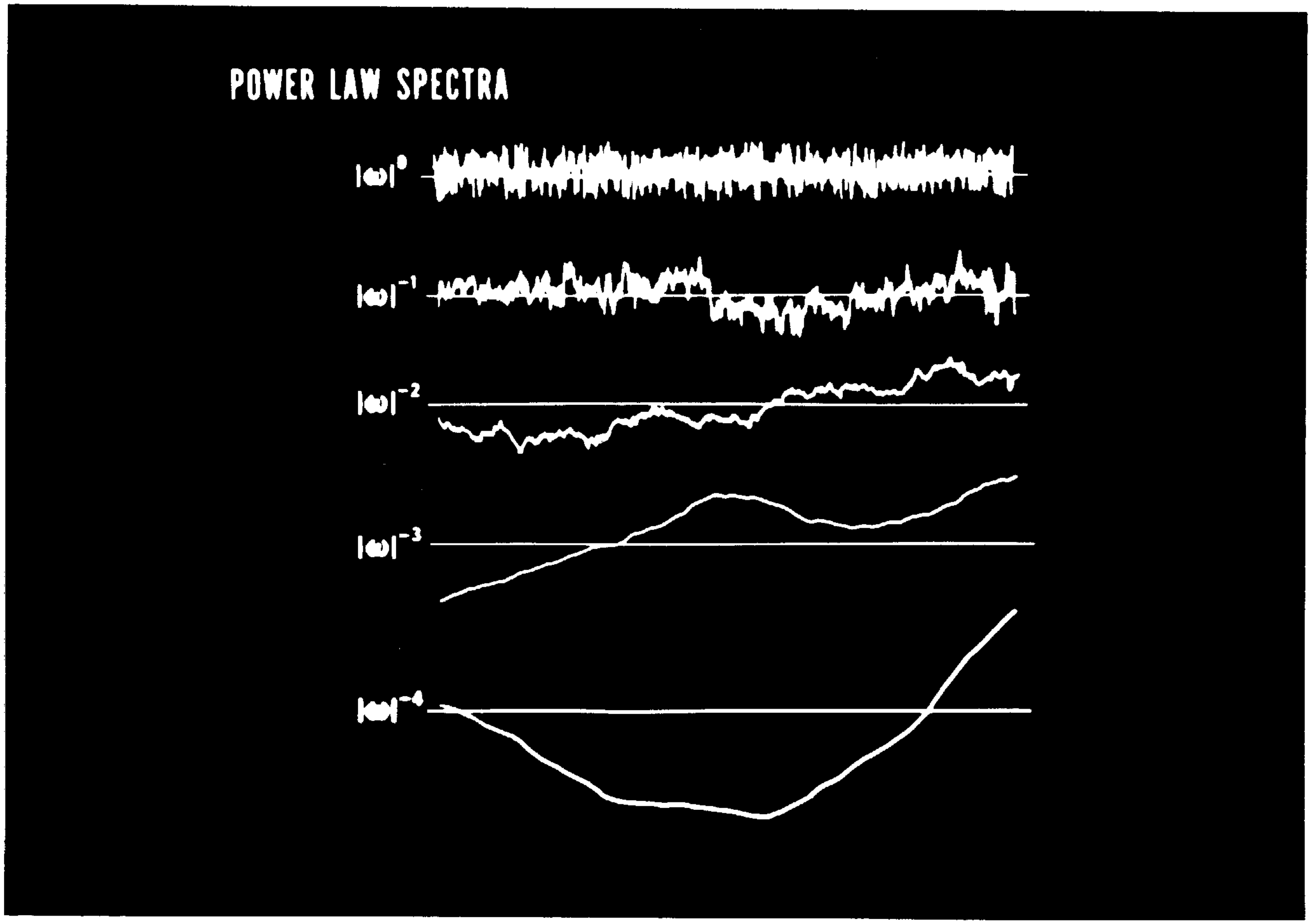

Figure 2. Simulated random processes commonly occurring in the output signal of atomic clocks. Power law spectra $S(\omega)$, are proportional to ω to some exponent, where ω is the Fourier frequency.

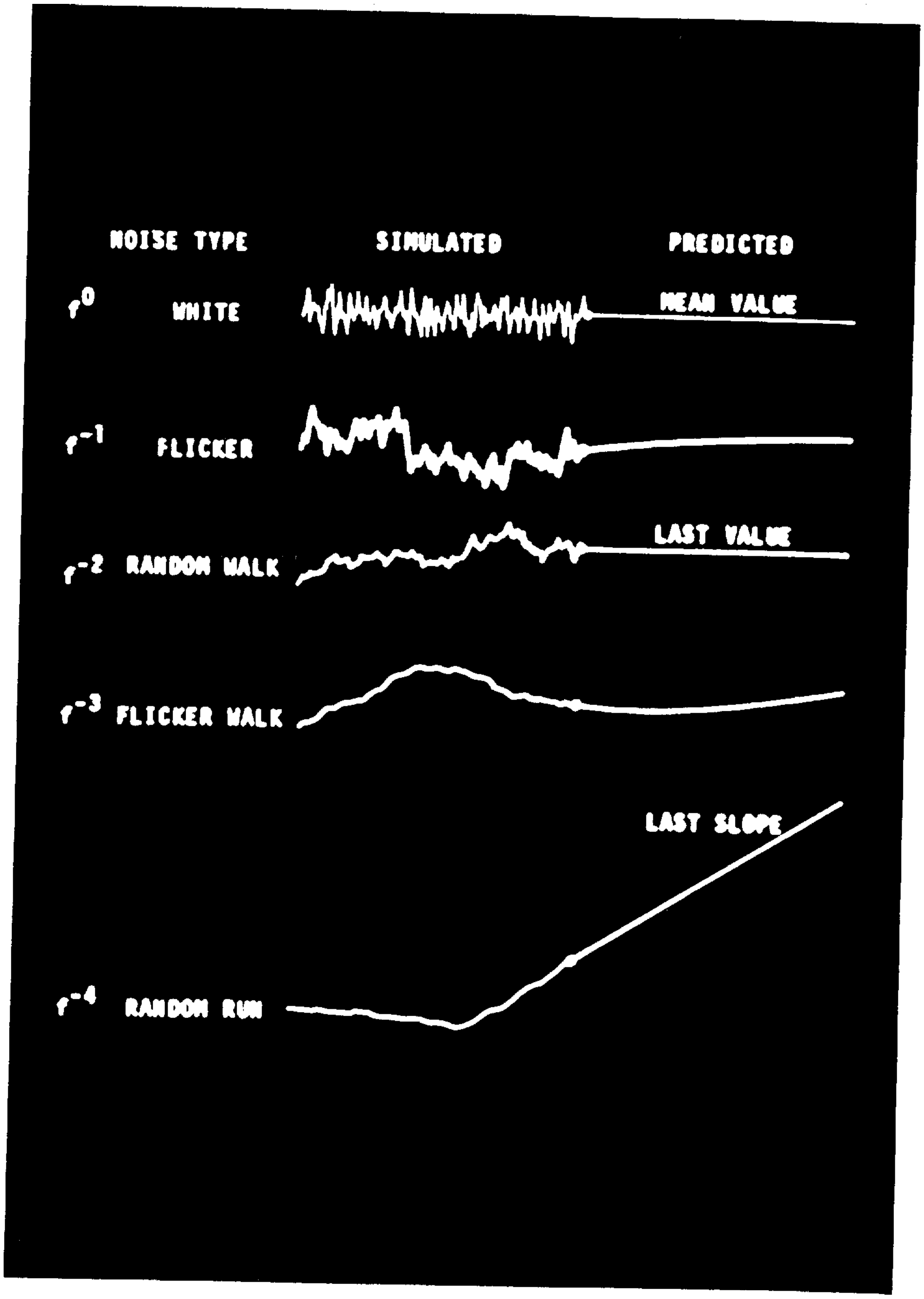

Figure 3. Simulated power law noise processes with their optimum predicted estimates.

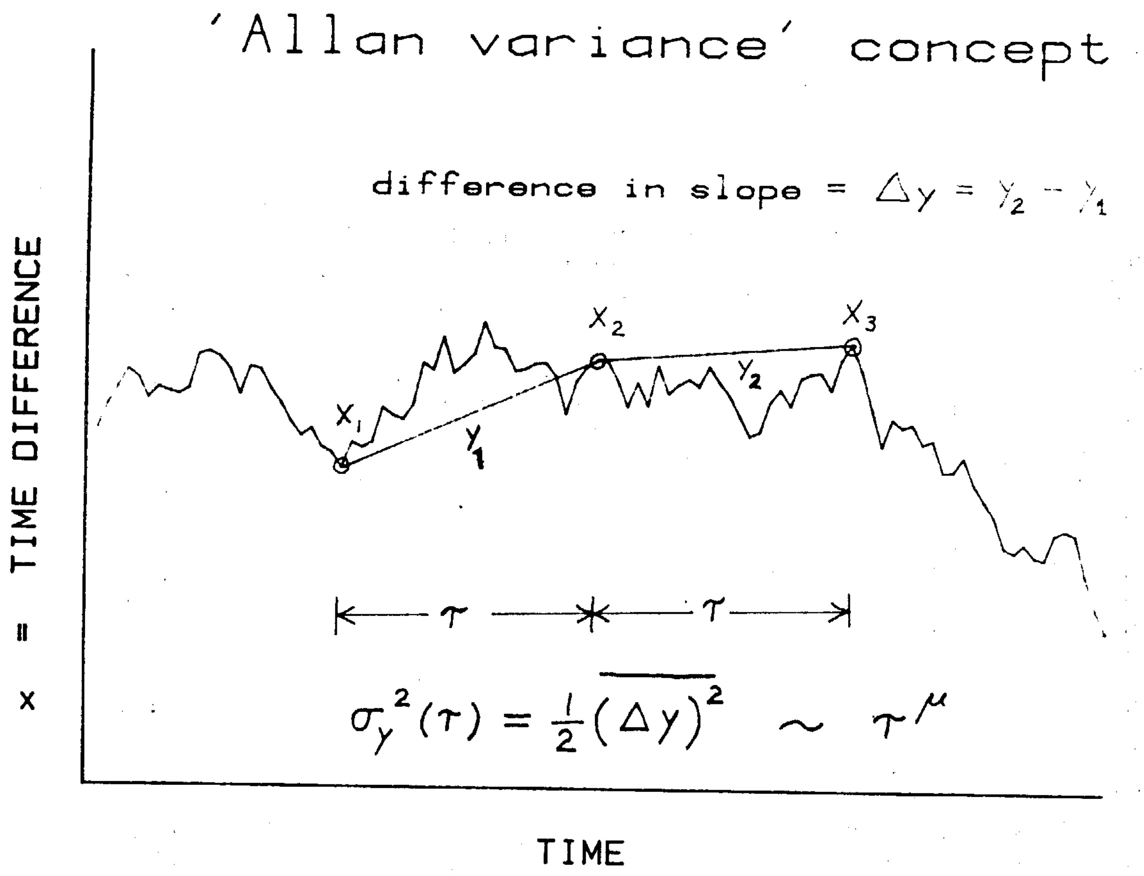

Figure 4. Pictorial of computation of "Allan variance".

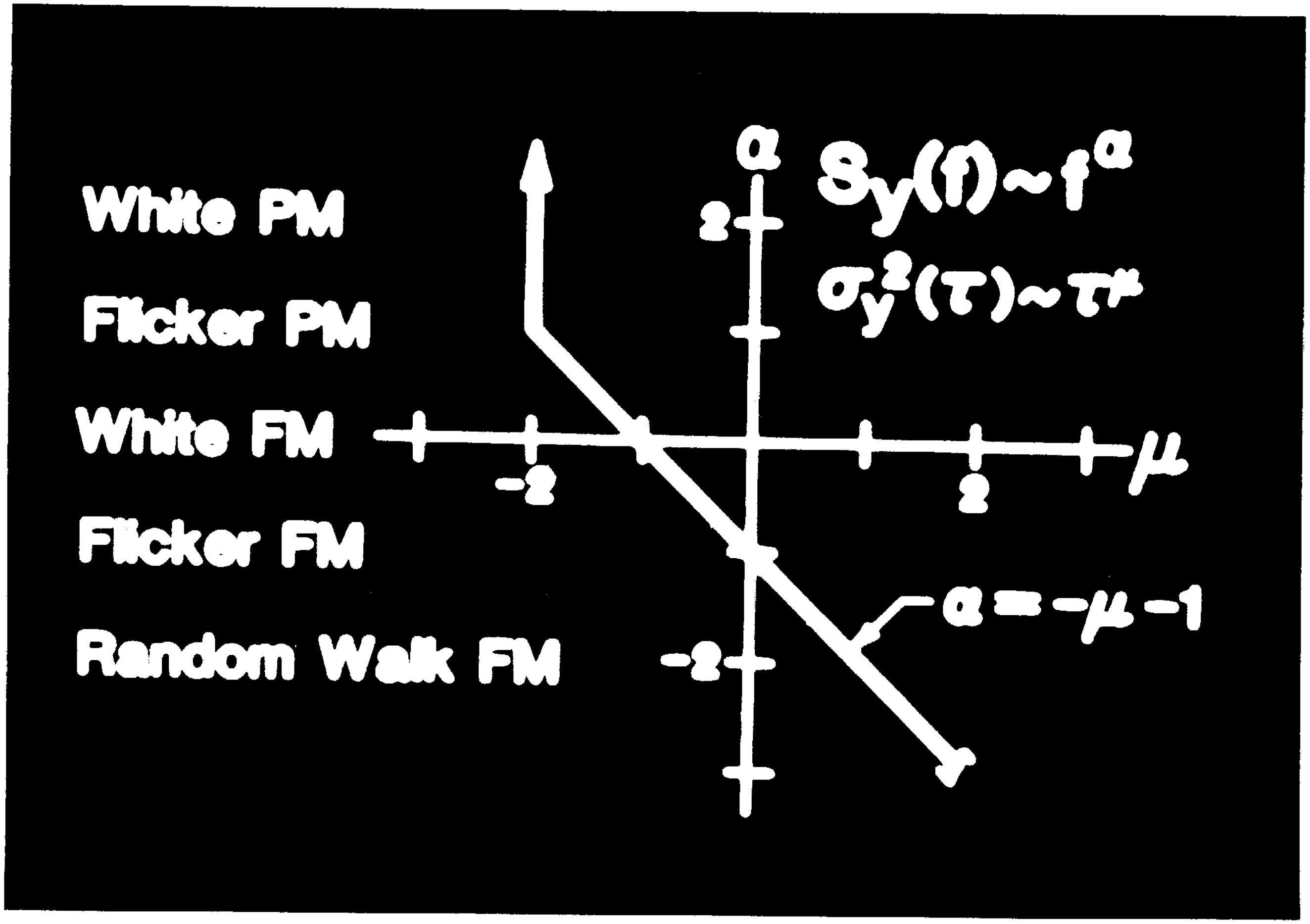

Figure 5. Various power law noise types commonly occurring in the precision clocks and the mapping between the exponent α of the frequency domain measure and the exponent μ of the time domain measure.

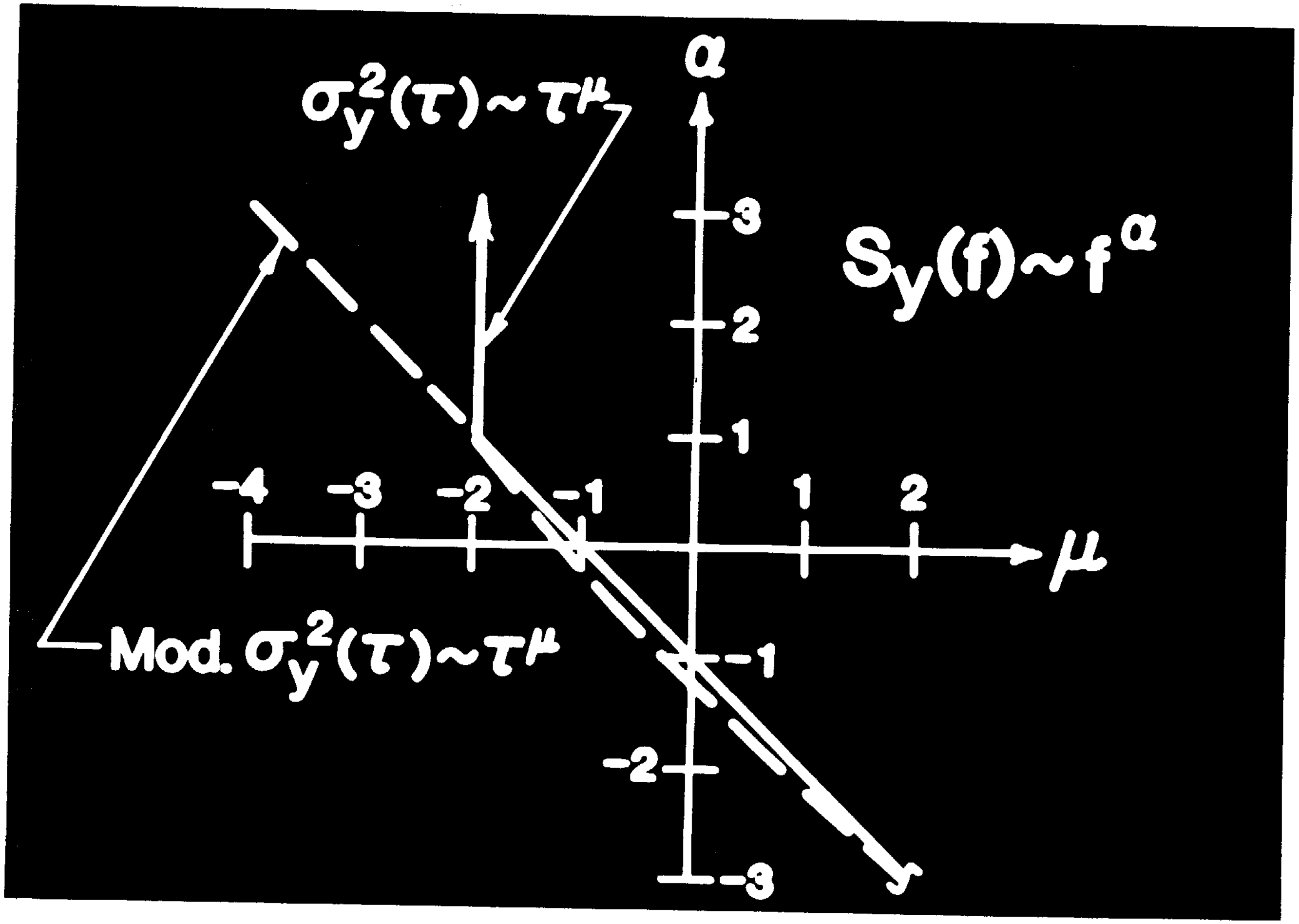

Figure 6. The mapping of the τ exponent μ of the Allan variance and of the modified Allan variance to the power law spectrum exponent α.

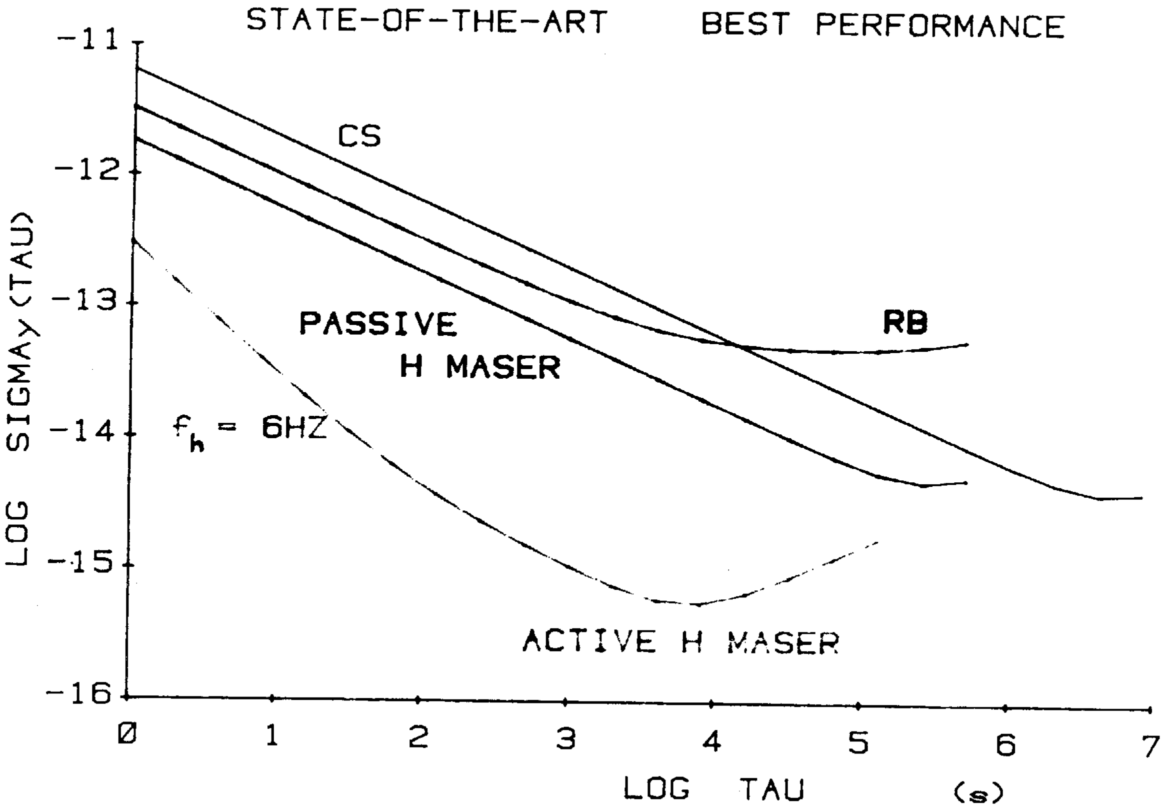

Figure 7. Frequency stability of some of the best performing frequency standards from each of four main types: CS = cesium beam, RB = rubidium gas cell, H = hydrogen (active and passive). Note: log 10^{I} = I; e.g. log 10^{-14} = -14.

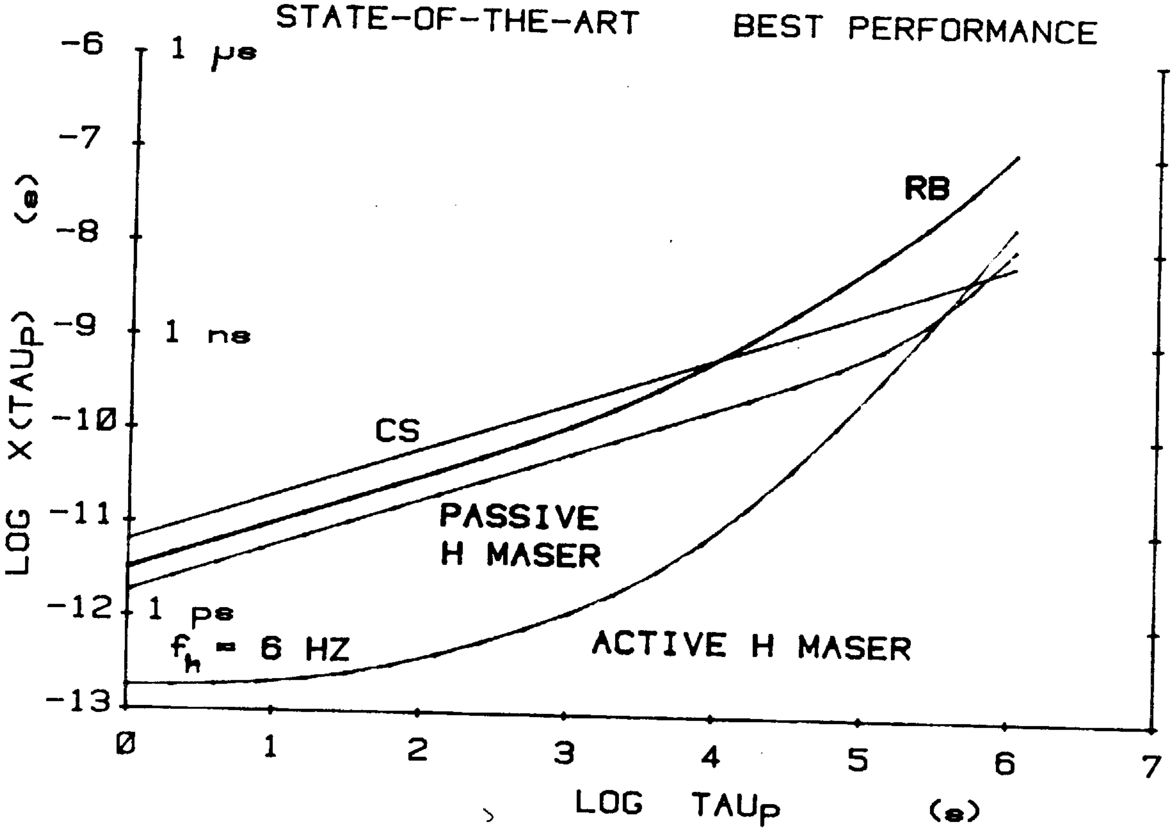

Figure 8. RMS time prediction error plot for the same frequency standards as shown in Figure 7. Note: log 10^I = I; e.g. log 10^{-14} = -14.

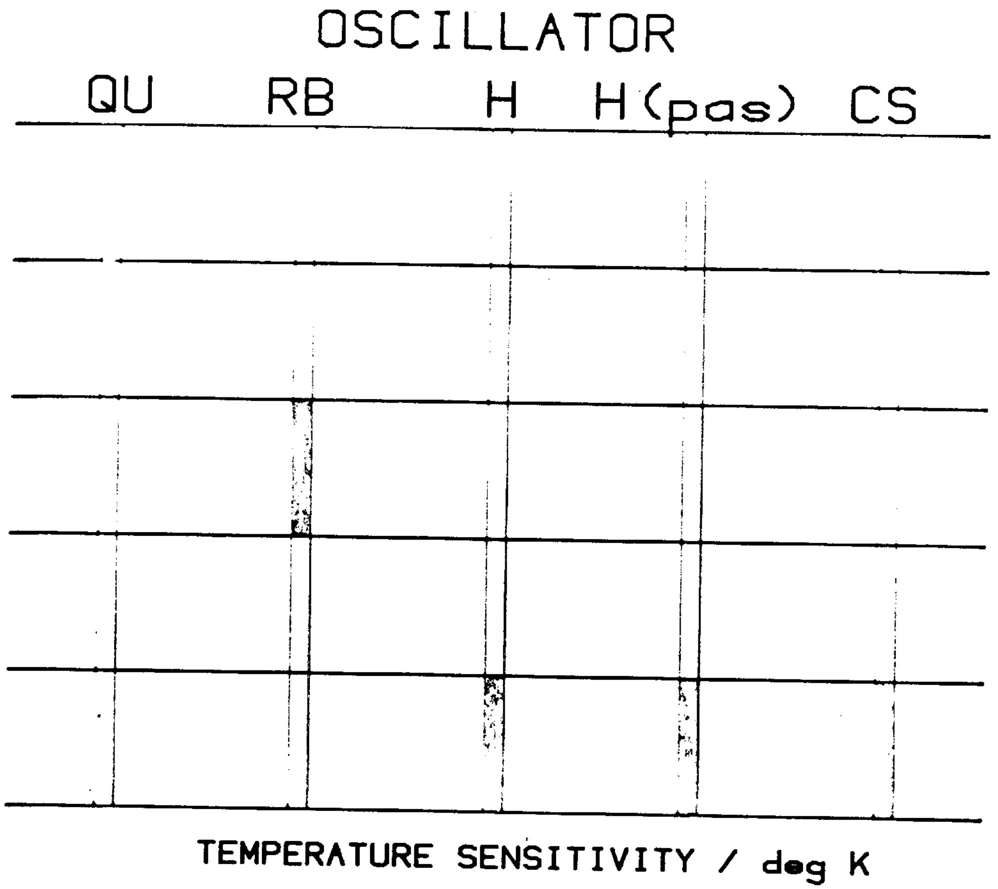

Figure 9. Nominal values for the temperature coefficient for the frequency standards: QU = quartz crystal, RB = rubidium gas cell, H = active hydrogen maser, H(pas) = passive hydrogen maser, and CS = cesium beam.

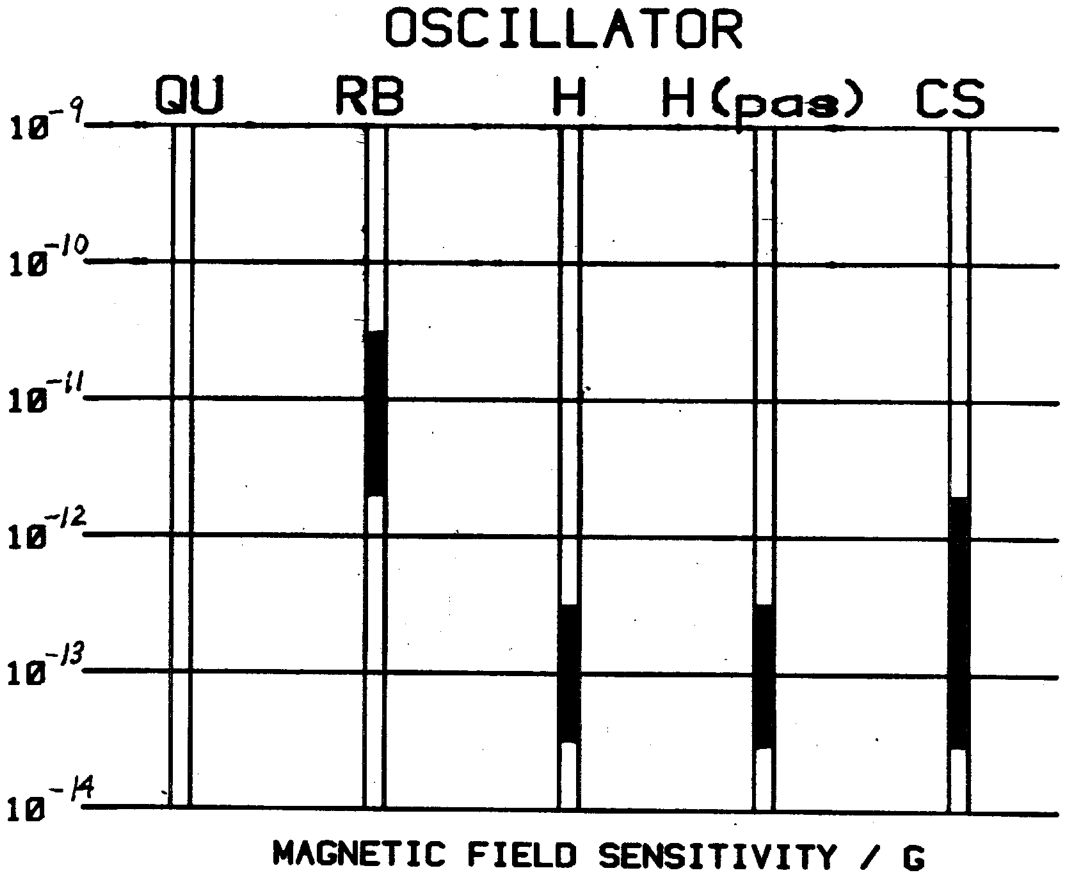

Figure 10. Nominal values for the magnetic field sensitivity for the frequency standards: QU = quartz crystal, RB = rubidium gas cell, H = active hydrogen maser, H(pas) = passive hydrogen maser, and CS = cesium beam.

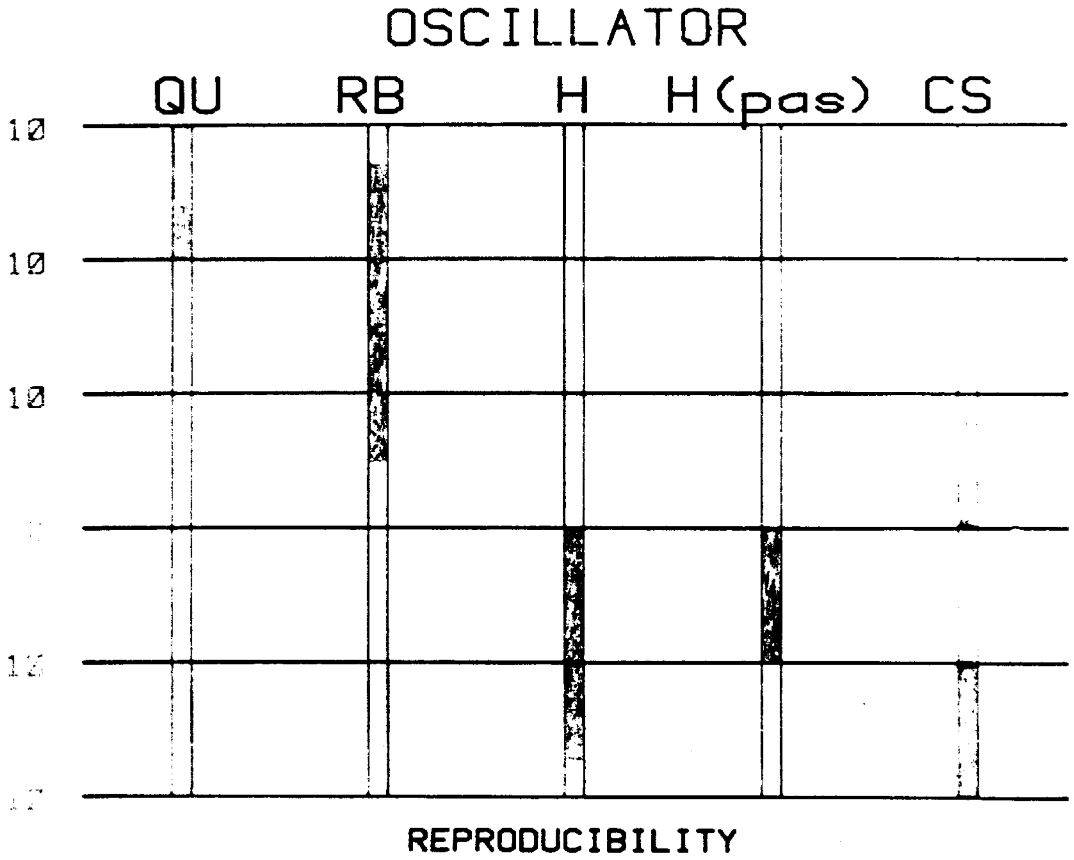

Figure 11. Nominal capability of a frequency standard to reproduce the same frequency after a period of time for the standards: QU = quartz crystal, RB = rubidium gas cell, H = active hydrogen maser, H(pas) = passive hydrogen maser, and CS = cesium beam.

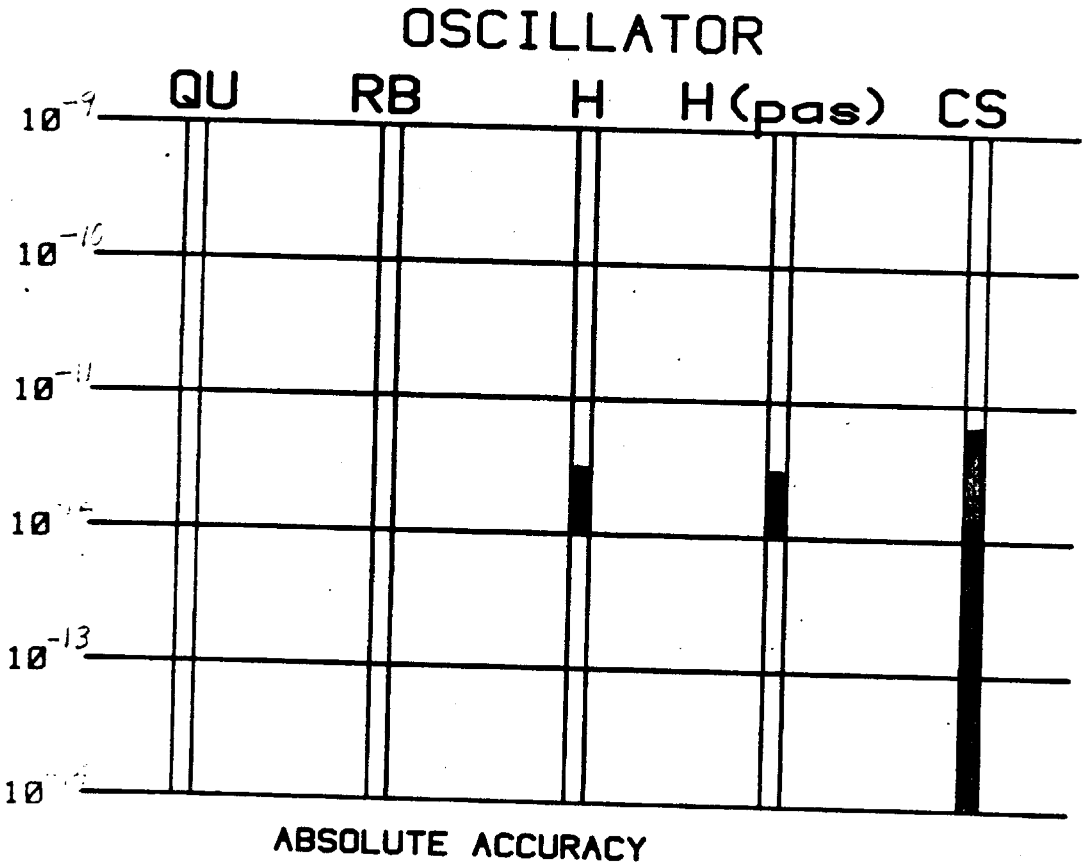

Figure 12. Nominal capability for a frequency standard to produce a frequency determined by the fundamental constants of nature for the standards: QU = quartz crystal, RB = rubidium gas cell, H = active hydrogen maser, H(pas) = passive hydrogen maser, and CS = cesium beam.

