ELECTRICAL COMMUNICATION

ITT

VOLUME 40 • NUMBER 4 • 1965

ELECTRICAL COMMUNICATION
Technical Journal Published Quarterly by
INTERNATIONAL TELEPHONE and TELEGRAPH CORPORATION
320 Park Avenue, New York, New York 10022
President: Harold S. Geneen
Secretary: John J. Navin

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Volume 40 **1965** **Number 4**

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Subscription: $2.00 per year
50¢ per copy

This Issue in Brief

The 25th Anniversary of Pulse-Code Modulation—E. M. Deloraine points out that through the years many concepts had been found to be impracticable because needed devices had not yet been invented. After many workers had attempted over several decades to transmit human speech by pulses, Bell succeeded so well with analog methods that pulses received little further attention for about half a century.

The problem of crosstalk in frequency-division-multiplex telephony drew attention to time-division methods about 1930 and pulse-amplitude modulation was tried. After developing pulse-width and then pulse-time modulations, Reeves based his pulse-code modulation on three basic requirements: (1) scan speech and measure the amplitude at suitable time intervals, (2) quantize these amplitudes to the nearest integer, and (3) transmit these integers by telegraph code. By reshaping pulses in repeaters, links could be established in which the quality did not directly depend on the length of the circuit.

This return of telephony to pulses with the present availability of appropriate digital devices promises sweeping changes in both transmission and switching of communication networks.

Alec H. Reeves, the inventor of pulse-code modulation in 1937, states that he knew when the idea was conceived that no tools then existed to make it economic for civilian use.

The principles were first translated into hardware a decade after the invention, by Bell Telephone Laboratories in the United States under a contract with the United States Army. Their papers were the start of a considerable literature from many countries.

A combination of the delta-modulation system invented by Deloraine with pulse-code modulation may give rise to telephone methods that are more efficient than when either is used separately.

The semiconductor era has greatly stimulated development of pulse-code telephony, which initially will fit more easily in local areas than in toll routes where it must interconnect with conventional systems. Developments have included 24-channel operation over junction-cable pairs. Switching, including parallel as well as serial transmission of digits, has received considerable attention. Much work has been done on coding and companding.

By the end of this century, the great mass of information needed by professional men, industrialists, and administrators will require television channels to information processing centers to supply information on demand. Difficulties in transporting people will be alleviated by additional television channels to transport only their brain skills. The application of pulse-code modulation to television is already well advanced and it is almost certain that the required large number of wide-band channels will compel the use of optical beams for transmission.

In the immediate future, pulse-code modulation will spread slowly as it must replace existing plant. Newly developing areas in Africa and Asia that have little existing plant may have an advantage in this respect.

Laboratoire Central de Télécommunications—The name of Les Laboratoires LMT, which was founded in Paris in 1927, was changed to Laboratoire Central de Télécommunications in 1945. This Laboratory is now staffed by 800 people, half of whom are engineers and technicians.

The Laboratory is primarily concerned with telecommunications, including the associated fields of electronics, radar, computers, and space techniques. A physics research service pursues active studies of lasers and magnetic materials. Close contact is maintained with universities engaged in fundamental research.

About half of the work in progress is for the French military and civil administrations. The other half is for the International Telephone and Telegraph System to provide support to its associated companies through a continuing coordinated program in the many rapidly expanding technologies of interest to them.

System Engineering: Its Approach and Operations—The demand for system engineers is a post-war phenomenon and thus relatively new in the history of engineering. Unlike, for example, electrical or chemical engineers, system engineers are not now graduated from universities as such, so they cannot be recognized by their academic diplomas. Indeed there is no universally accepted definition of either system engineering or system engineers apart from a somewhat vague assumption that there is involved some sort of merging and integration of diverse components into larger and more-complex networks.

Communication engineering evolved into the mid-twentieth century as an increasingly specialized component technology in the sense that an antenna is a component of a radio relay station and a radio relay station is a component of a trunk in a telecommunications network. It is a characteristic of sciences in their exploratory and developmental stages that they are occupied with discovery and invention of devices, which are offered to users to fit as well as they can into their living as well as to adjust their lives to fit the inventions.

After the war, the unprecedented creativity and productivity of engineers and technologists resulted in a flood of devices and subsystems coincidentally with an emerging need for vast technological complexes that utilized a great number of subsystems such as computers and telecommunications and had to perform in a coordinated way geographically dispersed tasks such as those in air defense, traffic control, banking, manned space ventures, and the like. These parallel developments of a technological outpouring of devices, which would not fit into coordinated networks, and the demand for vastly complex and systematic agglomerations of devices, created a demand for a new kind of engineer. He was expected to begin with the projected requirement and work his way back to a specification of the devices and subsystems required for the realization of the ultimate network and service. This man was needed, with his deductive methods, to supplement the inventor and developer by giving the latter goals toward which to work.

The system engineer is thus distinguished by operations that usually take him from a statement of a human or social need through an analysis of hypothesized operations for patterns, structure, and organization; the evaluation of already present facilities; and finally to the specification of devices needed to fill gaps and deficiencies. The tools of prediction, of combinatorial and matrix algebra, of cost-effectiveness trade-offs, and of a catholic comprehension of many disciplines, are all strange to the products of classical engineering institutions. The contemporary system engineer usually finds most available design tools too frail for his job and must invent more-powerful ones or borrow them from disciplines as remote as econometrics and biometrics.

In all, the author takes the evolution of the system engineer to be a mark of the growing maturity of technological man and a harbinger of a time when the domination of man by technology will be ameliorated in some part by the system engineers' moulding of the course of technology to the aspirations and explicit requirements of man.

Modulation and Coding—Emphasis is placed on systems using pulse-code modulation with fast coding suitable for high-speed data, multiplex telephony, and television. It is assumed that pulse-regenerating repeaters will be used in a disturbed transmission path.

Important features of the modulating system are the bandwidth and the ease with which a synchronizing wave can be extracted from the received signal.

The code structure substantially affects the accuracy of transmission. Its improvement by adding redundancy to the message does not necessarily reduce the maximum output of the channel. Both coding and modulation must be suited to each other.

A new method having wide application, great simplicity, high reliability, and low cost uses pulse-code modulation with low-disparity coding.

Small-Diameter Coaxial Cable Using Moulded-Shell Construction—Machinery has been developed for the continuous production of coaxial cable having a center conductor approximately 0.047 inch (1.2 millimeters) in diameter separated by a special polyethylene moulding from an outer conductor having an inner diameter of 0.174 inch (4.4 millimeters). Two steel tapes are added to improve crosstalk.

The center conductor is given a final drawing for uniformity. An extruded polyethylene tape is heat formed to produce two halves of a thin-walled tube with integral half-discs at suitable intervals for supporting the center conductor. This formed tape is slit lengthwise and the 2 resulting halves enter a heating unit in which they are joined face to face round the center conductor. All remaining excess material is then removed.

The outer conductor is formed from a flat strip the edges of which are corrugated to prevent overlap. Commercial variations in width are eliminated by drawing down in a final forming die. The 2 steel tapes are helically wound in reverse directions at an angle of 45 degrees to the length of the cable. To obtain satisfactory contact the inner tape is wound with a slight gap while the outer tape is overlapped. Deformation of the cable in this operation is prevented by a special supporting element.

The mechanical tolerances were determined by their effects on the electrical properties and particularly by the high uniformity required for television transmission. Data are given on these electrical properties.

Relationship Between Attenuation and Wire-Braid Design for Flexible Radio-Frequency Cables—The theory underlying the design of wire braids for conventional flexible radio-frequency cables is given, together with graphic representation of the length of lay required for any mean diameter of braid. The number of ends of wire per braiding spindle is also given in graphic form for a given braiding machine for the condition of minimum attenuation compatible with normal cable flexibility and ease of termination.

In conjunction with such braid designs, a rapid method for calculating the attenuation of coaxial cables over the frequency range from 10 to 1000 megahertz is shown together with examples.

Monitor for Color Television—This monitor for color-television signals is intended for use in studios and transmitter stations. It may be operated directly from the picture modulation or with a suitable radio unit from the transmitted broadcast signal. Based on a 625-line picture repeated 25 frames per second, it may be adapted to three color systems: National Television System Committee, Phase Alternation Line, or Sequential With Memory.

The 16-inch (41-centimeter) rectangular picture tube is manufactured by Toshiba Shibaura Electric Company (Japan). Silicon transistors are used for all but horizontal-deflection circuits and the design data may be useful later for home receivers. The monitor is small enough to be substituted directly for existing monochrome monitors.

Infrared and the Nimbus High-Resolution Radiometer—A radiometer for the meteorological satellite, Nimbus, uses a lead-selenide photoconductor type of detector sensitive to radiation at wavelengths between 3.4 and 4.2 microns, corresponding to a range of electromagnetic radiation having favorable transmission through the atmosphere of the earth.

The satellite travels in a near-polar orbit, and a rotating mirror scans transversely to this path to produce an output from the radiometer corresponding to the temperature variations of the earth below. The output is recorded and played back on command of the ground radio station to permit photographs to be produced. Several such photographs are shown. Bodies of water are warmer than land masses and appear darker; cloud formations are colder and appear whiter.

Recent Achievements

Early Bird Satellite Tested for Record Communication—On 19 August 1964 the communications satellite, Early Bird, was put in an equatorial orbit that synchronizes with the rotation of the earth. The satellite therefore seems to maintain a stationary position when viewed from the earth. Earlier it was placed above the Pacific Ocean to provide a relay for live television programs of the Olympic Games from Japan to the United States.

The satellite has now been moved east of the coast of Brazil, and the Communications Satellite Corporation—in anticipation of its use for relaying commercial record-communication traffic between Europe and the United States—assigned three voice-grade channels to ITT World Communications for selected tests on 9 and 10 June 1965. The channels were from New York over landlines to the ground radio station in Andover, Maine, thence via satellite to European ground radio stations in Goonhilly Downs, England; Pleumeur Bodou, France; and Raisting, Germany. These radio terminals were connected by land facilities to the respective telecommunication administrations in London, Paris, and Frankfurt.

Initial measurements were of amplitude distortion, delay, and phase perturbations over the satellite link. Traffic tests were then made over narrow-band telegraph channels and full-band telephone channels, the latter including telex operation from offices of commercial customers through existing automatic switching equipment, photo transmission using Videx slow-scan television, and high-speed data with three types of modem terminals. Pan American Airways in New York was connected to one of its aircraft in flight via London.