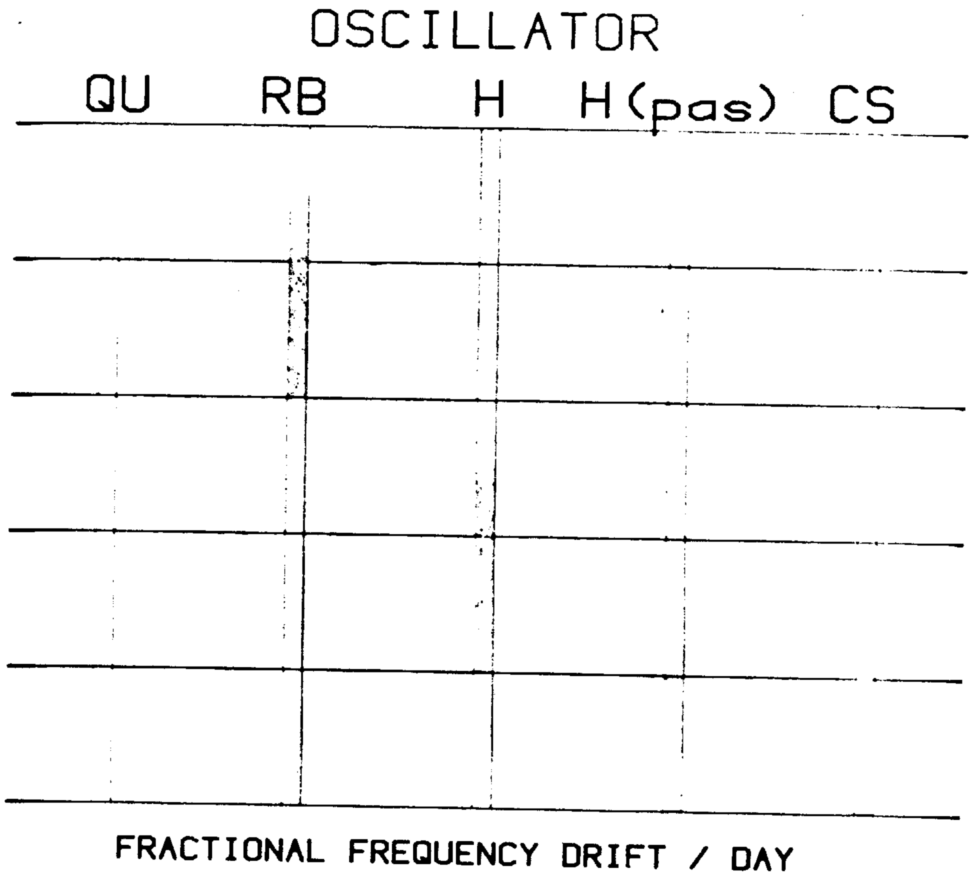

Figure 13. Nominal values (ignoring the sign) for the frequency drift for the frequency standards: QU = quartz crystal, RB = rubidium gas cell, H = active hydrogen maser, H(pas) = passive hydrogen maser, and CS = cesium beam.

NEW TIME AND FREQUENCY SERVICES AT THE NATIONAL BUREAU OF STANDARDS

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INTRODUCTION

The National Bureau of Standards (NBS) established two new time and frequency services in 1983. They permit, the user to obtain time and frequency traceable to the NBS with greater precision and less effort than previously possible. The new services are for users who require time transfer accuracies in the three nanosecond to one microsecond range or frequency calibration capability in the 1 part in 10^{11} to one part in 10^{14} range. However, many applications not requiring this level of precision may benefit from these services because of the high degree of automation, simplicity of use, and support from the NBS.

Frequency calibration requirements at the part in 10^{11} to part in 10^{12} level and timing requirements at the 1 microsecond. level can be satisfied using low frequency radio signals broadcast from stations such as WWVB or Loran C. The NBS Frequency Measurement Service helps the user set-up a low frequency receiver and data logging system most appropriate for his needs and location. A typical system includes a receiver, microcomputer, floppy disc units and printer-plotter. The user supplies a dial-up phone line and modem so that his data can be compared with data recorded at NBS when necessary, thus providing increased assurance that the measurements are valid. The user also receives a bulletin by mail containing NBS measurements of many signal sources. To assist the user in getting the most from his system, NBS provides specific training using the actual equipment in one of its seminars on frequency measurements.

The NBS Global Time service provides higher precision time and frequency data and a greater degree of automation. A Global Positioning System (GPS) receiver, located at the user s facility communicates automatically with an NBS computer that stores raw data, determines which data elements are suitable for time transfer calculations and provides an optimally filtered value for the time of the user s clock with respect to the NBS atomic time scales. The user is assigned an "account" on one of the NBS computers through which he may access the results of the NBS analysis. Tests, based upon receivers in Colorado, Germany, France, Washington, DC, Wyoming, California, demonstrate that the system can perform time comparisons with a precision of three nanoseconds and frequency comparisons with a precision of one part in 10^{14} after four days of operation.

THE MEASUREMENT ASSURANCE APPROACH

The most common way to relate industrial calibration measurements to the national standards is to have the local reference standards calibrated in a way that provides traceability to the national standards. Depending upon the required level of accuracy, these calibrations may be performed by private or governmental laboratories at the local, regional or national level. NBS provides approximately 12,000 calibrations per year for this purpose. NBS Calibration services are described in Special Publication 250 (available from the Office of Physical Measurement Services, National Bureau of Standards, Washington, DC 20234). The cost of each calibration is published in an Appendix to this publication.

The ordinary calibration process has serious deficiencies. First, the standard or instrument to be calibrated must travel to the calibration laboratory, so it is out of service for a period of time. For example, the complete characterization of a cesium beam frequency standard requires that it be at NBS for a period of not less than five weeks. Even more serious is that the confidence in the calibration deteriorates with the passage of time. The fact that the instrument must be shipped to and from the calibration laboratory contributes substantially to this problem. Finally, only selected individual standards or instruments are calibrated and thus little information is available concerning whether or not the total measurement process is under control.

A general goal of the NBS program is to increase the reliability and effectiveness of the national measurement system. The two new time and frequency services are examples of what is frequently called measurement assurance . In a measurement assurance program, most of the measurements are performed at the user s site rather than at the NBS and feedback and analysis of measured information is an important part of the process. In addition, the NBS establishes a long term interaction with the user and assists in training user personnel. The complete measurement process undergoes repeated scrutiny and is therefore likely to remain under control at all times. Of the six base units of measurement, -the kilogram, the second, the Kelvin, the candella, the ampere, and the mole -the second is unique by the relative ease with which it may be compared by radio at remote locations without the transport of physical artifacts†. Because of the unique property of the second, the new services provide the user the accuracy he requires through a simple program of coordinated measurements made at his site and at the NBS. No artifacts need be shipped to NBS, and the user exchanges calibration data with the NBS via telephone. Thus, the user obtains NBS traceable frequency measurements and time synchronization in real time. Traceability is provided at whatever level is required up to the ultimate stability of the NBS atomic time scales and the full accuracy of the NBS primary frequency standard. Since the link to NBS is established on a regular basis, the user s confidence in the performance of his in-house standards is greatly increased. Because of the high degree of automation, inherent in both of the new services, the improvements in precision and accuracy are obtained with negligible operational burden on the user.

NBS FREQUENCY MEASUREMENT SERVICE

This new Frequency Measurement Service, using straight forward measurement techniques [1], utilizes precision navigation and timing broadcasts from Loran-C and WWVB to provide frequency traceability to the NBS at approximately a one part in 10^{11} level. Prior to the introduction of this service, there did not exist a total measurement system with the following features : LF receiver and antenna; time interval counter ; dual floppy disc data storage system; printer/plotter; instrument controller; and telephone modem data line to the NBS.

Figure 1 shows the Loran-C version of the frequency measurement system. Using the NBS software, this system is capable of monitoring Loran-C transmissions, storing, listing and plotting tie frequency calibration data. Figure 2 is a sample plot of phase vs time. The slope calculated by the system program is the frequency offset of the user s clock. The numerical value of the calibration is printed on each plot. The plots are made automatically once each day. Four separate frequency sources can be calibrated simultaneously.

The new NBS Frequency Measurement Service is more than an automated data acquisition system. It begins with consultation between NBS staff and the user to determine the best method of satisfying the user s requirements. If the Frequency Measurement Service is selected, consultation continues to determine the most appropriate radio transmission including an analysis of possible propagation and reception problems. The second step is training of the user s technical staff.. A general foundation in time and frequency measurement techniques is provided by the two yearly NBS Seminars: Frequency Measurements and Frequency Stability and Its Measurement . Direct experience with the equipment used in the frequency dissemination service will be provided using equipment now operating at the NBS facility in Boulder, Colorado. Step three is the acquisition of the necessary measurement equipment. If desired, NBS can provide the complete integrated measurement system, insuring that all the parts are compatible and operate with the NBS software. Finally, the NBS will consult with the user during the installation of the antenna, the initial set-up of the equipment and verification of proper operation. Interaction between the NBS and the user will continue throughout the program and the user will receive NBS data via the monthly "Time and Frequency Bulletin." Also, through direct computer-to-computer data exchanges, the NBS will monitor the user s data without interfering with the operation of the user s measurement system. Thus the NBS will be able to help diagnose any anomalies. Finally, the NBS will provide additional training for newer staff members and will upgrade the calibration service with future releases of improved software and calibration equipment.

NBS GLOBAL TIME SERVICE

With this new service the user can synchronize his reference clock with respect to UTC(NBS) with state-of-the-art precision and accuracy. The service utilizes the clear access signal broadcast from the Global Positioning System (GPS) satellites. The time transfer measurements are made using a common-view technique, thereby eliminating the noise contribution from the clock errors of the GPS system and greatly reducing the effect of ephemeris errors [2]. When the NBS Calculated corrections are applied to the user s clock, that clock becomes a high performance reference with the following characteristics. Between one and four days, mod $\sigma_y(\tau) \cong 10^{-13}\tau^{-3/2}$[3]. For longer times, up to approximately one-month, $\sigma_y(\tau) \cong 10^{-14}$. Figure 3 shows the results of an analysis of data taken between Boulder and Paris confirming this performance level. As a result of these very high precision time transfers, the user not only has access to a very stable frequency reference but also gains direct access to the U.S. primary frequency standard NBS-6. Access to NBS-6 makes it possible to set an absolute limit of one part in 10^{13} on the frequency excursions of the user s clock. Another way to express the quality of this service is to say that, for time periods longer than approximately four days, the user can take advantage of the full capability of the NBS atomic time scale. The performance is almost the same as if the user were located in the next room and connected by a coaxial cable.

The NBS Global Time Service is more than just a GPS time transfer receiver. A receiver alone provides only short term measurements of the time of the user's clock relative to the time of a space vehicle clock or GPS time. The NBS service provides, in addition: determination of the user's position (necessary for time transfer measurements); scheduling of common view measurements between the user and the NBS; automatic collection by the NBS of the data from the user's receiver; computation by the NBS of the UTC(NBS) - user clock time differences; and optimum filtering of the data to provide a daily best estimate of the time of the users clock with respect to UTC(NBS). The NBS provides each user with a monthly report giving the computed daily time differences, the computed daily frequency differences and the Allan variance of the user's clock. Figure 4 is a plot of time difference data taken from one of the Global Time Service reports. The user is assigned an account on one of the NBS computers through which he may directly access the results of the NBS analysis.

The service utilizes a GPS receiver developed at the NBS and now in commercial production [4]. Figure 5 is a photo of the NBS prototype. The receiver has 0.1 ns precision and nonvolatile memory for data storage. A simple, small omni-directional antenna makes it possible to lock on to any satellite whose elevation angle is greater than 5 degrees. The receiver, interfaced to a printer allows local display of the raw GPS measurements and a telephone modem provides communications with NBS. The user is responsible for providing a dial-up telephone line so that the NBS may directly access the data from the receiver. This telephone link is an essential element of the data communications that gives the user access to UTC(NBS).

SUMMARY

The two new measurement services offered in 1983 extend the range and capability of the other frequency and time services offered by NBS:. telephone time of day; high frequency broadcasts (WWV and WWVH); low frequency broadcast (WWVB), the GOES satellite time code; and laboratory calibrations. These services previously provided routine time synchronization capability in the one second to 25 microsecond range. The new services offer enhanced automation and a greater confidence in the results of the measurements. In addition, NBS provides consultation to assist the user in selecting the best solution to his problems, initial training and follow-up consultation whenever measurement problems are detected. The new time and frequency services provide traceability to NBS and a direct link to one of the world's best time scales. They greatly reduce the need for the user to become an expert on the intricacies of navigation systems such as Loran-C and GPS. The systems reliability will be high because all the components are off-the-shelf commercial equipment and because NBS maintains the systems to minimize hardware failures.

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†The seventh base unit, the mole, is now defined in terms of the second.

††Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for that purpose.

REFERENCES

[1] George Kamas and Sandra L. Howe, Eds., Time and Frequency Users Manual, National Bureau of Standards Special Publication 559. Available from the Superintendent of Documents, U.S. Govt. Printing Office, Washington, DC 20402. Stock #003-003-02137-1. Price $6.00.

[2] Dick D. Davis, Marc Weiss, Alvin Clements and David W. Allan, Construction and Performance Characteristics of a Prototype NBS/GPS Receiver , Proc. 35th Annual Frequency Control Symposium, May 1981.

[3] David W. Allan and James A. Barnes, "A Modified Allan Variance with Increased Oscillator Characterization Ability , Proc. 35th Annual Frequency Control Symposium, May 1981.

[4] David W. Allan, National and International Time and Frequency Comparisons, Proc. 37th Annual Frequency Control Symposium, June 1983.

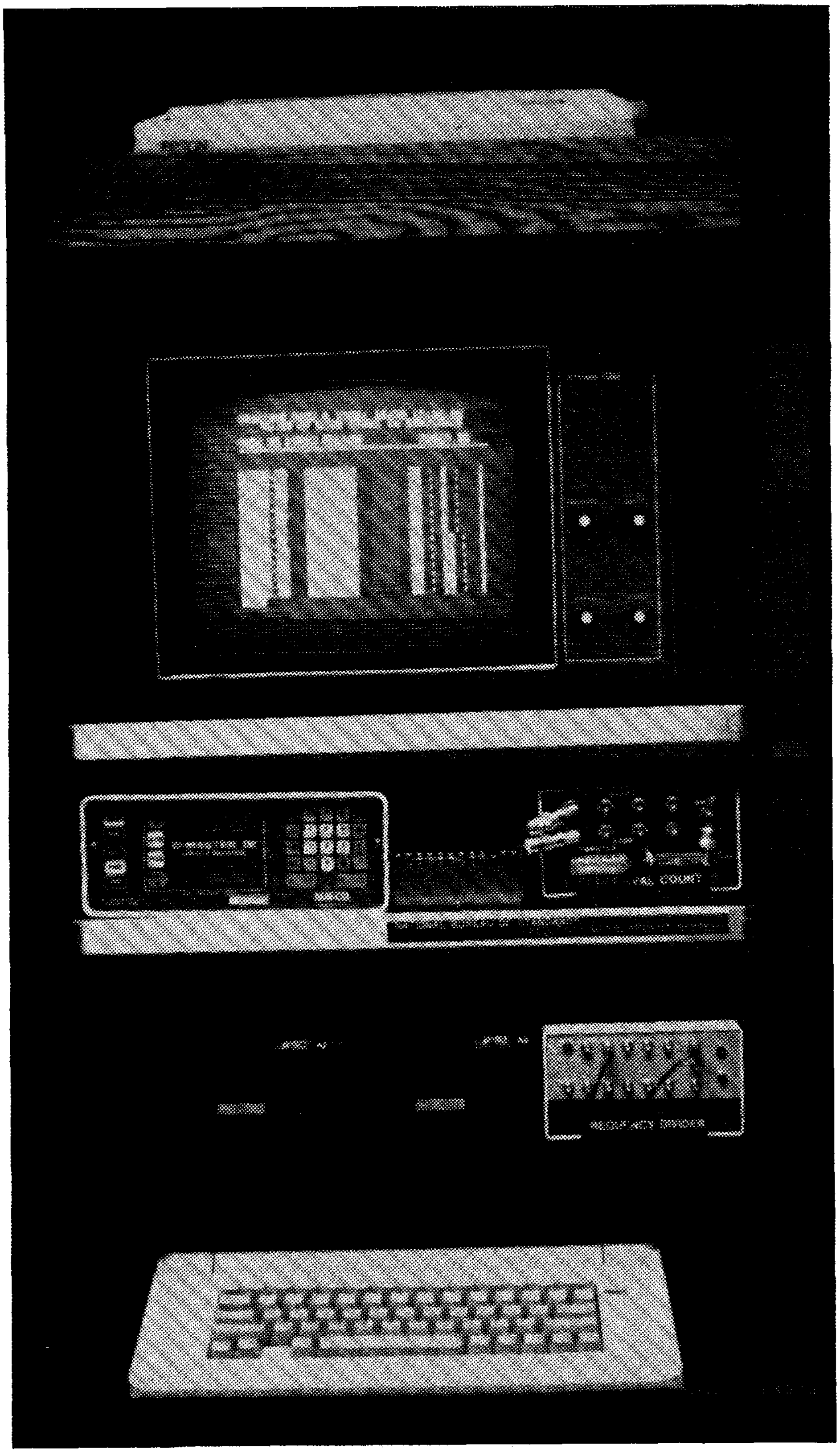

Figure 1. Photograph of frequency measurement system[†]

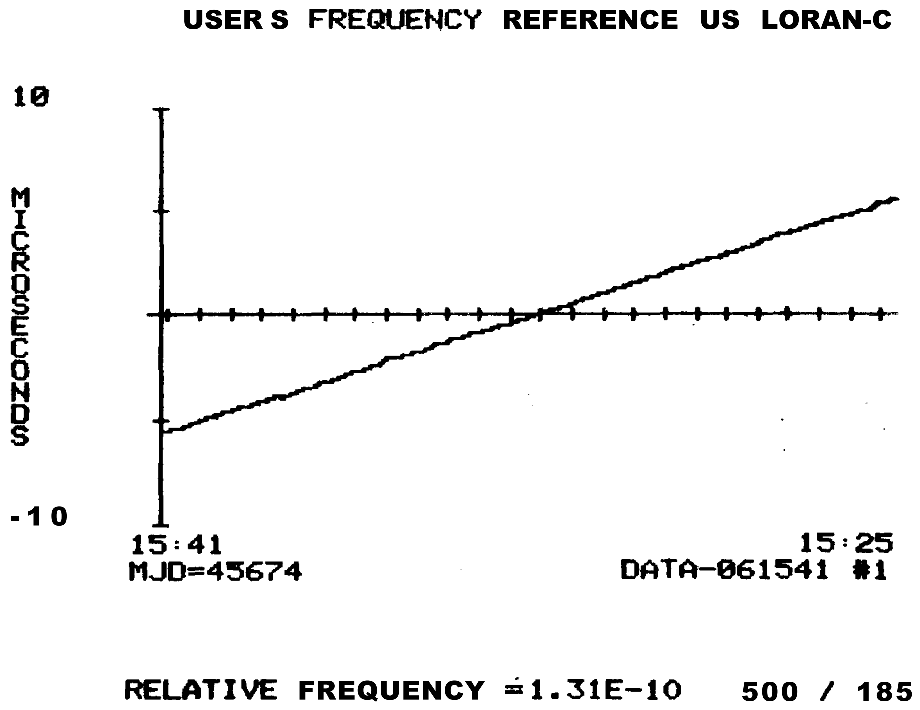

Figure 2, Sample plot of calibration data from the frequency measurement system

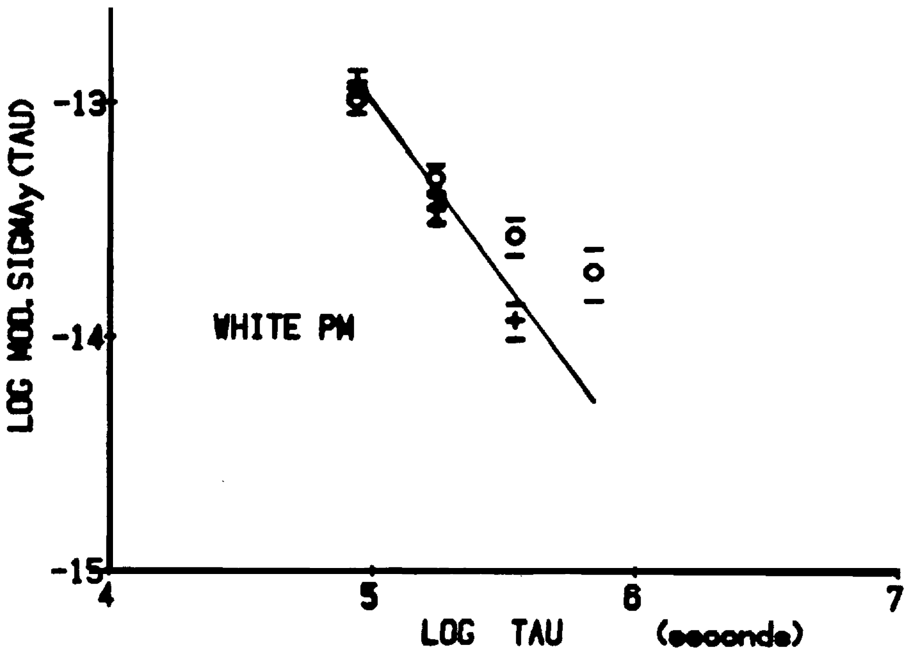

Figure 3. Modified Allan variance analysis of the NBS Global Time Service, The plus signs refer to measurement system noise and the circles refer to the noise of the reference clocks,

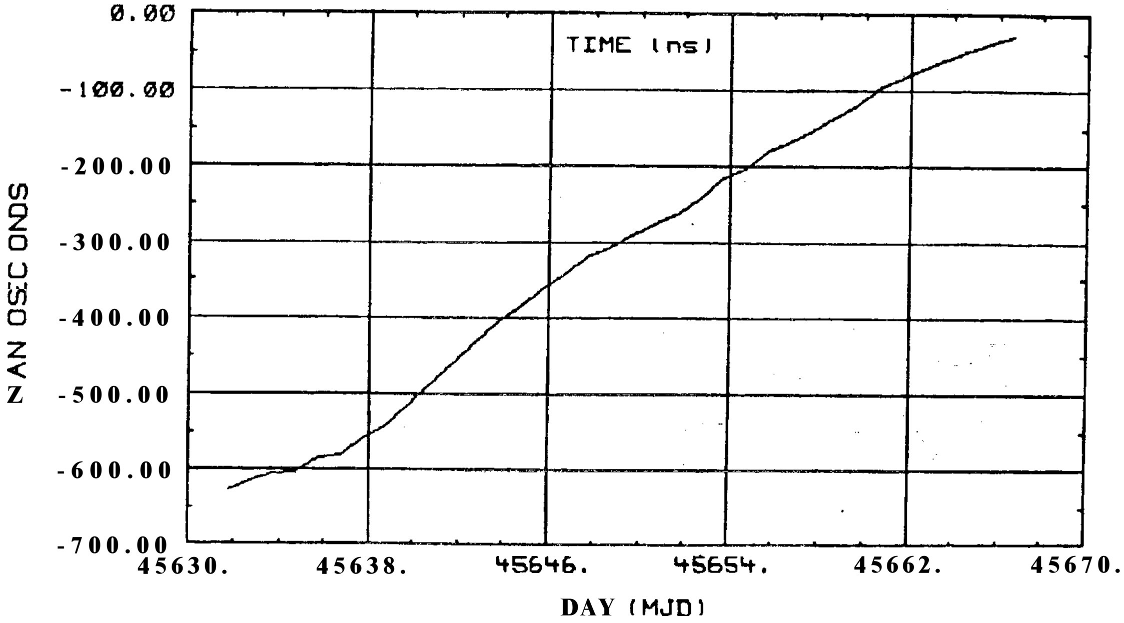

Figure 4, Sample plot of time transfer data provided monthly to users of the Global Time Service,

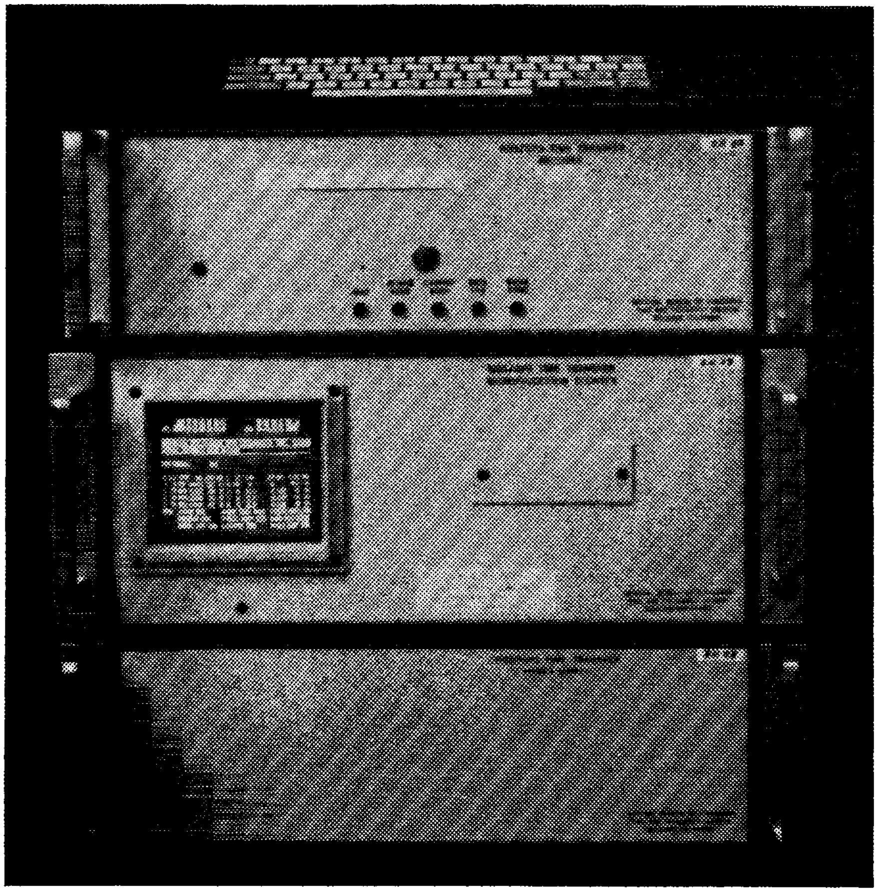

Figure 5, Photograph of prototype receiver for the NBS Global Time Service

SESSION V-D

SURFACE METROLOGY

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TRW Operations & Support Group

THE INTERACTION BETWEEN THE DEPENDENT MEASUREMENTS OF SURFACE FINISH AND SIZE

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Quality means better tolerances and more precise control over the production process. Surface finish measurement is a key element toward achieving these goals, but we must realize that they are not independent measurements and we cannot tolerance our way out of their dependency.

Surface finish is important for both cosmetic, function and performance reasons. Cosmetic obviously means having a better-looking product. As for function and performance, a particular surface finish may be required, for example, for the subsequent application of paint or a plating coat.

In another case, you might need an extremely smooth surface for a seal application, where you don't want anything to either penetrate or escape from the mating parts. For example, a fuel injection pump must seal properly so it won't leak gas - that is accomplished via proper surface finish.

Years ago, a cosmetic look was the main reason for surface finish. In those days, the fingernail and eyeball test, hold it up to the light and this kind of thing, were the rule. Today it's a different story. If you think back to the fifties, say in the automotive industry, you would have a 450 cu. in. engine and you'd burn the tires off the car and throw gasoline out the exhaust pipe. Who cared, as long as it made noise and moved?

But now we expect something with only 200 cu. in. to do the same thing. All the clearances have to be different, and there is an interaction between dimension and surface finish. Because when you measure a dimension with the stylus or point of an inspection tool, it rides on top of the finish, and the peaks and valleys that it encounters are, in the truest sense, both surface finish and dimension.

The automotive industry developed the first surface finish measuring gage in the late '30's. It was a profiling instrument that plotted a graph, enabling one to see in detail the nature of the surface. However, the instrument as very expensive, and not really what was considered at that time a "shop tool".

So they shelved what was a very good gage and adopted less accurate devices, the averaging instruments. These were more economical, both for their own costs and for the manufacturing practices their reduced accuracy permitted. And, they performed well enough In their time, when measuremerits were not so super-critical.

The problem with them is this; if you have a finish composed of many peaks and valleys, and they are widely separated and in between them the surface is smooth, YOU can get a very nice average reading. But yet, you might be a couple of hundred millionths of an inch above where the final wear line is going to be on that surface.

In other words, when you measure it, you see that it is "X" amount. But as soon as you assemble it to another part and run the assembly for five minutes or 'so, the clearances might have changed by some 200-300 millionths.

Now, if you look at the plunger of a fuel injector going into a body, you're talking about four surfaces. If each one of these surfaces is changed by only a hundred millionths each, the total clearancing has been changed by four hundred millionths, or four tenths of a thousand.

Today, the normal clearances for fuel injectors are 5-10 millionths. So surface finish is critical, and the averaging technique is not good enough, because a number of peaks with a good smooth surface between them and a number of valleys with good smooth surfaces between them can measure the same average.

If a part is to be prepared to a certain size and painted, the function of that part surface is to help the paint adhere to the surface in a smooth manner. should the end function of the part be the oiling or wiping of another surface, as is the case in the cylinder lines, a different pattern of surface finish is required.

The same pattern in one would not function in the other case, yet in using averaging (R_a) readouts as the sole method of determining surface finish, both patterns could have the same average reading, notwithstanding their unsuitability for the other's function.

And so, in some applications, more knowledge of the surface texture is required. We must go into greater detail about how we measure surface finish - the need for better clearancing has shown us the deficiencies of measuring averages. In the old days, when we had big clearances, it didn't matter.

It's time we went back to the original reason for dimensioning anything, to re-investigate why we want a particular tolerance. And the reason is the function of the part surface. And to make that part surface more exactly, in terms of its function, you need to measure more than average. There are more parameters to take into account and you are seeing them specified more and more on engineering drawings.

These parameters have been on European blueprints and specifications for some time now. They were forced to take an earlier look than we at energy conservation. For instance, at one time in the U.S., we'd make 200,000 parts and throw 50,000 away - because they didn't fit, because it didn't cost that much to make them and because it didn't pay to measure them.

We can't do that today. The material in those 50,000 we threw away costs money. And we expended energy making those parts. We now have to make sure those parts are right, whether the reason is the price of gasoline or electricity, the scarcity of a material, competitive pressures, or whatever.

Let's take the price of electricity as an example. When you go into the stores today/you'll see an energy efficiency reading on refrigerators, fans, air conditioners, and so on. This rating has to do with the motors and air compressors in the equipment, and it's all a question of tolerancing.

Think back to the transformers we had in the early fifties. Essentially a motor winding, the transformer was comprised of an assembly of laminates with wire wound around it. The buzzing noise you would hear from those transformers occurred because the assembly was packed loose.

Today that assembly pack is tighter, reducing core loss and subsequent energy waste. Previously, when the surface finish of the laminates was not controlled properly, the peaks on individual laminates poked through and touched another when they were pressed together. This would cause what, technically speaking, you could call a short and - core loss. Today the laminates for motors have almost the same surface finish specification as that of automotive sheet steel.

Anyway, the upshot is that averaging is not an adequate technique. In the mid-fifties, here in the U.S., we began to come around to the idea of a peak count, where you draw a mean line through the profile graph of a surface and then count the peaks and valleys above and below two other lines, which are parallel to the mean line and set a distance from it that represents some permissible deviation.

This technique originated in the automotive industry when they were looking for a way to reduce the amount of paint-they applied to their cars. If you recall, the automobiles from the forties and fifties, you'll remember really thick paint coats, perhaps they were something like 0.020 in. thick.

But that cost money, and the industry wanted to cut its costs. However, with thinner coats, they found that the irregularities of the sheet metal surface caused the paint to peel and chip somewhat. So they thought,"Well, if we make the sheet steel surface smoother, the paint will be smoother."

That's true, but another thing happens as well - by making the surface smoother, it was more difficult for the paint to properly adhere. Not only that - the metal surface became so smooth that the metal lost some of its malleability.

When you bend anything, you cause the material to flow, and if the material is too smooth, there's no place for it to flow. For example, when bending a fender with a draw die, a great deal of stress is created and a lot of material is moved. The auto people found that their newly-smoothed metal was tearing in the dies.

The solution was to create a surface that has some roughness to provide malleability to the metal. At the same time, that roughness had to be consistent to permit the paint to flow smoothly. The way to accomplish that was to specify so many peaks per inch, and to employ the appropriate surface finish measuring equipment to keep that figure consistent.

Peaks, valleys, Rt, Rp and so on are the "new" parameters that are turning up in surface finishing requirements. In reality, there's nothing at all new about them - the first profile recording instrument, developed in 1936, could plot a graph which contained all the information that you'd ever need to know about a surface. The difference now lies in the more sophisticated and detailed way we interpret that information.

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The United States and most of the major countries of the world have standards for the measurement of surface finish. At this point in time, all of them require stylus-type instruments, where a diamond tip contacts the part and moves along the surface,

Those little patch charts you see, with ten or so blocks on them, are a basically illegal eyeball scheme for measuring surface finish. Not only that - they don't work.

Those patches are made by a certain process and then duplicated. But if you machine your workpiece by a different process, the finishes will not compare to one another. If you happen to make your part the same way a patch was made - for example, if both surfaces are Blanchard ground - then you can compare one to the other.

But unless the surface finish comparator is made by the same process by which the part is produced, using those patches will never work. But they didn't cause much harm in the past, because you probably could have forgotten to measure surface finish in the old days and it wouldn't have mattered.

So you're forced, today, to go to a stylus instrument. The simplest ones use a skid - you simply drag the stylus/skid assembly across the part and an average reading can be derived from the multiple inputs.

Originally we used meters. They would jump and flicker, showing you the different readings from each point the stylus contacts. You had to eyeball the meter and average out all the flickerings. Now, with digital readouts, the instrument does the mathematical work, and when it's finished it gives you an average for all the readings it took along its stroke.

But, again, the averaging instruments don't tell you whether deviations are peaks or valleys. So the next level of sophistication is the profiling instruments, where the stylus transmits its readings to a hard-copy graph output.

And then we wanted to find out not only whether the deviations were peaks or valleys, but also info like how many of them occurred per inch, what is the total peak-to-valley distance within some specified section, and so on. So the next development, in fact the state-of-the-art, is the microprocessor-based profiling instruments. They not only collect information about parameters - they do statistical analysis as well.

You can instruct the instrument to take ten readings, and it will come back and not only tell you about the deviations - it will also tell you what the confidence level of its results are. If it gives you, say, a 60% confidence level, then it's up to you to decide whether that's a number you'd like to hang your quality control hat on, or whether you'd like to take some more readings.

Naturally, to get a good picture of surface finish, you'll want to measure in several different places. And if you do that, you're going to get some randomness in the numbers you pick up. Lots of people tend to blame the instrument when they get all kinds of funny numbers, but most likely the variance is from the surface itself.

In most cases, 5-10 readings should give you a clear idea of your surface finish condition. If the spread between those readings is extreme, however, you'll have to take more readings.

There's another way to look at it as well - if the spread is that bad, you may not want to make the surface the way you're making it now. You may want to process the part differently. And once you've established the optimum method for producing your part, you may be able to sit back and only select one or two surface finish parameters that need to be checked to control your process.

One thing you should be very careful to to is this; once you've established the correct process and a couple of control parameters to watch the process, don't change it. And that includes not buying grinding wheels from a different company than the one you bought your Original wheels from.

Surface finish is becoming more and more important, and design engineers are reflecting that trend with the specifications they put on their drawings. What the Quality Control Dept. has to do is thoroughly understand the surface finish terminology, monitor the machining process for repeatability, and have the equipment that will give them readings that match the standards.

We find that there is a tremendous lack of knowledge in America about the new parameters. In fact, there is even a tremendous ignorance about the old parameters. We give lots of talks on surface finish to customers and at various dinner meetings, and we find that even the original surface finish gage invented in the late '30's is sometimes not even being used properly,

A number of the larger corporations, however, have initiated studies into surface finish in the last few years, and I believe you're going to see a lot more of these new parameters coming out on their drawings soon.

My advice to the average designer, the average inspector, would be to learn a little bit more about the art of surface measurement and what these new parameters are. The actual measurement is relatively easy, because we still do it the same way - it's the calculations that the surface finish equipment are making that have changed.

Do some reading on the subject. You'll find that there are quite a few lectures and symposiums given by the different societies - SME, ASQC, and so on.

Learn what's coming down, don't just try to adapt and convert what you know to the new specifications. There are some people who insist that you can convert from one parameter to another mathematically, but that's not always true.

For example, they say a factor of four will convert Ra (average roughness) to Rt (the highest peak-to-valley reading). Mathematically speaking, if you confine yourself to a particular form, you can do it. But practically speaking, we don't make parts that way.

A very common master used in the U.S. for calibrating surface finish is cut with triangles, and the average reading on a triangle is exactly 1/4 of the peak-to-valley height of a triangle. But when you machine a part, you don't machine triangle patterns on your part surface.

So, that number '4' is incorrect already. But there are a number of people around the country who insist on "Well, if they want me to measure the Rt, which is the peak-to-valley high, I can just use my averaging instrument and multiply by four."

In reality, they can be as far out as ten. On a given part surface, if the average reading was 15, the peak-to-valley high could be 150. It could be 50. It could be 75. There is no graph, with those averaging instruments, to tell you what that difference is.

So this is a point of caution I would like to stress. Don't listen to math teachers, because the math is often only correct for the example that was used to create the formula. We don't make parts like models in space, we make them with grinding wheels, and other tools, which can leave a variety of different surface patterns, for which there is no one single mathematical equivalent.

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Another point I would like to stress is this - monitor your process closely. Different workpiece materials, different grinding wheels, different diamond compounds - they all cause surface finishes to come out differently.

There are certain centers you can consult that will tell you the proper feeds and speeds to use on different materials to produce a specific effect - the Met Cut facility in Cincinnati is probably the most famous.

The U.S. Standards Committee is now looking into the possibility of having a data bank, something like where you'd tell them you want to make some piston pins, and they'd say that piston pins should be like this, this and this, and have a surface finish like that, and so on.

This kind of thing will probably be a long time coming, though, because of the problems we face with proprietary processes in this country.

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AUTOMATED NONDESTRUCTIVE PBS^{TM} MEASUREMENTS OF SURFACE AND SUBSURFACE DEFECT DISTRIBUTION IN SILICON AND GALLIUM ARSENIDE WAFERS

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ABSTRACT

Measurement of scattered light has become more important during the past few years because of the increased ability to use this information for evaluating supersmooth optics and the polished surfaces of other materials including semiconductor wafers. Single point measurements, even of scattered light, are also no longer sufficient for characterizing surfaces since it has been found that point-to-point variations can be far greater than had been suspected. The instrument described in this paper is a highly accurate scatter measuring system capable of taking more than 100 million data points in a 125 x 125mm square area and displaying that data in the form of a map. The maps can be used to analyze both the surface and subsurface characteristics of a test article and the information used as a feedback mechanism to change the production process toward improved quality. Automated, the measurement method can be used for nondestructive inspection (NDI) of wafers in a cassette-to-cassette incoming quality control system.

INTRODUCTION

There are a variety of methods available for the characterization of polished surfaces which use light, particularly laser light, as the probe. Those that measure light scatter can be divided into two major methods, total integrated scatter (TIS) and scatter as a function of angle or bidirectional reflectance distribution function (BRDF) . The research instrument described in this paper falls into the second class. Although it was built as an internal research project by VTI (1), it can trace its roots to an earlier device (2). The older equipment showed the value of examining areas of an optical surface, as opposed to using single points, and the necessity for multiple degrees of angular freedom. Examinations conducted in References (3) and (4) showed how valuable the interaction between a detailed measurement scheme and the manufacturing process can be toward improving that process, and how the measurements can help in the understanding of the process and its effect on the material being processed.

Measurement Science has only one goal, to generate information. It is arguably true that physics makes no progress through the work of theorists but rather through the art and science of measurement. Clearly, they are interdependent, but only measurement can be proof. Industrial processes are also measurement driven. In-process measurement controls manufacturing quality within bounds, and after-process measurement provides assurance that the individual unit is worthy of further consideration.