The Videx slow-scan television equipment was supplied by ITT Industrial Laboratories Division, which sent an engineer to New York and another to London to monitor the operations.

Standard Telephones and Cables (United Kingdom) provided *GH205* data terminals suitably modified for the long-delay satellite path. Two engineers were sent to New York to handle the equipment.

Standard Elektrik Lorenz (Germany) also sent two engineers to New York with its *LO 2000* high-speed printer and associated transmission system.

Tests also included *GH201* data terminals supplied by Standard Radio & Telefon (Sweden) to New York. ITT World Communications used its *1070* magnetic-tape terminal also.

In Europe, complementary terminals and equipment were provided by these companies. In France, both Laboratoire Central de Télécommunications and Les Téléimprimeurs participated in the tests.

The tests were outstandingly successful. Communication via Early Bird proved to be as good as present facilities via North Atlantic repeatered cables. No unforeseen technical or operational difficulties were encountered. The channels were within internationally accepted tolerances and may need little or no equalization in commercial service.

Resistance-Capacitance Thin-Film Structure for Frequency Selection—It is desirable to avoid the need for inductances in microelectronic circuits. One way is to use a resistance-capacitance network having an appropriate impedance variation with frequency. A lumped twin-T, often composed of 3 resistance and 3 capacitance components, can provide a useful filter element.

It is now possible to fabricate thin-film resistance-capacitance combinations mutually distributed in 2 dimensions. Thus by sequentially depositing resistance, dielectric, and conductance films and by adding a resistor, a resistance-capacitance notch filter with electrical properties similar to a lumped twin-T network is obtained. By suitably tapering the resistance film it is possible to improve the Q of the filter.

A broad-band amplifier suitable for fabrication as an integrated thin-film circuit has a gain of 30 decibels over the range from 20 kilohertz to

15 megahertz. A distributed resistance-capacitance notch filter in the feedback line provides selectivity at any frequency in this range by appropriate choice of component values. The effective Q of the amplifier depends on the resistance ratio within the notch filter and the value of the negative-feedback resistor R_f shown in Figure 1. Q values up to 20 are possible with present manufacturing tolerances.

Standard Telecommunication Laboratories
United Kingdom

Push-Button Calling Applied to Step-by-Step Exchange—A field trial of push-button calling was inaugurated last spring in Erin, Tennessee, when 20 subscribers were so connected to the local step-by-step exchange.

Multifrequency-code signaling is used with 2 frequencies, each from a separate group of 4 frequencies, sent simultaneously. Signaling frequencies are in-band between 697 and 1633 hertz.

Applicable to all dial direct-control switching, the system allows intermixing of dial and push-button subscriber stations within line groups and as extensions on the same line.

ITT Telecommunications
United States of America

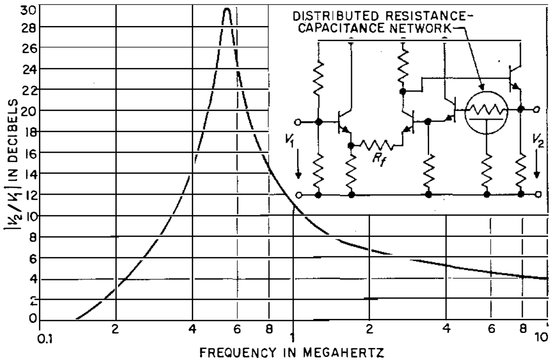


Figure 1—Amplifier using thin-film structure with a distributed resistance-capacitance network in the feedback line. The center frequency is at 550 kilohertz and the 3-decibel bandwidth indicates a Q of 8.

Pneumatic Tube Ticket Folder—Pneumatic tube systems for transporting paper slips or tickets without carriers require that one end of the ticket be folded at 90 degrees to make a small sail, thus ensuring the transport of the ticket by the flow of air in the rectangular tube. To avoid the necessity of folding the ticket by hand as is now being done, an automatic folder has been developed.

Normally the narrow rectangular gate at A in Figure 2 is open to admit an unfolded ticket. The ticket is stopped by gate D and a photocell arrangement at C is operated by the presence of the ticket. This closes gate A so that a second ticket cannot be inserted and also actuates the folding mechanism at B. On completion of the folding operation, gate D is first opened to release the folded ticket and then closed. Finally gate A opens, restoring the ticket folder to the waiting condition.

Standard Téléphone et Radio
Switzerland

Pneumatic Tubes for Hamburg Post Office—The 100th station in the pneumatic tube system for transporting mail within Hamburg was installed recently.

The use of compressed air to drive cylindrical load carriers through underground tubes was introduced in London in 1853. This technique came to Berlin a dozen years later and by the

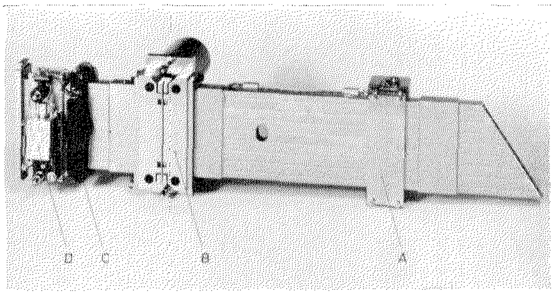


Figure 2—Automatic machine for folding one end of a ticket 100 by 60 millimeters (3.9 by 2.4 inches) to form a sail for propelling it without a carrier through a pneumatic tube.

end of that century the Berlin post office network totaled 118 kilometers (73 miles) and carried over 6 million postal items per year.

The German post office now operates pneumatic tube systems in 10 towns for a total length of 310 kilometers (193 miles). The model *52* station, contrasted in Figure 3 with equipment of about half a century ago, features low height for convenient mounting close to the public counters in post offices, complete electrical control, automatic reception of carriers, and simple dispatching. It is the accepted standard of the post office.

A high-capacity system is in experimental service in Berlin to avoid trucking some of the mail through heavy traffic. Numerous other systems serve banks, business offices, hospitals, and industrial installations.

Standard Elektrik Lorenz
Germany

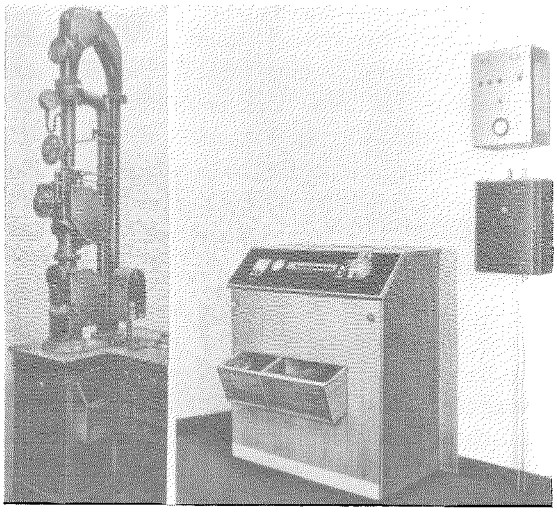


Figure 3—At left is an early pneumatic tube station and at right is the model *52* station now standardized by the German post office for its expanding pneumatic tube mail transportation system.

Radio Altimeter Approved—The United Kingdom Air Registration Board has approved the *STR 40* low-level radio altimeter for commercial application.

This equipment, shown in Figure 4, emits a frequency that sweeps repetitively across the band between 4200 and 4400 megahertz. It counts discrete cycles of the difference between the transmitted frequency and that of the reflected wave to determine the length of path of transmission between the aircraft and earth.

Standard Telephones and Cables
United Kingdom

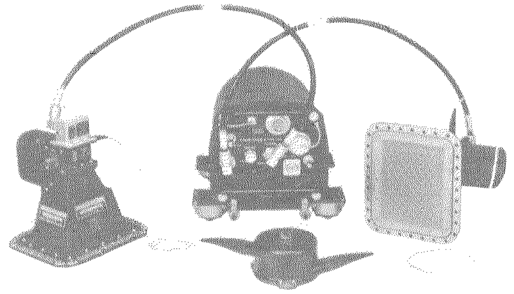


Figure 4—*STR 40* frequency-modulated radio altimeter.

Ion Laser—A class of lasers in which the conventional luminescent discharge is replaced by a low-pressure arc having current densities as large as 1000 amperes per square centimeter is well known.

Argon was first used and produced continuous operation at high power in the blue-green region of the spectrum. Recent work has shown that krypton advantageously provides radiation over

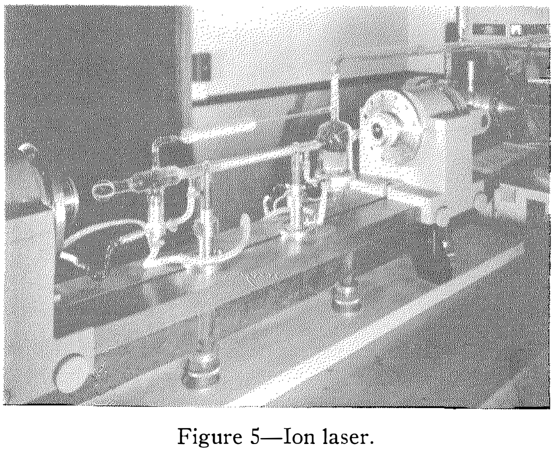


Figure 5—Ion laser.

the entire visible spectrum and that this permits a particular line to be selected by suitable mirrors in the cavity. The test equipment is shown in Figure 5.

Laboratoire Central de Télécommunications
France

Encapsulation Resins with Controlled Thermal Expansion—A range of filled epoxide casting resin compositions having certain advantages over commercially available materials has been developed on a laboratory scale for the encapsulation of small electronic components. In particular, they have a low controllable thermal expansion coefficient sufficiently matched to that of conventionally used component materials to permit relatively large temperature excursions without setting up unduly large stresses in either the component or the encapsulation resin. They are provisionally coded as Loex (**lo**w-**ex**pansion) resins.

The epoxide resin system has been carefully chosen for its favorable processing properties, such as low viscosity, low toxicity, good pot life, et cetera, and to give a cured product of high heat-deflection temperature and good thermal stability. Low thermal expansion is achieved by the addition of a high loading of inorganic filler specially treated to minimize absorption and transmission of water. The materials are compounded in two parts with a storage life of several months and are mixed together when required for use. Expansion coefficient is controlled by the proportion of filler, values down to 20 parts per million per degree Celsius can be achieved with pourable compositions, and even-lower values if injection methods are applied. Some properties of typical compositions are given in Table 1, which includes data on the unfilled resin for comparison.

Standard Telecommunication Laboratories
United Kingdom

TABLE 1
PROPERTIES OF LOEX ENCAPSULATION RESINS

Code Reference	Unfilled Resin	Loex *45 A*	Loex *50 A*	Loex *55 A*
Filler in percent	0	45	50	55
Pourability	Very good	Very good	Good	Difficult
Heat-deflection temperature in degrees Celsius	127	137	137	137
Linear thermal expansion in parts per million per degree Celsius	58	25	22	20
Curing shrinkage (volumetric) in percent	≈ 2	≈ 1	≈ 1	≈ 1
Water absorption in milligrams per 24 hours (British Standard *2782*)	13	<5	<5	<5
Water permeability in grams per centimeter per hour per millimeter of mercury ($\times 10^7$)	16	—	6	—
Flexural strength in pounds per square inch ($\times 10^{-3}$)	12	15	15	14
Flexural modulus in pounds per square inch ($\times 10^{-6}$)	0.5	1.4	1.6	1.9

Telephone Operator Training for Blind—Association Valentin Haüy, the most-prominent

French society for aiding the blind, has established in Paris a school for teaching manual operation of either cord or cordless telephone switchboards. The Paris Direction des Télécommunications approved the design of the telephone equipment.

The instructor's position provides simulated traffic for use in training. A tape recorder supplies certain tone signals for this purpose.

Under control of the instructor, signals can be transmitted in 3 forms: by sound in code groups; by dactyles, which are magnetically operated pins that extend for detection by touch; and by light, if some sight still remains. The latter is used only if medically authorized. The instructor may connect the student to trunk lines to the public network, thus progressing from simulated to real traffic.

Final training is on real traffic with direct access to the public network and transfer facilities to an *8E* Pentaconta private automatic exchange using keyset signaling.

Compagnie Générale de Constructions Téléphoniques
France

Interpreter Training Facilities—Facilities for the training of interpreters have been installed in the Commercial University of Antwerp.

There are 8 compartments, each accommodating 2 students, and 8 desks for instructors. Each student is provided with a microphone, 2 listening devices, key switches for selecting among 10 language programs, and an intercommunication set. The instructors have similar equipment with which they can monitor and control the activities of the students. A control room provides flexibility in connecting instructors and students with each other and also controls the distribution of languages to the students.

The installation may also be used for conferences and as a lecture hall. There are 200 seats for auditors, each with a headset, volume control, and selector switch for 10 language channels. A public-address system is also provided with as a special feature the possibility of intercommunication between the auditors and the speaker.

Bell Telephone Manufacturing Company
Belgium

Long-Range 3-Dimensional Radar—Based on company-sponsored studies, the *AN/SPS-48,* a very-high-power pencil-beam radar combined with a special computer, furnishes continuous bearing, range, and altitude data on flying targets.

Installed on surface missile ships of the United States Navy and unaffected by the motion of the vessels, these equipments will give the needed information on enemy targets traveling at supersonic speed in time to permit effective reply. Control of our own aircraft will also be facilitated by the *AN/SPS-48.*

ITT Gilfillan
United States of America

***GH-201* Demonstrated in United States**—At the Industrial Communications Association conference held in May 1965 in Pittsburgh, ITT World Communications introduced its international data service. The *GH-201* data system, which operates over a normal telephone channel at 1200 bits per second with automatic error correction, was used in a circuit from Pittsburgh to Honolulu via San Francisco. It was equipped for tape operation.

Standard Radio & Telefon
Sweden

Solid-State 4-Gigahertz Transmitter—A crystal oscillator operating at approximately 40 megahertz drives a transistor tripler and amplifier to provide a source at 125 megahertz. A helical line filter of 400-kilohertz bandwidth removes noise before further amplification raises the level to 25 watts. Three lumped-circuit doublers then produce 10 watts at 1 gigahertz. Another pair of doublers in coaxial and waveguide circuits gives 4.7 watts at 4 gigahertz.

Most of this power then goes into an up-converter consisting of a pair of crystals in waveguide. Suitable filters separate pump, upper-sideband, and lower-sideband frequencies. The upper sideband with 1.6 watts is selected and the diodes are modulated with a 70-megahertz intermediate-frequency signal. The measured noise is better than the 5 picowatts specified for a microwave link. The power supply is 40 watts at 28 volts.

Standard Telecommunication Laboratories
United Kingdom

Telephone-Traffic Measurement—Using Herkon relays and electronic switching, the *VGA* test set permits quick assessment of the volume of traffic on many telephone lines and switching equipments. It comprises the 3 units shown in Figure 6.

The control wires of the switching devices to be observed, which are terminated on plug strips in the intermediate distributing frame, are joined by plugs to the test equipment. A sampling or scanning unit connects these control wires sequentially to the test circuit to determine if they are free or busy. A signal goes to a counting circuit for each engaged switch and after the group has been scanned the number of engaged devices is recorded by a tape punch. The time of observation is also recorded and a computer calculates the traffic volume and busy-hour traffic.

A measuring cycle takes 3 minutes and may be repeated continuously. At 20 milliseconds per test, 50 wires can be checked per second. Over 8000 switching devices or lines can be observed in one measurement routine. Subcycles can be used for special purposes. Furthermore, test cycles for checking the operation of the *VGA* test set may also be set up.

Standard Elektrik Lorenz
Germany

Satellite Programers Tested in Flight—Under contract with Société pour l'Étude et la Réalisation d'Engins Balistiques (SEREB), a series of programers for use in experimental satellites were constructed. During launch they separate the payload from the last rocket stage, release the heat shield, and unfold the radio antennas. They also start and stop the telemetry equipment and radar responder as the satellite passes the control station in orbit.

In June 1965 at Hammaguir, Algeria, in the Sahara, 2 experimental payloads including these programers were tested in 20-minute parabolic flights. They were launched by Rubis engines, which make up the last 2 stages of the ultimate Diamant rocket. Measurements in both the propulsion and ballistic phases of the flight showed the programers to be completely satisfactory.

Laboratoire Central de Télécommunications
France

Satellite Repeater Uses Single Frequency Conversion—An engineering model of a single-conversion repeater providing 1200 duplex channels for use in a satellite in medium-altitude orbit has demonstrated superiority over conventional designs, which utilize double frequency conversion and intermediate-frequency amplification. The single conversion reduces

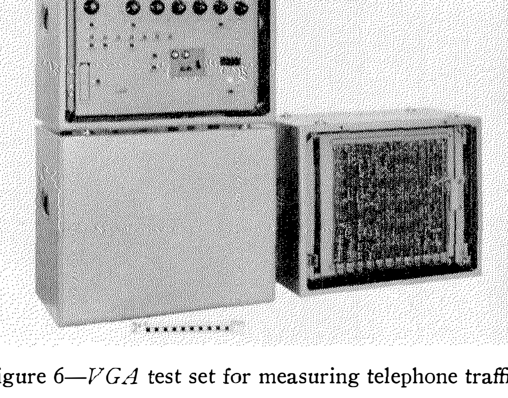


Figure 6—*VGA* test set for measuring telephone traffic.

distortion for high traffic capacity and simplifies equipment needs to improve life.

This design was developed for the Communications Satellite Corporation by ITT Federal Laboratories as the principal subcontractor to Space Technology Laboratories for a communications satellite for launch near the end of 1966.

ITT Federal Laboratories
United States of America

Satellite-Tracking Receiver—Model *4004* is an advanced monopulse tracking and telemetry receiver for satellite operation.

A third-order phase-lock loop permits rapid automatic acquisition of signals and provides rate memory. It also improves acquisition thresholds at high doppler offsets and rates, as it eliminates loop phase-velocity errors and significantly lowers phase-acceleration errors. A cross-modulation mode is provided for tracking signals having high-index angle modulation.

Compactness, interchangeable modules, long-term phase stability, simplified operation, and ease of maintenance are featured.

ITT Federal Laboratories
United States of America

Basildon Plant Opened in United Kingdom—The British Postmaster General officially opened last June the new Basildon (near Essex coast) manufacturing plant shown in Figure 7. It will produce long-distance telephone equipment for the British Post Office.

This is the largest factory the company has built since the second world war. It has a floor area of 400 000 square feet (37 200 square meters) and the initial 2000 employees will grow to 3000 by next year.

Standard Telephones and Cables
United Kingdom

X-Band Traveling-Wave Tube—Providing 35 decibels of gain in the band from 7 to 11.5 gigahertz, the *W3MQ/1A* traveling-wave tube features a typical noise factor of only 9 decibels. Maximum output varies between 2 and 15 milliwatts over the operating frequency range.

The tube works from a 1200-volt direct-current supply. It is packaged in a single-reversal permanent-magnet mount. It is available with tapered transitions for British *WG16* waveguide or with coaxial connectors, Similar tubes are also available for *S*-band operation.

Standard Telephones and Cables
United Kingdom

Pentaconta Switching for Rumania—The Rumanian Popular Republic has selected Penta-

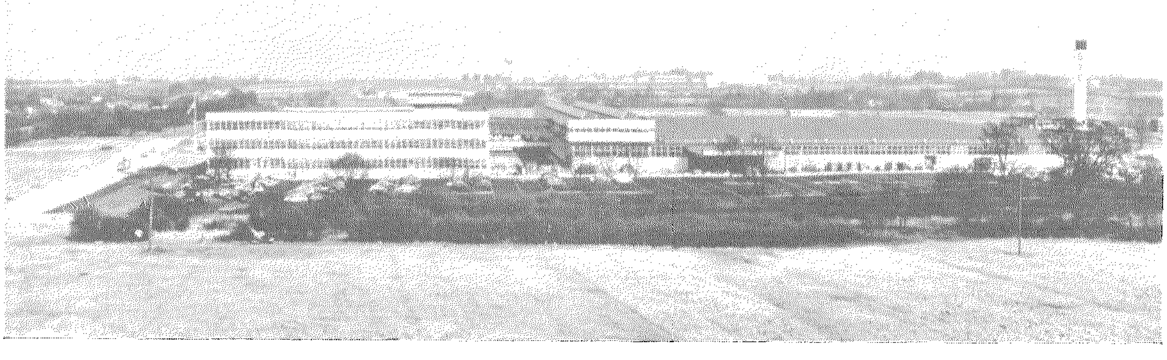


Figure 7—New manufacturing plant recently opened in Basildon.

conta for modernizing its telephone system. It has contracted for an initial installation of a tandem exchange and a 5000-line local central office in Bucharest and for trunk exchanges in 13 important cities. Furthermore, a plant will be built to manufacture Pentaconta switching equipment under license and within 5 years will have a capacity of 100 000 lines per year.