The instrument described in this paper provides new information on the areal distribution of the subsurface defects in semiconductor materials which are having a detrimental effect on device yield. It can have cost reduction value as an automated, cassette-to-cassette incoming wafer inspector and can be used in its research form by wafer suppliers to make better materials.

It has been stated by a major circuit manufacturer that current incoming wafer inspection methods are only 60% effective in catching wafers which should not be processed further. It will be possible to stop wafers which not only have detrimental surface defects but buried damage which effects VLSI and ULSI yields and is not seen by current inspection techniques. Since our instrument is capable of nondestructively seeing below a wafer's surface, the information it provides can be fed back to the wafering process toward producing damage-free material. That is, wafers can be made, measured, and returned to the process to see if they can be improved. Damage-free wafers not only will improve yields but allow circuits of larger areal extent to be built. In fact, subsurface damage reduction is the first step toward realizable wafer-scale integration. This will be true not only in silicon but in new semiconductor materials such as gallium arsenide, indium phosphide and the others because the PBST^{M} instrument sees below these surfaces with equal facility.

Our research instrument is capable of making precise angular scatter measurements as well as surface X-Y scans covering any shaped area which will fit in a 125 x 125mm square. Data points can be separated by as little as 10 microns; typically multiple steps are used between data points. All data are converted directly to bidirectional reflectance distribution function (BRDF) values in parts per million per steradian (PPM/Sr) of the incident beam (5,6).

Current studies with this equipment include measurements on optics, semiconductor wafers and Winchester disk platters, but a large variety of different materials and surfaces can be measured and new uses for this data continually arise.

EQUIPMENT DESCRIPTION

A block diagram of the VTI research instrument is shown in Figure 1; its measurement sequence is computer controlled. All the optical equipment and some of the electronics is mounted on a floated optical table inside a clean room. The computer and output devices are mounted in a rack outside the clean room. It should be noted that the research tool is somewhat overdesigned for the task described in the title of this paper. Figures 2 and 3 are photographs of portions of the research equipment to illustrate that point. In addition, the overall research system is calibrated on a regular basis by using a lambertian surface reflectance standard in place of the test piece. The reflectance standard is a barium sulfate plaque which has a diffuse reflectance of 98%,±2%. The surface is X-Y scanned as an optic would be with more than 60,000 data points being taken. This information is then averaged and used to compute a scale factor which converts the photomultiplier readings into PPM/Sr.

A He-Ne laser at a wavelength of 632.8nm is the incident light source, with the beam being spatially filtered and focused to a small spot on the surface of the test part. A small fraction of the light is extracted and used to monitor the incident beam intensity.

As each data point is taken, it is modified as shown in equation (1) before being stored on a disk:

$$DP = SF \frac{P}{R\cos\theta} \qquad (1)$$

SF = Scale Factor
DP = Data Point in PPM/Sr to be stored on disk
P = Photomultiplier reading
R = Reflectance of test part
θ = Observation angle of the photomultiplier system (6)

This information can then be displayed in a variety of ways for study, but most conveniently as BRDF maps on a color graphics monitor (Figure 3) or printed with a color ink jet printer. A color contour scattermap of the test surface or subsurface can then be plotted as desired. Color maps were not permitted in the written version of this paper.

MEASUREMENT RESULTS

Since the research equipment was put on-line in April 1984, a large number of optical and electronic parts have been examined. What this version of PBS has done with respect to silicon and gallium arsenide wafers is to show that it is possible to nondestructively measure a subsurface distribution of damage most people in the Industry thought had been eliminated. For the standard four micron geometry, this remaining damage may be a problem only if it is very heavy. For geometries below 1.2 micron, however, this slight remaining damage is a device killer. Figure 4 is a vertical section through a typical silicon wafer (caveats for GaAs are included in the figure title). It should be noted that the uppermost zone, the M-Layer (after Dr. Tom Magee, XMR Corporation, its discoverer) is comparable to the Beilby layer in optics; there are differences, however. The Beilby layer is really a mechanically applied coating which is an amalgum of glass, polishing compound and water, for the most part. It has an index of refraction which is slightly different from the bulk material and exhibits a tendency to debond when subjected to heat pulses or vibration.

The M-Layer has a different character, instead of being an amalgum, it appears to be a solid phase recrystallized layer. In the Beilby layer there are signs of incipient melting. Calculations show that with the low thermal conductivity of fused silica, it is possible for the polishing pressures and speeds to create temperatures high enough to cause local surface melting. The same pressures and speeds generate high temperatures on the surface of silicon during polishing, but the much higher thermal conductivity of silicon is enough to prevent surface melting. It is this thermal conductivity -which allows a layer 40 to 300 Angstrom thick to heat sufficiently for solid phase regrowth. Although the M-Layer is better in crystalline character than the damaged zone beneath, it is not as good as bulk material. If the polishing pressures happened to be very high, a region of voids is often found at the bottom of the M-Layer. The voids are generally horizontal (long axis parallel to the M-Layer) and tube-like. They seem to be simple pressure relief dislocations.

Below the M-Layer, damage increases with depth, peaking at 1000 to 3000 Angstrom depending on the polishing process parameters. Thereafter, the damage decreases with depth until it finally disappears into bulk characteristics at depths near 2.5 micron in some of the newer silicon wafers.

Gallium arsenide is somewhat different in that it exhibits a thinner M-Layer and can have deep damage which goes all the way through the wafer. Its sensitivity to normal processing is very great, leading to a description of the material as “very soft”. In fact, gallium arsenide is very brittle and has a low yield strength, thus even cleaning steps can generate subsurface damage, often without surface manifestation.

The subsurface crystal damage found in these wafer materials after etch and decoration varies with the manufacturer, however it generally falls into three categories: (1) lineations [scratches], (2) pits, and (3) swirls, or irregular shapes. containing smooth curves. Those whose experience in microelectronics goes back two decades will recognize this problem as an old one thought to have been solved. In truth, solutions to this problem depend on circuit geometries; what is adequate at four micron may be totally inadequate at 1.2 micron and below. The problem exists as one of magnitude and must be re-solved as geometries shrink.

The character of the damage mentioned above can be seen at the surface at various stages in the wafering process. The polishing step at the end leaves the surface very smooth and cosmetically free of most signs of damage. On the best wafers, a few pits a micron or two in diameter are all that can be seen in a dark field Nomarski after polishing. Below the surface, as depicted in Figure 4, damage is left in the crystal from the wafer's surface processing history. Saw damage is typically pushed into the crystal during the lapping (grinding) phase and lapping damage is added.

Consider an abrasive particle at the surface of a wafer. As it is being dragged along by the lap it digs into the wafer in order to remove material. Below its track on the surface, atoms are displaced downward in a groove which propagates into the wafer until the crystal lattice absorbs all of the stress. If the wafer were polished just until all of the physical surface groove was gone, residual stress and displacement would still exist in the sheets of atoms in the crystal below where the surface groove had been. New, very slow etchants can reveal this subsurface damage in destructive evaluation of the wafer. VTI's nondestructive Photon Backscattering (PBS^{TM}) method can also reveal this subtle subsurface damage. Other work by Dr. Magee, which is not yet published, has connected the subsurface damage delineated by the above nondestructive and destructive techniques directly to lower device yields in both silicon and gallium arsenide.

The restrictions applied to the publication of this short paper in the Conference Proceedings prohibit the use of color. Inasmuch as color is an essential part of the presentation of our data, no examples will be included in the written paper but will be presented at the 17-18 January '85 meeting, along with new photomicrographs of the type of damage revealed upon etching.

CONCLUSIONS

It might be useful to look at a PBS wafer inspector from the standpoint of impact on today's high quality fabrication, where yields are not so great, and assume that the whole silicon market was devoted to that type of fabrication. Although that is not true today, it will inevitably be so. In such a scenario, Table I could well be true.

It has been estimated by Government personnel working in the VHSIC program that at geometries below one micron, for the types of military circuits needed, yields will be 1-2% and costs will be approximately $5,000 per chip at such yields. If 100mm wafers are used and die sizes are approximately the same as the 64k DRAM (approx. 35,100 mils^2) 313 die per wafer will be manufactured, but only six circuits per wafer will be useful. In this case, processing costs of $30,000 per wafer would be experienced for geometries below one micron. This scenario is too harsh; greater efficiencies are possible and costs might well be only $5,000 per wafer.

Other work has shown that at geometries below one micron, subsurface defects dominate yield. Thus, to have only one bad wafer in 100 by today's technology is wildly optimistic for small geometries. Nevertheless, if we remain with that conservative assumption, the above processing cost losses would jump to $1.5 billion for small geometries. This is clearly an intolerable situation.

Of course, not all wafers made will be used for these geometries but unless both wafers and incoming wafer inspection improve, fab line processing losses will indeed rise toward those lofty heights, or geometries below one micron will be economically infeasible.

Our work indicates that some of the losses currently being experienced are not due to trained personnel missing bad wafers (because they are only 60% efficient), but are due to subsurface damage in wafers which otherwise appear to be perfect. Using VTI's technology as a guide, wafers can be improved. The heretofore unknown distribution of subsurface damage can be eliminated and, in at least one case, it has been. We hope to have the opportunity to discuss it during the oral presentation, as we do not now have permission to write about it.

Automated, cassette-to-cassette wafer inspection is now possible (Figure 5). Using VTI's technology as a guide, one silicon wafer has already been produced which is worthy of ULSI dimensions and wafer-scale integration. It was a factor of three better than the best experimental wafer we had ever seen and was about an order of magnitude better than the average VLSI wafer measured.

REFERENCES

(1) Silva, R.M., Orazio, Jr., F.D., and Sledge, Jr., R.B., "A New Instrument for Constant ($\beta-\beta_o$) Scattermapping of Contiguous Optical Surfaces up to 25 Square Inches." SPIE Conf 511-09, Aug 84.

(2) Orazio, Jr., F.D., Stowell, W. K., Silva, R.M., "Instrumentation of a Variable Angle Scatterometer (VAS) ," SPIE, Vol. 384.1982, p. 123.

(3) Silva, R.M., Orazio, Jr., F.D., Stowell, W.K., "Scatter Evaluation of Supersmooth Surfaces," SPIE, Vol. 384, 1982, p. 2.

(4) Stowell, W.K., Silva, R.M., Orazio, Jr., F.D., "Damage Susceptibility of Ring Laser Gyro Class Optics," SPIE, Vol. 384, 1982, p. 73.

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(5) Bartell, F.D., Dereniak, E.L., Wolf, W.L., "The Theory and Measurement of Bidirectional Reflectance Distribution Function (BRDF) and Bidirectional Transmittance Distribution Function (BTDF)," SPIE, Vol. 257, 1980, p.154.

(6) Harvey, J.E., "Light Scattering Characteristics of Optical Surfaces," SPIE, Vol. 107, 1977, p. 41.

(7) Strauss, William I., "Status 1983, a Report on the Integrated Circuit Industry," Integrated Circuit Engineering Corp., 1983.

TRAINING MODES AND TECHNIQUES

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Abstract

Describes the five modes of training developed by ISA in support of continuing education programs sponsored by ISA.

ISA's purpose, since its foundation in 1945, has been education. We have provided education through conferences, their published proceedings; we've produced training films, audio cassette programs, textbooks and periodicals, so, historically, the prime purpose of ISA is Education and because of our involvement and commitment to Education ISA enjoys a favorable not-for-profit tax status.

The acceleration in our Educational activities was brought about in December of 1978 when, under the leadership of ISA President Dr. Norman Huston, 22 leading executives were brought together comprising a Special Commission on Education and Training. The purpose of this Special Commission was to generate a set of policies, objectives and strategies that will provide explicit guidelines so that ISA, working with industry and academia, could develop extensive and intensive high quality programs of education and training for the total population of those interested in the field of instrumentation and process control.

The moving force behind this Special Commission was the firm conviction that there exists a constantly growing need in process control engineering for continuing education and training and that ISA must play a stronger role in developing and executing the education and training programs to meet these needs. Another conviction was that the effectiveness of our education and training programs will be the key to ISA's successes in coming years, and, finally, that we must undertake our educational goals in close cooperation with industry and academia.

The first priority objective was to develop, publish and distribute by 1982, a set of job skills and job descriptions associated with job titles that are recognized throughout the industry for engineers and technicians who are involved in developing, maintaining and applying instrument hardware systems.

The next priority was to develop curriculum guidelines for 2 and 4 year colleges and take steps to influence their acceptance by 1982. Such guidelines will encourage and assist engineering schools to either integrate instrumentation and control courses into existing engineering curricula or offer instrumentation or control options as a part of other disciplines.

Another objective was to expand our continuing education programs to complement existing programs so that instrumentation practitioners can obtain the job skills for desired level of competence. ISA uses five modes for the presentation of its continuing education programs. These modes are: Short Courses, Instructional Resource Packages, Self-Study, videotape based training systems and classroom "hands on" instruction.

Short Courses have been traditionally one of ISA's w-providing continuing education offering specialized training programs. The system that is in effect is a rather impressive one. ISA has offered short courses reaching 1,600 students, via 83 course offerings in 31 cities in a given year. Our courses are currently offered in Saudi Arabia, Abu Dhabi, South Africa as well as throughout the U. S. and Canada. But let's look at the system that is traditionally used for teaching short courses. I refer to it as the "star" system. We have identified a well known person who works for a company, who is able to get away from their duties two or three times a year, travel to cities around the United States, Canada and overseas to teach Short Courses. This means that we must rely upon this well-known individual, "the star," to be able to get release time, travel to a city where people are gathered to take the course offering. It is a rather inflexible system and its growth is controlled by several factors.

The first factor is the availability of the teacher to travel and teach a short course in usually 2 1/2 days - or approximately 16 hours of instruction.

The next factors are: expense to the student or the company - expense of employee release time, tuition for the course, travel, hotel and meals. In our current economy, this kind of training - as effective and excellent as it is - will be an increasingly expensive undertaking.

As good as our traditional offerings are, we still had to ask ourselves: how can we reach more students and at reduced expenses to them? One obvious answer was: to provide all the materials required to conduct the instruction. Thus, toward that end, ISA is creating packages of Instructional Resource materials which are transportable and the hours of the course offering are flexible. This program was developed in the following manner. We invited a specialist to draft a curriculum of the courses that were of greatest value to the instrumentation practitioner whether the student be engineer or technician. Some 55 courses were proposed, then reviewed by a panel of many experts. As a result, we ended up with a curriculum of 40 courses to be developed into training programs. The first 16 of these programs are now available, additional titles are in various stages of production, and additional authors are preparing manuscripts for Student Texts, Instructors' Guides and visual support materials.

The system, once understood, is simplicity itself. The materials of instruction consist of a student textbook, an elaborate instructors' guide and accompanying visual materials as required. This new configuration of training materials offers flexibility and opportunity for training in subjects that are of the greatest significance for process control.

The instructors' guides have been prepared by instructors who have offered these courses and know all of the "tricks of the trade" so the instructor's resource manuals, *in* the hands of a trained practitioner, will assist them in preparing the training and anticipating the kinds of questions and teaching problems that will arise as the course is offered.

The Instructional Resource Packages now available are on display in this room.

As indicated earlier, we use many different modes of instruction in reaching our goals. We offer training films, for instance, the 5 part Boiler Control film, films on Automatic Process Control, on Distillation Columns, on Control Valve Maintenance and others. We also use audio cassette modes reinforced by textbooks for each particular program. In addition to these modes, we publish and distribute textbooks, text workbooks and now something new - The Independent Learning Modules - for self-study.

The Independent Learning Module is an exciting concept. Dr. Paul Murrill, formerly Chancellor of Louisiana State University, now Chief Executive of Gulf States Utilities, known to many of you as a teacher and a writer, and ISA, have joined forces to develop an open-ended series of Independent Learning Modules designed for the **instrumentation** practitioner. These Independent Learning Modules are developed under Dr. Murrill's editorial direction, produced and distributed by ISA. The Independent Learning Modules are in four series of topics. The general series titles are:

1. Control Principles and Techniques
2. Fundamental Instrumentation
3. Unit Process and Unit Operation Control
4. Digital Computer Programing and Fundamentals

All ILMs are designed on the principle that they are for independent, self-paced, self-study instruction. No other texts or references are required when one starts to study each module. Each book is done in a unique two color format and a style of teaching techniques that make Independent Learning Modules a powerful addition to any resource or training library. ISA has plans to publish at least 4 ILMs a year. For the practitioner, or for the junior engineer coming to process control instrumentation for the first time, these books will form a living library for continued reference. Attention will be given uniformly to make certain that the mathematics required will be handled in as straightforward and as simple a manner as possible. One other feature of the Independent Learning Modules is that at the end of each unit there is a group of exercises. In an Appendix of the book, each exercise is worked out in detail so that there is no question as to how the solution was reached. We like to think that an instrumentation practitioner could sit on a desert island with an Independent Learning Module and be able to grasp the functions and procedures in 18 hours without any other assistance. We know that these materials will be basic for in-plant training of engineers, technicians, and other practitioners. We also know that these ILMs are being used as texts in study groups within the industrial as well as the academic setting.

The frosting on our "educational services cake" is the new videotape Instrument Technician Training Program.

ISA has long recognized that it was not serving the needs of instrumentation technicians in as dynamic a manner as, for instance, it serves the needs of process control engineers. There was on-going concern about reaching the technician with meaningful training programs, but as we explored the financial and manpower requirements, it seemed to us, at that stage in our growth that it was not feasible. Nonetheless, we had identified the great need for the training and retraining of instrument technicians and, quite frankly, we were stymied as to how to achieve this goal in a realistic time frame. When Industrial Training Corporation came to us to see if we could give them some support in their efforts of developing this program, which they perceived would be done by them over a period of 5 to 7 years, we immediately saw that this was the opportunity we had been looking for. The Education Department, sought and received approval from ISA Executive Board to enter into a production agreement to create, on an accelerated basis, the training progams that is now going to be demonstrated to you today. This is the largest investment ever made in ISA's history in a single venture and it is significant, we feel, that such an investment has been made in ISA's reason for existence - Education.

The learning objectives were established for each segment of each module by direct consultation with at least 10 technician training directors at 10 industrial training centers prior to script development. Many of these training directors are ISA members and are dedicated in their involvement. In addition to these experts, all aspects of the production drew upon technical resources as required. We emphasize this because we want to make absolutely certain that ISA uses the best resources, assuring that each module is technically accurate, reflecting standard practices in the field, as well as on the work bench, and we emphasize that all safety procedures are presented and followed in the correct manner.

The Instrument Technician Training Program consists of 22 training modules and the training is conveyed by the use of 59 one hour video tapes. Each "training segment" is approximately 8 minutes in length and at the end of each "segment" the trainee is referred to the text materials with the opportunity for the trainer to make the presentation "plant specific" by the introduction of hardware. As you will see in the demonstration, every aspect of the training program is covered for the trainee, trainer, and training administrator.

The final piece of news about ISA's increased participation in training is very exciting. In April of 1983 we opened our first training center in the heart of Raleigh. ISA acquired a fifty thousand square foot building in which we have arranged classrooms, and laboratories with the most modern equipment for "hands on" training. The equipment, either loaned or donated by the manufacturers, is valued at nearly one million dollars. In this facility ISA is offering a broad range of courses as described in the catalog available here. We invite you to visit us and inspect our training center; it may very well be the kind of a resource that will prove to be a valuable training opportunity for your personnel. If you will call me, or Dr. Douglas J. Kolb, Director of Educational Services, we will be pleased to make arrangements for your visit.

TABLE I

Silicon wafer sales 1984, approx.	$750,000,000
Assume avg. wafer $6, ea, approx.	125,000,000 wafers sold
If 1 wafer in 100 is bad, approx.	1,250,000 bad wafers which should not be processed
Assume only 60% caught (current efficiency) , approx.	500,000 bad wafers get through and are processed
If processing costs $100 /wafer (ICE est. 64k DRAM $120.43) (7) , approx.	$50,000,000 lost by the industry in processing bad wafers in 1984.

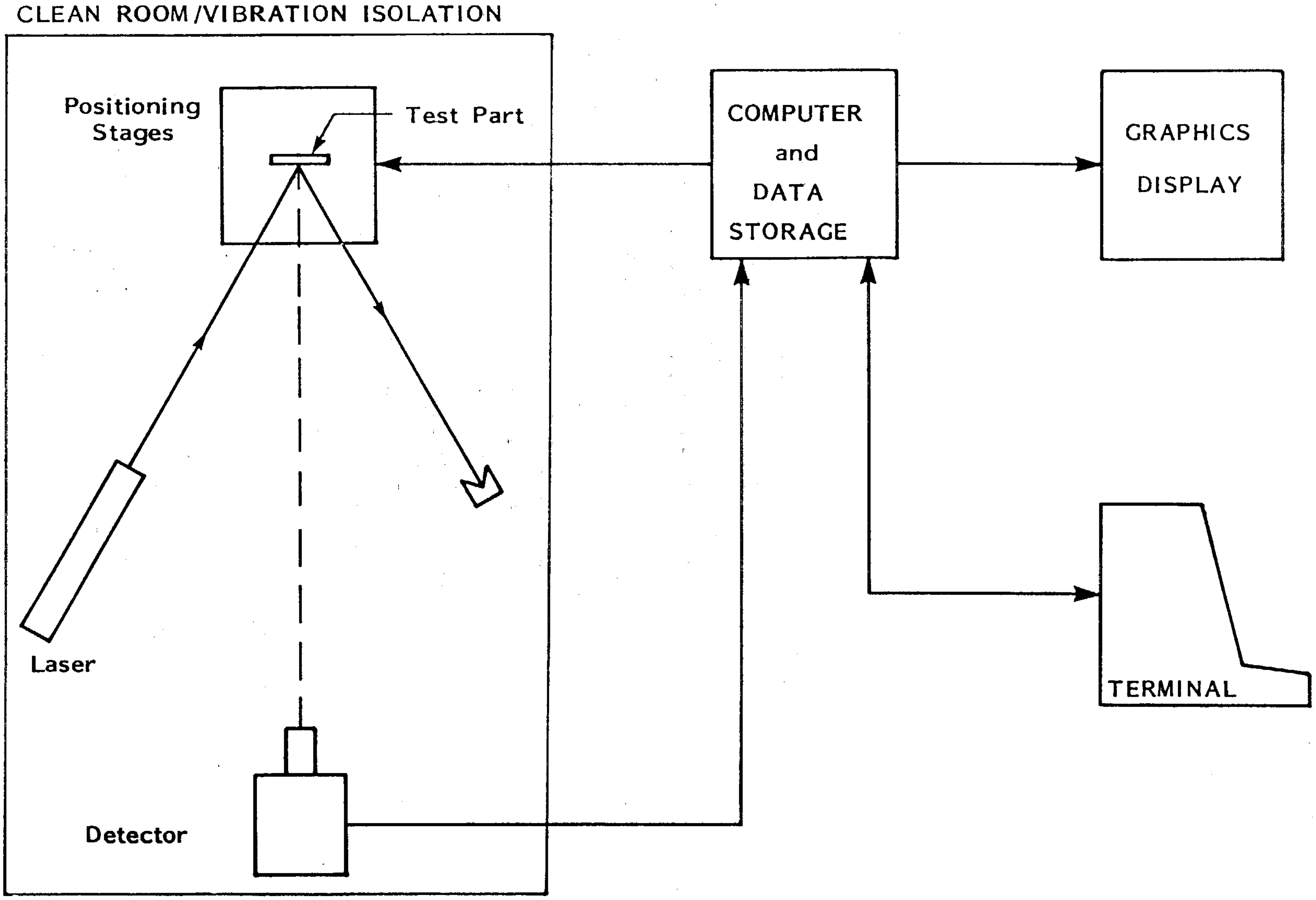

Figure 1. Block Diagram of the VTI Research PBS^{TM} Instrument.

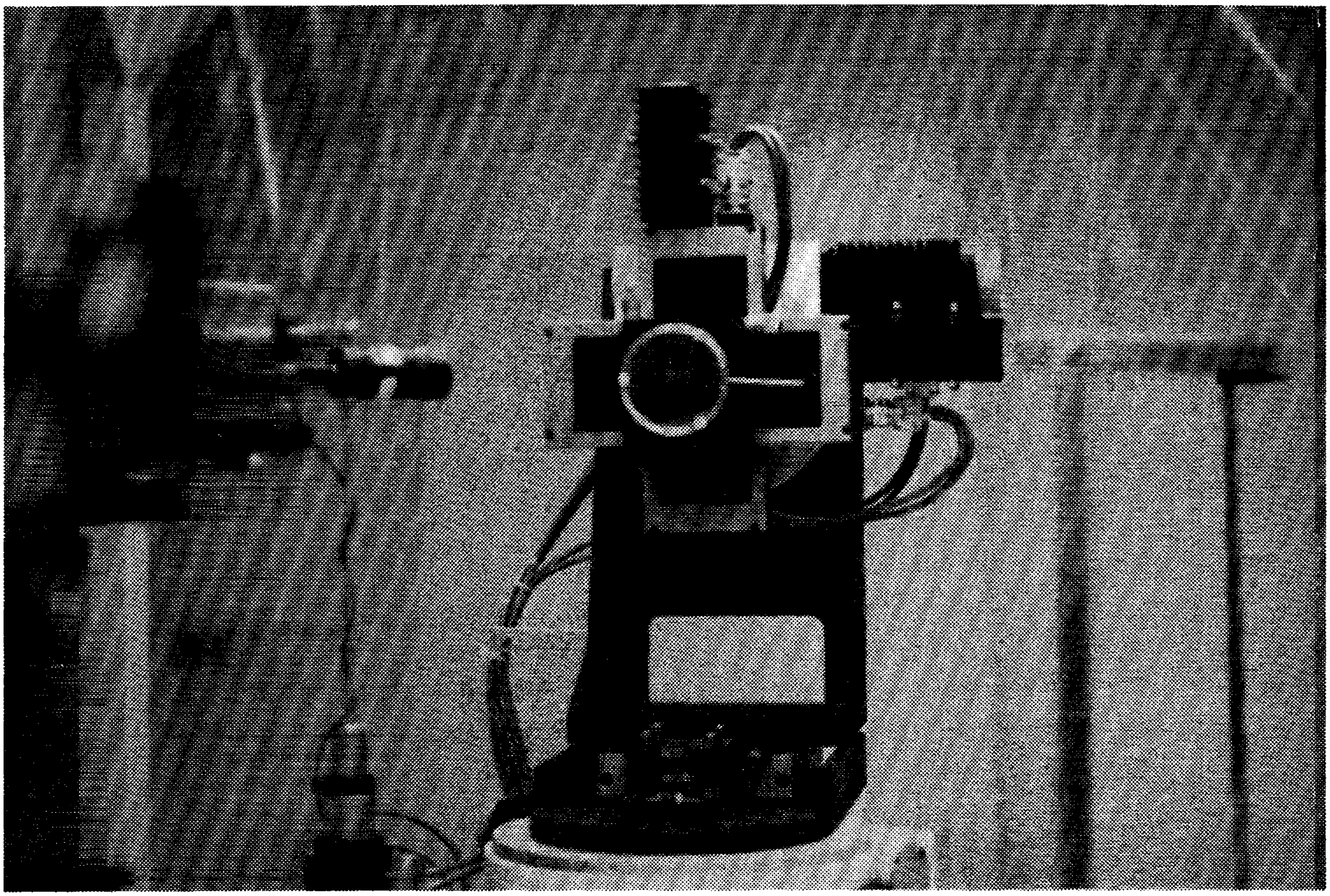

Figure 2. Test Part Manipulation System.

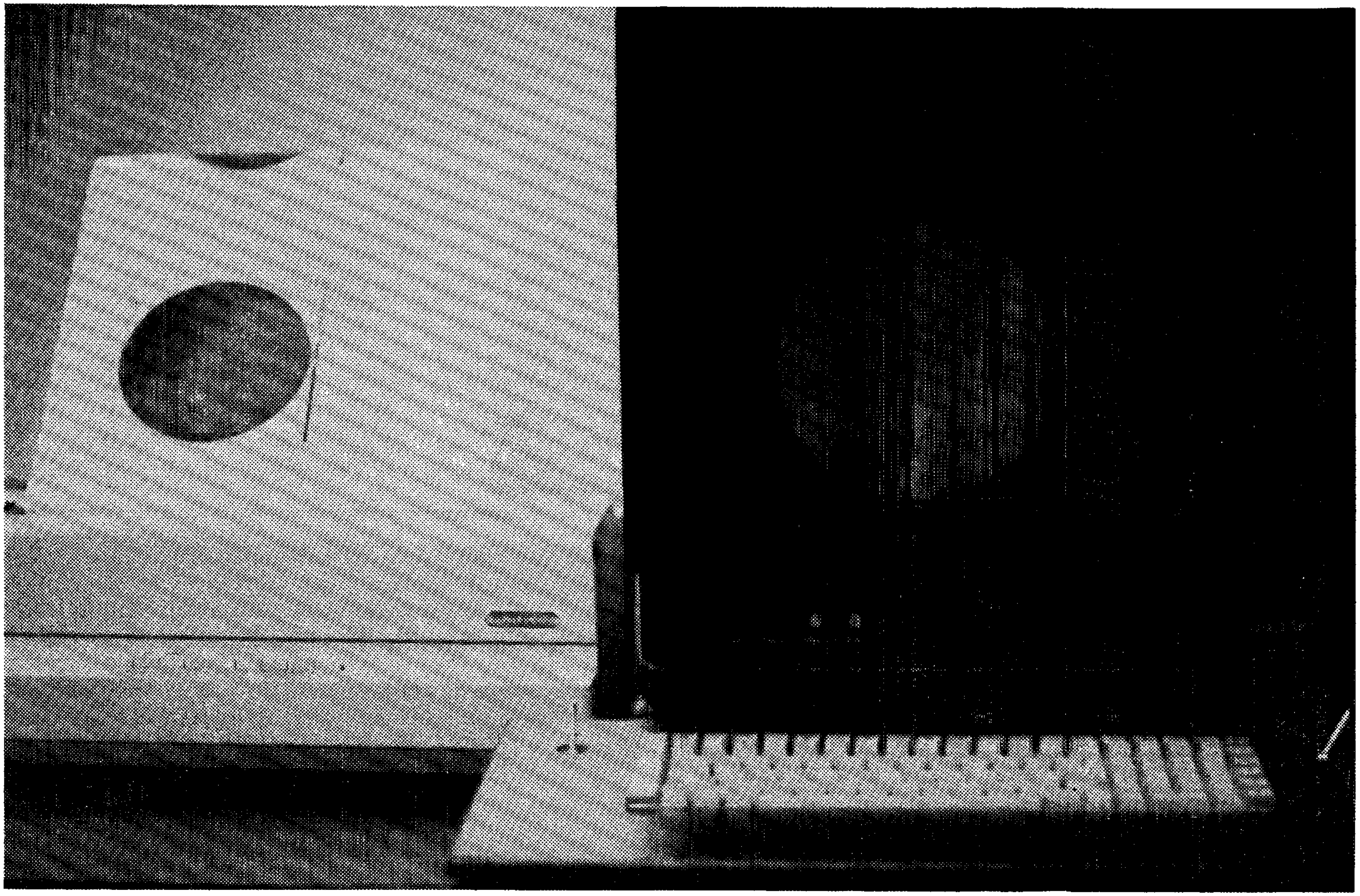

Figure 3. Color Graphics Output System.

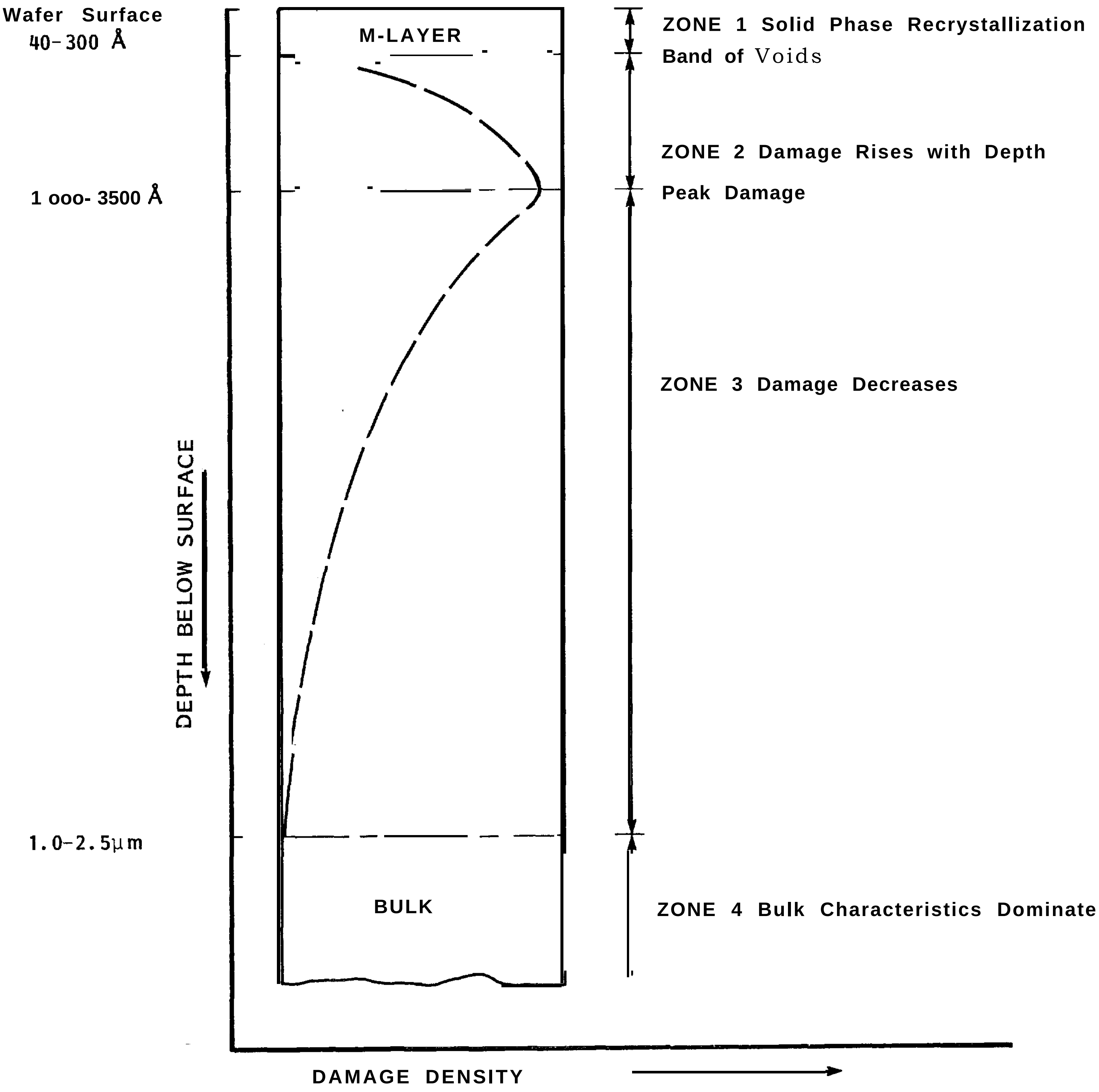

Figure 4. Damage density distribution with depth in silicon.
In GaAs Zone 1 is narrow and peak damage is closer to the surface.
Often GaAs damage goes all the way through the wafer.

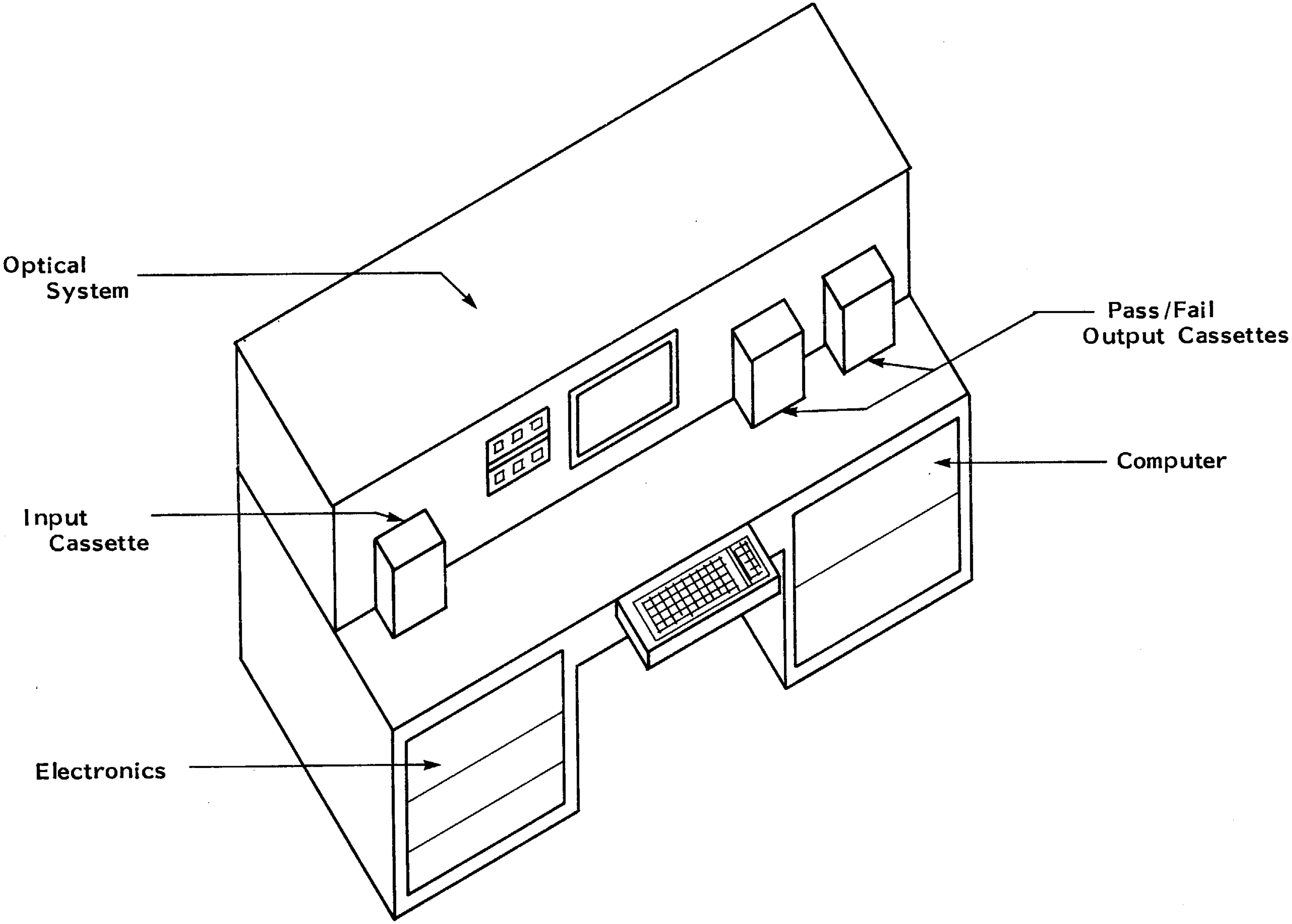

Figure 5. Artist's Concept of Wafer Tester.

SESSION VI-A

TECHNICAL EDUCATION AND TRAINING

John Martin
Westinghouse

SESSION VI-B

BAR CODING AND VOICE TECHNOLOGY

William A. Grant
TRW Operations & Support Group

VOICE DATA ENTRY APPLICATIONS

AT TEXAS INSTRUMENTS

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ABSTRACT

The Texas Instruments Professional Computer "Speech Command System" (tm) is being used increasingly for voice data entry (VDE) in production areas within the Equipment Group of Texas Instruments, Inc. This new data entry tool can potentially cut data entry task time in half by allowing hands and eyes to perform other tasks simultaneously. In addition, VDE reduces keystroke/translation errors and eliminates paper records for clean room environments. Applications, benefits and resolution of problems from a user's perspective will be presented.

INTRODUCTION

The Equipment Group of Texas Instruments, Inc. designs, develops and manufactures electronic parts and systems principally for the military services. The volume, complexity and exacting requirements of the processes involved have led to development and rigid application of sophisticated information management systems (on-line IMS inquiries and central data bases) for comprehensive realtime collection, analysis and reporting of activity, status and quality data covering the entire product cycle. One method of inputting the raw data necessary to feed these information management systems is to fully automate where possible with direct process-to-computer data transfer. However, this direct method is commonly not feasible and at the operator's workstation has been installed a computer input terminal with the additional operator responsibilities for keyboard data entry.

Most operators, although highly skilled in their manufacturing duties, are not usually proficient computer terminal typists. While the computer terminal clearly provides more timely data capture than manual paper logs which require keypunching, the terminal keyboard has not been an efficient input tool. To make an input on a keyboard the hands and eyes must be diverted from the normal manufacturing tasks. It is in this environment where the TIPC Speech Command System enables voice data entry (VDE) to offer significant potential for productivity gains.

TIPC SPEECH COMMAND SYSTEM (TIPC-SCS)

The current version (Release 1.03) of the TIPC Speech Command System, TIPC-SCS, includes software and hardware (speech I/O circuit board and headset microphone) to enable development of an application in a few hours. Using a TIPC-SCS software capability called the "Transparent Keyboard" the user can specify up to 9 vocabularies, with up to 50 "active words" each (450 words total). Every word (or short phrase) can be defined to replace up to a total of 40 individual keystrokes to represent any sequence of alphabetic, numeric, cursor controls, file names or batch commands, etc., when the VDE input is processed. This system is "speaker dependent", i.e., each individual operator says each of the words/phrases to create his/her personal set of stored voice print templates, a spoken input is compared with all the active word templates and the system produces an exact series of keystrokes for each input recognized. In bench mark tests, a substitution error occurs only 0.4% of the time, i.e., where the wrong word is recognized. This makes the TIPC-SCS especially appealing for voice data entry in selected manufacturing workstation applications.

EQUIPMENT GROUP VDE APPLICATIONS

Three years ago when VDE was first evaluated, using a competitor's system, a PWB (printed wiring board) assembly inspection activity was chosen for the pilot implementation. Procedures, equipment and workstation configuration vary somewhat from area to area within the Equipment Group depending upon the product size and complexity. But, the nature of the PWB inspection task, data recording time (2-4 hours per day) and the potential for fanout has kept the PWB assembly inspection application as the primary target for VDE implementation.

Three different PWB assembly inspection areas manufacturing radar, electro-optics and missile guidance systems, were each given a VDE application during 4Q83 for one TIPC-SCS workstation. The functional area managers responsible for these operations have conducted their own assessments, calculated the cost savings and decided further implementation based on their findings, budgets and hardware availability. All three functional area managers have concluded that the VDE application decreases data entry time (up to $0%), increases overall productivity (10-20%), and provides job enrichment for the employees. Based on these benefits, the PWB assembly inspection implementation is expanding from 3 workstations to 14 workstations.

Similarily, pilot applications were developed during 1984 for a fabrication gage operation to load calibration data, and for a clean room operation to load manufacturing process/status data. In these areas too, the findings indicate that VDE can free the hands and eyes to perform other tasks simultaneously. Each of these area managers respectively are expanding their implementation. The fabrication area has ordered additional TIPC-SCS terminals for five piece-part inspectors to use and the clean room area has plans to expand from 4 workstations to 40 workstations in early 1985.

PWB ASSEMBLY INSPECTION

In the PWB assembly inspection operation, the quality control inspector picks up each PWB and visually examines numerous features for possible defects. Based on size, complexity and requirements, many PWB inspections are performed under a magnification ring or a scope and during certain operations gloves must be worn. This activity fully occupies the operator's hands and eyes. Thus, to accomplish the required recordkeeping with manual data entry on either a log sheet or a computer terminal keyboard is very disruptive to the process. With a VDE equipped TIPC-SCS workstation data entry is accomplished with voice commands as follows: As the operator begins the inspection, he/she speaks a vocabulary word such as "POWER SUPPLY", which causes the system to fill in the IMS inquiry name and load the proper word order number and run number. Then the operator speaks "NEW BOARD" (or other type) and the system automatically fills in multiple fields of required data such as class of inspection, operation involved, and workstation number. A 4-digit manufacturing serial number and the latest revision letter are entered using vocabulary words. When a defect is observed, the operator speaks the descriptive phrase for a defect class, e.g., "EXPOSED COPPER", resulting in the entry of the corresponding symbolic code (which the operator no longer has to remember or look up on a list). The operator uses other verbal commands for cursor control and successive entry of multiple serial numbers and defect data until all the parts in a given lot - usually 50 to 100 - are inspected.

APPLICATION PROBLEMS/SOLUTIONS

After three years experience with VDE applications, the problems observed and resolved have occurred in four categories; application design, vocabulary selection, operator set-up (enrollment) and hardware limitations. The problems and solutions for each category are summarized as follows:

Application design problems start when the developer fails to learn the operator's existing procedures, natural words/phrases and syntax relationships. To solve these problems an experienced analyst must study the operation and identify the key words/phrases to employ in the application design. In addition, with the TIPC-SCS the opportunity to use the pre-defined 40 keystroke/command defaults for each word should be fully evaluated and incorporated into the design.

Vocabulary selection problems can be eliminated to a great extent in the application design, but a few phonetically similiar words can haunt an operator. This requires tailoring the application to each operator, Replace a specific problem word with another word or a two-word phrase. Certain rhyming letters of the alphabet frequently cause problems and therefore military words, e.g., "Alpha" = A, etc., should be used.

Operator set-up, or enrollment, problems are compounded by the operator's attitude towards and experience with a computer terminal. A new operator must get hands-on experience with the computer terminal and be introduced to the VDE application slowly (1-2 hours/day) the first week to gain familiarity without frustration. Some operators refer to their computer terminal with a "human-like name" to help overcome their own resistance and fears. A simple computer game, with speech controlled characters, is another technique to overcome fears. No matter what approaches are used, the final enrollment to create the operator's voice print templates must be made at the workstation with all the normal background noise.

Hardware limitations and the associated problems can be simple or complex based on the system employed. The TIPC-SCS hardware as purchased, off-the-shelf has been successfully used in the office and factory environment. Best performance for eliminating unwanted noise is obtained with the lower (0-3 scale) gain settings. Some workstation layouts or operator movement requirements may necessitate replacing the headset with a microphone on a gooseneck stand and/or adding an in-line on/off foot switch.

SUMMARY AND CONCLUSIONS

The PWB assembly inspection application is representative of a growing number of opportunities for utilizing voice data entry to enhance quality and productivity in manufacturing. Potentially, VDE can cut data entry task time in half by allowing the hands and eyes to perform other tasks simultaneously. Furthermore, since VDE requires no writing or typing skills it can reduce keystroke/translation errors, as Well as eliminate paper records for a clean room environment. The TIPC-Speech Command System is a very effective solution for voice data entry with less cost investment and more flexibility than the other new technologies, i.e., magnetic Strip readers, optical character readers, laser scanners, etc.

SESSION VI-C

MILLIMETER MEASUREMENTS/CALIBRATION CAPABILITIES

Algie L. Lance
TRW Operations & Support Group

CURRENT NBS METROLOGY CAPABILITIES AND LIMITATIONS

AT MILLIMETER WAVE FREQUENCIES

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ABSTRACT

The National Bureau of Standards (NBS) establishes national artifact standards and provides a metrology base for U.S. industry and technology. In the millimeter wave frequency spectrum, NBS has not established all of the required metrology to meet the needs of industry or government for this technology. It is the intent of this paper to describe the technical demands of responding to the challenger of millimeter-wave technology. A description of the current capabilities that exist at NBS will be given for those parameters and frequencies where measurement services exist. Where novel standards have been developed, such as the 94 GHz thermal noise standard, the physical basis for the standard will be described to indicate the changes from lower frequency designs and the challenges that had to be overcome. Limitations in services and in concepts of standards for providing those services will be described to indicate the degree of research that must be undertaken to satisfy future industrial needs in this evolving technology.

INTRODUCTION

There is a great increase in interest in the millimeter wave frequency spectrum for new and planned system applications. System performance and qualification require an established tnetrology foundation to assure compatible hardware from competing vendors and to validate the achievement of performance specifications. However, these metrology demands are often overlooked by system designers and their suppliers until disagreement over the level of achievement of systems, components, and devices can be verified to guarantee final performance specifications. When the system does fail and an intent exists to find fault, then a reliable metrology base is necessary to validate failure to perform to required specifications.

In some cases, military documents have also wrongfully assumed that NBS measurement support is available and accordingly call for traceability to, unfortunately, non-existing support services. NBS calibration services are listed in NBS Special Publication 250 (1,2), including special tests which are negotiated on an individual basis. However, millimeter waves are a rapidly advancing field, and it is therefore appropriate at this time to review the present status of NBS measurement services and plans for their further extension.

Within NBS the responsibility for services in the microwave and millimeter spectrum lies primarily with two divisions located within the Center for Electronics and Electrical Engineering, part of the National Engineering Laboratory. The Electromagnetic Technology Division is responsible for those parameters which are measured in, or relate to, guided wave structures, such as power, impedance, etc. The Electromagnetic Fields Division (EFD) has the responsibility for those quantities that are associated with free field measurements, such as, electromagnetic (EM) field strength and antenna parameters, In addition, EFD is also responsible for standards for broadband or thermal noise, In the following sections we will first look at the status of the guided wave parameter support services followed by the EM field related quantities. While some of the data presented will cover the upper microwave frequencies as a point of reference, the major emphasis will be on the millimeter wave area which, for the purposes of this discussion, are those frequencies above 18 GHz. In the material presented, no attempt will be made to cover the technical details of all of the various standards and calibration systems except in certain cases which are illustrative of trends in calibration technology, or where significantly different methods will be employed in the millimeter wave region. In the following sections the method of interface between NBS and its customers will be examined, followed by a discussion of guided wave and free field parameters.

METHOD OF SUPPORT SERVICE DELIVERY

Before continuing it might be well to briefly examine the method by which most industry and DOD laboratories make use of NBS measurement support services, since it is illustrative of how technology drives the state-of-the-art in these

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measurement services. Figure 1 shows a typical process by which the value of a national reference standard is transferred first to a working standard, then to a transfer standard, and finally to the industry working standard and test items. Note that both an artifact reference device (standard) and a mechanism for comparing the stdnddrd with an unknown are required. Both must be thoroughly characterized for stability and other necessary qualities. In most cases the transfer standard is supplied by the industry/laboratory requesting a calibration service and consists of the best commercially obtainable device related to the parameter in question. After calibration at NBS, its use is reserved for that of a laboratory standard. It is readily obvious that a national standard which either is no better than the transfer stdndard (in terms of accuracy and stahility) or is many orders of magnitude better, represents on the one hand a service of minimal usefulness or on the other, extreme overkill. In developing national standards the state of the technology is kept well in mind. However, with today's rapidly advancing science, it is often necessary to anticipate the accuracy that will be needed 5 to 10 years in the future.

POWER, IMPEDANCE, ATTENUATION, AND REFLECTION COEFFICIENT

The typical quantities for which measurement services are provided are power (P), reflection coefficient (Γ), attenuation (A), and scattering (S) parameters. Figure 2 illustrates over what frequency range, and through which method of comparison, these services are available. In the column labeled NBS system, the 100 kHz IF ANA refers to an NBS constructed comparison system which uses precision inductive voltage dividers operating at 100 kHz for ratio determinations. The precision rotary vane attenuator (RVA) is used for attenuation measurements in the 12 - 18 GHz range. The 18 - 26 GHz dual six-port referenced in the figure is presently under construction. Note that in some cases a coaxial instrument is made to serve a dual purpose by making use of coaxial to waveguide adapters. The uncertainties in measuring these quantities, as stated to the customer, are shown in figure 3.

In general, most of the recent internal development effort has been directed toward exploiting the six-port technology developed at NBS (3,4,5,6). Figure 4 shows a comparison between the older tuned reflectometer comparator, which is still used at some frequencies, and the newer six-port technique. The tuned reflectometer (7) consists of a generator connected to the device to be measured by a length of standard precision waveguide. By means of directional couplers, some of the forward power is sampled to maintain a constant level by which the reflected power is sampled and recorded. The reflection to be measured is compared to a standard quarter-wave short, using a piston attenuator in the IF portion of the phase locked detector for the ratio measurement. The unwanted reflections inherent to the system and the imperfect directivity of the couplers are compensated for by tuning stubs which must be adjusted at each measurement frequency. Attenuation can also be measured on such a system.

In contrast the sir-port is based on general principles of microwave scattering theory which can be applied to any arbitrary network of transmission lines. The most common configuration embodies six ports, one connected to a generator and any other defined as the reference measurement plane. Power detectors are connected to the remaining four ports. Linear functions relate the amplitude and phase of the incident and reflected waves to the power measured at the other four ports. A simple calibration procedure using arbitrdry but stable reference standdrds determines the coefficients of the linear equations. The only absolute standards required are a length of known-impedance transmission line (coaxial or waveguide) and a reference power standard if that quantity is also to be measured. Two six-ports connected to a common generator may be used to determine all of the scattering parameters of a two-port unknown. The whole measurement procedure can be controlled by a desktop mini-computer. Because of the versatility of the six-port, it is desirable to implement it in the millimeter-wave range also. An integrated broadband version using finline techniques, which is shown in figure 5, is currently under development at NBS. When power is to be measured, a thermal conversion device called a microcalorimeter is used as a standard at millimeter wave frequencies (8,9). By comparing the unknown power detection mount with the microcalorimeter on a six port, the efficiency and reflection coefficient of the unknown are determined.

The current future development plans for guided wave parameters are outlined in figure 6. Even at the projected rate of work it will be 4 to 5 years before the entire frequency range to 100 GHz is fully covered.

NOISE MEASUREMENTS

The NBS provides measurement services for the measurement of noise standards over a wide frequency range. Figure 7 shows the present and near future availability of the various comparators, radiometers, and the reference noise standards from 4 to 110 GHz. Note that there are wide areas where coverage is lacking. The reported uncertainties of measurements made with these systems are listed in figure 8.

Since the quantity to be measured exists by definition at a very low level, great attention must be paid to the comparison device, a radiometer, in terms of stability and resolution. Formerly individual tuned radiometers were used in each waveguide band, which required manual setup and operation. Recent advances in desktop mini-computers have enabled the development of six-port technology and broadband automated radiometers. Incorporating a built-in six-port at its input, such a radiometer can take account of various system mismatches besides applying statistical controls to evaluate system instabilities (10).

The extension of these services recently to the 90 - 100 GHz frequency range required the development of a new type of noise standard. This new design lends itself to exploitation for the millimeter frequency range. Traditionally, noise sources consisted of a coaxial or waveguide termination which was raised, or cooled, a certain number of degrees above or below room temperature (typically to 1235 K or 77 K). However, due to the large losses in the connecting waveguide, an analysis indicated that a specially designed horn antenna "looking at" a piece of microwave absorber which was cooled to 77 K would produce a known output temperature with the smallest uncertainty. Such a noise standard was recently constructed at NBS and is shown in simplified form in figure 9. Although deceptively simple in principle, a very elaborate analysis using optical ray tracing techniques, geometrical theory of diffraction, and techniques to analyze backlobe radiation effects was required in evaluating the effective output noise temperature (11).

Future plans in noise metrology are outlined in figure 10. However, since many of the requirements in the millimeter wave region are related to DOD requirements, progress is highly dependent on outside agency funding to NBS.

ANTENNA PARAMETERS

Except for the 40 - 50 GHz region, the measurement of antenna parameters of gain, polarization and pattern are fairly well established up to 75 GHz as shown in figure 11. The major deficiency is in the ability to conduct swept frequency measurements above 26 GHz. The estimated uncertainties of NBS measurements of on-axis gain and sidelobe level are displayed in figure 12. These uncertainties are dependent on the magnitude of the quantity and the gain of the antenna being measured.

The traditional method for measuring far-field on-axis gain and antenna pattern is to use an antenna range of sufficient dimensions to place the source (or sampling receiver) in the far field of the antenna. Figure 13 shows the separation distance required which becomes excessive for large, high gain antennas. While it is possible to measure on-axis gain in the near field using an extrapolation technique, accurate information on a sidelobe pattern is not attainable by this method.

For this reason NBS was instrumental in developing and implementing the near field scanning technique (12,13,14). If amplitude and phase are measured at points on a known grid in front of the antenna, as shown in figure 14, and the proper mathematical transforms applied to the data, it is possible to derive the far field amplitude and phase pattern of the antenna. The grid may be either planar or cylindrical, as shown in figure 14, or even spherical. In practice, the values derived by such a measurement technique are usually more reliable than those taken on far-field sites subject to atmospheric perturbations. This is particularly true in the millimeter wave region.

In planning to extend NBS antenna services as shown in figure 15, several problems must be addressed. Because of practical limitations in measuring physical displacements, electrical phase, and other quantities, there is an upper frequency limit beyond which the present NBS near-field scanning range will not be useful. It is believed this lies somewhere between 75 and 100 GHz. Beyond this limit, gain and polarization measurements will still be achievable using extrapolation techniques, once the necessary test equipment is on hand. Such measurement capability up to 220 GHz is planned by 1989.

OTHER MEASUREMENT QUANTITIES

Two other areas of measurement support will no doubt become important as use of the millimeter wave range increases. Phase noise measurements of synthesizers and stabilized signal generators will be necessary as these instruments become more common at millimeter wave frequencies (15). Although the Time and Frequency Division within the National Standards Laboratory has some capability for phase noise measurements there is no regular measurement service as such.

The electrical properties of materials used in the millimeter wave region must be measured and controlled more precisely if the cost of fabrication of components is to be reduced. The measurement of dielectric constant, permeability, and loss tangent up to 200 GHz, will have to be supported as major commercial uses for these frequencies develop. The Electromagnetic Fields Division is currently examining the need and justification for a measurement support program in this area.

SUMMARY

A basic review of present millimeter wave measurement services at NBS shows that there are many areas that are not covered, and probably will not be covered for many years. Various avenues are being explored, particularly within the DOD and its prime contractors, where the greatest need will exist, to generate support to guarantee there will be an adequate national millimeter wave measurement base (16,17).

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of Cletus A. Hoer of the Electromagnetic Technology Division for providing much of the data used in presenting the measurement services of that division.

REFERENCES

(1) Kieffer, L. J., Ed., "Calibration and Related Measurement Services of the National Bureau of Standards," Nat. Bur. Stand. (U.S.) Spec. Publ. 250. New editions published every two years. Appendix (price and current availability listing) to Spec. Pub. 250 published every 6 months.

(2) McClendon, L. T. and Kirby, R. K., Ed., "NBS Physical Measurement Services Status Report," Nat. Bur. Stand, (U.S.) NBSIR 84-2875.

(3) Hoer, C. A. "The Six-Port Coupler: A New Approach to Measuring Voltage, Current, Power, Impedance and Phase," IEEE Trans. Instrum. Meas., Vol. IM-21, 1972, pp. 466-470.

(4) Hoer, C. A. "A Network Analyzer Incorporating Two Six-Port Reflectometers," IEEE Trans. Microwave Theory Tech., Vol. MTT-25, 1977, pp. 1070-1074.

(5) Hoer, C. A. "Performance of a Dual Six-Port Automatic Network Analyzer," IEEE Trans. Microwave Theory Tech., Vol. MTT-27, 1979, pp. 993-998.

(6) Weidman, M. P. "A Semiautomatic Six-Port for Measuring Millimeter-Wave Power and Complex Reflection Coefficient," IEEE Trans. Microwave Theory Tech., Vol. MTT-25, 1977, pp. 1083-1085.

(7) Yates, B. C. and Larsen, W. "Millimeter Attenuation and Reflection Coefficient Measurement System," Nat. Bur. Stand. (U.S.) Tech. Note 619; 1972.

(8) Harvey, M. E. "WR15 Microwave Calorimeter and Bolometer Unit," Nat. Bur. Stand. (U.S.) Tech. Note 618; 1972.

(9) Weidman, M. P. "WR10 Millimeter Wave Microcalorimeter," Nat. Bur. Stand. (U.S.) Tech. Note 1044; 1981.

(10) Counas, G. J. "2.0 GHz - 4.0 GHz Automated Radiometer Operation and Service Manual," Nat. Bur. Stand. (U.S.) NBSIR 83-1697, January 1984.

(11) Daywitt, W. C. "Design and Error Analysis for the WR10 Thermal Noise Standard," Nat. Bur. Stand. (U.S.) Tech. Note 1071; 1983.

(12) Wacker, P. F. and Newell, A. C. "Advantages and Disadvantages of Planar, Circular Cylindrical, and Spherical Scanning and Description of the NBS Antenna Scanning Facilities." Proc. European Space Agency Symposium. Noordwijk (Netherlands), June 6-8, 1977, pp. 115-121.

(13) Repjar, A. G. and Kremer, D. P. "Results of Planar Near-Field Measurements on a Compact Range at 18 and 54 GHz," Digest, 1980 IEEE/AP-S Symposium.

(14) Stubenrauch, C. F. and Newell, A. C. "Some Recent Near-Field Antenna Measurements at NBS," Microwave Journal. Vol. 23, No. 11, November 1980, pp. 37-39.

(15) Lance, A. L., Seale, W. D., Mendoza, F. G., and Hudson, N. W., "Automated Phase Noise Measurement," Microwave Journal. Vol. 20, No. 6, June 1977, pp. 87-103.

(16) Koide, F. K. National Measurement Requirements Committee Report on RF and Microwave. National Conference of Standards Laboratories National Measurement Requirements Committee, NMRC 83-01, June 1983.

(17) Fitzpatrick, J. "NBS and Microwave Metrology - Growing Concern Within the Industry," Microwave Systems News. Vol. 14, No. 5, May 1984, p. 48.

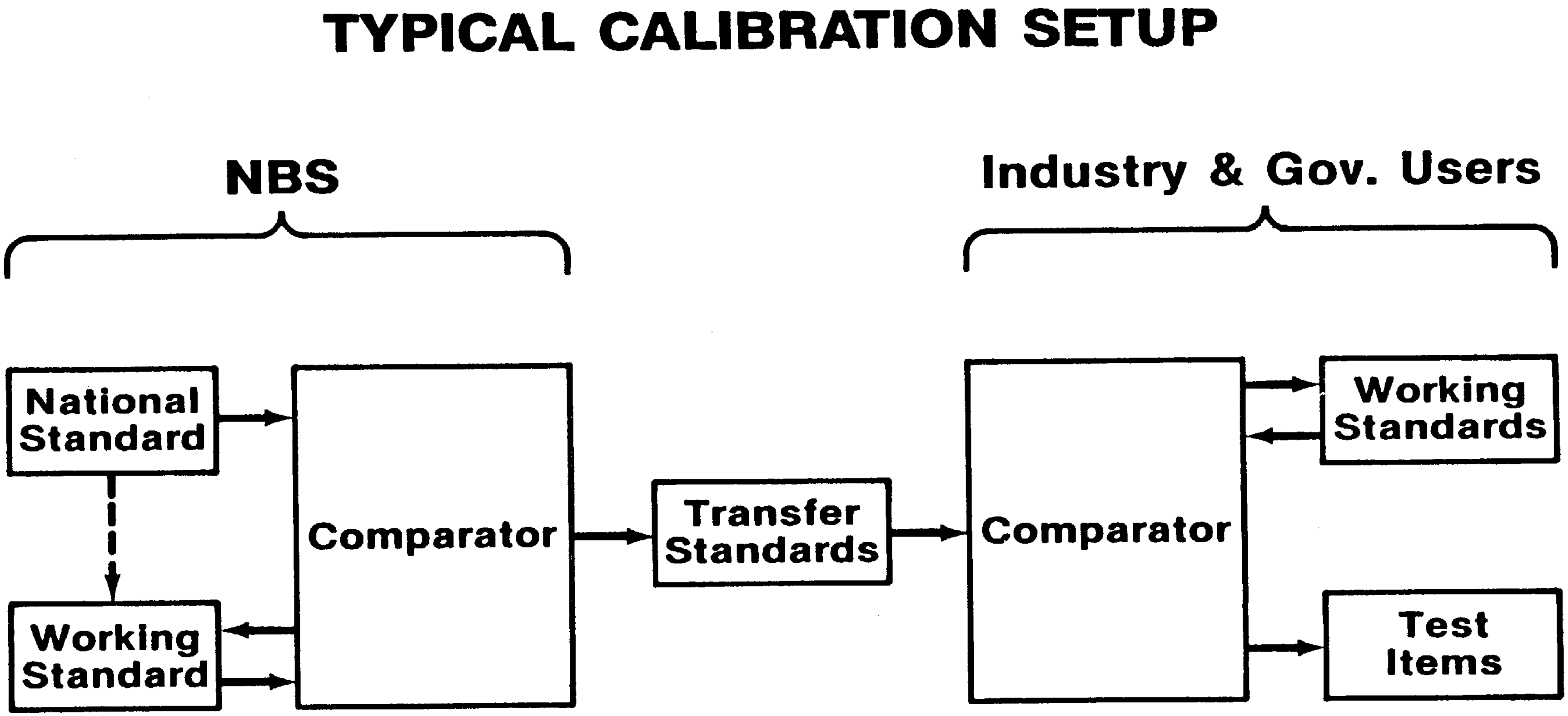


Figure 1. Method of Calibration Transfer.

COAX

GHz

F =1 18 26

NBS System		1–18	18–26
Microcalorimeter.	P	|——→|	
Broodbond Reflectometer.	|Γ|,P		
Single 6- port.	Γ,P	|——→|	
Dual 6-port.	Γ, P,S	←——→	- - →
100 kHz IF ANA.	Γ,S	|——→|	

WAVEGUIDE

GHz

f =12 18 26 40 50 75 110

NBS System	WR =	62	42	28	19	15	10
Microcolorimeters	P	x	x	x		x	x
Tuned w/g reflectometers 30 MHz IF	Γ,P,A	x	x	x		x	
Precision RVA	A	x					
Cooxiol single 6-port	Γ,P	——→					
w/g single 6-port	Γ,P		x			x	
Duol 6-port	Γ,P,S		---				x

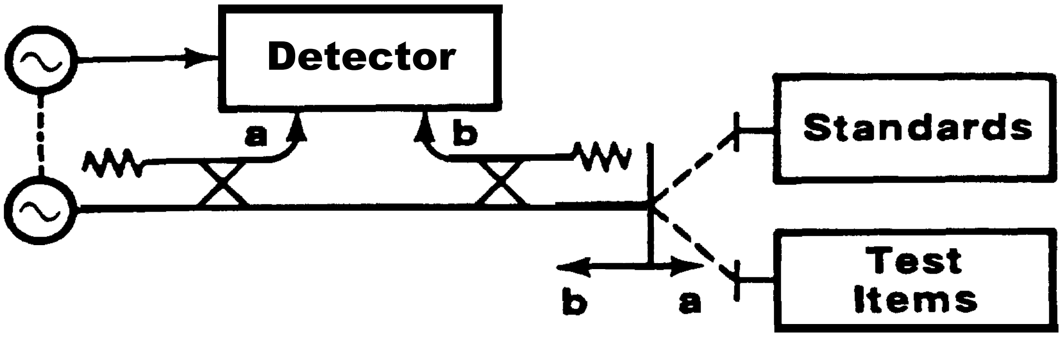
Figure 2. Guided Wave Available Services

UNCERTAINTIES

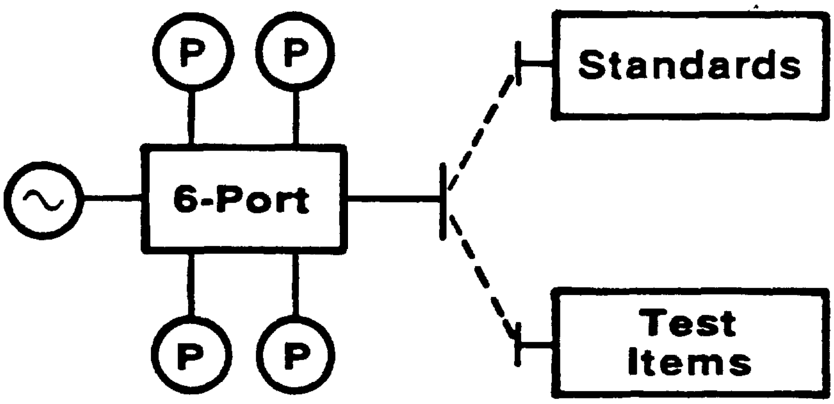
Frequency =	1-18 GHz	18-40 GHz	55-65 GHz	95 GHz
Attenuation				
$\alpha = 0 - 50$ dB	0.003α	0.005α	0.005α	0.006α
$\alpha = 0 - 140$ dB				
Reflection Coef, Γ	0.005	$0.001 +$ 0.003Γ	$0.001 +$ 0.003Γ	$0.008 +$ 0.002Γ
Power, 10 mW	1%	1%	2%	3%

Figure 3. Uncertainties for Guided Wave Quantities

Traditional Reflectometer (comparator)



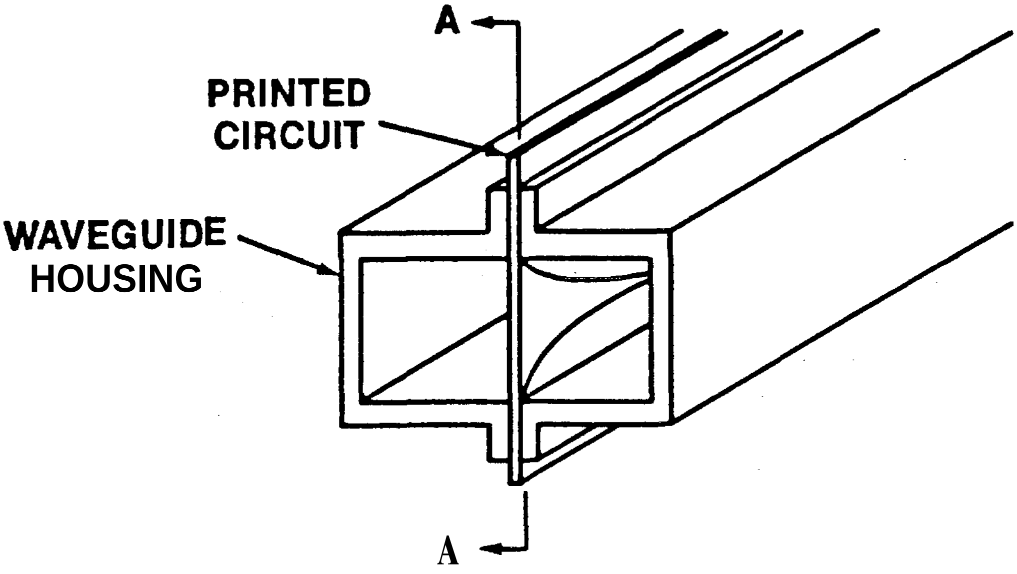
New 6-Port Reflectometer



Advantages of 6-Port

- **exact** model
- redundancy
- high accuracy
- phase from magnitude
- simple, stable calibration
- easy to automate

Figure 4. Comparison of Calibration Techniques



FINLINE 6-PORT

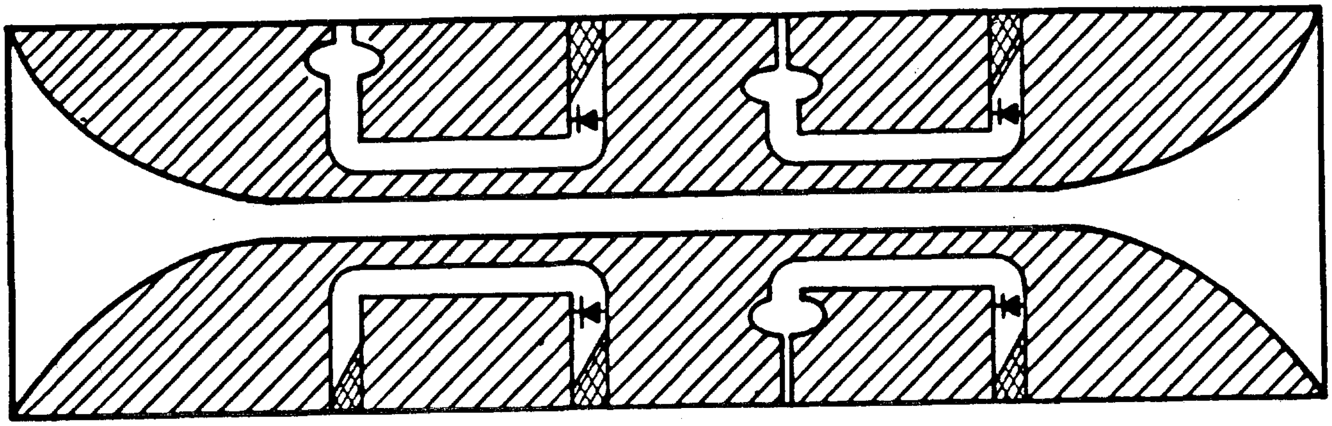


Figure 5. Implementation of a 6 Port at mm Wave Frequencies

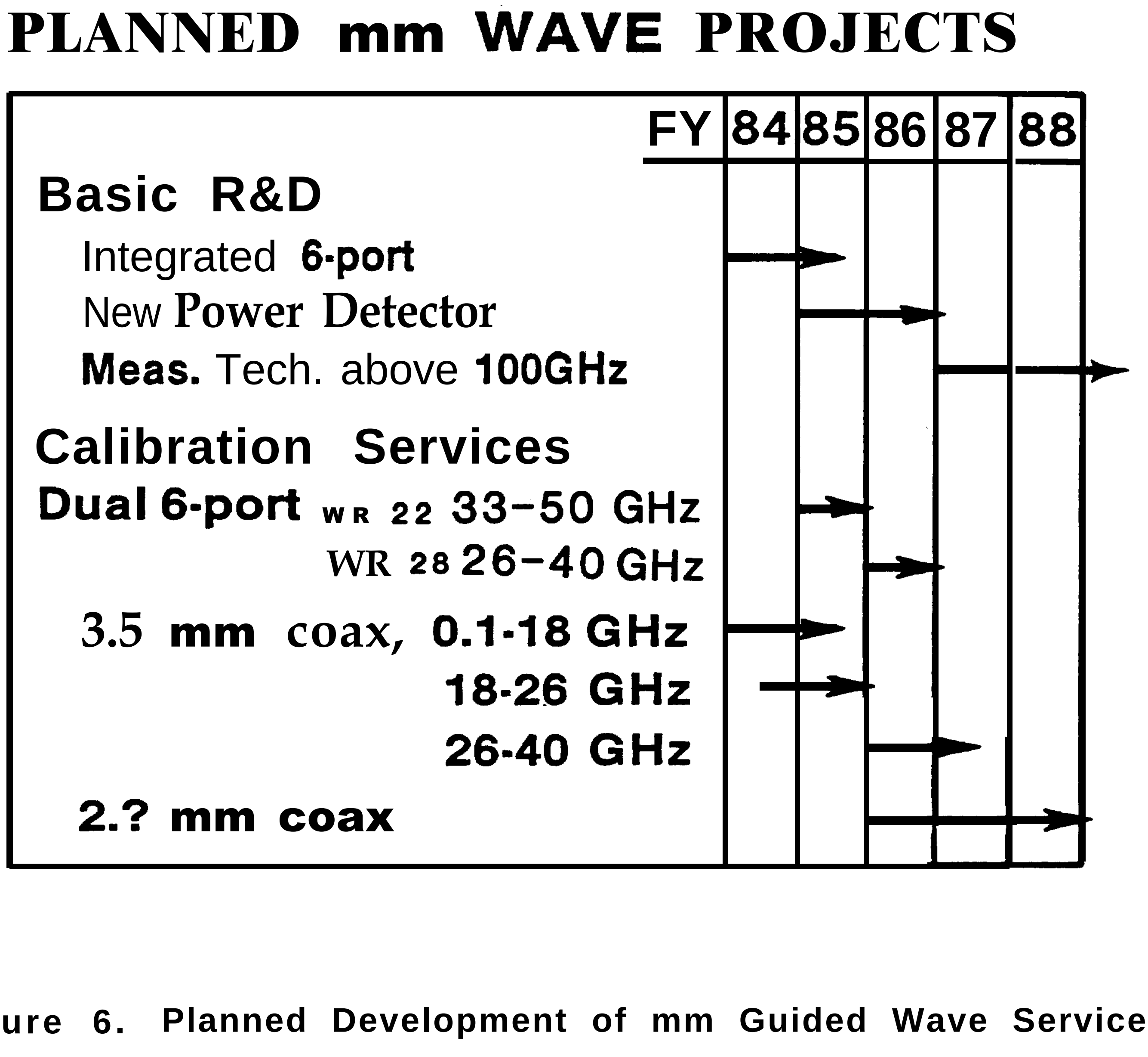


Figure 6. Planned Development of mm Guided Wave Services

FREQUENCY COVERAGE OF NOISE MEASUREMENT SERVICES

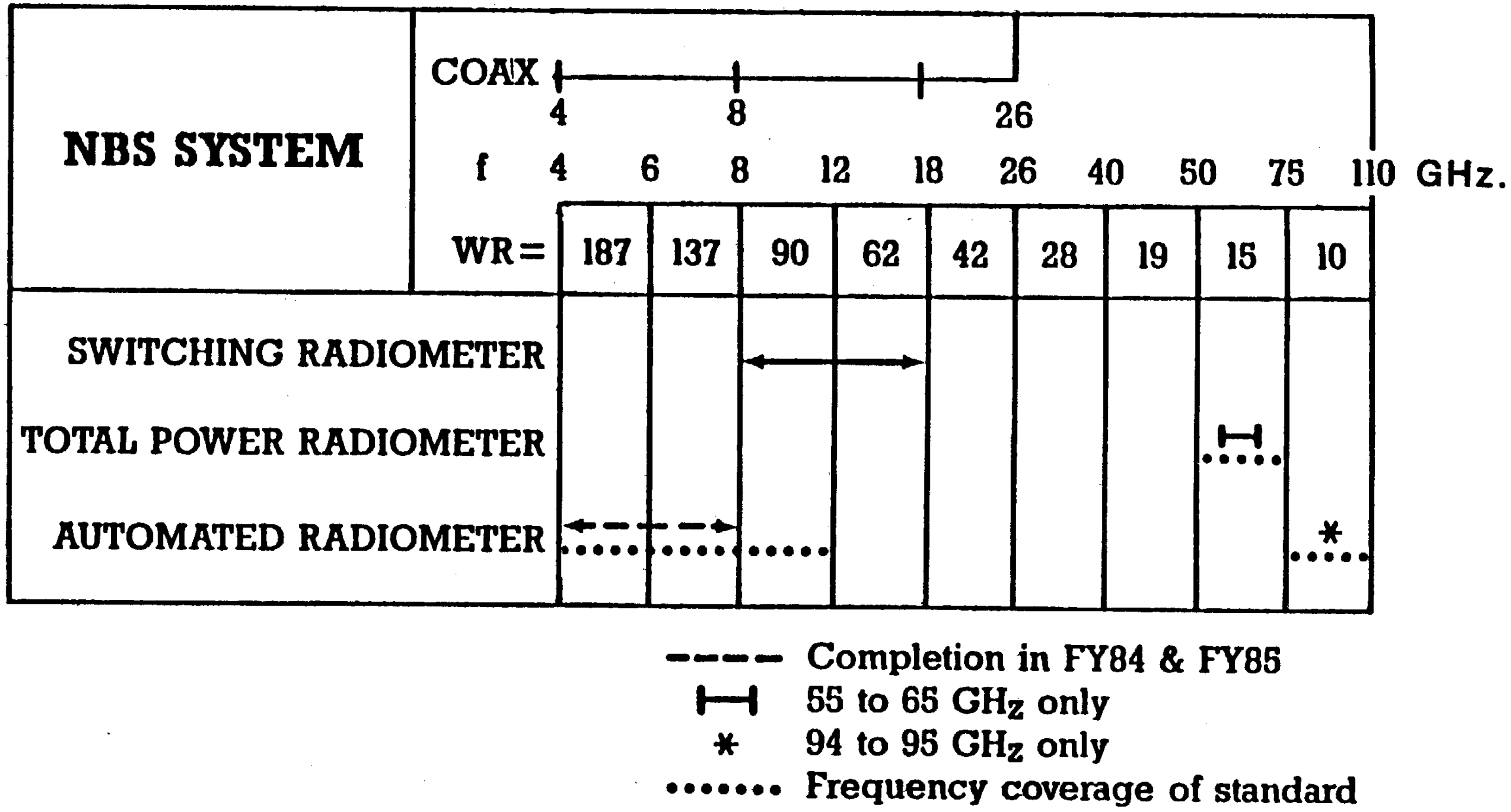


Figure 7. Noise Calibration Services

ESTIMATED ACCURACY OF EXISTING NOISE MEASUREMENT SERVICES

	ENR (dB)	Percent
Microwave		
Waveguide (WR 90, WR 62)	±0.1	±2.3
Coax (2 to 8 GHz) using automated radiometer		expect ±1.0 to ±2.0
Millimeter Wave		
WR 15 (55 to 65 GHz)	±0.15	±3.5
WR 10 (94 to 95 GHz)	±0.13	±3.0