Knowledge of the public telephone network of Rumania obtained over the past 40 years has contributed importantly in plans for modernizing and expanding the network.

Bell Telephone Manufacturing Company
Belgium

Automatic Testing of Long Lines—The apparatus shown in Figure 8 automatically tests telephone lines and the associated transmission equipment including that for subscriber long-distance dialing. Line sections are checked for overall attenuation and for signal transmission in both directions.

A punched card identifies and gives the necessary information for each line that is to be tested. Special time cards control when the tests are to be made to ensure that the distant station is not in use. A fault will be recorded on the card for that line and it will be sorted into a special file. Other files are provided for acceptable lines and for engaged or blocked lines on which tests could not be made.

Standard Elektrik Lorenz
Germany

Infrared Filters—An accurate method to identify an unknown compound is to analyze its infrared absorption spectrum. Filters for the infrared range between 20 000 and 71 000 angstrom units are now available for such optical systems. They weigh only a few grams and are 7/8 inch (22 millimeters) in diameter by 1/8 inch (3.2 millimeters) thick.

Standard Telephones and Cables
United Kingdom

Concorde Aircraft Simulator—The design of an aircraft as complex as the Concorde supersonic transport requires extensive research of not only the component systems of the craft but of human engineering in working out crew duties. Long before the maiden flight of the prototype, much of this research can be carried out with a simulator that conforms to the calculated characteristics of the aircraft and its various systems such as undercarriage, flight controls, autopilot, stabilizers, radio and navigation aids, power plant, and fuel, hydraulic, and electrical systems.

A prime contract for the design and construction of the Concorde research simulator has been accepted, with Redifon Limited of England as main subcontractor.

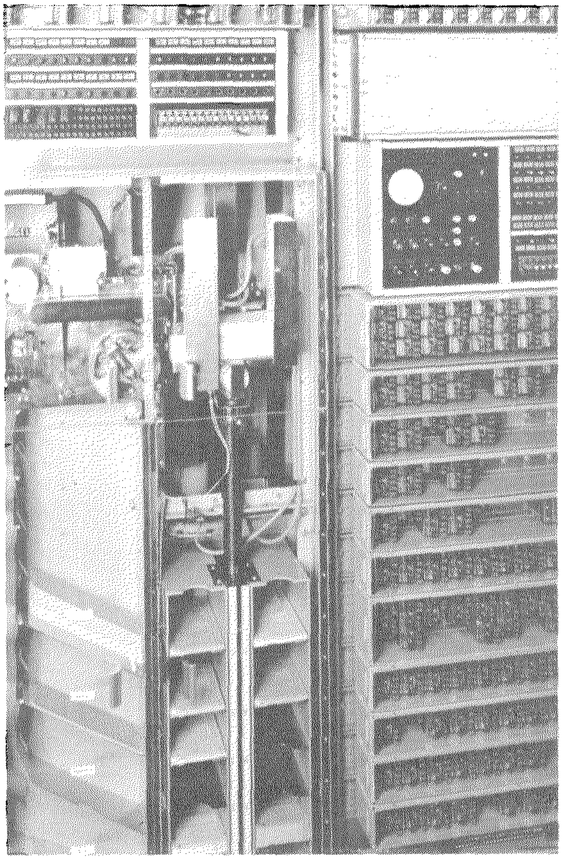


Figure 8—Automatic test equipment for checking lines of the subscriber long-distance dialing network.

A Concorde flight deck completely equipped with its hundreds of controls and indicators is linked to a general-purpose digital computer via complex interface equipment containing various kinds of analog-to-digital and digital-to-analog devices together with control and computing logic circuits. Control is maintained of a flight-deck-motion platform and a color closed-loop television visual display.

Le Matériel Téléphonique
France

Intercommunication System, Dirigent 2/80—A master station for the Dirigent *2/80* industrial intercommunication system is shown in Figure 9. Designed for use in industrial plants and repair workshops, it may include 1 or 2 master stations and between 20 and 80 extensions.

Calls are initiated from the master station by pressing the button of the called station. The called party may reply from a distance as no buttons or switches at the extension set need be operated. The master station may be called from any extension and if more than one such call is made at a time, the later calls are queued. The extension telephones are also available in splash-proof or explosion-proof designs. Protection against high ambient noise may also be obtained.

Figure 9—Master station of Dirigent *2/80* industrial intercommunication system.

Standard Elektrik Lorenz
Germany

Silicon Avalanche Rectifier in 10-Ampere Rating—A 10-ampere unit has been added to the range of silicon avalanche rectifiers. The *RAS508CF* rectifier has a reverse-power surge rating of 8 kilowatts. The mean forward current is 10 amperes and the crest working voltage is 800 volts. It has a minimum avalanche characteristic of 1000 volts. In dimensions it conforms with the IEC *A3U* and Jedec *DO-4* designs.

Standard Telephones and Cables
United Kingdom

Magnetic Marking of Mine Trucks—A new magnetic method of marking conveyer and ore trucks used in mines permits automation of identifying, counting, switching, and unloading operations.

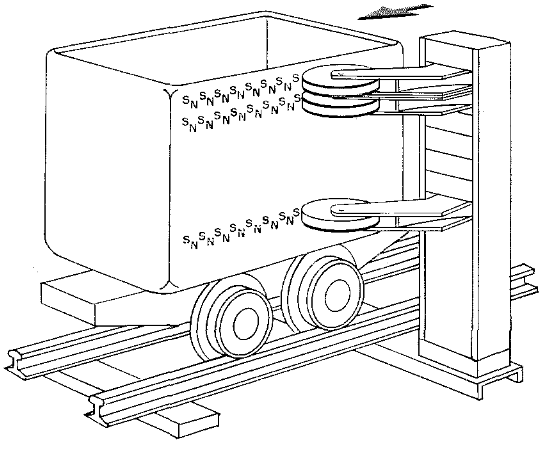


Figure 10—Magnetic reader for identifying magnetic tracks recorded along the wall of a mine truck.

One or more permanent magnetic tracks are written into the steel walls of a truck by permanent magnets mounted on a frame past which the truck moves.

These permanent magnetic fields induce currents in read heads (Figure 10), which on evaluation initiate the required operations. The magnetic recordings may be cancelled by subjecting them to reverse magnetic fields but are not cancelled by the read action. As no electric current is required for either writing or reading, there is no danger of igniting explosive gases.

Standard Elektrik Lorenz
Germany

High-Speed Data System Transmits Newspaper Copy Across Atlantic—The first transatlantic production of a newspaper used *GH 205* high-speed data equipment for both ends of the line. A computer in the London headquarters of Thomson Newspapers sent copy and layout instructions to a corresponding unit in Wilmington, Massachusetts, where Photon equipment, a photographic typesetter, produced offset plates for a web-fed press.

Information was transmitted from 7-track paper tape over a 2-way telephone channel at 80 characters per second. An error-detecting code gave an improvement of 15 000 times over an unprotected link.

Standard Telephones and Cables
United Kingdom

Portable Telephone-Cable Test Set—Mutual capacitance, capacitance unbalance, and percentage resistance unbalance are measured with the *74226* portable self-contained telephone-cable test set. Measurement of capacitance unbalance is particularly useful in minimizing crosstalk and interference in joining cable sections.

Capacitance unbalance of 2 conductors of a pair may be measured in 2 ranges: 280-0-280 and 1100-0-1100 picofarads within ±1 percent +2 picofarads. Mutual capacitance values up to 112 100 picofarads may be measured within ±50 picofarads. Percentage resistance unbalance of the 2 conductors of a pair may be measured to ±0.5 percent within an accuracy of 0.01 percent.

Two versions differ only in providing either an 800-hertz or a 1000-hertz transistor oscillator for driving the bridge. A null amplifier is included. Power is from 9 volts of dry batteries. The wood cabinet, which has a detachable cover and carrying handles, is 17 by 12 by 10 inches (43 by 30.5 by 25.4 centimeters) and weighs 43 pounds (19.5 kilograms).

Standard Telephones and Cables
United Kingdom

Mobile Radiotelephone Set—A very-high-frequency 10-channel radiotelephone equipment is shown in Figure 11 installed in an automobile. It provides for simplex operation with a central station that may be located at and connected to a private branch telephone exchange. Individuals, groups, or all mobile stations in the system may be called from the extensions of the branch exchange. Intervehicle traffic is also possible.

Standard Elektrik Lorenz
Germany

Figure 11—"Standafon" very-high-frequency radiotelephone equipment installed beneath the dashboard of an automobile.

Radiation-Resistant Regulator for Orbiting Reactor—A regulator to control the electric output from an orbiting nuclear power plant was built for the Atomic Energy Commission under contract with the Lockheed Missiles & Space Company. An essential design feature was that it be resistant to the radioactive environment near the reactor.

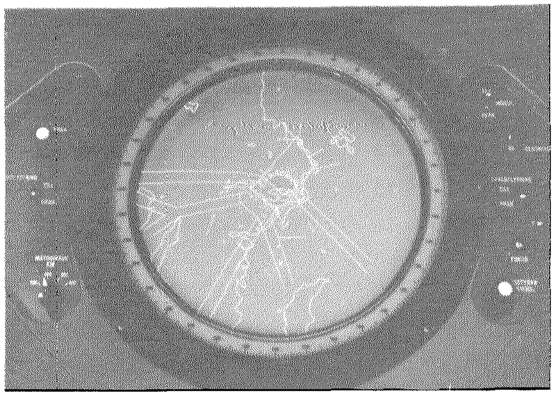
Still orbiting in *SNAP 10A,* the first nuclear-powered satellite, the regulator must compensate for the varying power loads imposed by the ion propulsion motor and for various test instruments that make up the payload.

ITT Industrial Products Division
United States of America

Digital Radar Bright Display—Information from a surveillance radar is renewed on a plan-position indicator only once per revolution of the antenna, which is of the order of every 10 seconds. The normal cathode-ray tube requires more-frequent renewal if it is to produce and store sufficient light to be visible in bright daylight. A new display system to overcome this handicap was demonstrated at the Paris International Air Show.

The system is based on extracting the plotted positions of the target echoes by means of a coordinate generator using a digital time-base system and a video extractor or digitizer. Plots from 16 or 30 antenna revolutions are stored in a ferrite-core memory, which is scanned 16 times per second for display on the cathode-ray tube.