Figure 8. Uncertainties of Noise Measurement Services

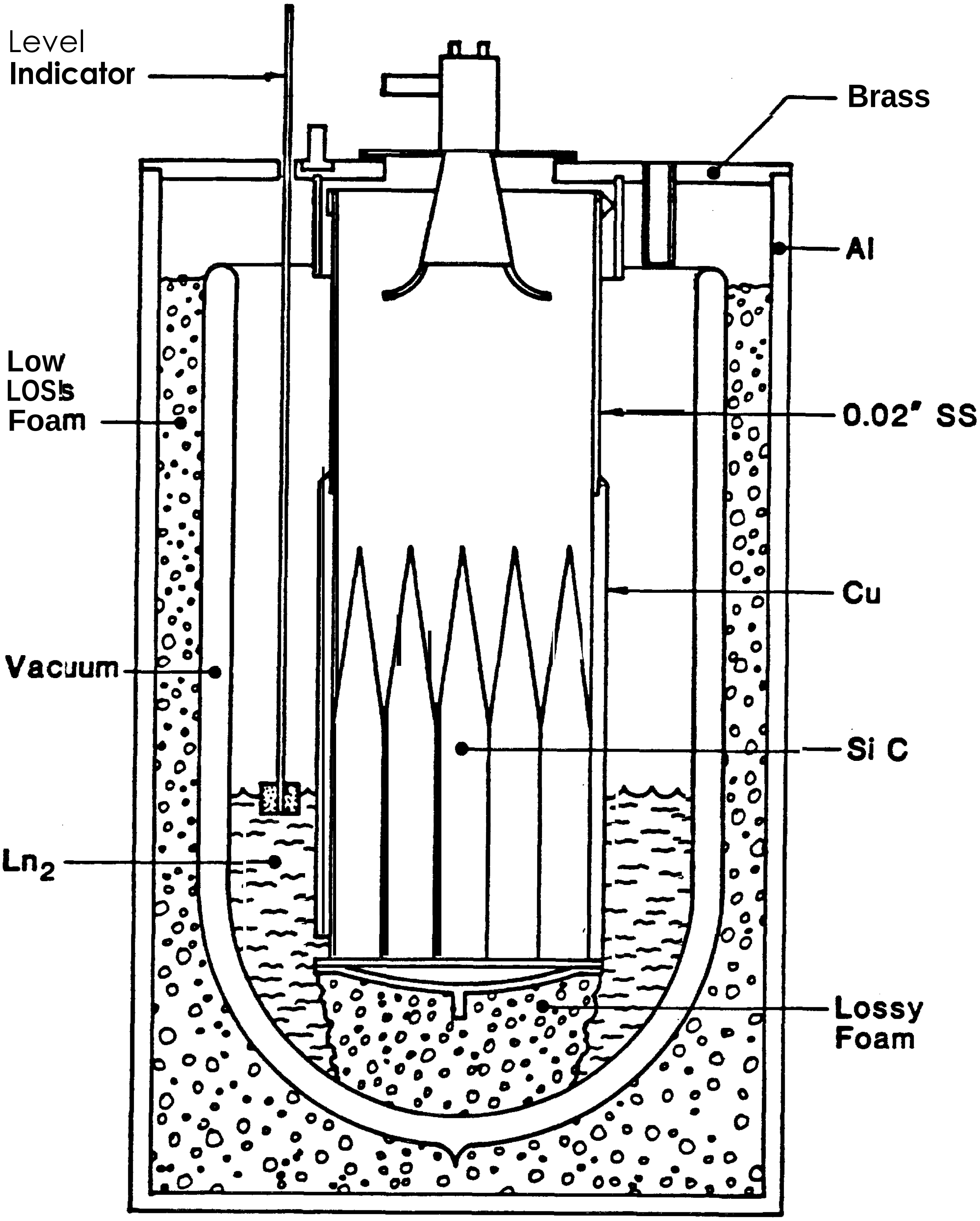


Figure 9. Crossection of New 94 GHz Noise Standard.

PLANS FOR FUTURE WORK IN NOISE METROLOGY

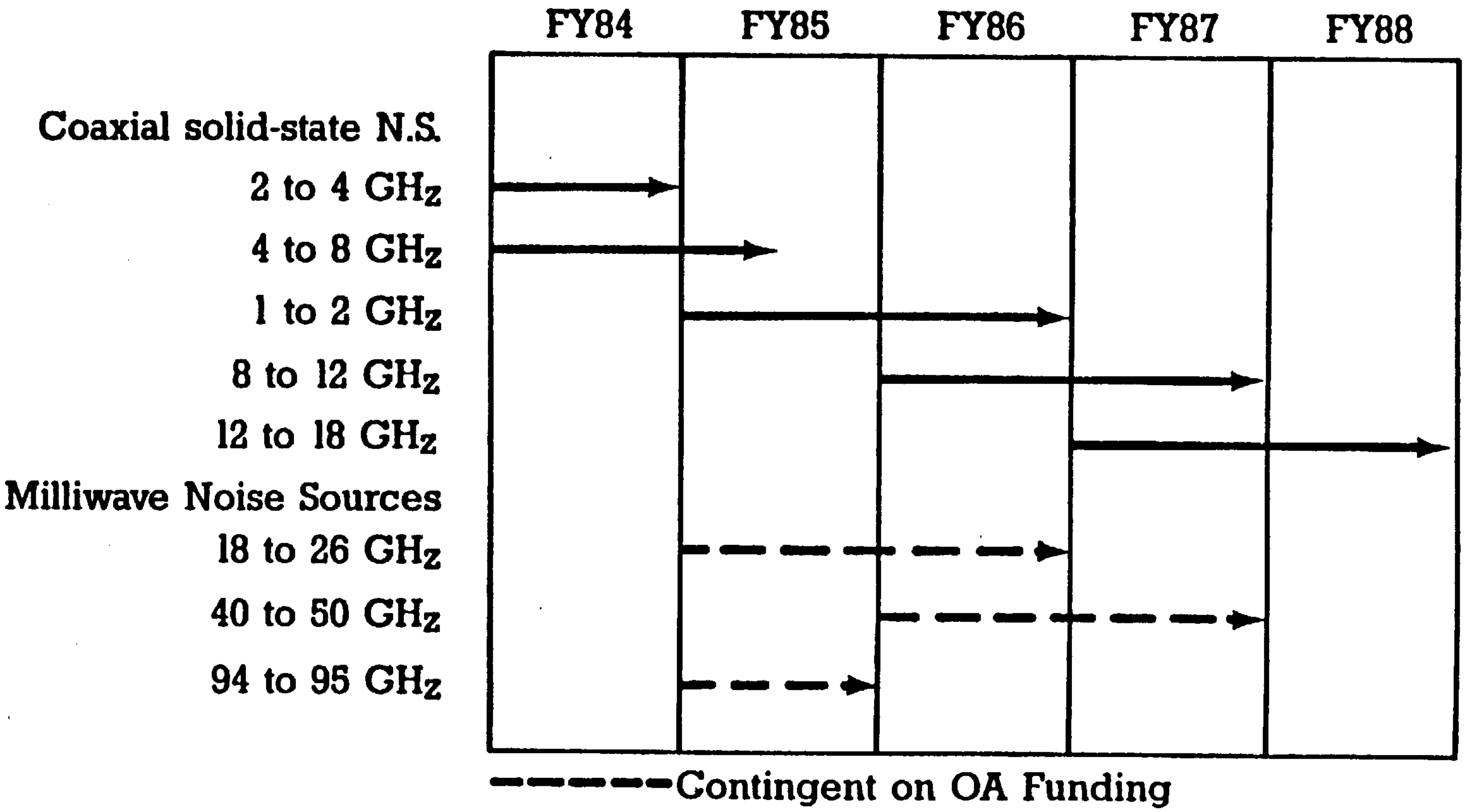


Figure 10. Future Plans for Noise Measurement Services.

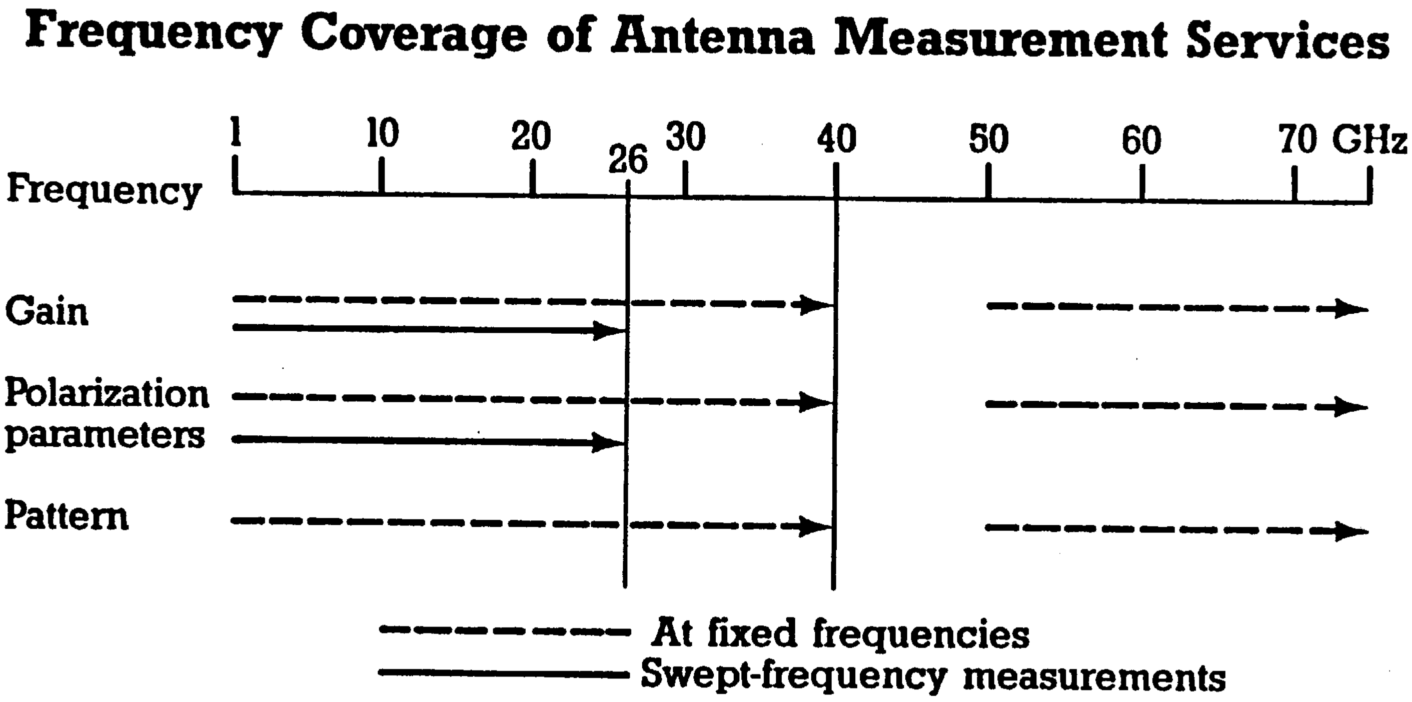


Figure 11. Present antenna Measurement Services.

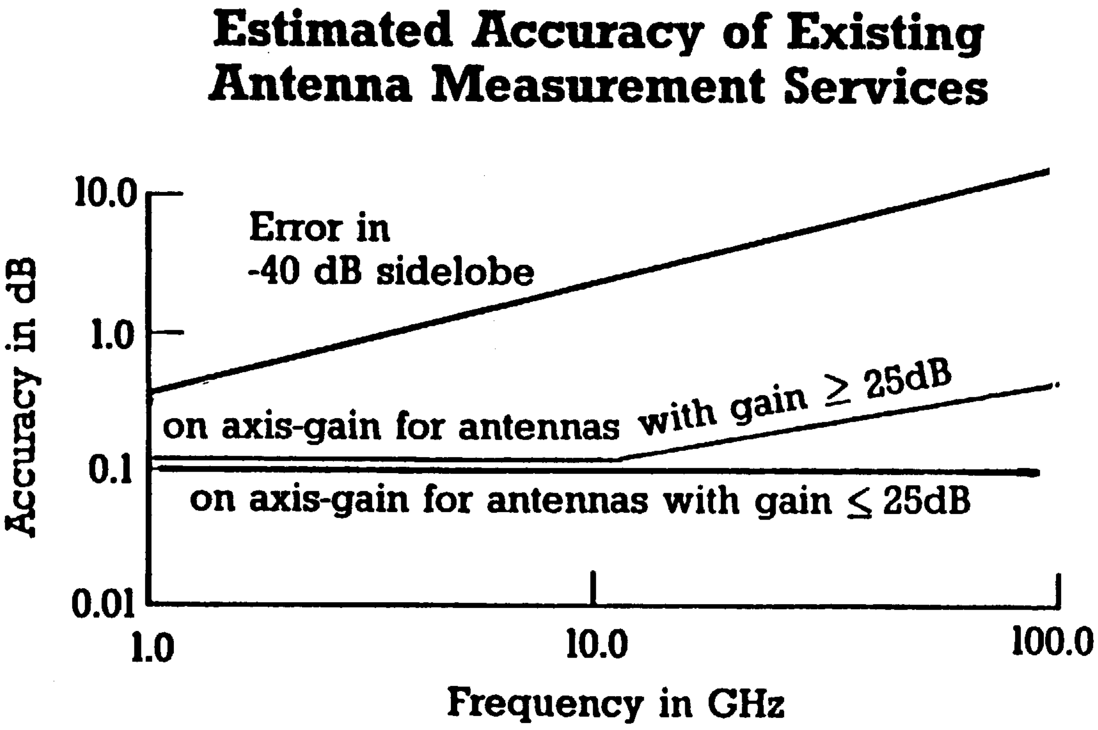


Figure 12. Antenna Parameter Measurement Uncertainties.

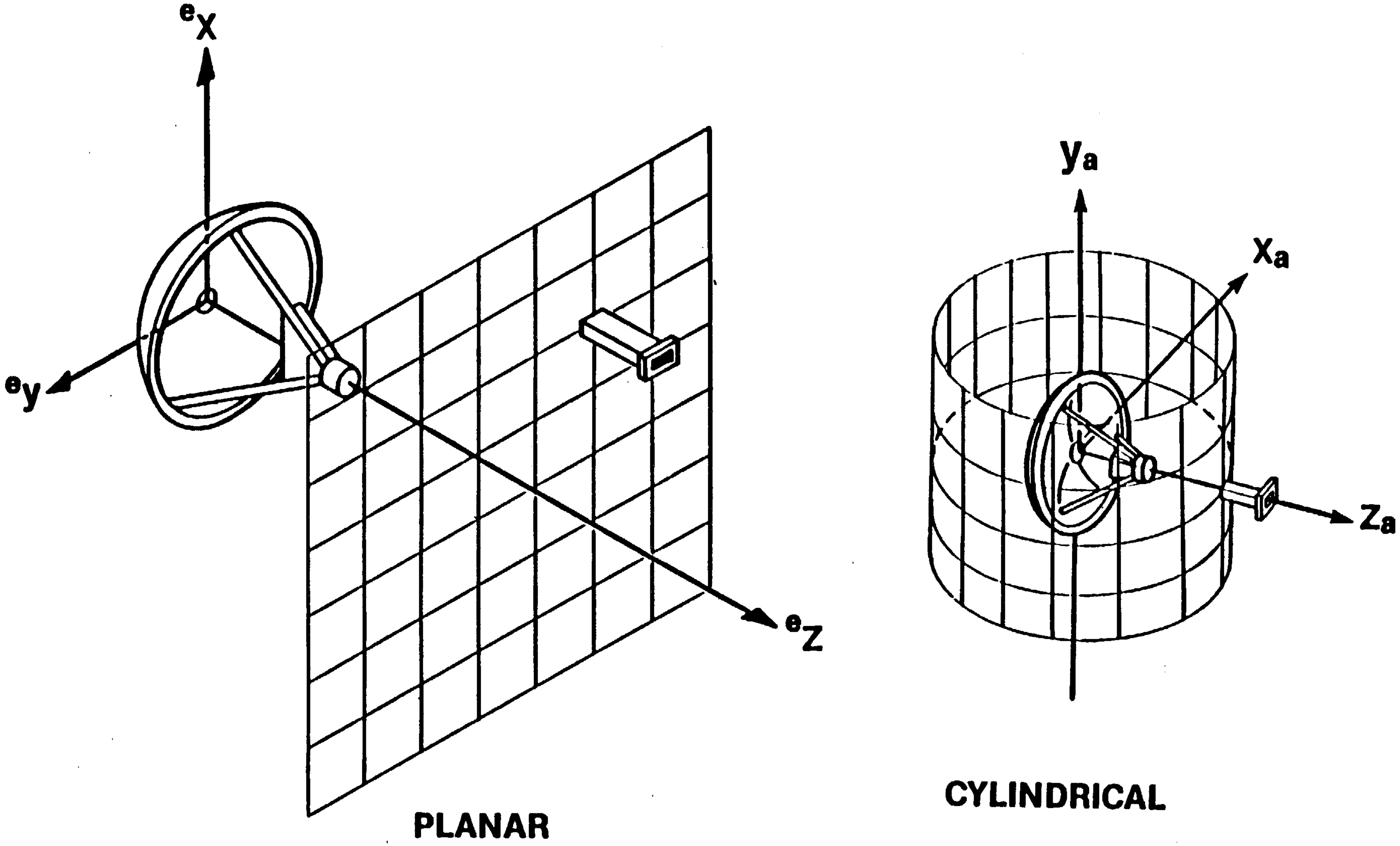
Far-Field Approach

$$\text{Far-field} = \frac{2D^2F}{c}$$

D is antenna diameter
F is frequency
c is velocity of light

D	F	Far-Field
3 m (10 ft.)	10 GHz	0.64 km (0.4 miles)
18 m (60 ft.)	10 GHz	21.8 km (13.6 miles)
0.6 m (2 ft.)	100 GHz	0.24 km (0.15 miles)
3 m (10 ft.)	100 GHz	6.1 km (3.8 miles)

Figure 13. Traditional Approach to Antenna Measurements.

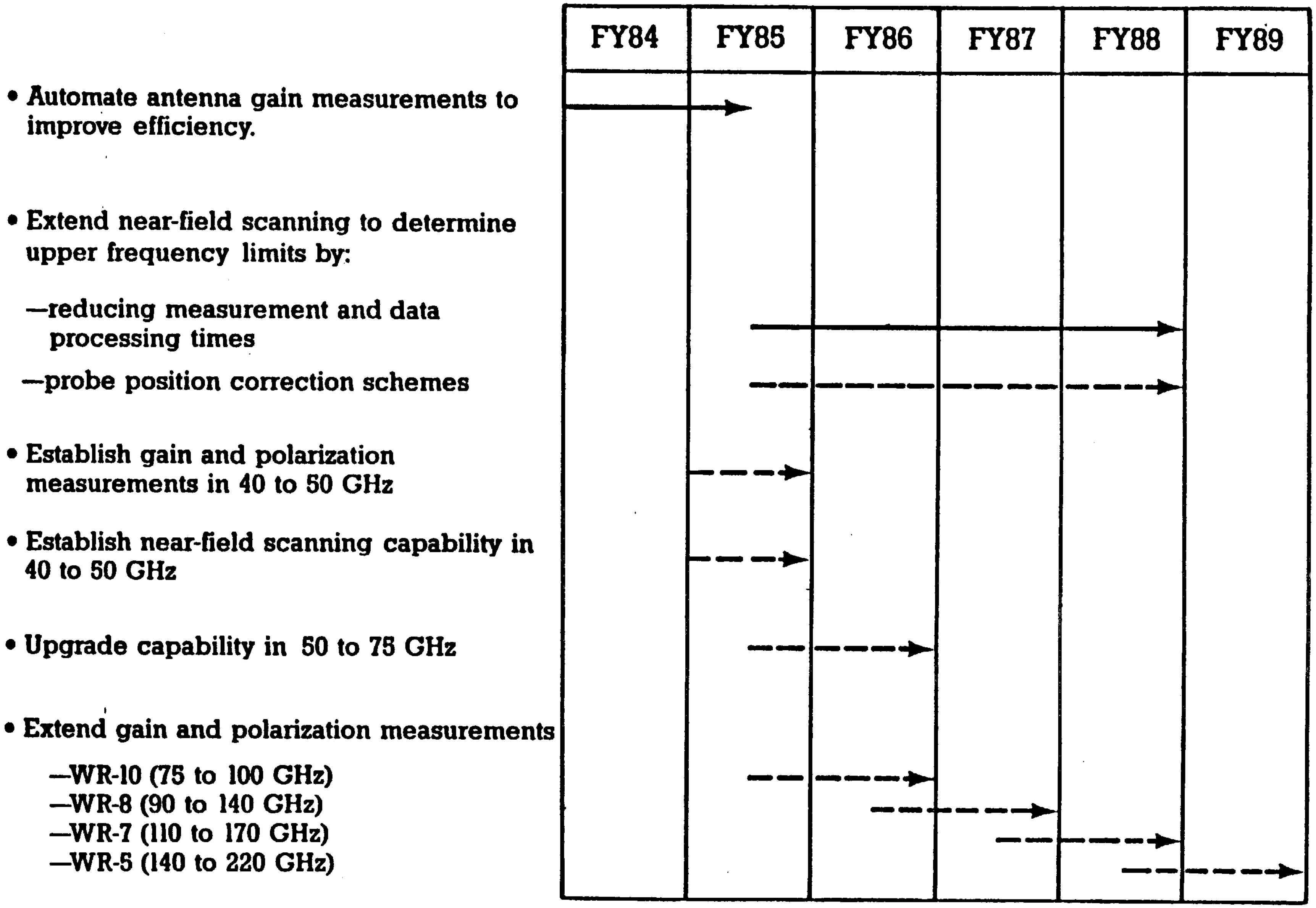


PLANAR

CYLINDRICAL

Figure 14. Near Field Scanning Method.

PLANS FOR ANTENNA MEASUREMENT SERVICES



- Automate antenna gain measurements to improve efficiency.
- Extend near-field scanning to determine upper frequency limits by:
  - —reducing measurement and data processing times
  - —probe position correction schemes
- Establish gain and polarization measurements in 40 to 50 GHz
- Establish near-field scanning capability in 40 to 50 GHz
- Upgrade capability in 50 to 75 GHz
- Extend gain and polarization measurements
  - —WR-10 (75 to 100 GHz)
  - —WR-8 (90 to 140 GHz)
  - —WR-7 (110 to 170 GHz)
  - —WR-5 (140 to 220 GHz)

---- Contingent on OA Funding

Figure 15. Future Plans for Antenna Measurement Services.

AN INTERFEROMETRIC APPROACH TO VECTOR NETWORK ANALYSIS AT W-BAND

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ABSTRACT

The design, construction, and performance of a W-band waveguide vector network analyzer are described. The heart of the instrument is a waveguide interferometer, which enables a comparison of the power emerging from the device-under-test (DUT) with a reference standard. Thus, the reflection/transmission coefficient of 'the DUT can be determined at a given frequency. An inherently wideband reference condition can be established by equalizing the lengths of the test and reference arms of the analyzer, but achieving this requires special attention to the specification and the physical coupling of the component parts. The requisite procedures for component specification and assembly are described. Experimental data indicate that amplitude and phase tracking between the interferometer arms are within 1.2 dB and ±8 degrees, respectively, over a frequency range of 88 GHz to 99 GHz. Sample measurements at 94 GHz are presented to indicate the resolution, repeatability, and dynamic range possible with the source-detector combination currently used. Some performance limitations and possible modifications for performance improvement are also discussed.

INTRODUCTION

Microwave and m-a-wave interferometry has enjoyed an enduring interest through the decades since World War II. In 1952,(1,2) the technique was used at 24 GHz to determine the wavelength of the microwave signal in air, correct it for various effects, and then multiply it with the corresponding frequency to give the velocity of light, c. This method was extended to 72 GHz(3) by the late 1950s.

Microwave and mn-wave interferometry also has been applied in precise non-destructive determinations of thickness,(4) velocity,(5,6) and range(7,8) of a movable object, often in corrosive or other hostile environments, and in the study of liquids,(9) for aircraft navigation,(10) and in radar imaging.(11)

Here, we describe the application of interferometry to determination of vector network parameters. Specifically, we seek to determine the magnitude and the phase of reflection and/or transmission coefficients of a mm-wave component over a range of frequencies. Such determinations are referenced to certain "terminal planes." In practice, these planes often coincide with the interface that connects the measuring instrument with the component under test. Interferometry furnishes an elegant method for determining these network coefficients when appropriate standards are available. Fortunately, methods for designing these standards are already in place.(12-16)

OPERATING PRINCIPLE

Figure 1 shows a schematic design of the interferometer set-up for making reflection coefficient measurements. The instrument is powered by an IMPATT diode source with an integral isolator. A small fraction of the generated power is extracted by a 20-dB directional coupler to determine the frequency of the source. The bulk of the power is split equally into reference and test arms by a Magic Tee. Each wave travels past a variable attenuator, an isolator, and the main line of a high-directivity quadrature hybrid to their respective terminal ports. Ideally, only the reflected waves from these ports are coupled into a second Magic Tee via Rotary Phase Shifters as shown. The connection to the second Magic Tee is made at those ports that are ideally isolated from each other, e.g., the E- and H-arms.

If the reference and test ports terminate in perfect reflectors and the components that constitute the reference and test arms have identical electrical characteristics, then the power in the second Magic Tee combines constructively at one colinear port and destructively at the other colinear port whenever the path travelled by the two waves differs by an integral number of half wavelengths. Destructive interference gives rise to a null at the corresponding port. If the path lengths travelled by the waves are equal, then the null condition is ideally independent of the frequency of the source. This equal-path configuration carries the important benefit of establishing a reference condition that, in practice, is immune to small frequency fluctuations in the source. Detection of a null furnishes the additional benefit of immunizing the measurement from noise in the source.

The measurement itself proceeds by replacing the reflector in one arm by the component under test. The Phase Shifter and the attenuator in the other arm are then adjusted to restore the null condition and are then read directly to give the return loss and the phase shift of the component under test. From the return loss, the magnitude of the reflection can be readily computed.

DESIGN AND CONSTRUCTION

The ideal conditions described above are only approximately approached in practice. This is because the performance of the various components deviate from their ideal as the frequency is varied, and these deviations do not necessarily track for the same component type. Also, parasitic effects, such as reflections (VSWR), losses, and stray leakage, contrive to further compromise the ideal behavior described above. The problem is aggravated by the need to interconnect the various components far more precisely at mm-wave frequencies than at lower frequencies in order to minimize reflections from these interfaces.

An investigation into the different designs of the components used revealed that each had some inherent frequency-sensitive characteristic. In a directional coupler, for example, the key performance parameters are the coupling, directivity, and main and auxiliary line VSWRs. In most of the common designs, the frequency sensitivity resides in either the coupling (Shwinger design) or in the directivity (multi-hole design). Significantly, any attempt within a design to flatten the frequency response of the sensitive parameter while simultaneously minimizing the VSWR, results in an even smaller variation of the other parameter. In this case, we specified a high directivity for the quadrature hybrid (minimum 40 dB) and further stipulated that it remain flat within 5 dB over the frequency range 88-99 GHz. Similar considerations were applied to the other components of the interferometer in order to achieve the closest possible tracking in magnitude and in phase between the arms. In all cases we sought components with the lowest VSWR consistent with the above criterion.

Interconnection of the components was accomplished by shining a divergent beam of a He-Ne laser at one port of the waveguide component and imaging the kaleidoscope pattern emerging from the opposite face on a screen as in Fig. 2. A second component was then attached such that the optical patterns of the two components merged. In practice, the laser is not needed for connecting straight sections. However, its intensity is useful when connecting bends.

PERFORMANCE

Intrinsic Rehavior

Figure 3 shows the tracking of the null with frequency using micrometer-driven shorts attached to the reference and test ports and adjusted to obtain the best null at 94 GHz. Thereafter, no further adjustments were made while the frequency was varied between 88 and 99 GHz. Figure 3a shows the actual data, and Fig. 3b shows the null depth defined as the ratio of power at the in-phase port to that at the null port expressed in dB. A worst-case null depth of 21 dB was determined. This was found to be due to reflections from a thermistor mount used to terminate the other arm of the second Magic Tee. When this mount was replaced by a matched load, the worst-case null depth increased to 36 dB.

Figures 4 and 5 display the amplitude and phase tracking of the arms that would produce a null depth in excess of 45 dB. Using this value as a criterion, we obtain a worst-case amplitude tracking of 1.2 dB and a corresponding phase tracking of ±8 degrees over the operating range.

Standards Development

Having established the intrinsic limits of the instrument, we next sought to calibrate it using quarter-wave short-circuit impedance standards. These have the advantages of being well characterized, insensitive to the conductivity of the metal walls, and somewhat insensitive to mating imperfections. The designs were adapted from previous work at NBS(13,14) with some additional modifications.(16) Quarter-wave and five quarter-wave shorts were designed and built at 2-GHz intervals between 92 and 98 GHz. Only two of these were within the range of the six-port calibration facility at NBS. Table I shows the results of that calibration run and, for comparison, the theoretical predictions. Reasonable agreement is shown for the quarter-wave shorts. The agreement is poorer for the five-quarter wave shorts. Part of the problem arises from deviations in the actual length from the computed length. Every 11 microns represents one degree of electrical phase at 94 GHz. In the five-quarter wave shorts, however, an additional problem arises due to stray reflections at locations other than the back shorting plane. This manifests itself in the inability to secure a perfect null with the interferometer even though such a null is obtained with the corresponding quarter-wave short. This stray reflection may occur from surface roughness that arises when the mandrell, on which the short was electroformed, is removed. We may reasonably suppose greater roughness for the longer component. Furthermore, any five-quarter wave short has two additional current maxima in its' interior whereas a quarter-wave short has a current maximum only at the back shorting plate. Therefore, a five-quarter wave short circuit is expected to show greater sensitivity to surface condition.

Sample Measurements

Table II shows the results of measurements made on some sample components. A matched load was used to obtain some indication of phase sensitivity at high return loss, However, the return loss was not high enough to challenge this aspect of the instrument. A thermistor mount was also measured to establish consistency with the vendor-supplied correction factors. The measured return loss was consistent with the correction factors.

SOURCES OF ERROR

Systematic errors

The systematic errors in the system arise principally from the finite directivities and coupling variations in the quadrature hybrids, finite isolation and coupling imbalance of the Magic Tees, VSWR and insertion loss variations between similar components in the two arms, spurious responses *in* the input source, and leakage in the components. The leakage in the rotary vane attenuators was particularly evident, taking the form of a discontinuous phase change of approximately 11 degrees for attenuation levels between 30 and 36 dB depending on the frequency. Subtle errors also arise due to a finite phase shift with attenuator setting at constant frequency. Finite insertion loss changes also occur in the phase shifters with phase shift setting. By actual measurement with standards at 94 and 96 GHz we have determined a phase shift increase of about 2 degrees/decade of attenuation and an insertion loss variation of less than 0.1 dB/180 degrees of phase shift. The sign of the former shift changes at around 30 dB attenuation due to the leakage mentioned earlier, but otherwise displays a linear response at a given frequency. The error in the dial calibration of the attenuators has been specified by the manufacturer as being < 0.1 dB for attenuator settings < 25 dB, and < 1 dB for settings > 25 dB. Similarly, the calibration of the phase shifter dial is ± 4 degrees.

Random Errors

These are errors associated with random frequency fluctuations in the source. They are intensified by the rate at which the magnitude and phase of the reflection/transmission coefficients vary with frequency. The phase derivative at near unity reflection tend to cause the most rapid variations. For example, with the sources used, a null that is only 5-dB deep will be obtained if the phase variation with frequency is greater than 190 degrees/GHz approximately.

Other random errors include errors due to noise in the detectors and their associated instrumentation and display, instabilities in the mm-wave circuit and instrumentation, and repeatability errors associated with interface connectors and the manual waveguide switches. Table III demonstrates the connector repeatability with the quarter-wave and the five quarter-wave short at 96 GHz. In this case the two shorts were alternately connected and disconnected at the test port, and the interferometer was adjusted to read the best null. As mentioned before, the five quarter-wave short does not produce as good a null as the quarter-wave short. This brings up a possible limitation of this set-up, namely, that in a multi-obstacle and/or multi-port network, where reflections can occur at several planes, there are potential ambiguities that can arise from an inability to secure a null. Although, in certain circumstances, these can be resolved by making measurements under different terminating conditions and *over* a range of frequencies, no general model exists to encompass the variety of circuits that could require such characterization. We therefore expect that the characterization of extended interaction and distributed devices and circuits will not be meaningful unless a reasonably accurate model of its terminal characteristics is available from other sources. At these frequencies, this is not a trivial task. Fortunately, most of the usual components produce a reasonably deep null so that such an elaborate model is not required within the accuracies available here.

SUMMARY

We have described the design, construction, and performance of a mm-wave interferometer applied to making vector network measurements between'88 and 99 GHz. The analyzer shows amplitude and phase tracking of 1.2 dB and ±8 degrees, respectively, over the frequency range. This performance is achieved, in large part, by specifying individual components appropriately, and by using optical techniques *to* interconnect them. A brief discussion of some of the error sources is also presented.

ACKNOWLEDGEMENTS

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REFERENCES

(1) Froome, K.D., "Determination of the Velocity of Short Electromagnetic Waves by Interferometry," Proc. Roy. Soc., Vol. 213A, 1952, pp. 123-141.

(2) Froome, K.D., "Investigation of a New Form of Micro-wave Interferometer for Determining the Velocity of Electromagnetic Waves," Proc. Roy. Soc., Vol. 223A, 1954, pp. 195-215.

(3) Froome, K.D., "A New Determination of the Free-space Velocity of Electromagnetic Waves," Proc. Roy. Soc., Vol. 247A, 1958, pp. 109-122.

(4) Augustine, C.F. and Merlo, A.L., "Microwave Thickness Measuring Apparatus," U.S. Patent #3,258,688, Issued June 28, 1966.

(5) Schultz, H., Thomas, C.E., and Hanks, H.C., "Microwave Interferometer," U.S. Patent #2,735,981, Issued Feb. 21, 1956.

(6) Maron, Y. and Rlaugrund, A.E., "Measurements of High Surface Velocities Using K-band Microwave Interferometry," Rev. Sci. Instrum., Vol. 51, No. 5, 1980, pp. 666-669.

(7) Hotston,E.S., "Microwave Interferometers," U.S. Patent #3,757,330, Issued Sept. 4, 1973.

(8) Chivers, J.W.H., "Microwave Interferometer," U.S. Patent #4,359,683, Issued Nov. 16, 1982.

(9) Wright, T., and Campbell, D.D., "A UHF Ultrasonic Interferometer," J. Phys. Electron., Vol. 10, No. 12, 1977, pp. 1241-1244.

(10) Cooper, H.W., "Precision Interferometer Navigation System," U.S. Patent #3,434,144, Issued March 18, 1969.

(11) Tricoles, G.P., and Rope, E.L., "Method and System for Microwave Interferometry," U.S. Patent #3,909,827, Issued Sept. 30, 1975.

(12) Beatty, R.W., "Impedance Measurements and Standards for Uniconductor Waveguide," Proc. IEEE, Vol. 55, 1967, pp. 933-941.

(13) Beatty, R.W., and Yates, B.C., "A Graph of Return Loss versus Frequency for Quarter-wavelength Short-circuited Waveguide Impedance Standards," IEEE Trans. Microwave Theory Tech., Vol. 17, No. 5, 1969, pp. 282-284.

(14) Yates, B.C. and Larson, W., "Millimeter Attenuation and Reflection Coefficient Measurement System," NBS Tech. Note #619, U.S. Dept. of Commerce, 1972.

(15) Ibid, pp. 28-31.

(16) Sequeira, H.B., and Yates, B.C., "Approach for Evaluating Effects of Wall Losses on Quarter-wave Short-circuit Impedance Standards," Submitted for publication to IEEE Trans. Microwave Theory Tech.