Figure 12—Digital bright radar display photographed under normal daytime ambient lighting.



In addition to the target information, alphanumeric identification can be inserted from a symbol generator and moved at will. As shown in Figure 12, maps including air corridors and airport runways may be written into the memory from punched tape. Contrary to conventional radar map presentation, the sharpness is maintained independent of range and off-center position.

To indicate speed and heading of targets, an apparent movement is introduced by a spot of increased light intensity "walking" from dot to dot along the trail of a target in the direction of target motion thereby giving the flight history for the immediate past 30 revolutions of the antenna, which is approximately 5 minutes.

Standard Radio & Telefon
Sweden

The 25th Anniversary of Pulse-Code Modulation *

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1. Historical background

E. M. Deloraine

The history of technological development is full of examples of returns to previous concepts that were originally impracticable because the devices necessary to implement them had not been invented. The result is that the art develops over an alternative route and, taking the long way around, returns to the starting point, but at a higher technological level.

The history of telephony and of pulse-code modulation has followed this pattern. The early investigations of the transmission of music and speech, in 1837 and during the following 40 years, all attempted to "telegraph" music and speech. Dr. G. G. Page in the United States, Charles Bourseul in France, and J. P. Reis in Germany described various methods of causing a membrane to open or close an electric circuit at each vibration, transmitting as many electric pulses as there were sound vibrations. The pulses at the receiving end caused a device to produce a sound of a pitch corresponding to the number of pulses.

Numerous observations were published at the time, including the following by Reis: "Hitherto it has not been possible to reproduce human speech with sufficient distinctness. The consonants are for the most part reproduced pretty distinctly, but not the vowels as yet in an equal degree."

Today, some 100 years later, we know how to explain the difficulty. The experimenters were attempting to code speech with an exceedingly simple code that was not capable of giving enough information to the distant end.

Perhaps if these early attempts had been continued with more-elaborate coders, we would have seen a telephone art developed on the basis of coded pulses, but Alexander Graham Bell's research was based on a different concept. His aim was: ". . . by means of the undulation of pressure of sound on a membrane, to produce an electric current the strength of which should at every instant vary directly as the pressure varied."

We can now understand what happened: After there had been 40 years of unsuccessful attempts to reproduce speech by digital methods, Bell turned our attention to analog techniques. He succeeded so well that telephony remained basically analog in concept until fairly recently, when the digital possibilities returned to the attention of the inventors. It was probably the difficulties encountered in the simultaneous transmission of a number of telephone conversations over a single transmission path that provided the stimulus.

The past 30 years witnessed outstanding success of multiple-channel transmission; however, in early attempts, crosstalk between channels appeared to be an almost insurmountable obstacle, and filters were also complex and expensive structures. Several groups or individuals started to wonder whether it would not be easier to transmit channels successively on a time-division basis rather than simultaneously by frequency separation.

The invention of inverse feedback in amplifiers by H. S. Black removed the difficulty to a large extent, but attention had been drawn to time-division multiplex and it was to be maintained as the possibilities started to unfold.

It is not surprising to find that the first studies and trials of time multiplexing of speech started about 1930, using pulses modulated in amplitude, each pulse corresponding to the speech amplitude of the corresponding channel at the time of the pulse. However, here accurately shaped pulses had to be used to avoid crosstalk between channels, and the shape of the

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* Reprinted from *IEEE Spectrum,* volume 2, number 5, pages 56–63; May 1965.

pulses was affected by noise or distortion, with a corresponding loss of quality [1]. In 1937 Alec H. Reeves, then a member of the International Telephone and Telegraph Corporation laboratory in Paris, perceived that the handling of pulses of varying amplitude was not a long-range satisfactory solution. He came back to the early idea of telegraphing speech with pulses of constant amplitude.

A first solution [2] proposed by Reeves was to vary the width of the pulses in accordance with the speech amplitude at the corresponding time. However, soon appreciating that the information was in the start and end of the pulses, Reeves transmitted groups of two pulses separated by the same time interval as the width of each pulse. Finally, considering that the two pulses thereby produced moved symmetrically with respect to a center reference, Reeves proposed to send only one of these two pulses. The result was his invention [3] of pulse-time modulation, which has since had numerous applications.

However, Reeves and his associates realized that they had not really solved the problem they had in mind at the start. The effect of noise and distortion on the quality of transmission was still great, since such disturbances could displace the pulses in time. Furthermore, it was understood that, as in all previous systems, the deterioration of the signals was cumulative over a long link with many repeaters. To have a real parallel to telegraph transmission, the pulses must remain in fixed positions and only the presence or absence of pulses should be the criterion.

Reeves understood and clearly expressed in his pulse-code-modulation patent [4] that three steps in succession were necessary. The first, not new, was to scan speech at a suitable rate and measure the amplitude of the speech wave at each time interval. The second was to quantize the amplitudes thus measured to a nearest integer. The third was to code such integers in ordinary telegraph code.

This pulse-time and pulse-code series of concepts of Reeves occurred in a period of only two years. It was understood at once that pulse-code modulation was an important invention, and the International Telephone and Telegraph Corporation filed the patent widely. It represented the solution for multiplex systems with signals of such type that pure regenerative repeaters could receive and retransmit pulses in their original form, as long as some minimum requirements were met. Links could be established in which the quality was not directly dependent on the length of the circuit.

The invention of pulse-code modulation in 1937 was so basically different from then-current concepts in telecommunication circles that its importance was not widely understood or appreciated. Furthermore, the provision of the rather-complex triple process described called for components that at the time were not well adapted. In consequence, although during and immediately after World War 2 pulse-time modulation was used to a fairly large extent, the use of pulse-code modulation had hardly begun.

Interest grew after the war, and several basic studies of pulse-code modulation were made and published, particularly by the Bell Telephone Laboratories. Applications to multichannel transmission have taken place over the Bell System network, in England, and elsewhere. Various branches of the military also have shown a keen interest in pulse-code-modulation systems, and development of such integrated networks or transmission systems are in process in several countries.

Today, the advantages of information in digital form are increasingly apparent and we are becoming more and more expert in handling pulses. As more-appropriate devices are constantly becoming available, one can appreciate fully that the return from analog telephony to digital telephony is a technological trend that is likely to produce significant modifications in the field of telephony, data, and television, not only in systems of multichannel transmission, but also in methods of switching channels and indeed on the basic design of communication networks.

2. Past, Present, and Future of Pulse-Code Modulation

A. H. Reeves

Twenty-five years after its invention, it can be said that pulse-code modulation has little past as yet; the real interest is in its future. This future depends a great deal on how well or how badly its main planning problems are tackled during the next decade or so. There is little or no agreed view on the technical and more-general points involved in this planning. It is therefore vital that such points should be freely discussed now, to try to avoid irreversible wrong decisions.

I am hoping that my own views given in this article will do something to stimulate such discussion—and the fiercer the criticism, the better!

2.1 Early Progress

Pulse-code modulation, or coded-step modulation (which I think would have been an apter name), is a good example of an invention that

Alec H. Reeves, inventor of pulse-code modulation, examines a circuit board for the British Post Office trial inter-exchange telephone system between Guildford and Haslemere, near London, England. The system was designed and built by Standard Telephones and Cables. Sampling rate is 8000 per second, and the system transmits 23 channels per cable pair.

came too early. I conceived the idea in 1937 while working at the Paris laboratories of the International Telephone and Telegraph Corporation. When pulse-code modulation was patented in 1938 [4] and in 1942 [5], I knew that no tools then existed that could make it economic for general civilian use. Only in the past few years, in this semiconductor age, has its commercial value been felt.

In 1937 I realized, though, that it could be the most-powerful tool so far against the effects of interference on speech—especially on long routes with many regenerative repeaters, since these devices could easily be designed and spaced so as to make the noise nearly noncumulative.

The quantizing noise was foreseen, as was the fact that its effects on the listener could not a priori be calculated, since it would be neither constant and additive nor of a nature to produce simple, fixed harmonic content for a given waveform and volume as with simple nonlinear distortion. It was clear that nothing but subjective tests could provide the information needed for design; and it is strange that even now some pulse-code-modulation planners and committees seem to place a magical reliance on calculated quantizing-noise power, before those few subjective tests now in progress have even been completed, let alone interpreted for the designer. It is strange too that these very-necessary, systematic, subjective tests were not started by someone much sooner; it was probably the doubt about the need for pulse-code modulation itself that delayed them.

My guess of 32 levels for constant speech volume was not far out, although I made a bad, avoidable mistake in not realizing that these levels should be logarithmically companded.

Pulse-code modulation was invented mainly for line-of-sight microwave links or link sections, where in 1938 the needed extra bandwidth would have been cheap and easily obtainable, rather than for more-limited frequency bands, as in cables, which are now in fact the main fields of application. It is this change of aim for pulse-code modulation, for quite-sound reasons, that has caused most of the technological difficulties so far in its application.

Having had it patented, for understandable reasons I then let the invention slip from my mind until the end of the war. It was in the United States during World War 2 that the next step in progress was made, by Bell Telephone Laboratories. In this important stage, a team under Harold S. Black designed a practical pulse-code-modulation system later produced in quantity for the United States Army Signal Corps. Research was also done under Ralph Bown. It is appropriate that this early Bell System work should be stressed, for it was the first time that the principles underlying the new system were translated into hardware.

No doubt as the result of their wartime work, Bell Telephone Laboratories took the next steps forward. Although suitable cheap long-life components were still not available, they took a long shot, eventually proved correct, in deciding that efforts steered toward pulse-code modulation would be justified at that date as a reasonable bet for future civilian networks.

Apart from patents, the first public disclosures concerning pulse-code modulation came from Bell Telephone Laboratories in 1947 [6, 7]. In these articles Goodall and Black described many of the basic principles, and some coder and decoder circuits are given. During the same year, International Telephone and Telegraph Corporation engineers published three papers relating to noise and distortion in pulse-count and pulse-code systems [8–10]. The next publication [11] is a landmark; it is the first account, by Bell Telephone Laboratories, of an experimental multichannel link meeting toll quality. The stress was on technical feasibility: in 1948 the economics of the method could be left to the future. In the same issue of the *Bell System Technical Journal* is the first description [12] of the Bell Telephone Laboratories' electron-beam coder tube, which in a more-sophisticated form is proving useful to this day. In principle it is elegant and simple; but it suffers from the disadvantage of a fairly short life, and needs a feedback loop for sufficiently accurate beam alignment—which problem has been solved, up to a point, quite neatly.

The next article [13] is also a landmark. In it Shannon, with Oliver and Pierce, explained the philosophy of pulse-code modulation in terms of previous theoretical work by Nyquist and Hartley but in more-usable form, thus making possible a little later his important contributions to information theory, a branch of science vital to telecommunication and computer engineers alike. At the end of that same year, too, Reiling [14] discussed the use of companding in pulse-code modulation—a point, as I have already said, that might well have been foreseen in 1937.

By December 1948, then, most of the main factors required for efficient long-distance pulse-code modulation were well realized, together with its advantages and basic theory. The date marks the end of an important phase.

After 1948 there was a growing emphasis on pulse-code-modulation studies in a number of other countries—for example, Great Britain, France, Japan, and Germany—as well as in the United States. Anything approaching a complete review of it is impossible in this brief article; the examples that follow, chosen partly at random, are intended merely as typical of this worldwide effort.

Though invented by E. M. Deloraine in 1945 [15], a different digital method for speech, now called delta modulation, did not claim serious attention until 5 or 6 years later [16, 17]. As is now well known, the delta method has a basic advantage for the particular nature of speech waveforms in that it has less redundancy than pulse-code modulation in the effective number of levels per signal-frequency period. On the debit side, however, the coding means is inefficient, because there are only two possible output levels per sample. As will be explained later, there are good grounds for thinking that speech networks of the future may use a combination of pulse-code and delta modulations. That is why this non-pulse-code-modulation method is included here.

Japan, now one of the most-active countries in the pulse-code-modulation field, also started serious studies on the subject during this period, in 1951, at the Electrical Communication Laboratories of the Nippon Telegraph and Telephone Public Corporation. In the first few years the work here and elsewhere in that area included 24-channel systems using coding tubes, together with improved quantized feedback methods to stabilize their beam alignments. The reflected-binary-pattern technique for coding was invented by Dr. Kiyasu during this phase.

After the start of the practical semiconductor era, about 1954, pulse-code-modulation planners and circuit designers began to re-evaluate their projects, for at last suitable tools to justify the relative complexity of the terminal equipment were not only on the horizon but practically within their grasp. Although pulse-code modulation for civilian uses got off to a good start, progress was nevertheless slow. I think there were two main reasons. First of all, a vast amount of capital was already tied up in the world's existing telephone plant, which at first sight is not readily compatible with pulse-code modulation. This type of consideration on a number of other occasions has been decisive in delaying improvements, as Deloraine pointed out in 1956 [18]. The second reason is that at the time pulse-code modulation was being developed the older analog methods were themselves being improved. It is always a healthy cold shower, and a challenge, for a pioneer to have to remember that his "wonderful new system" must compete not just with current equipment but with improved versions of the older art at the time his invention is in production—and that if he is too slow he may never catch up at all!

Feedback coding, an older idea, was explored more fully by B. D. Smith in 1953 [19]; and additionally a digitally companding type was discussed by J. C. H. Davis in 1962 [20]. The possible advantages, especially in accuracy, of companding digitally within the coder itself rather than externally by a separate device were by then beginning to be realized.

In 1956 an interesting new type of parallel coder, elegant and simple in conception, was invented by A. T. Starr [21]. It used a square-loop ferrite core, a reliable passive element, as a near approach to a true level-decision device. Experiments showed, however, that because of magnetic breakthrough it would be difficult to get beyond about 32 levels usefully, at present an insufficient number for straight pulse-code modulation with a practical range of input volume.

Soon after about 1950 it was beginning to be realized that if in electronic exchanges the speech information were in digital form, a number of switching problems could be simplified. A little later it was also realized by planners that pulse-code modulation would initially fit much more easily into the local areas, where the parts had to be compatible only internally, than into the toll routes, where it must interconnect with conventional systems.

Considerations of this kind led Laboratoire Central de Télécommunications, our Paris laboratories, in 1958 to introduce pulse-code modulation as a basic feature of their studies into electronic switching methods [22], and led the International Telephone and Telegraph System (in our London Standard Telecommunication Laboratories) and the American Telephone and Telegraph Company (in their *T1* system) to begin to develop and introduce a self-contained 24-channel method on individual junction-cable pairs into such local areas [23, 24]. Actual and experimental operational results have been most promising and, at least for this application, pulse-code modulation is proving economical already, even without integrated circuits, which should provide even-greater savings.

Since 1961 Japan also has been very active in this short-haul field, mainly on a 24-channel-per-group basis. The rapidity of growth of its industry and the consequent fast increase in telephone demands have made Japan one of the most-promising areas for early application and further development of pulse-code modulation. The first field trials of such a 24-channel system were satisfactorily completed in 1964.

Japan's work during this period also included a method, attributable to Professor Osatake, for transmitting the code digits on a parallel basis within exchanges, rather than by the serial means more-usually employed. It is now being applied to the switching system. Considerable economies are claimed in high-capacity exchanges. In my opinion this version, though specifically foreseen in the first pulse-code-modulation patent [4], has been neglected.

In 1963 a new type of digitally companding system was disclosed [25], based on sending the information in two parts, as is done when expressing the characteristic and mantissa of a logarithm. Also in 1963, what seems to be a new circuit principle was invented, applicable basically to other problems as well as to pulse-code-modulation coding. Called the equilibrium method [26], it has potentially for pulse-code modulation nearly the speed capabilities of a parallel coder and, in addition, it is believed that the circuits can be still simpler and cheaper than in the serial variety. Improved methods for digital companding by the equilibrium process have also been studied [27].

One further coder idea should be mentioned here: It is a many-level time-counting version, believed operable at high bit rates, that does not suffer from the disadvantage of needing a very-high speed at the input stage of a binary counter [28]. Because time is the coded parameter as in the first coder designed [4] it is believed that a high degree of linearity can be obtained cheaply in a coder-decoder combination. Such linearity would of course be essential in any pulse-code-modulation equipment that was used for coding a frequency-division-multiplex group or supergroup directly, without prior separation and demodulation.

Much work has also been done in the past 16 years on codes other than simple binary, for two main purposes: (*A*) to reduce the effects of single-digit errors from any cause, and (*B*) to reduce repeatering errors caused by occasional code groups heavily loaded with low-frequency components, in combination with cables or cable pairs in which attenuation falls steeply as the frequency falls. The second of these efforts has led to a number of special codes and coders, examples of which are the alternate-mark-inversion ternary type used in the *T1* equipment of the American Telephone and Telegraph Company, and our own low-disparity code for the same purpose [23, 24].

We now come to the progress toward a solution that may prove to be a better answer than any other for transmission of speech, whether single-channel or time-shared. This log-differential method, which is a coded form of delta, was studied first in the United States. Although in principle it is not a new idea, it did not arouse much interest until recently [29, 30]. Like delta it can avoid for speech an unnecessary number of transmitted levels; but unlike delta the level number that is still needed—for example, about 32 to 128—is sent in efficient binary-coded form. Further statistical tests on articulation, naturalness, et cetera, are essential before we can truly assess the new method, but so far results seem to show that 16 suitably spaced levels on log-differential pulse-code modulation are about equivalent to direct pulse-code modulation using 32 levels at optimum speech volume, and of perhaps a few more if the range of volume is the limiting factor. The resultant saving of at least 1 transmitted digit is quite important for reducing the transmission bandwidth in most applications. Moreover, the coder is simplified, but not, as first expected, at the expense of the channel equipment.

In theory, the log-differential method in its simplest form is equivalent to a network suitably emphasizing the high-frequency speech components, followed by a normal log-law compandor and coder. The log-differential method has one drawback: it is not suitable for every waveform, but only for those of the nature of ordinary speech. If multitone signaling were used on it, for example, we do not yet know whether the resulting intermodulation terms would be acceptable, although some early tests have shown that they may be acceptable in normal cases. The digital speech systems of the longer-term future, however, will undoubtedly be efficient in both the signaling and speech paths, and will therefore use digital methods for signaling as well.

Progress also has been made on pulse-code modulation for television applications. In one case in point [31] the object was to make television transmission possible on a long-haul waveguide, which almost unavoidably has phase-distortion characteristics, due to many slight discontinuities, that make it unsuitable for nearly every other method. In Japan too a pulse-code-modulation coder for television has been developed. It employs Esaki diodes, with 10-megahertz sampling and 6-bit coding. In addition, the Bell Telephone Laboratories now have a pulse-code-modulation television system in an advanced state of development.

No mention has been made so far of decoders. The reason for their scanty coverage in this article is that they do not have to be decision devices, and therefore their design is basically easy. However, particularly in conjunction with special coding methods—for example, those of digitally companding types—the circuit research worker can still find many interesting problems. To reduce costs, unconventional circuit methods can sometimes be justified. One such unusual design, a revival in new form of an older idea, has been studied by Standard Telecommunication Laboratories [32].

2.2 PRESENT POSITION

Pulse-code modulation has been a child with a long infancy; except for certain military uses not described here, in application it is still only in the adolescent stage. As of early 1965 the only pulse-code-modulation systems definitely known to be in regular commercial operation comprise 3000 or so 24-channel groups of the *T1* type, all in the United States, and about 12 similar groups designed and used in Italy. Quite a few more *T1* trunks, though, are expected to be operating in the United States in the immediate or near future, nearly all of which use pairs in existing cables. Inasmuch as a fair number of such circuits had become full when employed in the usual way and would have been expensive to duplicate, especially in city areas, there was an immediate demand here for a cheaper way of extending the interoffice service. It is most likely that the first sales of commercial-type pulse-code modulation both in Europe and Japan will also be to meet this kind of demand, probably within the next year or two.

In the immediate future it is probable that the civilian market for pulse-code modulation will be confined to local-area applications, mainly because the longer routes are in any case becoming cheaper to service by conventional methods, and comprise only 15 percent of the total global investment in telephone plant. This immediate need for only self-contained types of pulse-code modulation will perhaps prove beneficial in the long run for the future of the new art, because by these first steps any "teething" troubles can easily be cured without causing widespread inconvenience.

In pulse-code-modulation techniques we have now almost a multitude of coder and decoder ideas to choose from. Much work has been done on repeater design as well, including the problem of timing the regenerative variety. But interterminal synchronizing plans, though now being discussed, are by no means completed.