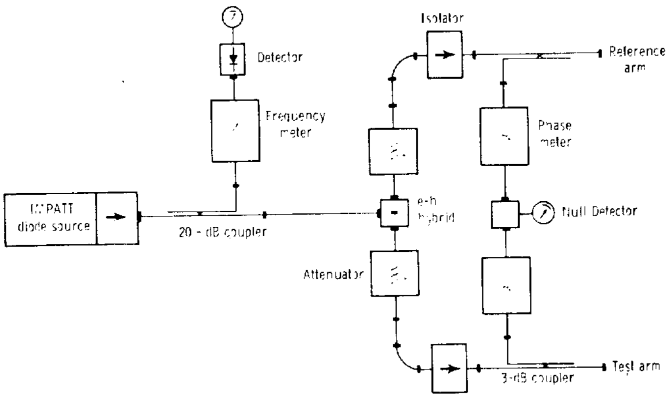

Figure 1. mq-wave Michelson Interferometer - Type Network Analyzer

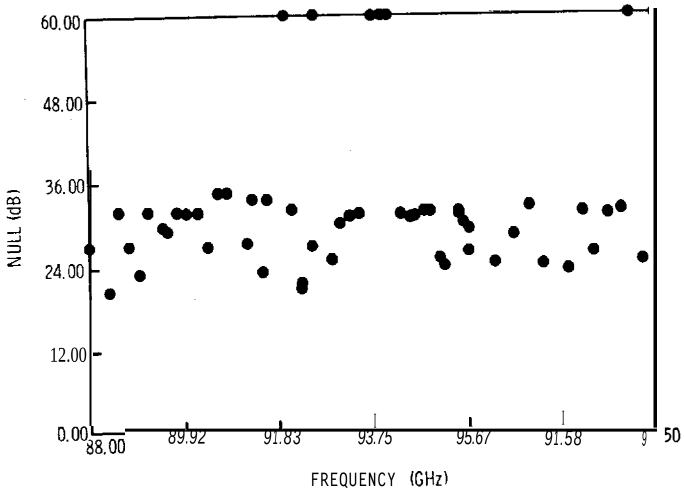

Figure 3. Tracking response of the network analyzer

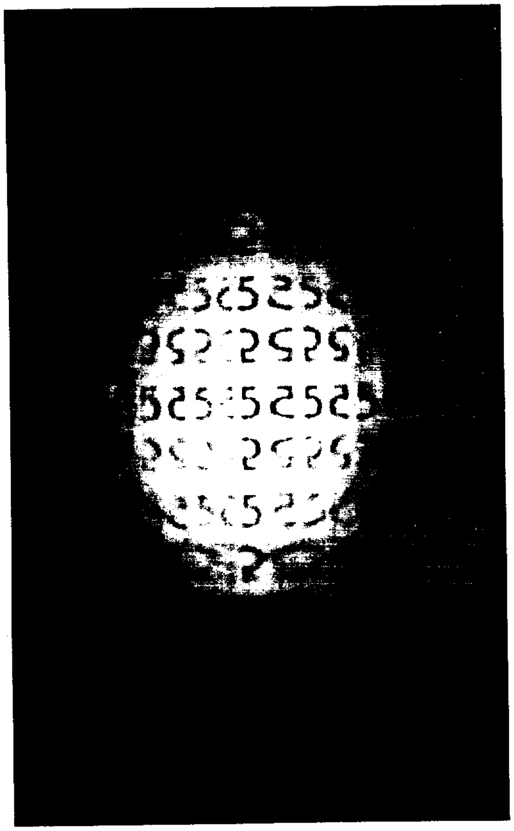

Figure 2. Kaleidoscope pattern of source imaged through aligned lengths of waveguide.

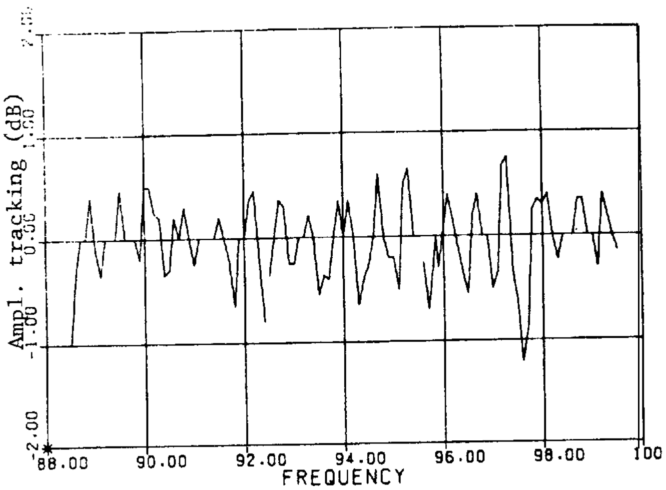

Figure 4. Amplitude tracking of the interferometer

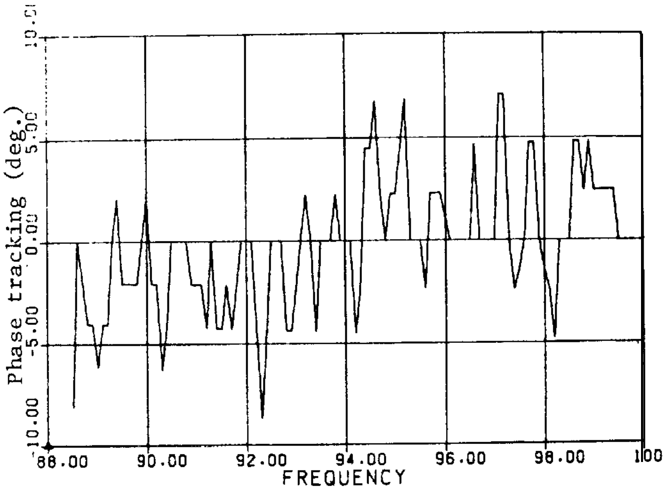

Figure 5. Phase tracking of the interferometer

TABLE I - CALIBRATION OF QUARTER-WAVE SHORT-CIRCUIT STANDARDS

Frequency (GHz)	I.D. Number	Reflection Coefficient Magnitude Theory	Measured	Uncertainties (plus or minus) Random	Systematic	Total
94	94-1	0.9991	0.9996	0.0073	0.0010	0.0083
94	95-5	0.9966	0.9963	0.0075	0.0010	0.0085
96	96-1	0.9991	0.9948	0.0075	0.0010	0.0085
96	96-5	0.9967	0.9925	0.9981	0.0010	0.0091
		Phase (degrees)				
94	94-1	0	2.05	3.36	0.52	3.88
94	94-5	0	6.21	3.54	0.52	4.06
96	96-1	0	1.08	2.66	0.52	3.18
96	96-5		3.92	2.62	0.52	3.14

TABLE II - SAMPLE MEASUREMENTS (Uncorrected)

	Frequency (GHz)			
	94		96	
Component	Return loss (dB)	Phase (deg)	Return loss (dB)	Phase (deg)
Thermistor Mount	10	-80	14.3	-12
Matched Load	35	73	30	23

TABLE III - CONNECTOR REPEATABILITY @ 96 GHz (Test port signal = 11 dBm)

	λ/4			5λ/4		
Trial	Null Port Power (dBm)	Attenuation (dB)	Phase (deg)	Null Port Power (dBm)	Attenuation (dB)	Phase (deg)
1	-40	0.2	0	-40	0.2	2
2	-40	0	0	-40	0.05	0
3	-40	0	0	-40	0.15	2
4	-40	0	-1	-40	0.15	2
5	-40	0.15	2	-33	0.10	1
6	-40	0.05	0	-33	0.10	2
7	-40	0.05	0	-33	0.10	2
8	-33	0.15	-3	-40	0.15	3
9	-40	0.15	-1	-37	0.15	2
10	-40	0.15	0	-40	0.15	2

SESSION VI-O

MEASUREMENT POTPOURRI

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Software Product Assurance in the Metrology Lab

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Abstract

Software has always been a problem. In the beginning the problem was not enough software and too few programmers. Now the problem is too much software and not enough control. There is too much software because there are many near duplicates of programs in use. Using the right program is more of a problem than finding a program. The software problem is a surprise only because of its gradual build up. The problem started as computers moved into the metrology lab. Desktop computers or instrument controllers are now an integral part of the metrology lab. These devices were introduced over several years and this gradual appearance has masked some of the problems. Now the desktop computer is no longer feared; there are many more potential programmers and little control. Everyone in a metrology lab would be shocked if the dc standard used to calibrated digital voltmeters were not carefully controlled. Not nearly as many are surprised to find the software to calibrate the same digital voltmeter is not controlled.

A portion of the software collection of every metrology lab is not maintainable or is of uncertain quality. Quality in software is not only how well the program does the job intended, but how easily the program can be modified when a problem is found, how well the program is documented and how well the program will act as a standard. The software collection is a valuable resource requiring care. This paper presents the steps found necessary to begin a software product assurance effort in the Metrology Lab at Ford Aerospace and Communications Corp., FACC, at Newport Beach. The objective of the effort is to reduce costs and improve the quality of software

Introduction

Computers and software offer many advantages, and disadvantages. The instrument controllers in the metrology lab allow more to be done more accurately than is possible with manual methods. The assumption is what is being done faster every time is being done right. The weak link in this logic is often the software.

Software is everywhere. Nearly every new instrument contains software or can be controlled by software. The growing use of software means growing software problems. Many of these problems are caused by the lack of resources, either hardware or human. The problems addressed by this paper are the rising costs and unknown quality of software used in the metrology lab.

The Metrology Lab at Ford Aerospace Newport Beach uses two HP 9825s, four HP 9826s and one HP 9836. Most of the programs in use were written in HPL. During 1984 concerns were raised about the software in use in the lab. An inventory was conducted and over 800 programs were found on 25 disks. During development of a software catalog many near duplicate programs were discovered. A near duplicate is two programs of the same or nearly the same size but different checksums. Changes in Ford Aerospace and Communication Corp's, FACC's, quality procedures are being made and a software library has been started. This paper presents FACC's efforts to start an effective software product assurance program.

Definitions

Checksum: A unique number calculated for each program. The algorithm used is so sensitive a change of a lower case letter in a comment to upper case will change the check sum.

Controller: Desk top computer or instrument controller used to control instruments over a digital bus.

Disk: A unit of storage, can be magnetic floppy disk, hard disk, cassette, etc.

Quality: The degree a program is maintainable, controllable and performs the job intended.

Software: Programs written to calibrate instruments or test systems.

User: The technician or engineer using a calibration program.

The Software Problem: Yesterday

Today s software problems developed as controllers were introduced into the met lab. Controllers were slowly introduced because there were few instruments and standards that could be controlled digitally, and not many controllers were available. Many labs obtained their first instrument controllers as spares to test systems. This also meant few labs had chosen the controllers they use.

The limited memory of the early controllers required ingenious techniques to squeeze programs in; programs had to be tight. Everything superfluous, like comments, was deleted in the effort to get the program to fit. Besides, as we all know, comments can be inserted later. The techniques used by many of the early programmers were self taught. Consequently many programs are difficult to debug and impossible for someone other than the original programmer to maintain. Software in the met lab developed out of sight of the quality control system. Manual procedures are better controlled than software. Software was a black art, its practitioners magicians, and software s secrets were not for the common man.

The slow introduction of controllers mitigated some of the problems. The lack of people that could and would program was a problem. Often the programming was done by those who would, not by those who could. Writing programs to automate calibration procedures was not the highest priority and often took a back seat to other business. The slow introduction of controllers may have seemed evolutionary at the time, but the controllers were really revolutionary. Instrument controllers and automation are making fundamental changes in metrology. The trickle of controllers to the met lab and the few programs written where handled by an ad hoc approach.

Having a controller without any software is like having a very dry farm. When the water, or software comes a little does a lot of good. As the water keeps flowing, a few problems show up; a quagmire develops unnoticed. Over a period of time the bottom forty is taken over by the alligators.

The software problem: Today

Today the ad hoc approach cannot work. Nearly every lab has a large body of useful software of unknown quality Technology is changing rapidly; many of the first generation of controllers and their software are obsolete. Converting programs written in HPL to Basic may not be cost effective. The tight programs written in the early days are not only difficult to maintain, but the cost of converting them to a new machine or language may exceed the cost of writing a new program from scratch. There are few software control systems in place in metrology labs, even though more attention is being paid to the costs and problems of software than ever before. The time to develop a system is before one is required by the government, or the costs get completely out of hand.

Software Product Assurance Objectives

The solution to the software problem is to develop a system to write, use, control and maintain software. This systematic approach will reduce cost and improve quality. Software has to be brought under control in the same manner manual procedures and other met lab activities are. There are three main elements of a software product assurance effort: development, maintenance and control (1). The objectives of a software product assurance effort are to guarantee the right software is used, the software does the job intended, new software is maintainable and old software is useable. The right software means the correct version. There are usually several versions of the same program in a met lab. Each version may have a different bug fixed or a new one inserted. The software in the metrology lab has not gone through the vigorous verification and validation required of prime system software. The lab s software is much simpler, but is worth verifying. Without guidelines, whether or not a program is verifiable is a function of the programmers style. Many of the earlier programmers developed their own special style. This individuality was acceptable in the days of the black art, but is expensive now. Maintainability is a key word today; programs should be written to be modified (2).

The software product assurance effort must work with the hardware and software in the lab now. After all this is the combination we are having problems with. The amount of software written for the met lab is small, at least compared to the output of a software engineering department. The system should be tailored to the needs of the lab. The system should control the development and maintenance of calibration software generated in the metrology lab. Every lab has a system for handling manual procedures and the system for software should be similar. There are limits to the system. There is little point in making software tamperproof. The extra trouble of having protected software used by the techs is not worthwhile considering a manual procedure can be changed on the spot. The change most often made is a mistake in following instructions. One last requirement for the software product assurance effort is small steps. This will not be a crash program; other business has to be taken care of at the same time.

Steps to a Solution

Once the problem is recognized the basic steps to a solution are easy to determine; implementing the steps is the real problem. The steps to draining the software swamp are:

Find out what is out there.
Discard the duplicates.
Save the software worth keeping in a library.
Keep the library software clean.

The piecemeal approach will not work. Each of these steps are important, but doing all is most important.

Inventory

The first software inventory at FACC was a simple paper one and was abandoned quickly. The Metrology Lab at FACC had over 800 programs, most of them duplicates or near duplicates. There were too many programs to handle manually; software is needed to control software. The first software product assurance objective is to collect a table of contents from each disk. This table of contents is the disk directory with one thing added, the checksums for each of the programs.

The process of disk "branding" records the table of contents on the program disk, on a master directory disk and provides a hardcopy. The table of contents for a disk is recorded for a specific date, and can be compared later. The configuration of the user's disk can be checked later by comparing the table of contents file to the disk's current configuration. When each disk in use is branded the master directory disk contains a list of all the programs, their sizes and their checksums. Figure 1 is a sample printout from the table of contents program. The first column is the program name; the asterisk indicates a secured program. The second column is the type and was included because some programs require a data file or a key file. The third column is the size of the program and the fourth is the checksum. The first line of the header is the disk identification number. The "F" in means a five and a quarter inch floppy disk. The second line of the header is the date the table of contents was obtained and any comments. The comments are used to record the cryptic labels used on the disks.

```
DISK ID= F001
9/4/84 MAIN BACKUP DISK

Filename       Type      #Bytes        Checksum
ELECMP         PROGRM     5926         11602
bkglog         TDATA
COPY       *  PROGRM      3968
dvm            KEYS        266
34971          PROGRM     6324         24395
3455A          PROGRM     6392         20285
345611         PROGRM    11678         6184
3438A          PROGRM    31598         1848
3478A          PROGRM    30642         26959
33141          PROGRM     3778         13626
wavedata       TDATA
```

Figure 1. Table of Contents Printout

The Software Catalog

The data stored on the main directory disk will be a software catalog when all the disks in the lab are "branded" and all the directory data are collected. This data is sorted by the second of the control programs. The sorting program produces sorts by name and by checksum. Programs with the same checksum are assumed to be the same and are flagged. This way duplicate and near duplicate programs can be eliminated. There were two types of duplicates uncovered during our sort. The first was the same program under different names. These are found during the numerical sort by checksums. The second type of duplicate is different programs under the same name. There was also many near duplicates, the same or similar names with nearly the same size but different checksums. The next big problem is finding the versions worth keeping. Often programs were changed for good reasons, but nobody remembers the reasons. Finding the right version is the hard part. The only software that could help here is a compare program to show the differences between programs. This sorting is intended to show which programs are worth saving.

Figure 2 is a sample printout from the sorting program, in this case a numerical sort of the checksums. The printout is similar to the table of contents, but a column for the disk identification and one for the duplicate flag have been added. The files "5328A" and "59501A" are duplicated and the duplicates are exact. The files "9872A" and "7225A" are also exact duplicates. Figure 2 shows these two programs to be identical, same checksum, same size.

```
FILENAME      #BYTES    CHECKSUM      DISK ID
5328A          6882     17017         E001   *
5328A          6882     17017         E002   *
59501A         4108     17166         E001   *
595016         4108     17166         E002   *
595016         4108     17166         E004   *
A59260         1302     17321         F010   *
A59260         1302     17321         F011   *
980346         8642     17583         E004
PRT2           3426     18100         F024
9872A          2836     18326         E001   *
7225A          2836     18326         E001   *
98726          2836     18326         E002   *
7225A          2836     18326         E002   *

* INDICATES DUPLICATE FILES
```

Figure 2 Checksum Sorting Printout

Figure 3 is another printout from the sorting program, but a sort by name. Figure 3 shows there are several copies of the "3455A" file. The version on disks F001 and F002 are the same size as the others, but have a different checksum. A single letter change from "a" to "A" could produce this result. The "5328A" and "59501A" files have two versions of similar size and different checksums. These present a special problem. The difference between the two may be legitimate corrections , but which version is the right one? The answer to this question requires a careful look at both versions, A program to do the compare would help, but the reason behind the differences requires some research.

```
FILENAME     #BYTES    CHECKSUM      DISK ID
3438A        31598     1848          F001    *
3438A        31598     1848          F002    *
3455-o        5686     24232         E004
3455A         6392     18481         F003    *
3455A         6392     18481         E001    *
3455A         6392     18481         E002    *
3455A         6392     18481         E004    *
3455A         6392     20285         F001    *
3455A         6392     20285         F002    *
5328A         7178     1105          E004    *
5328A         6882     17017         E001    *
59501A        4150     5043          F002    *
59501A        4108     17166         E001    *
59501A        4108     17166         E002    *

* INDICATES DUPLICATE FILES
```

Figure 3 Name Sorting Printout

One limitation of the table of contents and sorting programs is a secured program has a zero checksum. Most of the time this is not a problem, but if someone has secured part of program for some reason two programs that produce different results could have the same checksum.

The Software Library

Creating a master file of golden copies of the programs worth keeping is an excellent start, however the master file does not remain a master file long unless there are some controls placed on who can get into the master file, who can put programs in the master file and who can change the master file. Once the master file is established the problem become one of keeping the master file clean; that the master file remains a master file.

In many ways a software library should work like a public library. A public library is a collection of books worth keeping, and some simple procedures to maintain the collection. There is a list of patrons and the books they have checked out. There is a definite way of checking out books. The librarians maintain the collection by acquiring new books and discarding books that no longer circulate. Not everyone is allowed to chose new books for circulation. Finally a catalog of the books is kept.

A software library works in a similar manner. The collection is software not books. The list of patrons and the books they have checked out is the disk users log. The sorted disk table of contents functions as the catalog. The software librarian helps to control the acquisitions and deletions to the software collection. The software library does have records that have no equivalent in a public library, the program history folders, **PHF's.**

The **PHF's** are functionally the same as the history folders for individual instruments, but contain information on a program. The folders maintain the traceability and control of the software. The PHF contains the information to prove the program works, the changes made were done correctly and the documentation to help the programmer when the program must be changed. The PHF should contain; the specifications for the instrument or test system, the bus commands used, a variable cross reference with the source code, programming notes, a change record and verification results. The last two are very important.

The change record ties the revisions of the software together. **Why** the changes were made and what they were expected to do can be important later, especially if a new bug is introduced. Before software is entered into the library it must be verified, before it goes in you have to prove it works. This can be as simple as some manual checks on an instrument or as complicated as a step by step test of the software. As more and more instruments and test systems use software calibration the more important verification becomes.

The software library needs a librarian and some operating instructions to work. The operating instructions to add, delete and change software must be established. The calibration procedure approval cycle has to be changed to accommodate a review of the software before it goes into the library. A controlled software environment requires guidance; there should be a central point of contact for software related problems. This function can best be described as a software specialist.

Software is a discipline like dc, low frequency or rf; the major difference is software is a broad instead of a narrow discipline. Software cuts across all specialties in the met lab because computers and microprocessors are now part of nearly every measurement process. The software specialist s function is to keep order. He reviews all the software submitted for proper documentation and style, and participates in the verification of new software. The software specialist handles the updates and changes to existing software. He is also responsible for the programmer s style guide and software tool kit. The programmer s style guide is not a restrictive how to do it book. Instead it is a guide to writing modular software that is maintainable and verifiable. Modularity helps make a program easy to verify, by breaking the process into digestible blocks (3). One other function of the metrology software specialist is the collection of often used modules into the programmer s tool kit. By providing the tools, the guide and reviewing software and documentation the metrology software specialist controls the software environment.

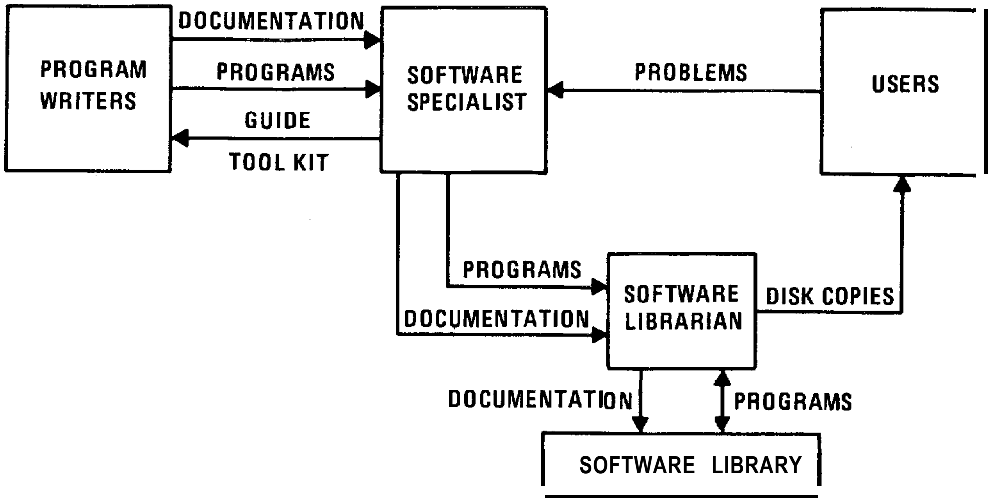

Figure 4 Controlled Software Environment

Figure 4 illustrates a controlled software environment in a met lab. The users obtain copies of programs from the software librarian. Because disk can hold more than one program the disks are organized by function. For instance there will be a dvm disk having only programs to calibrate digital voltmeters. When a problem with a program has been found and corrected the librarian checks the users log to locate the disks with the program on them. The entire disk is update and "branded." No disks are returned to the library.

The users notify the software specialist of problems. The software specialist and the user then solve the problem, and the program is changed as necessary. Depending on the changes made all or some of the verification is run again. After the modified program is verified the software specialist gives a copy of the program to the librarian. The librarian uses the disk user information to locate all the users of the program and makes sure each user has the most up to date program.

New programs are added after they have gone through the approval cycle. Calibration software goes through the same reviews as a manual procedure plus the verification, documentation and style reviews. The software specialist deletes programs as they become unnecessary.

At FACC we have completed. our HPL program inventory and are purging the unnecessary programs. The sorting program was written in Basic and works on the ASCII files generated by the HPL table of contents program. The table of contents programs for Basic has not be written yet. Basic is coming into use; all new programs will be written in Basic. A preliminary version of the operating instructions for the library is being reviewed. Information for the style guide is being collected, and some utilities are available for the software tool kit.

Lessons

1. The systematic approach is the most viable. A piecemeal effort would just have to be redone when the problem is worse.

2. The steps to starting a software product assurance effort are:

Find out what is out there.
Discard the duplicates.
Save the software worth keeping in a library.
Keep the library software clean.

3. Software is required to control software.

4. The software specialist and librarian functions are needed for a controlled software environment.

5. Software is a broad discipline, not a narrow one.

References

(1) **Cox,** John W., 1981, "Software Quality Management," 1981 NCSL Symposium.

(2) **Baroni,** R. Anthony, 1984, "Writing Test Programs That Are Maintainable," AutoTestCon 1984 Proceedings, pp 102-108.

(3) Wade, Gerald T., "Programming for Survival," 1978, Abstracts & Proceedings-78, HP General Systems Users' Group

LIFE-CYCLE OBJECTIVE MEASURING OF THE SOFTWARE PRODUCT

BY

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Software product measurement has become a high priority concern for both government and commercial industries. This paper examines a technique for obtaining a highly objective measurement of the software product throughout its life cycle. The technique presented is Software Quality Metrics, defined as a methodology whose primary objective is the measure of software quality attributes using a set of software life cycle properties called quality factors. The author, Gerald E. Murine, president and founder of METRIQS, Inc., is considered the most experienced and knowledgeable person in the application of Software Quality Metrics. Conclusions resulting from his research, and the application of Software Quality Metrics on six major military projects form the basis of this paper. The evolution of Software Quality Metrics has been from university research projects and a classroom science topic to an effective, practical methodology is discussed. The selection of the software quality factors are discussed together with methods for assigning appropriate criteria. Examples of element selection conclude the pre-measurement section of this paper. Various scoring techniques are then presented; two are presented as the author's choices. The role of automated management reporting tools is also discussed Quality Measurement management reporting Anomoly detecting and predictive metrics are considered with particular emphasis placed on designing reliability into the software. Methods for reporting S/W product status are also given together with the suggested guidebook usage.

The Problem of Quantifying Software Quality

The development and introduction of Software Quality Metrics (SQM) as a software quality assurance tool was motivated by numerous influences on software development. Certainly, the problem of subjective vs. objective assessments served as a basis of thought in the evolution of a "finitely countable" or, perhaps, measureable set of software quality attributes which eventually settled into the SQM methodology. The problem of early identification and measurement of long range software quality factors, coupled with the need for precision in the software requirements analysis phase of development for measuring these factors, also contributed to the development of the SQM methodology. Other needs prompting development and validation of the SQM methodology were both a desire for deductively translating individual or "element" measurements into a larger life-cycle property or quality factor and the further association with some functional partitioning of the software system itself. The use of SQM in addressing these and other problems inherent in any software quality assurance program is a current high item of interest. Specific reference to individual software environment is the basis of any proposed SQM approach. The paper will include a short summary of an approach to the hierarchy of SQM; an examination of the Quality Factor set; the proposed criteria set to support the above Quality Factors; some comments on the element selection process; some potential problem areas which may result from inexperience with the methodoloy; manual procedures used in implementing the process; and finally, the automation of SQM reporting.

SQM AS A SOLUTION

Recent applications of SQM enable the incorporation of validated techniques in support of an overall Software Quality Assurance program. Eleven of the twelve Software Quality factors identified by Boehm and later reiterated by Walters and McCall have been applied by Murine on six major military projects and several commercial ones.

The list of twelve quality factors is shown in Table 1.

Table 1: Software Quality Factors

Correctness	Flexibility
Reliability	Portability
Efficiency	Maintainability
Integrity	Testability
Reusability	Interoperability
Usability	Intraoperability

Each unique system, subsystem, or functional partition, is measured against a selected subset of the factors. Quality factors are usually associated with particular systems and are the only members of the SQM hierarchy which are independent of development phase. Not all of the factors need be selected for a particular system. Only those quality factors judged applicable to that system should be measured. Some reasons for not including certain quality factors might be cost, time, application, mission objective, and physical environment. Each system will, therefore, have its set of quality factors identified prior to the beginning of the SQM analysis. Special note is given to the definition of reliability (extent to which a program can be expected to perform its intended function with required precision) which is predictive thus allowing the continuous measure and designing in of reliability.

SELECTING QUALITY FACTORS

There are several methods of associating quality factors with a system. One method has been alluded to above whereby the factors are manually selected (by use of a checklist, standards list or other such device) at the start of the analysis. A second method is one which is better suited to a ranking or priority approach. In this method, coefficients are attached to each quality factor, such as

$$S_q = a_{11}q_1 + a_{12}q_2 + a_{13}q_3 + \dots + a_{1,n}q_n = \sum_{j=1}^{n} a_{1,j}q_j$$

where $a_{1,j}$ is the coefficient and q_j is the quality factor. (For example, q_1 = correctness, q_2 = reliability, etc., and S_q is some quality score discussed later.) Two subscripts are used here to illustrate criteria association discussed in the next section. In this method all quality factors which will be used for a particular subsystem are given non-zero coefficients and all factors of equal weight are given equal coefficients. Thus, if all twelve factors are used and have equal value,

$$S_q = \sum_{j=1}^{12} q_j \quad (a_{1,j} = 1 \ \forall j).$$

If, for example, correctness (q_1) is to be assigned twice the weight of the first nine factors and the twelfth factor say q_{12} = reusability) is not to be measured, . then

$$Q_s = 2q_1 + \sum_{j=2}^{11} q_j.$$

As we will see later, the scoring is not as simple as this example implies, but nonetheless, the example illustrates our second quality factor selection method.

A third method is the "popular vote" method which is illustrated by the following real example.

At the time this method was initiated, a software development plan (SDP) had been approved and the program performance specification completed. Our SQM approach to measuring the quality of the software was first to identify the software goals, and then to select the appropriate metrics from various sources. The goals were extracted from the SDP as inferred by the software development team.

A total of 217 requirements which related to the 12 quality factors were extracted from the software development plan. A frequency of occurrence of these requirements, as they related to the software quality factors (explicitly or implicitly), was established and plotted (Figure 1). The three factors occurring most frequently were selected as the trial set of objectives.

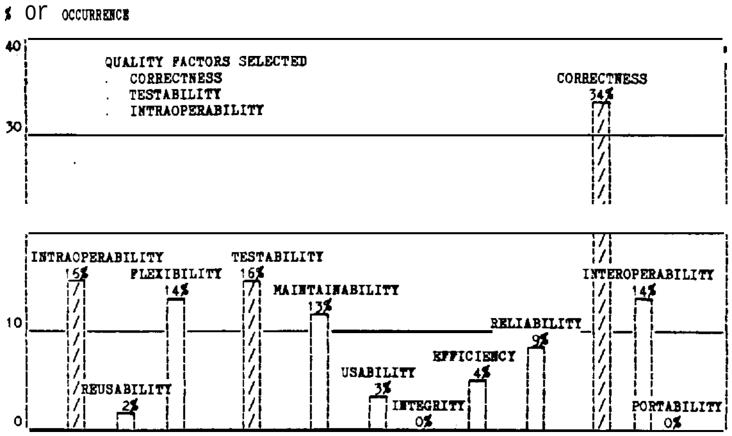


Figure 1: Importance of Quality Factors as Expressed in the Wording of the Software Development Plan

The SDP document analysis provided sufficient data. to establish an ordering of the software quality factors by group. The first group, considered to be of the highest priority, contained the factors of correctness, testability, and intraoperability.

The definitions used were those produced by Boehm[1] and since accepted by practitioners such as McCall[2] and Murine[4]. For the sake of completeness the definitions are given here as follows:

Correctness: Extent to which a program satisfies its specifications and fulfills the user's mission objectives.

Testability: Effort required to test a program to ensure it performs its intended functions.

Intraoperability: Effort required to totally communicate between software components.

From this group, a list of criteria was defined which, themselves, were measures of the three factors. A complete list of criteria is given in Table 2. These criteria were traceability, completeness, consistency, simplicity, modularity, instrumentation, self-descriptiveness, communications commonality, and data commonality.

TABLE 2: CRITERIA

TRACEABILITY
COMPLETENESS
CONSISTENCY
ACCURACY
GENERALITY
SIMPLICITY
MODULARITY
TRAINING
CONCISENESS
EXPANDABILITY
ACCESS CONTROL
ACCESS AUDIT
OPERABILITY
STORAGE EFFICIENCY
DATA COMMONALITY
COMMUNICATIONS COMMONALITY
SELF-DESCRIPTIVENESS
EXECUTION EFFICIENCY
COMMUNICATIVENESS
MACHINE INDEPENDENCE
SOFTWARE SYSTEM INDEPENDENCE
INSTRUMENTATION
ERROR TOLERANCE

The SQM Hierarchy

Once the quality factors have been selected for a particular application, the SQM process may begin. SQM is a precise, deductive, quantitative hierarchy which associates criteria to quality factor and countable element to criteria. The SQM process is built upon the principle that some set of measurable attributes may be used to define (measure) a particular quality factor. These attributes (called criteria) need not be unique to a particular factor and, in general, are not. Thus, some dependence is established between the quality factors themselves. The SQM process further relies on the premise that each criteria is itself measurable by some finite set of countable events or elements. The measure to be obtained for each element is otherwise referred to as a metric although metric may also be used to represent the quantification of a higher level (criteria, factor, or functional component). Some discussion of metric convolutions will be presented in this paper. For the moment, it is sufficient to relate metric to element and to observe that the set of elements is one-to-one onto the set of criteria.

A last point of discussion on the SQM hierarchy mentioned here relates to the methodologys dependence on developmental phase. Even though the quality factors are phase-independent, the criteria (and, of course, their associated elements) are not. The selection of criteria supporting a given quality factor may .pa vary with developmental phase. (We will consider three such phases for the purpose of discussion: requirements, design, and code.

Tailoring SQM

As mentioned in the previous section, the quality factors selected for a specific project should be determined as early as possible and weighting coefficients, if desired, selected at the same time. The selection (and weighting) process must be thoroughly analyzed in order to establish a set of characteristics for the system from which the best possible choice may be made. Heavy dependence on past experience with similar systems should be paramount in the generation of these characteristics. Other influences such as expected length of life-cycle, real vs. off-line applications, special purpose vs. general purpose, size, on-board or stand-alone, distributive characteristics, security, software vs. firmware, physical constraints (memory size, timing, etc.), human interfaces, type of application, and others.

The SQM Criteria Set

Once a set of quality factors has been selected unique to a particular system, the selection of criteria may then take place. Recall the association of criteria to factor is phase-dependent and not necessarily one-to-one onto the factors. Figure 2 is the Factor-to-Criteria pairing without phase partitioning.

FACTOR	CRITERIA
1. CORRECTNESS	TRACEABILITY COMPLETENESS CONSISTENCY
2. RELIABILITY	CONSISTENCY ACCURACY SMPLICITY ERROR TOLERANCE
3. TESTABILITY	MODULARITY SIMPLICITY SELF-DESCRIPTIVENESS INSTRUMENTATION
4. FLEXIBILITY	MODULARITY GENERALITY EXPANDABILITY SELF-DESCRIPTIVENESS
5. PORTABILITY	MODULARITY SELF-DESCRIPTIVENESS S/W SYSTEM INDEPENDENCE H/W INDEPENDENCE
6. INTRAOPERABILITY	MODULARITY DATA COMMONALITY COMMUNICATIONS COMMONALITY
7. EFFICIENCY	EXECUTION EFFICENCY STORAGE EFFICIENCY
8. INTEGRITY	ACCESS CONTROL ACCESS AUDIT
9. USABILITY	TRAINING COMMUNICATIVENESS OPERABILITY
10. MAINTAINABILITY	CONSISTENCY SIMPLICITY CONCISENESS MODULARITY SELF-DESCRIPTIVENESS
11. REUSABILITY	GENERALITY MODULARITY S/W SYSTEM INDEPENDENCE MACHINE INDEPENDENCE SELF-DESCRIPTIVENESS
12. INTEROPERABILITY	MODULARITY COMMUNICATIONS COMMONALITY DATA COMMONALITY

Figure 2

Element Selection

The selection of elements is perhaps the most critical issue in the success of measuring quality factors by the use of the SQM methodology. As we mentioned above, the elements are phase-dependent just as are the criteria. The elements need not, however, transverse phase, even though their associated criteria may support factors in different phases. Elements are, however, one-to-one onto criteria.

With this background, *we* may now investigate other influences on the selection of a particular set of elements. The phase-dependency is basically resolved first by criteria (via factor) presence and thereby the existence and form of measurable data or documentation. For example, measurable data at the requirements analysis phase generally will take the form of specifications where, on the other hand, measurable data at the code phase.may well be code itself (or structure of code). Each of these is influenced *by* other factors such as military standard compliance, programming standards, programming language, etc. In addition, many of the selection factors discussed for criteria will also apply here (e.g. operating system software vs. application training software).

By nature of their position in the hierarchy, the elements provide the mechanism for fine tuning or changing the software quality measurements. This provides a means of modifying analysis (form and content) without disrupting or redoing the entire evaluation history. Hence, as ongoing experience suggests new or additional measurements, the quality score may be adjusted without a total rework of the SQM measurements. Only those factors directly affected need be changed. The hierarchy also provides the ability to cross-reference techniques (e.g. changes in programming methodologies) without total duplication of cost or effort. In general, its element set provides the vehicle to effectively analyze the software quality impacts of dynamically changing influences--influences which may span the spectrum from changing software methodology to changing system requirements. Cost saving is apparent not only in the early detection of errors (as early as requirements definition phase) but also in the flexibility of the methodology. A few element examples for the Design Phase are given in the next section.

Element Examples

We have selected an arbitrary factor (correctness) and listed a few elements for a particular criteria (completeness) over the requirement, design, and code phases. The elements listed here are a few examples only having been selected expressly to illustrate the element phase crossing mentioned above. It is not proposed that these elements have any special preference over the several hundred we have collected and have at our disposal.

Phase	Some Completeness Metrics	
Requirements Analysis	CP 1.1.1	All functions must be unambiguous.
	CP 1.4	All referenced functions must be defined.
	CP 1.5.1	Each decision point must have all conditions defined.
	CP 1.5.2	Each decision point must have all processing defined.
	CP 1.8	All data item units must agree.
Design	CP 1.3.1	All functions must be referenced (used) in the application.
	CP 1.6.1	The number of parameters must be the same in both the calling and the called programs'parameter lists.
	CP 1.6.2	Calling parameters must be passed in the same order (sequence) as defined by the called program.
	CP 1.6.3	The full compliment of defined calling sequence parameters must be used.
	CP 1.8	All data item units must agree (used in requirements analysis).
Code Analysis	CP 1.2	All data references must be defined, computed, or obtained from an external source.
	CP 1.2.1	All data items must be used.
	CP 1.1.2	Input references(parameters) must be uniquely identified.
	CP 1.9	Code must agree with the design.
	CP 1.1.1	All functions must be unambiguous.
	CP 1.3.1	All functions must be referenced (used) in the application (used in design analysis).