Many national telephone administrations or public utility corporations are showing increasing interest in pulse-code modulation, and international bodies such as the Comité Consultatif International Télégraphique et Téléphonique are studying it closely; but it will be approximately another 5 years until the real, relatively wide exploitation of the method will begin.

It is the purpose of the present article to describe the civilian, rather than the military, aspects of pulse-code modulation. In several countries, however—for example, the United States—defense departments have studied the subject closely for some years and have now decided that it will be a major factor in their communication networks [33].

2.3 THE FUTURE

Pulse-code modulation is known to work. It is known that its principles are sound. It is known that it has many basic advantages, coupled with some limitations. In the world's networks, will it ever be used on a really large scale? Or will it, except for military and other special applications, remain a mere scientific curiosity? In making informed guesses on these questions let us start by seeing the forest rather than the trees—by analyzing the ways, if any, in which pulse-code-modulation principles are likely to be needed to meet the probable general trends in the world's telecommunication expansion, rather than concentrating on its ability to solve specific, detailed problems. And let us take the unusual course of dealing first with the most-distant future date that, except in science fiction, it is sensible to think of, and then the near future, and ending with the middle distance. In that way we can see immediate practical difficulties in better perspective and yet keep our feet sufficiently on the ground. To me the problem is one of boring a tunnel through the next 36-year time span—for I can see the two ends more clearly than I see the middle. In tunneling, it is usual to complete the middle section last.

2.3.1 *The Long-Term View*

Let us take the year 2000. Consider first what new factors could then make more-efficient methods really necessary in a communication network, not just marginally or even economic to install widely. In a newly developing area, such as many in Africa or Asia, various new systems will have little or no backlog of older methods to link up with or to replace, and for that reason may well come earlier than in the more-established areas. Thus, there is a greater freedom of choice in these regions. In already highly industrialized parts of the world, especially where the average man and woman are very telephone-minded both for social and business purposes, basically new methods may become almost mandatory if the daily demand for interconnections should exceed a certain figure.

The obvious example to take, then, is the United States. If we extrapolate from the present growth rate and include saturation effects, there should be about 220 million telephone subscribers in the year 2000, compared with the figure of 87.3 million for July 1964 [34, 35]. This is not a startling increase. An unforeseen chain reaction between reduced costs and demand would no doubt steepen the curve; so would a still-further rise in telephone consciousness than we now expect. But it would be unwise, I think, to assume an extra factor of more than about 50 percent on these two counts combined. There will no doubt be a great increase in data traffic that could react on the telephone networks; but because some data transmission will use relatively small bandwidths, the total required information capacity will probably not be affected greatly.

By the year 2000 new telephone methods, of which pulse-code modulation is an example, will by no means be a "must" on a truly wide scale anywhere in the world, although economics may well justify a fairly large mileage by such new and improved means. We shall have to seek another reason, if it exists, for the really large-scale introduction of pulse-code modulation into the world's civilian networks.

In my view, this "other reason" by that date will be the necessity for widespread closed-loop television—a necessity, I repeat, not just the urge for a status symbol that is likely to start this kind of demand in the nearer future. The first need will arise in the field of information retrieval. Consider my own case as an example. It would take me even now about 30 hours in each day of a 7-day week to keep thoroughly up to date in all the scientific and technological subjects that I really need to know in my own sphere of circuit research alone, if I were to digest and consider properly all that I read. By the year 2000 it would be even-more impossible.

Although increased specialization and teamwork will help, there are limits to the usefulness of "knowing more and more about less and less." The only possible answer will be a very greatly streamlined means for getting information, in the form needed and at the exact moments that the needs arise. Every professional man, industrialist, and administrator will require this service.

The only adequate answer will be for a few information-processing centers to be set up in each large industrialized area, staffed by top-grade people, with the information being made available to the public immediately and automatically when a dialed request is made. An ordinary high-speed data link may be adequate for the next 20 years, but by the year 2000 the only way to pass the information fast enough to the caller's brain will be to use moving pictures. By then a service of this general kind must come, for without it no nation will by modern standards be able even to survive, as the very lifeblood of that survival will be the most-effective use of knowledge.

It is my opinion that a second vital need will arise from the almost-impossible transportation problem in the year 2000. Commuters will refuse to accept the delays and inconveniences that even a moderate journey to and from their place of work would entail. Decentralized town planning will alleviate this nuisance, but it is only in light industries that plants and offices can, without undue loss, be sufficiently divided. We shall have to transport the brains, the skills of the staff—not their bodies—to their daily jobs, again involving not merely ordinary data links but a great-many private television channels as well. This new service will raise the communication demand in the area, measured in megahertz-miles, by several orders of magnitude—which would soon justify complete modernization of the network to suit it.

But will such a large increase in network bandwidth be technically possible? Yes, but—to make economic sense at all—only by transmitting on optical beams. Some of the needed techniques are not yet with us but, helped by the laser, a fair start has been made [36, 37], and what we lack now can be available well before the end of the century if the conditions that we must all meet at that date are realized by enough skilled people, and in time. It will happen; only short-term economics make optical methods look relatively unpromising for public use.

What effect will this revolution have on improved digital methods, such as pulse-code modulation? We have here the reason for including optics in this article, since from basic physics we know that because of the high energy per photon at optical and infrared frequencies the efficiency of optical methods, for a given signal-to-noise ratio, is many times greater if digital rather than analog methods are employed. Pulse-code modulation, with between 16 and about 80 levels, would meet many of television's requirements very well; and of course on wavelengths from the visual to the near-infrared, the basic bandwidth available is many times the bandwidth that will be required for a long time to come.

In my view, therefore, by the year 2000, pulse-code modulation in some form will be the very backbone of the world's communication systems that are internal to national or still-larger units. But except for satellite routes, the widespread transoceanic use of pulse-code modulation may have to wait until later, because the severe technological problems inherent in an optical submarine cable may not be solved until some years further ahead.

It is premature to make any predictions as to the pulse-code-modulation equipment that will probably be used at that time; even now there are many designs, and principles, to choose from. A vital point, though, is the means used to line up the gate-opening timings at the many regenerative repeaters, terminals, and drop-off equipments, a matter that is presently being debated. One school of thought favors a start-stop method at the distribution points, with storage and retiming where necessary; another sees this answer as one that could mortgage future good planning for the convenience of only short-term goals. Although the arguments are fairly well balanced, I share the second view. I believe that with the right principles and devices a network truly synchronous in average frequency, which can also operate as independent local units in emergencies, is not only feasible technically but is economically justifiable at a fairly early stage [38].

2.3.2 *The Next 12 Years*

In the period immediately ahead pulse-code modulation is likely to continue at first from a relatively small number of nucleation centers, and then to show accelerating growth. In the United States the Bell *T1* system and its successors have a promising early future, especially for the extended-area type of application, with two separate charging rates, that has been so far one of the main factors in the early success of *T1*. It can be expected that similar systems, for example the International Telephone and Telegraph System version [23], will be installed within the next two years in Europe, and in Japan there will be a short-haul system operating by the end of 1965. In France we can foresee in 1966 a trial switching system for local areas, probably decentralized to concentrators and using pulse-code modulation throughout. If these systems are successful, other countries will no doubt follow suit.

It is likely that by 1968 Europe and the United States will start to use pulse-code modulation for tandem-exchange working, with integrated switching and transmission by pulse-code modulation being fully operational on an experimental basis in some urban and suburban areas by 1969.

As to long-haul pulse-code-modulation systems, true operational trials will probably be delayed until a little after this 12-year period, the work in this time span being confined to extended planning and apparatus development. On the longer routes the relative economics for the next 12 years or so of frequency-division multiplex versus digital schemes such as pulse-code modulation is at present a very-controversial issue. One authoritative view from Bell Telephone Laboratories is that digital methods will be cheaper if a facility is provided for carrying mixed traffic. A 2000-channel digital pipe, using from 200 to 300 megahertz per second, is foreseen in these quarters.

For the very-heavy real-time traffic in terms of bits per second per mile that I have predicted for the year 2000 there is no doubt that optical pulse-code-modulation methods will have to be used; but for shorter-term comparisons many opposing factors must be considered.

The need to provide for mixed traffic on some toll routes for perhaps a fairly long time raises a rather-severe technical problem that is both interesting and challenging. For efficiency and economy, demodulation into separate channels followed by time-shared pulse-code modulation must be avoided; but to code the whole frequency-division-multiplex group into pulse-code modulation directly requires a degree of linearity in the coder of a much-higher order than in anything so far needed in practice. I think it unlikely that the "tour de force" method, by extending present coder designs to their very limits by good engineering, can give the cheapest long-term answer; history is against this kind of approach. The Karbowiak-Craven variety of time-counting coder [28] is probably sounder. We can keep in reserve an additional principle, stored negative feedback [39], for the most-difficult cases.

In at least the next 12-year period priority needs for widespread, efficient, secure defense networks will give a large extra stimulus to digital systems, which will undoubtedly help to speed up the more-general applications of pulse-code modulation. Despite some obvious arguments to the contrary, satellite planners too are beginning to press for digital speech, since such methods may prove more suitable than analog for satellite sharing by more than one pair of countries.

In Japan it is planned to connect the industrial centers by toll paths using pulse-code modulation on free-space microwave links, each equipped with 120 channels. The target date is well-before 1976.

2.3.3 *The Middle Period (1976 to 1988)*

By 1976 or so, many pulse-code-modulation-type interexchange trunks will be operating, both in the United States and elsewhere. In all major countries we can expect to see in operation at least a few complete pulse-code-modulation local-area networks, as well as a few toll routes by new, digital cables. A civilian pulse-code-modulation international network, however, is unlikely until the end of this period, largely because of delays in reaching the necessary political and technical agreements.

Toward the end of the phase the United States will probably have installed a fairly long experimental section of optical pipe. There may be some rather-short free-space laser-beam trunks operating between the tops of city buildings, with or without added towers. The economics of pulse-code modulation for combined transmission and switching will have been proved.

Telephone signaling, now still lagging behind current progress on the speech paths, will probably have nearly made up the lost ground by the end of this period. The technical advantage of digital signaling will be clear to all long before 1988; it is the present investment in the older plant and ideas that will set the changeover dates.

2.4 CONCLUSION

We have seen that pulse-code modulation has had a slow growth. We have examined some of the salient points in its early stages and in present-day thinking and trends.