A second example of element selection is given in the following real example. In this example, MIL-STD-1679 had been invoked on the project.

Since MIL-STD-1679 is not directly metric oriented, it was necessary to identify its individual requirements, separate them into categories, and group the metric-related requirements by criteria. A total of 416 requirements were extracted from the relevant sections of MIL-STD-1679 and divided into four categories. The distribution of the metric requirements by category is shown in Figure 3.

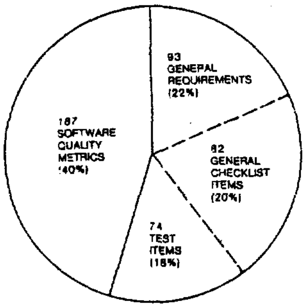


Figure 3: Distribution of 416 MIL-STD-1679 Requirements

Nine criteria directly related to the three selected factors contained 97 of the MIL-STD metrics. Some criteria were found to be without direct reference in the MIL-STD whereby additional metrics were needed. From the Murine Metric Set (MMS), 87 additional metrics were identified to support the defined criteria (Table 3). A final set of metrics was generated from the various Data Item Description (DID) documents.

Table 3: Selected Criteria--Metric Set

	MIL-STD-1679		
Criteria	Metrics	Metrics	Metrics
Traceability	0	6	6
Completeness	29	13	42
Consistency	4	22	26
Simplicity	12	19	31
Modularity	10	5	15
Instrumentation	1	0	1
Self-Descriptiveness	37	13	50
Communications Commonality	0	5	5
Data Commonaiity	4	4	8
	97	87	184

Scoring

The level (factor, criteria, element, or functional partition) as well as the method of convoluting scores throughout the hierarchy, unless treated carefully can be misinterpreted. Past applications have used the Murine SQM Scoring Algorithms in determining a software quality factor "goodness" score. This state-of-the art scoring technique has been used on real data and has shown a less than 10% variance at the Quality Factor level. The nine Murine Scoring Algorithms (MSA) are given in Table 4:

TABLE 4: MURINE SCORING ALGORITHMS

Direct Ratio Scoring
Second-Order Averaging
Direct Ratio Weighted
Second-Order Averaging, Weighted
Direct Ratio, Criteria Dampened
Second-Order Averaging, Criteria Dampened
Direct Ratio, Weighted, Criteria Dampened
Second-Order Averaging, Weighted (maximum), Criteria Dampened
Second-Order Averaging, Weighted (average), Criteria Dampened

Preferred algorithms are the direct ratio and second order averaging ones. Many influences establish a preference.

Special Considerations for the Requirements Phase

The Requirements Phase of software development has historically been the most difficult phase to measure in any fashion. It is particularly difficult to measure software quality since neither code or detailed design exists at this point. Additionally, certain software quality factors such as Efficiency, Maintainability, and Reusability have generally not been addressed this early in the developmental process. Others, such as Correctness and Reliability, have more apparent and sometimes obvious roots in higher-level system specifications. Also, there is the problem of completeness of user requirements--often not established until much later in the developmental process. This may lead to a good but incomplete (and, hence, inaccurate) software quality score.

SQM Guidebooks

As mentioned above, the measurement of quality factors by the team is an ongoing engineering process. The quality factors are measured continuously and in conjunction with the developmental process. Scores can be made available continuously but are usually reviewed at major milestones (Design Reviews, for example) or weekly. Hence, there is a close association between the SQM analyst and the programmer. Many problems can occur here unless special precautions are made.

Programmers need to know at the start which criteria and elements will be measured for quality. The issuance of a SQM Requirements Guidebook listing the quality factors, associated criteria and related elements serves as both a bridge between the SQM analyst and the programmer and as a constant software quality reminder to the programmer. This document can be distributed at the beginning of each phase (once the criteria and elements sets have been approved by developmental engineering and the SQM team).

In addition to the SQM Requirements Guidebook, an SQM Scoring Guidebook is also helpful.-This book elaborates on the meaning of each element identified in the SQM Requirements Guidebook and also gives both scoring algorithm and element, criteria, factor priority data. This answers the questions about element interpretation, method of determining quality compliance, and order of importance of factor, criteria, and element. It has been found to be advantageous having this as a separate document since the Requirements document is continuously used for its own sake. The same distribution parameters are required here as with the Requirements document and, hence, it can be made available to the programmers at about the same time. (Sometimes an extra day or two is necessary to establish priorities.)

Reporting Software Product Quality Status

Two procedures used to implement the software quality factors and their corresponding criteria and elements are discussed here. One is a manual process (The SQM Notebook) and the other is the Software Metrics Automated Reporting Tool (SMART).

The SQM Notebook is similar in many ways to a well-organized Unit Development Folder (UDF) for software. Some major areas included are:

1. Scores for the functional Software Segment
   a) Segment Scores (using any of the MSA)
   b) Factor Scores (see Figure 4)
   c) Criteria Scores (see Figure 5)

2. Individual Element Scores grouped by Criteria

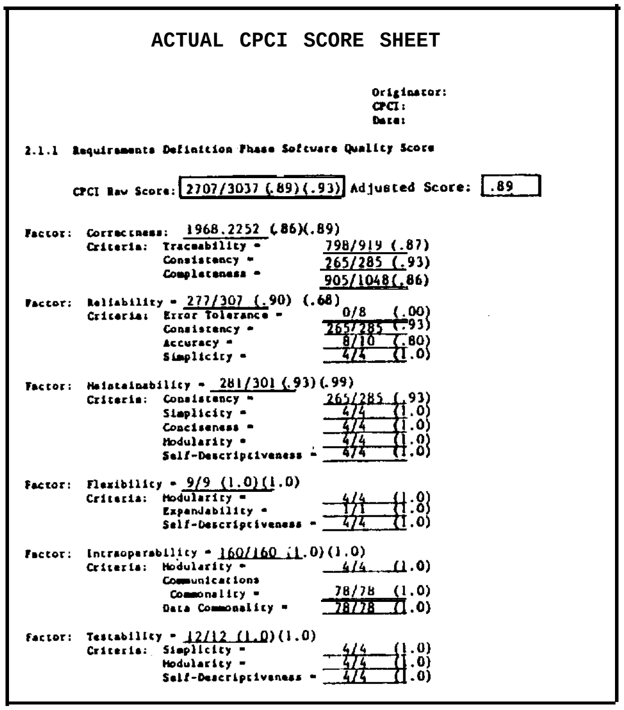
3. Tally Sheets (each individual item's pass or

fail--1 or 0--is recorded against each element.

4. Software Discrepancy Report (SDR) numbers for each failure.

5. SDR defining the problem (Problem Reports)

6. Requirements by specifications and traceability information.



ACTUAL CPCI SCORE SHEET

Originator:
CPCI:
Date:

2.1.1 Requirements Definition Phase Software Quality Score

CPCI Raw Score: 2707/3037 (.89)(.93) Adjusted Score: .89

Factor: Correctness: 1968.2252 (.86)(.89)
Criteria: Traceability = 798/919 (.87)
Consistency = 265/285 (.93)
Completeness = 905/1048(.86)

Factor: Reliability = 277/307 (.90) (.68)
Criteria: Error Tolerance = 0/8 (.00)
Consistency = 265/285 (.93)
Accuracy = 8/10 (.80)
Simplicity = 4/4 (1.0)

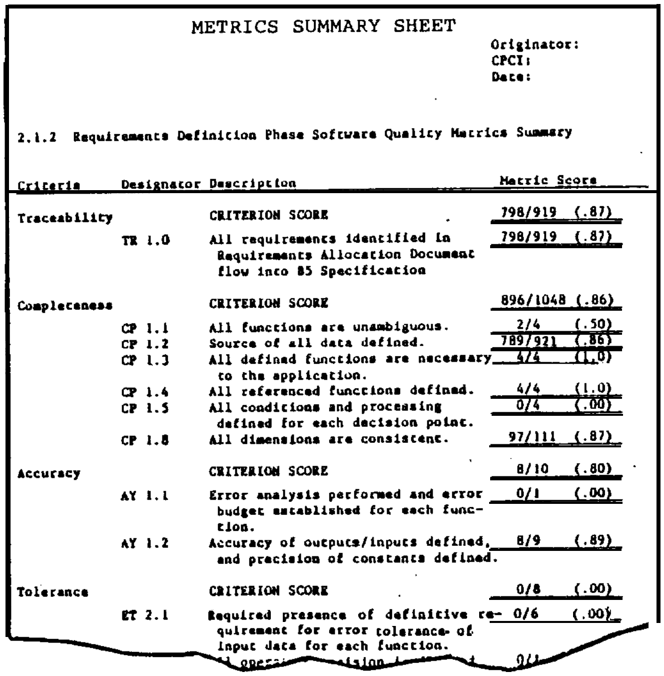
Factor: Maintainability = 281/301 (.93)(.99)
Criteria: Consistency = 265/285 (.93)
Simplicity = 4/4 (1.0)
Conciseness = 4/4 (1.0)
Modularity = 4/4 (1.0)
Self-Descriptiveness = 4/4 (1.0)

Factor: Flexibility = 9/9 (1.0)(1.0)
Criteria: Modularity = 4/4 (1.0)
Expandability = 1/1 (1.0)
Self-Descriptiveness = 4/4 (1.0)

Factor: Intraoperability = 160/160 (1.0)(1.0)
Criteria: Modularity = 4/4 (1.0)
Communications Commonality = 78/78 (1.0)
Data Commonality = 78/78 (1.0)

Factor: Testability = 12/12 (1.0)(1.0)
Criteria: Simplicity = 4/4 (1.0)
Modularity = 4/4 (1.0)
Self-Descriptiveness = 4/4 (1.0)

Figure 4: Factor Scores



METRICS SUMMARY SHEET

Originator:
CPCI:
Date:

2.1.2 Requirements Definition Phase Software Quality Metrics Summary

Criteria	Designator	Description	Metric Score
Traceability		CRITERION SCORE	798/919 (.87)
	TR 1.0	All requirements identified in Requirements Allocation Document flow into B5 Specification	798/919 (.87)
Completeness		CRITERION SCORE	896/1048 (.86)
	CP 1.1	All functions are unambiguous.	2/4 (.50)
	CP 1.2	Source of all data defined.	789/921 (.86)
	CP 1.3	All defined functions are necessary to the application.	4/4 (1.0)
	CP 1.4	All referenced functions defined.	4/4 (1.0)
	CP 1.5	All conditions and processing defined for each decision point.	0/4 (.00)
	CP 1.8	All dimensions are consistent.	97/111 (.87)
Accuracy		CRITERION SCORE	8/10 (.80)
	AY 1.1	Error analysis performed and error budget established for each function.	0/1 (.00)
	AY 1.2	Accuracy of outputs/inputs defined, and precision of constants defined.	8/9 (.89)
Tolerance		CRITERION SCORE	0/8 (.00)
	ET 2.1	Required presence of definitive requirement for error tolerance of input data for each function.	0/6 (.00)

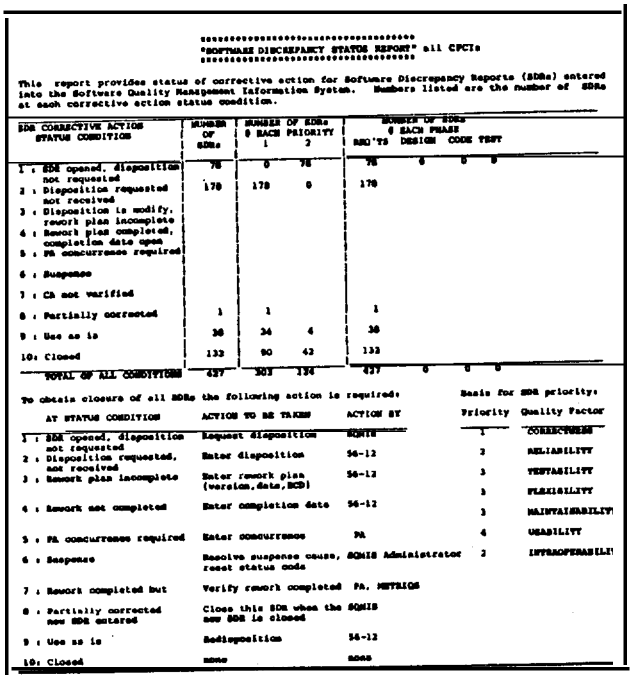
Figure 5: Criteria Scores

Each of these major areas is included by developmental phase (Requirements Analysis, Design Analysis, and Code Analysis). The SQM Notebook is continually updated throughout the development cycle. A notebook is kept for each Function Segment of the system.

The SQM Notebook, although thorough in itself, can become very large and, hence, difficult to quickly extract SQM summary data for management use. An automated system, the "Software Metrics Analysis Reporting Tool" (SMART) was developed to quickly report SQM status. The SMART system is designed to accept tally data for automatic SQM hierarchial chaining as follows:

Individual pass/fail item data is generated, either by automated tool or manually. The SQM data is extracted by functional block or by unit of product. For example, if five elements require input data for inspection, then all input data (the unit of product) is entered into the system and each of the five element analyses is performed against it. The numerical scores are distributed to their respective element bins for convolution into the appropriate criteria whenever other element scores become available.

As each fail (0) condition is recorded, an interrupt is invoked by the system requiring the analyst to input via the keyboard, the text describing the discrepancy. The SMART system assigns the SDR number, a priority number, the associated criteria with designator, module name or other functional grouping name, dates, analyst's name, and other supplementary version information. The SQM analyst enters reference information (e.g., specification's paragraph number) and the problem description. Disposition tracking data is then listed for selection on the form itself. A Software Discrepancy Status Report Summary (see Figure 6) then is made available for review showing



"SOFTWARE DISCREPANCY STATUS REPORT" all CPCIs

This report provides status of corrective action for Software Discrepancy Reports (SDRs) entered into the Software Quality Management Information System. Numbers listed are the number of SDRs at each corrective action status condition.

SDR CORRECTIVE ACTION STATUS CONDITION	NUMBER OF SDRs	NUMBER OF SDRs @ EACH PRIORITY 1	2	NUMBER OF SDRs @ EACH PHASE REQ'TS	DESIGN	CODE	TEST
1 : SDR opened, disposition not requested	78	0	78	78	0	0	0
2 : Disposition requested not received	170	170	0	170			
3 : Disposition is modify, rework plan incomplete							
4 : Rework plan completed, completion date open							
5 : PA concurrence required							
6 : Suspense							
7 : CA not verified							
8 : Partially corrected	1	1		1			
9 : Use as is	38	34	4	38			
10: Closed	132	90	42	132			
TOTAL OF ALL CONDITIONS	427	303	134	427	0	0	0

To obtain closure of all SDRs the following action is required:

AT STATUS CONDITION	ACTION TO BE TAKEN	ACTION BY
1 : SDR opened, disposition not requested	Request disposition	SQMIS
2 : Disposition requested, not received	Enter disposition	56-12
3 : Rework plan incomplete	Enter rework plan (version, date, BCD)	56-12
4 : Rework not completed	Enter completion date	56-12
5 : PA concurrence required	Enter concurrence	PA
6 : Suspense	Resolve suspense cause, reset status code	SQMIS Administrator
7 : Rework completed but	Verify rework completed	PA, METRICS
8 : Partially corrected new SDR entered	Close this SDR when the new SDR is closed	SQMIS
9 : Use as is	Redisposition	56-12
10: Closed	none	none

Basis for SDR priority:

Priority	Quality Factor
1	CORRECTNESS
2	RELIABILITY
3	TESTABILITY
3	FLEXIBILITY
3	MAINTAINABILITY
4	USABILITY
2	INTRAOPERABILITY

Figure 6: Software Discrepancy Status Report

the number of SDRs by priority and phase as reported against any of ten closure codes. This information can be generated at any reporting level such as module, computer program component, functional segment, subsystem or total system. Other information which may be called up from the SMART system is numerous and includes the calculation of scores by factor, criteria, element, priority, data, and phase. The availability of this data in turn provides the basis for trending analysis and data history logging.

The SMART system is a device for reporting summary information in a clear, concise manner. This summary data is designed to directly interface with other Q.A. information as a supplement and not as a replacement. The SMART system can be adapted to any environment with minimal modifications. Extensions to the system which would directly measure any unique features inherent in individual software systems could easily be accomplished via the built-in "unit of product' and SQM hierarchy provisions.

Conclusions

We have discovered that incorporation of the Software Quality Metrics methodology into a SQA program has satisfied all our initial quality objectives as well as some not previously contemplated. It provides a real, positive quality impact on software product development and measurement and can be used as a major cost reduction tool as well. Some of the benefits derived were:

- Meaningful product quality measures.
- Frequent software quality measure which permits timely detection of errors.
- Project management visibility of software quality during each phase (not only at code completion).
- Much better documentation.
- A basis for objective evaluation against the user's requirements.
- Early establishments of quality goals which would not have been considered until solidification of code.
- Cooperative association with software developers.
- Complete traceability from evaluation to disposition.
- Measurable QA impact during software development.

We have concluded that it is indeed feasible and, in fact, desirable, to include Software Quality Metrics as a SQA tool to support managements commitment to improve software quality. Even though the methodology requires additional validation, we have found it a valuable technique for continuously monitoring the pulse of software quality development. Quantifying the measurement of unique quality requirements is possible and unambiguously reportable. Visibility of the software quality process and product is facilitated by the use of SQM. It is our recommendation that SQM become an integral part of any SQA program.

REFERENCES

(1) B.W. Boehm, Quantitative Evaluation of Software Quality, Proceedings 2nd International Conference on Software Engineering, pp. 592-605, October 1976.

(2) G.F. Walters and J.A. McCall, Factors in Software Quality, RADC TR-77-369, 1977.

(3) G.E. Murine, Applying Software Quality Metrics in the Requirements Analysis Phase of a Distributive System, Proceedings from Minnowbrook *Conference,* 1980.

USING GIDEP TO IMPROVE YOUR METROLOGY POSTURE

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ABSTRACT

The author presents a metrology oriented overview of the Government-Industry Exchange Program, GIDEP, including its evolution, types of data banks, communication networks, and areas of application as related to metrology. Information is provided on the current capability and future potential of this viable data exchange program in terms of technology transfer and resources conservation as a key to technological growth and profit. Specific examples of data utilization for metrology enhancement and case histories of cost avoidance/savings benefits are also presented.

INTRODUCTION

It is becoming a well known fact that technical information is an important resource for private and public productivity. The days of automatic advancement of technology and economy are fast disappearing. Technical information and how we collectively manage and centralize it as a resource for meaningful productivity gains will play an important part in any progress. The harnessing of technical information will be one of the basic tenets of corporate management in the 1980s, and may well be management's most important resource for productivity. The corporations that will excel in the coming decade will be those which have the competitive edge in managing technical information. It is recognized that organizations cannot operate in a vacuum and remain profitable. They must interface with outside technical data sources and be aware of the state-of-the-art and technology changes occurring in their industry and related industries. Availability and accessibility to technical data sources other than their own can improve their competitive status and technical expertise. Organizations can meet the challenge of accelerating change by participating in technology transfer and information exchange programs. This applies particularly in the field of metrology.

BACKGROUND

One of the most unique data exchangeprogram operations developed to accomplish the information transfer function and maximize the utilization of new technology for quality/reliability improvement and increased productivity is the Government-Industry Data Exchange Program (GIDEP). GIDEP has focused its attention on amalgamating specialized technical information and making it available to design, laboratory, quality assurance, reliability, safety and metrology specialists both in government and industry organizations. The Program (Ref. 1) which was developed by the government with the aid of industry, was previously restricted in participation to government activities and their contractors. However, with the current trend in government procurement toward commercial-off-the-shelf items, it was decided to open the program to any qualified organization that is generating or using the types of data GIDEP exchanges. The program specifically excludes classified and proprietary data.

In addition to government agencies and contractors in the United States, the Canadian government and many Canadian industrial organizations have been participating in GIDEP since 1966.

WHAT GIDEP PROVIDES

Engineering, quality, safety, reliability, and metrology enhancement procedures, and components developed from military and aerospace programs have produced some exceptionally reliable equipment. GIDEP's data interchanges contain much valuable information generated by DoD and NASA related organizations. The technology transfer from aerospace and military developments offers commercial and industrial contractors significant opportunities in consumer product development. The utilization of this information, and application of these techniques could result in rewarding pay offs and profitability. Consumer products need to be of higher quality and made increasingly reliable and safe. These improvements are necessary in order to remain competitive, and to avoid the cost impact of excessive warranty claims, recall, and rework of products already in consumer use, and product liability claim losses.

The availability of specific engineering, quality, safety, reliability, and metrology data is of major concern to all organizations involved in the development of systems and equipments. Frequently, the bottom line of the statement is whether the equipment met its performance, quality, safety, and reliability goals. And, since reliability and safety are in a large measure a function of design, the design engineer must be motivated and given the tools to build reliability and safety into the system from the beginning. In addition, improved reliability and quality reduce life cycle costs. It is much the same way that good health reduces the costs of medical care.

GIDEP Provides some of the tools to accomplish this end. Participants in the program are presently provided access to four major data interchanges:

- Metrology Data interchange
- Engineering Data Interchange
- Failure Experience Data Interchange
- Reliability-Maintainability Data Interchange

METROLOGY DATA

The Metrology Data Interchange (MDI) contains metrology related engineering data on test systems, calibration systems, measurement technology, and test equipment maintenance manuals and calibration procedures, and has been designated as a data repository for the National Bureau of Standards (NBS) metrology related data. This data interchange includes a Metrology Information Service (MIS) which provides rapid response to GIDEP participants on queries related to test equipment and measurement services.

Test and measurement equipment utilized in laboratories, factories, and field operations must be calibrated properly in order to accept good parts or reject defective parts in systems and equipments. In order to maintain effective test equipment facilities, it is necessary for test and measurement organizations to have information regarding test equipment calibration procedures and to identify test equipment problems and hazards, as well as, specification deficiencies. The availability of this valuable information in the MDI permits a company or laboratory to take advantage of data generated previously by other organizations. A calibration procedure costs from $500 to $2,500 to write. To use one directly from the MDI, or parts of one already written, can save proportionate amounts of money and time. Participating organizations doing studies in the area of nondestructive testing and evaluation find the MDI useful in providing information on new equipment, techniques and methods used in test, and measurement.

- For example, a participant was establishing a program for scheduling calibration of his organization's test equipment. He was required to determine the periodicity between calibrations. In reviewing the GIDEPMDI he found calibration intervals and techniques developed by other government and industry activities. This permitted him to utilize the experience of other organizations in the metrology field and reassured him of the adequacy of his planning.

- Another example involved a report received that indicated unsatisfactory performance had been experienced from feelimpulse, adjustable, presetting micrometer type torque wrenches made to a federal specification. Seven (7) new wrenches were submitted for calibration check and were found to be out of specification accuracy requirements. The wrenches were returned to the supplier and recalibrated, but failed to meet specifications. It was also found that results with these wrenches were dependent upon the manner of usage and that the wrenches possessed a "memory" of previous usage that affects current usage and accuracy. The information from these findings and report resulted in a recommendation that deflecting-beam or indicator-dial type torque wrenches be used in critical or safety applications where accurate torque measurements were required.

- For example: A participant was developing software for an automated multimeter calibration system, menu driven by manufacturer and model number. The GIDEP MDI provided some documented packages of software with a variety of the same instrumentation the participant was interested in, including complete program listings. This resulted in substantial (80 hours) design, write, and debug time savings. The examples provided by the program cited were used/emulated to accomodate instrumentation not covered by the GIDEP information.

ENGINEERING DATA

The Engineering Data Interchange (EDI) contains engineering, evaluation and qualification test reports, nonstandard parts justification data, parts and materials specifications, manufacturing processes, and other related engineering data on parts, components, materials, and processes. Typical parts/components/materials would be pumps, motors, valves, servos, compressors, electronic controls, microcircuits, waveguides, relays, tubing, fittings, shaftseals, adhesives, epoxies and lubricants. The interchange also includes a section of reports on specific engineering methodology and quality techniques, air and water pollution reports, alternate energy sources, and other subjects.

Tests on parts or components cost from $5,000 to $25,000 to conduct in a laboratory environment. Engineering time runs approximately $60 per hour, including overhead. Utilizing data in the ED1 to reduce or eliminate testing can save equivalent amounts of dollars or hours.

Organizations developing and producing test equipment and instrumentation utilize the ED1 in selecting high reliability parts and components for their systems and equipments.

- For example: A participant was experiencing a high failure rate of special capacitor installed in some high frequency measurement equipment. The GIDEP data permitted the identification of a substitute capacitor with an improved specification and lower failure rate. The substitute capacitor cost less than the original made by the manufacturer. The substitute capacitor was identified to all users of the measurement equipment. The participant also initiated the process of purging the system of the old capacitor in cooperation with the Navy supply system. Based on the failure rate of the old capacitor, the participant calculated a cost-savings of $7,500 the first year of conversion.

- For example: Dielectric constant and loss information was needed for special measurement studies. In going through the GIDEP EDI the participant found a 90 page report on dielectric constant and loss information, including data on Hi-temperature materials, inorganics, liquids, minerals, organics, and plastics. The report also contained measurement techniques and calculation methods which enabled the participant to be consistant in his data gathering techniques. This helped the participant avoid the purchase of a $10K-12K device and avoided approximately one year of measurement studies.

- For example: A participant was involved in testing an electro/mechanical assembly. In researching the EDI, he found test procedures that led quality control engineering to develop a simplified test system and methodology for test ing of the assembly. This reference material for quality control engineering resulted in a savings of $3,400.

Information in the EDI can also assist in developing test plans and procedures, as well as, establishing criteria for evaluating shock, vibration, temperature, and humidity requirements during testing. You have an opportunity to see how others have done it, since all evaluation reports include the test procedures used.

The EDI has amassed considerable information on critical parts which have the greatest potential effect on test equipment reliability. They may be parts that historically cause trouble or whose composite failure rates contribute significantly to field failures. Each month approximately 200-300 new reports are added to the data bank.

The EDI has data stored in 16-m roll microfilm cartridges, with computerized indexes for search and retrieval of the data. The sort, search, and retrieval capability is also available from on-line remote computer terminals.

FAILURE EXPERIENCE DATA

The Failure Experience Data Interchange (FEDI) contains objective failure information generated when significant problems are identified on parts, components, processes, fluids, materials, or safety and fire hazards. This data interchange includes the ALERT and SAFEALERT system, failure analysis studies, and problem information. It shows where one activity has experienced or discovered a problem that might have universal application and may affect other participants who are using that part or material but are unaware of the problem.

Every failure occurring is not made an ALERT, only where there is a possibility of a trend or pattern, or a safety hazard. ALERTs can be on potential problem areas such as deterioration, handling, transportation, contamination, faulty design, faulty production, or faulty processes. Some typical items reported to GIDEP as ALERTs recently were pressure regulators, hydraulic fluid filters, connectors, tubings, bearings, check valves, microcircuits and relays.

This information is also very valuable to those who are doing laboratory failure analysis since these ALERTs demonstrate some of the techniques, methods, and test equipment utilized by others to perform failure analysis.

Some recent examples of ALERTs identifying problems which, if they had not been detected, would have had considerable impact on equipment reliability, quality, safety, and increased costs resulting from delays in delivery schedules, are shown below:

- A potential safety hazard existed with some test equipment. A GIDEP SAFE-ALERT reported a hazardous condition existing with a certain manufacturer's signal generators. The participant found seven of the reported signal generators in use in his organization. Ground wire assemblies, as recommended in the SAFE-ALERT were installed. Thus, a potential shock hazard was eliminated.

- An ALERT identified a certain manufacturer's spectrum analyzers which erupted in a fire if the power supply and calibration control switches were set in a particular manner when electrical power was applied to the instrument. The identification of this problem and corrective action information supplied in the ALERT prevented a possible fire hazard from occurring in the participants facility.

A copy of the alert is always sent to the manufacturer of the product. This feedback of ALERT data to the manufacturer frequently results in rapid corrective action, and in many cases, product improvement. Manufacturers are anxious to know how their product was applied in equipment and how it performed. To assist GIDEP in getting the information to the right person, the Electronic Industries Association (EIA) has established ALERT coordinators in each member organization to act as a focal point in the company of all ALERTs received.

ALERT information is sent out in hardcopy paper form. Summaries of ALERTs are issued. All ALERTs are filmed and available on microfiche. Search and recall through remote computer terminals is also available.

A "Diminishing Manufacturing Sources and Materials Shortages (DMSMS)" reporting system was re-. cently incorporated in the FEDI. The system identifies manufacturers and products that are being discontinued.

RELIABILITY-MAINTAINABILITY DATA

The Reliability-Maintainability Data Interchange (RMDI) contains failure rate, failure mode, and replacement rate data on parts and components based on field performance information and/or reliability demonstration tests of equipment, subsystems and systems. Data from extended or accelerated laboratory life testing is included. The data interchange also contains reports on theories, methods, techniques, and procedures related to reliability and maintainability practices, such as Prediction Techniques, Reliability Improvement Warranty Studies, Failure Mode and Effect Analyses, Math Models and Reliability Growth Plans.

RMDI information is very valuable to help determine the high failure rate items and shows where you should place your quality improvement and reliability testing emphasis. Since failure rate and field reliability information is Often lacking in the early stages of systems development, the RMDI can be used to facilitate the selection of types of parts and components that will give an adequate failure rate at a reasonable cost. It also identifies high failure rate items, and provides information on predominent failure modes during field operation.

- For example: A participant required a failure rate for specific thermisters in a piece of test equipment for which he was performing a Failure Modes and Effects Analysis (FMEA) study during design. In accessing the RMDI he was able to locate suitable data that provided him the necessary information to complete the FMEA and estimated a savings of $3,000 in man-hours.

The RMDI has information in hardcopy paper summary form, with back-up information of the complete reports on 16-mm microfilm. The summary data is also available from on-line computer terminal s.

URGENT DATA REQUEST (UDR) SYSTEM

In addition to the four data interchanges, a unique special service provided through GIDEP is the Urgent Data Request (UDR) System. It is a system where a GIDEP participant may query all other participants on specific problems, especially where he has already exhausted his internal, and other known information sources. He has also searched the GIDEP data interchanges without success. Any participant receiving the UDR and having information gets back to the requester with the information. Many point-topoint contacts in organizations are established as a result of the UDR system use. Also, many dollars in research time are saved by getting the data quickly. This system is of great importance to those involved with test equipment in failure analysis studies and nondestructive test and evaluation technique development, since it puts them in touch with others working on related problems.

- For example, an engineer may have a safety problem with the use of some test equipment in a particular environment or application. He can utilize the UDR system to determine if any one else has experienced the same problem, and also might find that someone has already solved the problem and has the information available.

- For example: A participant was unable to find a maintenance procedure for a certain manufacturer's oscilloscope. The manufacturer had gone out of business. The participant made a UDR inquiry of all GIDEP participants searching for a test equipment maintenance procedure. His UDR request was successful. He obtained a manual that also contained a parts list and wiring schematic, He was able to save many man-hours of fault isolation testing and avoided using other time consuming trouble shooting methods.

DATA FLOW

Since the inception of GIDEP, emphasis has been placed on the immediate transmittal of current information to the potential users and to have the information readily available upon demand. The philosophy is to have the information waiting for the user, rather than the user waiting for the information. This has been accomplished through the implementation of a microfilm data storage system coupled with remote terminal computer search and retrieval capability.

Each participant, depending upon the data interchanges with Which he is involved, submits data to the GIDEP Operations Center. The Operations Center reviews, processes, computer indexes and microfilms the data for distribution to program participants. This cross-fertilization of information results in tremendous technology transfer benefits. GIDEP has developed a rapid data retrieval system which makes the microfilmed information in the data banks immediately accessible to all participants through either computerized hardcopy paper indexes or the use of remote computer terminals. The retrieval system is "User Oriented."

MANUAL DATA RETRIEVAL

Participants normally use the hardcopy paper indexes provided by the Operations Center to retrieve specific data from the microfilm cartridges and microfiche, using a microfilm reader-printer. The indexes are prepared in various sorts and formats depending upon anticipated usage. The system primarily utilizes and provides participants with 16-mm cartridges which may be used in many of the major manufacturers' microfilm equipment. GIDEP utilizes a 24X reduction for microfilming. All GIDEP film images are blipcoded to facilitate page search.

Military specification and standards, as well as vendors catalogs, are available in 16-mm cartridges from private subscription services. The

GIDEP microfilm system is compatible with these other data sources.

REMOTE TERMINAL RETRIEVAL

Participants having remote terminal equipment compatible with the Operations Center UNIVAC 1100/83 computer may directly query the data interchanges utilizing a simplified operator's manual. The participant pays the phone charges and GIDEP pays the computer costs. The searcher does not have to be a computer analyst or a programmer to use the system. It is very simple to use. The user can search, sort, and select in many ways:

- by subject
- by key-word
- by date
- by application
- by originating organization

PARTICIPATION REQUIREMENTS

Organizations may participate without charge in any or all of the above data interchanges by agreeing to abide by pre-established requirements for participation. GIDEP participants are not subject to any fees or assessments. Primarily, the GIDEP interchange involves the reciprocal exchange of data, or in lieu of data, the reporting of cost savings attributed to the use of the information by the recipient. Government specifications, contractor proprietary data, and classified data are not within the scope of GIDEP, and acquisition of technical data solely for the use of GIDEP is not authorized.

In DoD-NASA organizations, participation in GIDEP may be mandatory through a number of regulations. Previously, GIDEP participation was on a voluntary basis, the military recently decided to make GIDEP participation a contractual requirement. Military contractors may be required to participate as prescribed in MIL-STD-1556A(AF).

The GIDEP Operations Center provides participating organizations with a Policies and Procedures Manual and Representative Handbook which provide operational guidelines for GIDEP implementation.

MINOR OPERATING COSTS

At relatively little internal operating cost, an organization may have available to them convenient access to a large body of technical data, and a communications network system relating to the quality and reliability of parts, components and materials. Proper utilization of GIDEP's technology transfer techniques permits companies to be more effective in achieving their equipment reliability/quality goals.

MONETARY BENEFITS

Cost avoidance savings through GIDEP have been averaging about 14 to 1, about $14 returned for every dollar invested. Last year participants reported a cost savings of 53 million dollars, and it is believed GIDEP is only scratching the surface in the dollars reported, in addition to all the other tangible benefits. It is difficult to place a dollar value on all the tangible benefits. For example, how do you place a monetary value on the prevention of a death, or a major injury, or a fire? Perhaps the most important aspect of all is the broad range of direct contacts provided by the program in almost every technological area. These contacts result in dollar and man-hour savings, by providing accurate information rapidly.

Almost any industrial contractor or government activity can realize similar savings by centralizing its technical data resources and making the data available to the entire organization and to all its projects. Too much valuable technical information is lost in someone's desk or file cabinet when it should be made available to others needing it within the organization.

CONCLUSIONS

It is evident that the quality and reliability of sophisticated test systems or equipments is dependent greatly upon the design process. Therefore, access to technical information data banks such as GIDEP, which have these necessary quality and reliability data elements are vital to the success of programs and to an organization's profitability. Proper utilization of the information can also save costly test equipment retrofit programs, and prevent or reduce safety and fire hazards, as well as product liability actions due to defective or unsafe test equipment being placed in operation. You can improve your metrology posture by utilizing GIDEP.

REFERENCES

(1) Government-Industry Data Exchange Program (GIDEP), Program Summary, GIDEP Operations Center, ~~Corona, CA 91 0~~, June 1979.

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(213) 535-1497

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Santa Rosa, CA 95407
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DALFI, Inc.
10080 Carroll Canyon Rd., Ste. B
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(619) 578-9500

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P. 0. Box 800, 2570E/D187
Richland, WA 99352
(509) 373-1907

Vasaeline, Iraj B.
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Teledyne Systems Co.
19601 Nordhoff St.
Northridge, CA 93124
(818) 886-2211

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3370 Miraloma Ave.
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(714) 632-3560

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Sunnyvale, CA 94088-3504
(408) 756-2377

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(312) 567-4499

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A117 Metrology
Gaithersburg, MD 20878
(301) 921-2159

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Ford Aerospace & Comm. Corp.
Ford Rd., B/8, Rm. 26
Newport Beach, CA 92663
(714) 720-4729

Wagner, Kenneth
SC2-791
Intel Corp.
3065 Bowers Ave.
Santa Clara, CA 95051
(408) 987-4925

Walker, David
National Program Manager
Datron Inst.
3401 S.W. 42nd. Ave.
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1151 Triton Dr., Suite B
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Westinghouse Elec. Corp.-SMP
RD #4, Box 333
Blairsville, PA 15717
(412) 459-9400, X363

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488 Tasman Drive
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(408) 734-5780

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P.O. Box 7188, MS 4610
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Richardson, TX 75081
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General Dynamics
P. O. Box 2507, Mail Zone 2-60
Pomona, CA 91769
(714) 620-7511

Wilson, Roy G.
Metrology Supv., D/421
Allied Bendix Aerospace
Bendix K.C. Div., P. O. Box 1159
Kansas City, MO 64141
(816) 997-3157

Wilson, Warren
Sys. Test Engr. Sr.
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EG & G, Inc.
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Workman, David R.
Grp. Ldr., Met. Eng.
Martin Marietta-Denver Aero.
P. O. Box 179, MS P9682
Denver, CO 80201
(303) 977-8471

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3003 Bunker Hill Ln.
Santa Clara, CA 95050
(408) 496-0800

Wright, Arthur J.
Supervisor, Physical Stds.
Monsanto Res. Corp.; Mound
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Miamisburg, OH 45342
(513) 865-3386

Zintel, James
Quality Control Manager
Data Magnetics
445 Laurelwood Road
Santa Clara, CA 95054
(408) 727-1424

MEASUREMENT SCIENCE CONFERENCE

1985

MARRIOTT HOTEL, Santa Clara, California
January 17 and 18, 1985

Please Address Reply To:

DOOR PRIZE PROGRAM RESULTS

3:45 p.m. Friday, January 18, 1985

The quality and quantity of prizes donated for this year's Door Prize Program exceeded that of all previous years -- 44 contributors and 75 prizes having a total value in excess of $13,750.00. Included were analog and digital hand-held and bench-top electronic and mechanical measuring instruments, calculators, textbooks, cash and other goodies ranging in individual prize value from $7.00 to $3,485.00. A one-week's use of a 1985 Lincoln Automobile (Prize No. 1), a one-week's use of a four-bedroom condo in a Durango, CO ski area (Prize No. 10), a used, but fully operational personal computer system in mint condition (Prize No. 14), an advanced programmable calculator (Prize No. 25), two lithographs: "Fish Camp" (Prize No. 31) and "Homeguard Tuna" (Prize No. 73), a gaussmeter (Prize No. 43), a six-pen plotter (Prize No. 50), a "Valentine Week-end for Lovers" (Prize No. 51) and a case of California wine (Prize No. 53) were among some of the unique prizes offered. In addition to the above, a free registration to the 1986 MSC in Irvine, CA was awarded to one of the 1985 MSC attendees.

A complete listing of all prizes, donators, and lucky winners is given on the following pages. A copy of the instructions given to attendees at the start of the Conference is also included.

Special Recognition and our Sincere Thanks is hereby extended to the many organizations and individuals who donated the prizes to this year's Conference. It was these organizations and individuals, through their gracious contributions, that made this year's Door Prize Program such a fantastic success.

For the Conference Committee,

Bob

Bob Couture
Door Prize Chairman
Measurement Science Conference, Inc.

1985 MSC

DOOR PRIZE CONTRIBUTORS

Our very special thanks go to the 'organizations and individuals listed below. Without their gracious contributions the 1984 MSC Door Prize Program would not have been possible.

- Aeronutronic-Ford
- Ballantine Laboratories, Inc.
- Bruel & Kjaer Instruments
- Calex Manufacturing Co., Inc.
- Cutlass Electronics
- Dalfi Cal Labs
- Dalfi, Inc.
- Datron Instruments, Inc.
- Dranetz Engineering Labs, Inc.
- EFRATOM, Division of Ball Corporation
- EIP Microwave, Inc.
- ElectroRent Corporation
- John Fluke Manufacturing Co.
- Grumman Aerospace Corporation
- Guildline Instruments, Inc.
- Hewlett Packard Company
- Instrulab, Inc.
- Integra Microwave
- Prof. Robert Irvine (Author)
- Kinemetrics/True Time
- Mr. Frank Koide (Artist)
- Lakeshore Cryotronics, Inc.
- Martin Marietta Measurement Systems, Inc.
- Measurement Science Conference
- Metron Corporation
- Micro-Tel Corporation
- Polarad Electronics, Inc.
- PROBE MASTER
- QUALITY Magazine
- Racal-Dana Instruments, Inc.
- RD Technology, Inc.
- RFL Industries, Inc.
- Ruska Instrument Corporation
- Mr. DeWayne Sharp*
- SIMCO Electronics
- Spectracom Corporation
- Standard Reference Labs, Inc.
- Tektronix, Inc. - Santa Clara
- U.S. Instrument Rentals
- Valhalla Scientific, Inc.
- Viking Laboratories, Inc.
- Volumetrics, Inc.
- Wahl Instruments, Inc.
- Ward-Davis Associates
- Weinschel Engineering, Inc.

*DeWayne Sharp (IBM) of San Jose Provided Display Cases

MEASUREMENT SCIENCE CONFERENCE

DOOR PRIZE LISTING

January 18, 1985

PRIZE NO.	DONATOR	PRIZE	WINNERS
(1)	AERONUTRONIC DIVISION of FORD AEROSPACE and COMMUNICATIONS CORP. FORD MOTOR COMPANY Ford Road, P. O. Box A Newport Beach, CA 92663 Arranged by: John Schulz (714) 720-4787	● One-week use of 1985 Lincoln Automobile Winner will arrange with FORD Motor Co. (John Schulz) for a mutually agreeable delivery date and pick-up in Long Beach, CA. The automobile will come with a full tank of gasoline and be fully insured. Additional gasoline must be purchased by winner. Upon completion of the one-week (7-day) use period the automobile must be returned to the same Long Beach location. This prize must be redeemed within the 1985 model year. Approx. retail value: $500.00	Kevin M. Ruhl, Section Head TRW Redondo Beach, CA
(2)	BALLANTINE LABORATORIES, INC. P.O. Box 97 Boonton, NJ 07005 Arranged by: Milt Lichtenstein (201) 335-0900	● Ballantine Laboratories Model 3100A 3 1/2 Digit LCD Hand-Held DMM with eight functions (AC, DC, Res.), 29 ranges, diode test, peak hold, and continuity beeper. DC voltage accuracy is +0.1% of input + one digit. Approx. retail value: $129.00	David K. Bradley, National Sales Manager Integra Microwave Santa Clara, CA

DOOR PRIZE LISTING (continued)

PRIZE No.	DONATOR	PRIZE	WINNERS
	BRUEL & KJAER INSTRUMENTS, INC. 1151 Tritron Drive, Suite 'B' Foster City, CA 94404 Arranged by: Ian Lynas and John Pryshepa (415) 574-8155	• Three (3) Complete Sets of Five (5 each Handbooks with a 1985 pocket calender. (See below for description and prize number.)	
(3)		• Set of Five (5) Handbooks Acoustic Noise Measurements Architectural Acoustics Frequency Analysis Mechanical Vibration and Shock Measurements Noise Control Approx. retail value: $35.00	W. J. Stringham, Instrumentation Engr. Garrett Pneumatic Systems Division Tempe, AZ
(4)		• Set of Five (5) Handbooks Acoustic Noise Measurements Architectural Acoustics Frequency Analysis Mechanical Vibration and Shock Measurements Noise Control Approx. retail value: $35.00	Gary A. Meyers, Assist. Sup. Cal Lab Intel Santa Clara, CA
(5		• Set of Five (5) Handbooks Acoustic Noise Measurements Architectural Acoustics Frequency Analysis Mechanical Vibration and Shock Measurements Noise Control Approx. retail value: $35.00	Charles Alexander, Metrologist Hewlett Packard Rohnert Park, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
	CALEX MFG. CO., INC. 3355 Vincent Road Pleasant Hills, CA 94523 Arranged by : Steve Cuff and Steve Mathias	● Two (2) Donations (See below for description and prize numbers.)	
(6)		● Cross Pen in classic black Approx. retail value: $20.00	Geo L. Sherback, Division Leader C. D. Draper Lab Cambridge, MA
(7)		● Cross Pen in classic black Approx. retail value: $20.00	Tad Kuga, Engineer IBM Corp. San Jose, CA
(8)	CUTLASS ELECTRONICS P.O. Box 6503 18039 Crenshaw Blvd. Torrance, CA 90504 Arranged by: Dean Marxer (213) 324-7360 (714) 549-9358	● Valhalla Scientific Model 3302 Hand-Held DMM Approx. retail value: $123.00 (Used as demo unit but in excellent condition.)	0. C. Stone, Research Specialist LMSC Tracy, CA
(9)	DALFI CALIBRATION LABS 100 W. 35th Street, Suite "S" National City, CA 92050 Arranged by: Peter La Costa (619) 578-9500	● Certificate for Calibration Service Approx. retail value: $100.00	Paul S. Roberts, Head RF/Microwave Sect, Hughes Aircraft Co. El Segundo, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(10)	DALFI, INC. 100 Carroll Canyon Road San Diego, CA 92131 Arranged by: C. Van Winkle (619) 578-9500	● Seven (7) Days Use of Condo in Duranao. Colorado. close to Purgatory Ski Area, Mesa Verde National Park in the heart of the San Juan Mountains. Condo has four (4) bedrooms, (sleeps ten (10)) and is completely furnished--silverware to linens. CONDITION OF USE PRECLUDES CHILDREN UNDER FOURTEEN (14) YEARS OF AGE. Winner will arrange with LARITA HENDERSON of DALFI, INC., (619) 578-9500 x 261 for mutually agreeable date(s) of use. Approx. retail value: $1,000.00	Walter E. Dietz, Sales Manager Guildline Instruments Orlando, FL
(11)	DATRON INSTRUMENTS, INC. 3401 S.W. 42nd Avenue Stuart, FL 33497 Arranged by: Ed Nemeroff (305) 283-0935	● Kodak Model 6100 Disc Camera Kit Includes: 2.8 lens. close-up lens, built-in flash, instant flash recycle, motorized flash advance, cover, handle, neck strap and one package of film. Approx. retail value: $80.00	Lee Klein, Market Manager NBS Gaithersburg, MD
(12)	DRANETZ ENGINEERING LABS, INC. 1000 New Durham Road Edison, NJ 08817 Arranged by: Tony Orlacchio (201) 287-3680	● Hardwood Desk Set, laser engraved, with solar calculator and paper. Approx. retail value: $100.00	Arthur E. McKinney, Product Support Mgr. Sanders Associates Nashua, NH
(13)	EIP MICROWAVE, INC. 2731 North First Street San Jose, CA 95134 Arranged by: Bob Loft (408) 946-5700	● Selection of California Wines Approx. retail value: $50.00	Laverne C. Hamann, Engineer Boeing Co. Issaquah, WA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(14)	ELECTRORENT CORPORATION 4131 Vanowen Place Burbank, CA 91505 Arranged by: Howard Blackman (818) 843-3131	● Hewlett-Packard Model 85F Personal Computer System (Donation is approximately 2 years old but in excellent condition.) Consists of HP 85A personal computer, 82936A ROM Drawer, I/O ROM, with HPIB Interface. The HP 85A has 16 k RAM, expandable to 32 k, built-in 5" CRT, B/in thermal printer and b/in 250-k bite magnetic-tape cartridge. Can be used as computer or system controller. (A wide assortment of I/O interfaces and software is available.) Approx. retail value: (1983) **$3,485.00** (See Unit demonstrated at ElectroRent Exhibit Space.)	Paul J. Messinger, Metrology Supervisor So. Calif. Edison Westminster, CA
	JOHN FLUKE MFG. CO. 2300 Walsh Ave., Bldg. K Santa Clara, CA 95051 Arranged by: Steve McPherson (408) 727-0513	● Six (6) John Fluke Co. Model-70 series Hand-Held DMM's with both analog and digital displays. (See below for prize numbers.)	
(15)		● John Fluke Model 77 H-H DMM, Analog and digital displays; AC, DC, Res., manual or autoranging, extra 10-A current, "Touch Hold" function, continuity beeper, +0.3% basic DC accuracy, and custom-holster. Approx. retail value: $129.00	John P. Marcum, Group Engineer Lockheed Missiles & Space Co. Sunnyvale, CA
(16)		● John Fluke-Model 77 H-H DMM, as above. Approx. retail value: $129.00	Thomas B. Miller, Lab Manager Lawrence Livermore Lab Liver-more, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(17)	JOHN FLUKE MFG. CO. (continued)	● John Fluke Model 75 H-H DMM, analog and digital displays; AC, DC, Res., manual or autoranging, extra 10-A current range, continuity beeper, basic DC accuracy is ±0.5%. Approx. retail value: $99.00	Glenn F. Engen, Scientist National Bureau of Standards Boulder, CO
(18)		● John Fluke Model 75 H-H DMM, as above, Approx. retail value: $99.00	Randy W. Ahlkvist, Customer Service Engr Argosystems Sunnyvale, CA
(19)		● John Fluke Model 77 H-H DMM, analog and digital displays; AC, DC, Res., manual or autoranging, extra 10-A current range, "Touch Hold" function, continuity beeper, ±0.3% basic DC accuracy, and custom holster. Approx. retail value: $129.00	Mark A. Kaufman, Sr. Engineer Ford Aerospace Newport Beach, CA
(20)		● John Fluke Model 77 H-H DMM, as above. Approx. retail value: $129.00	Gordon B. Vail, Group Engineer Lockheed Missiles & Space Co. Sunnyvale, CA
	GRUMMAN AEROSPACE CORP. Bethpage, NY 11714 Arranged by: Charles Weber	● Three (3) Separate Donations (See below for description and prize numbers.)	
(21)		● A.W. Sperry Model DM-6590V H-H DMM (Electra-Probe); AC/DC, ohms, 3-1/2 digits and autoranging. Approx. retail value: $64.00	George G. Erickson, Metrology Supervisor LMSC Sunnvale, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(22)	GRUMMAN AEROSPACE (continued)	● Set of 6 Grumman Aerospace Brandy Drinking Glasses Approx. retail value: $15.00	David R. Workman, Group Leader-Metrology Martin Marietta - Denver Aerospace Denver, CO
(23)		● Set of 6 Grumman Aerospace Wine Drinking Glasses Approx. retail value: $15.00	Larry K. Noe, Engineering Tech. Supvr. Alameda Naval Air Station Alameda, CA
(24)	GUILDLINE INSTRUMENT CO. 4403 Vineland Road, Suite B-10 Orlando, FL 32811-9998 Arranged by: Walt Dietz (305) 423-8215	● Radio Shack Model ET380 Chronofone cordless AM/FM Digital Clock Radio Approx. retail value: $139.00	Edward L. Rader, Metrology Manager GMC, Allison Gas Turbine Division Indianapolis, IN
(25)	HEWLETT-PACKARD CO. Stanford Park Division 1501 Page Mill Road Palo Alto, CA 94303 Arranged by: John Minck (415) 857-2060	● Hewlett-Packard Model 15C Advanced Programmable Scientific Calculator Approx. retail value: $120.00	Andre Perman, Regional Appl. Engineer Bruel & Kjaer Instruments, Inc. Foster, City, CA
(26)	INSTRULAB, INC. P. O. Box 98 N.D. Station Dayton, OH 45420 Arranged by: Phil Alterton (513) 223-2241	● Talking Weather Station Wall mounted. Approx. retail value: $60.00	Henry F. Gonzalez, Project Leader USATMDE Support Center, AMXTM-CW-WS WSMR, NM
(27)	INTEGRA MICROWAVE 2368 Walsh Avenue Santa Clara, CA 95051 Arranged by: Len Johnson (408) 727-9601	● Textbook: Practical Microwave, by Thomas S. Laverghetta, 1st Edition, 1st Printing, 1984 by Howard Sams Pub. Co. (Autographed by author) Approx. retail value: $40.00	Robert W. Miesbauer, Engineer Specialist E G & G Goleta, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(28)	PROFESSOR ROBERT IRVINE of Cal Poly - Pomona (a personal donation by the author) (714) 598-4542	● A reference text book "Operational Amplifiers". Published in 1981 by Prentice - Hall. Book covers the construction and characteristics of the various types of Op Amps, and their use as a circuit element in digital, non-linear and active filter circuits. Approx. retail value: $32.00	David C. Thompson, Metrology Engineer Ford Aerospace & Communications Newport Beach, CA
	KINEMETRICS/TRUE TIME 3243 Santa Rosa Avenue Santa Rosa, CA 95401 Arranged by: Rick Dielman (707) 528-1230	● Two Donations (See below for description and prize numbers.)	
(29)		● Time Cube WWV Receiver Approx. retail value: $30.00	William M. Coe, Service Manager Honeywell, Inc. Van Nuys, CA
(30)		● Time Cube WWV Receiver Approx. retail value: $30.00	Harald Bratlien, Product Assurance Engr. Hewlett-Packard Santa Rosa, CA
(31)	FRANK KOIDE of Rockwell International Anaheim Metrology Laboratory 3370 Miraloma Avenue (HC02) (a personal donation by the artist) (714) 632-3923	● A signed and serialized limited edition (No. 26/50) 18" x 22" lithograph in pastel mounted in an attractive silver-colored frame. The painting depicts the homes of the early commercial fisherman of San Diego during the 1930's and is titled "Fish Camp." The original painting by Frank Koide is hanging in the San Diego, California Historical Museum. Approx. retail value: $100.00	Bob E. Loft, Reg. Sales Manager EIP Microwave, Inc. San Jose, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(32)	LAKESHORE CRYOTRONICS, INC. 64 E. Walnut Street Westerville, OH 43081 Arranged by: Warren Pierce (614) 891-2243	● Lakeshore Cryotronics, Inc. Model GR-200A - 1000 Germanium Temperature Sensor. Specially calibrated over 1.4 to 100 K range; comes with calibration certificate and data plot. (Note: Readout requires 4-terminal resistance bridge or DVM and constant current source which are not supplied.) Approx. retail value: $365.00	Marisela Y. Blasini, Prodt Mkt. Engineer Hewlett-Packard Palo Alto, CA
	MARTIN MARIETTA MEASUREMENT SYSTEMS, INC. Maitland Center, Suite 408 851 Trafalgar Court Maitland, FL 32751 Arranged by: Bryan Butler (305) 660-9255	● Certificates for Two (2) Workmanship Standards Manuals (See below for description and prize numbers.)	
(33)		● Martin Marietta Measurement System Inc. Electro Mechanical Workmanship Standards Manual. Approx. retail value: $385.00	Selden W. McKnight, Dir. of Metrology USAF-/AGMC Heath, OH
(34)		● Martin Marietta Measurement Svstem Inc. Microelectronics Workmanship Standards Manual. Approx. retail value: Q495.00	David R. Block, Q.A. Engineer Fleet Analysis Center Corona, CA
(35)	MEASUREMENT SCIENCE CONFERENCE, INC.	● Free Registration to 1986 Measurement Science Conference Approx. retail value: $150.00	David Daellenbach, Standards Engineer Fluke Mfg. Co. Everett, WA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(36)	METRON CORPORATION 9681 Business Center Drive Rancho Cucamonga, CA 91730 Arranged by: Garry Smith (714) 980-6166	● Complete Set of (20) Textbooks for Metron Institute of Measurement Technology (MIMT) Courses in Physical and Electronic Metrology Approx. retail value: $250.00	John T. Flower, Product Manager John Fluke Mfg. Co. Inc. Everett, WA
(37)	MICRO-TEL CORPORATION 10713 Gilroy Road Hunt Valley, MD 21030 Arranged by: Jerry W. Spero (301) 667-0077	● Textbook: Microwave Measurement and Techniques, published by Artech House, a subsidiary of the Microwave Journal. Approx. retail value: $25.00	Herman B. Sequeira, Scientist Martin Marietta Laboratories Baltimore, MD
	PROBE MASTER 4898 Ronson Court San Diego, CA 92111 Arranged by: Jimm Hoffmann (619) 560-9676	● Three (3) Separate Donations of Probe Master Products. (See below for description and prize numbers.)	
(38)		● Probe Master Model PM-2026 Designer Test Lead Set Approx. value: $15.00	James D. Tostenson, Manager Lockheed Missiles & Space San Jose, CA
(39)		● Probe Master Model PM-1058 40-dB, 2-watt, N-Type Attenuator Approx. retail value: $79.00	Paul A. Seuferer, Supervisor, Cal Lab Fisher Controls Marshalltown, IA
(40)		● Probe Master Model PM-2405 250-MHz Engineering Series Probe, with a PM-262 Engrs. Accessory Kit Approx. retail value: $61.00	Bob Hesselberth, President Spectracom Corp. E. Rochester, NY

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(41)	QUALITY MAGAZINE Hitchcock Publishing Co. Hitchcock Building Wheaton, IL 60187 Arranged by: D. Templeton (312) 665-1000, and Dennis Seger (714) 891-2633	● $25.00 Cash	Gene M. Stolarz, Metrology Supervisor Bendix, Oceanics Division Sylmar, CA
(42)	RACAL-DANA INSTRUMENTS, INC. #4 Goodyear Street Irvine, CA 92714 Arranged by: Dan Varnadore and Linda Beck (714) 859-8999	● Racal-Dana Instruments Model 2000A Danameter Hand-Held DMM Approx. retail value: $400.00	Iraj B. Vasaeline, R.F. Engineer Teledyne Systems Co. Northridge, CA
(43)	RFL INDUSTRIES, INC. Boonton, NJ 07005 Arranged by: Brad Bradbury (201) 334-3100	● RFL Model 904 Gaussmeter; AC Operated with RFL Model 904039 Flat Probe Includes built-in calibration reference, automatic polarity, push-button range selection and analog output (for strip chart recorder). Designed to measure permanent magnets and DC and AC fields (up to 1 kHz) over range of 1 G to 1 kG. Approx. retail value: $775.00	Donald D. Peck Donald D. Peck & Associates Newport Beach. CA
(44)	RUSKA INSTRUMENT CORP. P. O. Box 742688 Houston, TX 77274 Arranged by: Elliot Moser (713) 975-0547	● Leather Bound Rand McNally World Atlas Approx. retail value: $60.00	Bruce F. Field, EE NBS Gaithersburg, MD

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
	SIMCO ELECTRONICS 382 Martin Ave. Santa Clara, CA 95050 Arranged by: Carl Quinn and Mike Schmahl (408) 727-3611	● Two (2) each Keithley Measurements Instruments (See below for prize number and description.)	
(45)		● Keithley Inst. Corp. Model 130 H-H DMM 3-1/2 digit, basic accuracy of 0.5%. Approx. retail value: $125.00	Robert C. Powell, Chief Scientist Weinschel Engineering Gaithersburg, MD
(46)		● Keithley Inst. Corp. Model 871 Digital Thermometer with dual type-K thermocouple input. Basic accuracy is 0.25% + 1°C. Approx. retail value: $225.00	Dennis M. Koep, Vice President-Sales Standard Reference Labs, Inc. Metuchen, NJ
	SPECTRACOM CORPORATION 320 N. Washington Street Rochester, NY 14625 Arranged by: Bob Hesselberth (716) 381-4827	● Two Quartz Travel Alarms (See below for prize number.)	
(47)		● Quartz Travel Alarm Approx. retail value: $25.00	Karen R. Bonner, Product Support Engr. Hewlett-Packard Palo Alto, CA
(48)		● Quartz Travel Alarm Approx. retail value: $25.00	Alan F. Ho, Engineer Ford Aerospace Newport Beach, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(49)	STANDARD REFERENCE LABS, INC. Coan Place/P.O. Box 388 Metuchen, NJ 08840 Arranged by: Dennis Koep (201) 549-9280	● Sony Model WM-10 II Stereo Cassette Player. Approx. retail value: $100.00	G. E. Rasmussen, Manager Northrup Ventura Newbury Park, CA
(50)	U.S. INSTRUMENT RENTALS 2988 Campus Drive San Mateo, CA 94403 Arranged by: Jim Ingram (415) 572-6756	● Western Graohtec Model MP 1000 Six-Pen Plotter, comes complete with: RS232 cable, application software, manual, etc., and one-year warranty. Approx. retail value: $1,190.00	Moses S. Sun, Test Engineer Manager Endevco San Juan Capistrano, CA
(51)	VALHALLA SCIENTIFIC 7576 Trade Street San Diego, CA 92121 Arranged by: Kevin Clark (619) 578-8280	● Valhalla's Valentine Week-end for Lovers. Complimentary stay at San Diego's Half Moon Inn on Shelter Island with passes to San Diego's Fine Arts Museum and Sea World. Reservations set for Saturday, February 16th, 1985. Also includes wine and cheese/fruit basket. Contact Kevin for further details. Approx. retail value: $150.00	Brian F. Conroy, Supervisor Teledyne Systems Northridge, CA
(52)	VIKING LABORATORIES, INC. 440 Bernardo Avenue Mountain View, CA 94043 Arranged by: Ms. Kelly McGinn (415) 969-5500	● Certificate for Calibration Services up to $100.00 Approx. retail value: $100.00	James A. Zintel, Q. C. Manager Data Magnetics Santa Clara, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(53)	VOLUMETRICS, INC. 741 Paso Robles Paso Robles, GA 93466 Arranged by: Sam Seigal (805) 239-0110	● Case of 12 bottles of Martin Wineries California Nebbiola (a premium red) Wine Approx. retail value: $100.00	Patsy M. Dea, Statistician TRW Redondo Beach, CA
	WAHL INSTRUMENT CO. 5750 Hannum Ave. Culver City, CA 90230 Arranged by: Hank Voznick and Mike Bedaux (213) 641-6931	● Eleven (11) Wahl Instrument Co. Products. (See below for description and prize numbers.)	
(54)		● Wahl Inst. Co. Model 732-25 24-hour spring-wound Chart Temperature Recorder. Covers range of 20 to 140°F. Approx. retail value: $185.00	Robert M. Lady, Lead Engr.-Cal Lab Lockheed-Georgia Co. Marietta, GA
(55)		● Wahl Instrument Co. EGGRIGHT Egg Timer Approx. retail value: $7.00	Howard W. Blackman, Vice President Electro Rent Corp. Burbank, CA
(56)		● Wahl Instrument Co. EGGRIGHT Egg Timer Approx. retail value: $1.00	Jerry J. Niedrauer, Manager Lockheed MSC Sunnyvale, CA
(57)		● Wahl Instrument Co. EGGRIGHT Egg Timer Approx. retail value: $7.00	C. S. Tanaka, Standards Engineer Lockheed MSC Sunnyvale, CA
(58)		● Wahl Instrument Co. EGGRIGHT Egg Timer Approx. retail value: $1.00	Woodward G. Eicke, Consultant NBS - Retired Rockville, MD

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(59)	WAHL INSTRUMENT (continued)	• Wahl Instrument Co. **EGGRIGHT** Egg Timer Approx. retail value: $7.00	Gary J. **McNamara,** Sales Manager Weinschel Engineering Malibu, CA
(60)		• Wahl Instrument Co. **EGGRIGHT** Egg Timer Approx. retail value: **$7.00**	Dennis V. Pinnecker, Manager Rockwell International Anaheim, CA
(61)		• Wahl Instrument Co. **EGGRIGHT** Egg Timer Approx. retail value: **$7.00**	William H. Pedersen, Supervisor Lockheed Austin, TX
(62)		• Wahl Instrument Co. **EGGRIGHT** Egg Timer Approx. retail value: $7.00	Robert B. Willett, Manager Rockwell-Collins TSD Richardson, TX
(63)		• Wahl Instrument Co. **EGGRIGHT** Egg Timer Approx. retail value: **$7.00**	Robert W. **Schmid,** Sr. Consultant Digital Equipment Corp. Santa Clara, CA
(64)		• Wahl Instrument Co. **EGGRIGHT** Egg Timer Approx. retail value: **$7.00**	Bob E. Woerner, R.D. Engineer **E G & G** Los **Alamos,** NM
(65)	WEINSCHEL ENGINEERING 29169 Heathercliff, No. 213 Malibu, CA 90265 Arranged by: Gary **McNamarra** (213) 457-4563	• $25.00 Cash	Kurt G. **Solis,** Vice President, Engineer **Ruska** Instruments Corp. Houston, TX

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(66)	EFRATOM, Division of Ball Corporation 18851 Bardeen Avenue Irvine, CA 92715 Arranged by: Hienz Badura (714) 752-2891	● Polaroid Model 600 Sun Camera Includes carrying case and roll of film. Approx. retail value: $56.00	Benny R. Smith, Metrology Manager Hewlett-Packard Santa Rosa, CA
(67)	RD TECHNOLOGY, INC. 3744 N. Industry Ave., Suite 404 Lakewood, CA 90712 Arranged by: Dave Collins and Bob Merritt (213) 895-9468	● John Fluke Model 75 H-H DMM analog and digital display; AC, DC, Res., extra 10-A current range, ±0.7% basic DC accuracy; with manual or autoranging features and continutity beeper. Approx. retail value: $99.00	Bob Rose, Section Manager Litton G/C Woodland Hills, CA
	TEKTRONIX, INC. 3003 Bunker Hill Lane Santa Clara, CA 95050 Arranged by: Darwin Chapman (408) 496-0800	● Five (5) separate Tektronix, Inc products. (See prizes below for description and prize number.)	
(68)		● Tektronix, Inc. Model P6122 General Purpose 10X Oscilloscope Probe Pair. Accommodates oscilloscopes with bandwidths up to 100 MHz. Approx. retail value: $154.00	H. L. Stott, Staff Engineer John Fluke Mfg. Co. Everett, WA
(69)		● Tektronix, Inc. Model P6122 General Purpose 10X Oscilloscope Probe Pair. Accommodates oscilloscopes with bandwidths up to 100 MHz. Approx. retail value: $154.00	William J. Garbett, Consultant William J. Garbett San Jose, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(70)	TEKTRONIX, INC. (continued)	• Tektronix, Inc. Model P6122 General Purpose 10X Oscilloscope Probe Pair. Accommodates oscilloscopes with bandwidths up to 100 MHz. Approx. retail value: $154.00	John A. Pryshepa, Field App. Engineer Bruel & Kjaer Foster City, CA
(71)		• Tektronix, Inc. Model P6122 General Purpose 10X Oscilloscope Probe Pair. Accommodates oscilloscopes with bandwidths up to 100 MHz. Approx. retail value: $154.00	John L. Van Groos, General Manager Kinematics/True Time Santa Rosa, CA
(72)		• Tektronix, Inc. Model C4 high quality Oscilloscope Documentation Camera. Hand-held ooeration (pistol grip), four element f4.5 glass lens system, mech. shutter, no focussing required. Adapts to most TEK and Non-TEK scopes and CRT displays. Approx. retail value: $370.00	Mark L. Longfield, Supvr Instrumentation Vickers, Inc. Troy, MI
(73)	FRANK KOIDE of Rockwell International Anaheim Metrology Laboratory 3370 Miraloma Avenue (HC02) (a personal donation by the artist)	• A signed and serialized limited edition 20" x 26" lithograph in pastel mounted in an attractive silver-colored frame. The painting early commercial fishing during the 1930's and is titled "Homeguard Tuna." The original painting by Frank Koide is hanging in the San Diego, California Historical Museum. Approx. retail value: $150.00	John R. Sexton, Sales Engineer Mark J. Associates Mtn. View, CA

DOOR PRIZE LISTING (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(74)	WARD-DAVIS ASSOCIATES 2615 Manhattan Beach Blvd. Redondo Beach, CA 90278 Arranged by: Ken Wirgler (213) 643-6977	● $35.00 Cash	John T. Martin, Manager Westinghouse Pittsburgh, PA
(75)	**POLARAD** ELECTRONICS Lake Success, NY Arranged by: Rod Ramirez	● AM/FM Stereo Great Escape Headset-Cassette Player Model GE35273 Approx. retail value: $60.00	Jerry **O.** Bosh, Section Head Hughes Aircraft Co. El Segundo, CA

"WINNERS" IF THEY HAD ONLY BEEN PRESENT!

DRAW	
9th	Mike Cruz Chula Vista, CA
13th	Kent L. Sorensen Redondo Beach, CA
14th	Robert Lyons Mountain View, CA
24th	Paul Halvorson Concord, CA
40th	Karl Kurtz Temple, AZ
62nd	Bob **Prosin** **Corvallis,OR**

DRAW	
65th	Dennis **Barstow** Corvallis, OR
71st	Joseph Santo Granville, OH
77th	J. R. **Innis** Newport News, VA
83rd	Dave Upton Houston, TX
84th	John **Minck** Palo Alto, CA
86th	Richard E. Drews Altamonte Springs, FL
88th	George M. Trinte Alta **Loma,** CA

MEASUREMENT SCIENCE CONFERENCE

MARRIOTT HOTEL, Santa Clara, California
January 17 and 18, 1985

1985

Please Address Reply To:

DOOR PRIZE PROGRAM

3:45 p.m., Friday, January 18, 1985

Note to Attendees - Please read the following to assure that you will be eligible and ready to participate in **this** year's Door Prize Program. The prize you save may be your own!

1. All registered attendees*: Audience, Session Developers, Speakers and **Exhibitor's** Representatives are invited to participate; however, *to be* eligible to win you must:

   A. Complete and turn in your Conference Evaluation Questionnaire, and

   8. Be present at the Door-Prize Drawing.

   *(the 1985 MSC Board of Directors and Conference Committee have declared their members ineligible.)

2. The Door Prizes available for this year's Drawing are very exciting in terms of kind, quality and quantity **(65** individual prizes having a total in excess of $12,000 retail value). This unique situation has been made possible by the graciousness of many individuals and various organizations through their contributions to our Door Prize Program. We have therefore listed the donators (in alphabetical order) along with their donation(s) so that they may be properly recognized.

3. Prizes will be drawn on a sequential first-call basis; therefore, due to the large number of prizes and the relatively short time available for the Drawing, you must study the list of prizes and prioritize your personal choices in advance.

   NOTE: You will only have 30 seconds to state your selection by prize number; winners failing to make their selection within 30 seconds will be given a prize at random.

4. Prizes will be available for viewing in the Exhibits Area.

The Measurement Science Conference Board of Directors and Conference Committee wish each of you the best of luck at the Drawing. We sincerely hope that you enjoy the *program* and facilities organized for this year's Conference; and we urge you to plan on attending and participating in next year's Conference at the IRVINE-MARRIOTT Hotel in Irvine, California on January 23 and 24, 1986.

Bob

Bob Couture,
Door Prize Chairman

Enclosure: Door Prize Listing

MEASUREMENT SCIENCE CONFERENCE

CALL FOR PAPERS
1986 CONFERENCE

JANUARY 23 & 24, 1986 | **IRVINE MARRIOTT** | **IRVINE, CA 92715**

WHAT IS THE MSC?

The first Measurement' Science Conference was in 1969. Originally established to promote measurement education and professionalism, the conferences have matured to serve as a continuing source of new technical and management information relating to measurement and quality assurance. Based in California, the MSC has increasingly attracted representatives from all geographic areas of the country.

This conference provides a forum for the exchange of ideas, techniques and innovations of interest to those engaged in the field of measurement, product design and test and in all other fields of metrology. Experts in the measurement sciences are invited to present sessions, workshops, or papers on subjects of concern to the measurement community, including subjects addressing the state-of-the-art.

This is the only national conference of its kind. If you are involved in any area of measurement assurance, product testing and quality control, you should take this opportunity to participate with others in the field. Scientists, engineers, managers and technicians all find the programs stimulating and informative.

THEME — METROLOGY – THE FOUNDATION FOR QUALITY

TOPICS INCLUDE

- Metrology and Quality Assurance
- Process Control/Measurement Control
- Productivity and Quality
- Promulgation of Uncertainties
- International Traceability
- Developments at NBS
- Automation of Calibration
- Computer Applications in the Laboratory
- Technical Disciplines Including –
  - Electro Mechanical
  - Dimensional
  - Time and Frequency
  - Optical Electronics
  - Microwave/Millimeter
  - DC/Low Frequency
  - Bio Medical
  - Statistics

ABSTRACT DEADLINE

June 1, 1985

AUTHORS

You are invited to participate in MSC '86 by presenting an original paper in one of the topics listed or a related subject. Notify the Program Chairman as soon as possible of your interest together with our name, address, telephone number and a short biographical sketch. A 200 word abstract should be submitted with your reply, if possible, or by June 1, 1985.

SESSION DEVELOPERS

If you are interested in developing a technical session in one of these or a related topic, you are requested to notify the Program Chairman at the earliest possible time. Send your name, address, telephone number and a short biographic sketch with your topic of interest as soon as possible.

RESPOND TO

John Van de Houten, Program Chairman
TRW S/937
One Space Park
Redondo Beach, CA 90278

(213) 535-1497

LUNCHEON

PRESENTERS AND DEVELOPERS

PRESENTERS AND DEVELOPERS

ATTENDEES

"THIS hotel is on fire?"

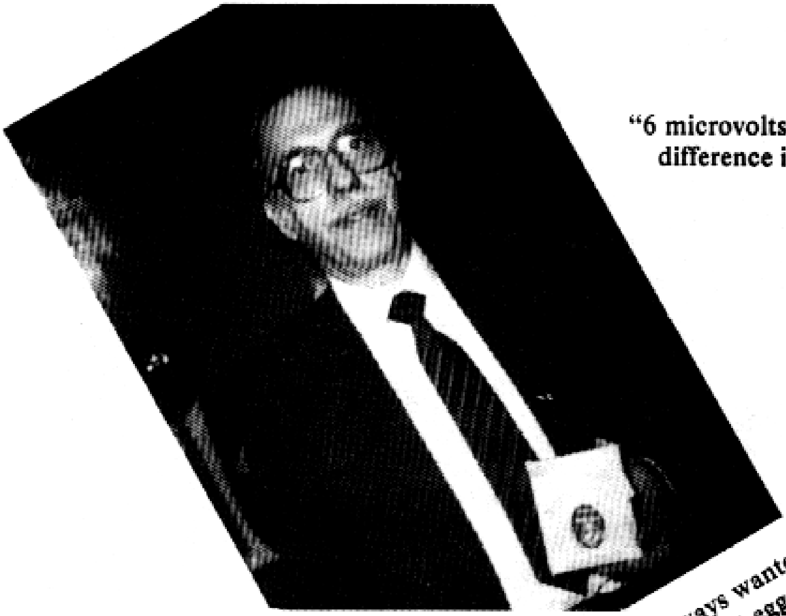
THURSDAY NIGHT RECEPTION

AWARDS

BEHIND THE SCENES

THE HIGH AND THE LOW

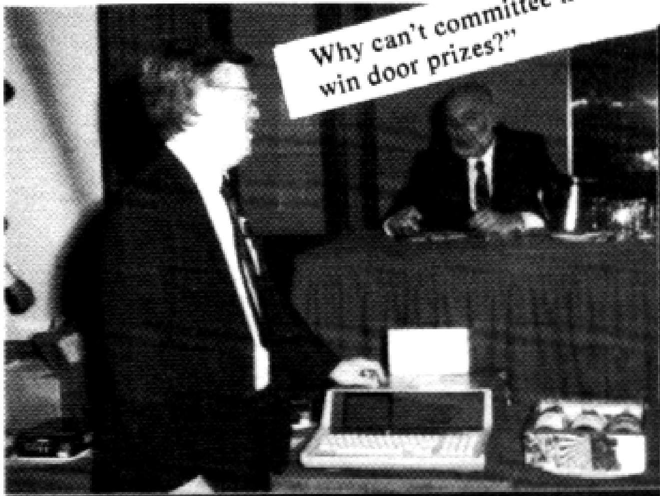
WOODINGTON AWARD



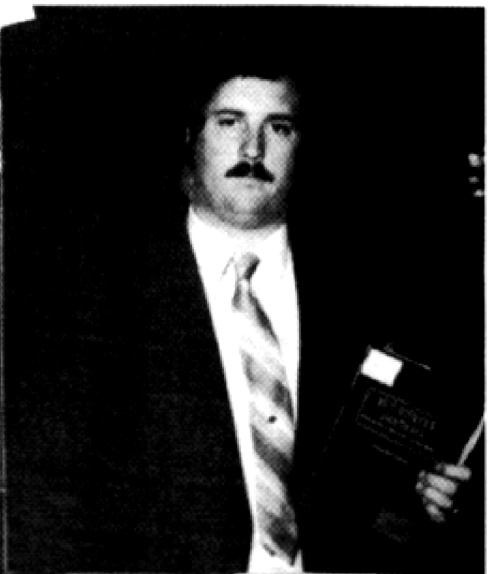
"6 microvolts makes all the difference in the world"

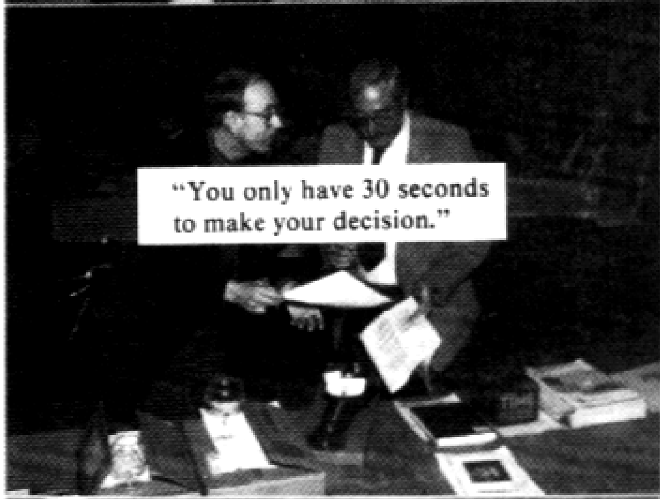
"I've always wanted to make perfect eggs."

DOOR PRIZES



"Why can't committee members win door prizes?"





"You only have 30 seconds to make your decision."

GUEST'S PROGRAM

"I've got two tickets to the super bowl, honey"