Crystal balls do not usefully mix, so I have looked through just one of them, my own, to describe what I see of the general communication landscape in the year 2000 and, in particular, of the place of pulse-code modulation in it—to my eye a major place in a wider digital background. The scenery as a whole can be ignored only at the peril of any nation that at that date wishes to survive even by today's standards. If this picture is deemed wrong, so be it; but if it is thought right in its essentials, let us do our utmost to avoid at least the major kind of mistake that has so often been made in the past, the lack of adequate foresight in planning, national and international, that can hang a millstone around our necks that may take decades to remove.

3. Acknowledgments

Mr. Reeves is indebted to many of his colleagues in the International Telephone and Telegraph System for their advice and assistance in the preparation of this article, particularly David Thomas (London), J. W. Halina (Brussels), E. M. Deloraine (Paris), and Henri Busignies (New York) and his staff. He also gratefully acknowledges the help of Dr. Harashima and Dr. Susuki of the Nippon Electric Company (Tokyo) on Japanese activities in pulse-code modulation.

4. References

1. A. H. Reeves, French patent 837 921; 30 October 1937.

2. A. H. Reeves, French patent 833 929; 18 June 1937.

3. A. H. Reeves, French patent 49 159/833 929; 5 July 1937.

4. A. H. Reeves, French patent 852 183; 3 October 1938.

5. A. H. Reeves, United States patent 2 272 070; 3 February 1942.

6. W. M. Goodall, "Telephony By Pulse Code Modulation," *Bell System Technical Journal,* volume 26, number 3, pages 395–409; July 1947.

7. H. S. Black, "Pulse Code Modulation," *Bell Laboratories Record,* volume 25, number 7, pages 265–269; July 1947.

8. A. G. Clavier, P. F. Panter, and D. D. Grieg, "Distortion in a Pulse Count Modulation System," *Transactions of the American Institute of Electrical Engineers,* volume 66, number 11, pages 989–1005; November 1947.

9. P. F. Panter and W. Dite, "Quantization Distortion in Pulse-Count Modulation with Nonuniform Spacing of Levels," *Proceedings of the IRE,* volume 39, number 1, pages 44–48; January 1951; *Electrical Communication,* volume 28, number 2, pages 121–126; June 1951.

10. A. G. Clavier, P. F. Panter, and W. Dite, "Signal-to-Noise-Ratio Improvement in a PCM System," *Proceedings of the IRE,* volume 37, number 4, pages 355–359; April 1949; *Electrical Communication,* volume 26, number 3, pages 257–262; September 1949.

11. L. A. Meacham and E. Peterson, "An Experimental Multichannel Pulse Code Modulation System of Toll Quality," *Bell System Technical Journal,* volume 27, number 1, pages 1–43; January 1948.

12. R. W. Sears, "Electron Beam Deflection Tube for Pulse Code Modulation," *Bell System Technical Journal,* volume 27, number 1, pages 44–57; January 1948.

13. B. M. Oliver, J. R. Pierce, and C. E. Shannon, "The Philosophy of PCM," *Proceedings of the IRE,* volume 36, number 11, pages 1324–1331; November 1948.

14. P. A. Reiling, "Companding in PCM," *Bell Laboratories Record,* volume 26, number 12, pages 487–490; December 1948.

15. B. Derjavitch, E. M. Deloraine, and S. Van Mierlo, French patent 932 140; August 1946. Also filed as United States patent 2 629 859; October 1947.

16. J. F. Schouten, F. de Jager, and J. A. Greefkes, "Delta Modulation, New Modulation

System for Telecommunication," *Philips Technical Review,* volume 13, number 9, pages 237–245; March 1952.

17. F. de Jager, "Delta Modulation, Method of P.C.M. Transmission Using I-Unit Code," *Philips Research Report,* volume 7, number 6, pages 442–466; December 1952.

18. E. M. Deloraine, "Pulse Techniques with Particular Reference to Line and Radio Communication," *Electrical Communication,* volume 33, number 3, pages 183–194; September 1956.

19. B. D. Smith, "Coding by Feedback Methods," *Proceedings of the I.R.E.,* volume 41, number 8, pages 1053–1058; August 1953.

20. J. C. H. Davis, "A P.C.M. Logarithmic Encoder For A Multichannel T.D.M. System," *Proceedings of the Institution of Electrical Engineers* (London), volume 109, part B, number 48, pages 481–483; November 1962.

21. A. T. Starr, K. W. Cattermole, and J. C. Price, British patent 806 397; November 1957.

22. E. Touraton and J. P. Le Corre, British patent 932 612; October 1958.

23. K. W. Cattermole, D. R. Barber, J. E. Price, and E. J. E. Smith, "Experimental Pulse-Code-Modulation Transmission for Local-Area Telephony," *Electrical Communication,* volume 38, number 1, pages 56–75; January 1963.

24. C. G. Davis, "An Experimental Pulse Code Modulation System for Short-Haul Trunks," *Bell System Technical Journal,* volume 41, number 1, pages 1–24; January 1962.

25. A. H. Reeves and D. R. Barber, "Digital Companding Coder," British patent 3250/63 (provisional).

26. A. H. Reeves, "Equilibrium Coder," British patent 20842/63 (provisional).

27. A. H. Reeves and R. S. Grant, British patent, applied for.

28. A. E. Karbowiak and G. Craven, "Time Quantisation, a New Approach to the Design of Ultralinear Analogue-to-Digital Conversion Equipment for Application of PCM Communication Systems," presented at the Transmission Aspects of Communications Networks Conference, Institution of Electrical Engineers, London, England; 24–28 February 1964.

29. C. C. Cutler, United States patent 2 605 361; 29 June 1950.

30. E. A. Feuell, J. M. Gardner, and B. J. Feenaghty, "Log Differential Coder," British patent 9637/64 (provisional).

31. W. Neu, "Some Techniques of Pulse Code Modulation," *Bulletin des Schweizerischen Elektrotechnischen Vereins,* volume 51, pages 978–987; 8 October 1960.

32. A. H. Reeves, K. W. Cattermole, and R. Kitajewski, "Vibrational Decoder," British patent 37714/63 (provisional).

33. *Signal,* Journal of the United States Armed Forces Communications and Electronics Association, volume 18, number 11; July 1964.

34. G. E. Hams, "Numbering for the World-Wide Automatic Telephone System." *Telecommunications Journal of Australia,* volume 13, pages 453–455; February 1963.

35. "The World's Telephones—1963," American Telephone and Telegraph Company, New York, New York. *Electrical Communication,* volume 39, number 3, pages 451–457; 1964.

36. C. C. Eaglesfield, "Optical Pipeline: A Tentative Assessment," *Proceedings of the Institution of Electrical Engineers* (London), volume 109, part B, number 43, pages 26–32; January 1962.

37. G. Goubau and J. R. Christian, "Some Aspects of Beam Waveguides for Long-Distance Transmission at Optical Frequencies," *IEEE Transactions on Microwave Theory and Techniques,* volume MTT-12, pages 212–220; March 1964.

38. A. H. Reeves, "PCM Synchronizing Methods," to be published.

39. A. H. Reeves, "Stored Negative Feedback for PCM Coders," to be published.

Alec H. Reeves was born at Redhill, Surrey, near London, in 1902. He received an Associate of the City and Guilds Institute, equivalent to a bachelor of science in engineering, in 1921 and the Diploma of the Imperial College of London University in 1923. In his postgraduate work, he invented a cathode-ray-tube radio direction finder.

In 1923 he joined the International Western Electric Company, which became part of the International Telephone and Telegraph System. In 1928 he was transferred to the newly founded Paris laboratory and in 1945 to Standard Telecommunication Laboratories in England.

Among his many developments and inventions are: a multistage aperiodic binary counter, the first single-sideband high-frequency radiotelephone system, automatic frequency control, circulating delay-line store for digital information, multiplex telephony by pulse-amplitude modulation, superheterodyne receiver for microwaves, and a multichannel carrier system for ultra-high-frequency radiotelephony. Between 1936 and 1940 he worked on pulse-time modulation, which culminated in his invention of pulse-code modulation. His latest invention is the equilibrium method of data processing that is being applied to solid-state coders for pulse-code modulation.

During the second world war he worked for the Royal Air Force with Sir Robert Watson-Watt on radar and, with F. E. Jones, invented the Oboe system for bombing through overcast.

Mr. Reeves was made an Officer of the Order of the British Empire for his wartime services. He is a Member of the Institution of Electrical Engineers.

E. M. Deloraine. Biography appears in volume 40, number 1, page 32; 1965.

Reeves Receives Ballantine Medal

The Stuart Ballantine Medal has been conferred by the Franklin Institute on Alec Harley Reeves for outstanding achievements in the fields of communication. His invention of pulse-code modulation, which was used for transmitting pictures of Mars from the Mariner satellite to earth, was specifically noted.

Mr. Reeves has been a research worker for the International Telephone and Telegraph System since graduation from college in 1923. He was at the Paris Laboratory 25 years ago when he invented pulse modulation and is now at Standard Telecommunication Laboratories in England.

Laboratoire Central de Télécommunications

H. TANTER

P. GRANDRY

Laboratoire Central de Télécommunications; Paris, France

1. History

The Laboratoire Central de Télécommunications (LCT), known to Parisian passers-by for its large white façade and wide windows evident in Figure 1, stands at the far end of a garden bordered by railings that run parallel to the fine Avenue de Breteuil. The latter stretches between two centers of attraction: to the north, the dome of the Invalides, which shelters Napoleon's tomb as well as those of other famous generals; to the south, the Place Breteuil, with its statue of the great French scientist, Pasteur.

Numerous passers-by may wonder what can occupy the attention of the people in white overalls who can be seen quite clearly from the street when the whole façade is lighted in the evening. Some of them are working on mysterious-looking equipments.

We shall therefore enter this building and open wide its doors to disclose its functions and objectives.

The older generation knows that this bright façade has not always been there. They have a recollection of having once seen these same grounds encumbered with small ill-assorted structures and a rather unattractive factory at the far end.

It was in fact before 1925 the Western Electric Company's French factory called Le Matériel Téléphonique (LMT).

Figure 1—East front of Laboratoire Central de Télécommunications.

The purchase of the Western Electric properties outside the United States by International Telephone and Telegraph (ITT) in 1925 was followed by the adoption of the rotary automatic telephone system for Paris and several large French cities. The existing factory was soon inadequate to meet the increased production requirements and in 1927 a new factory was completed near Paris at Boulogne-sur-Seine; the Avenue de Breteuil premises were placed at the disposal of a new division then called Les Laboratoires LMT. E. M. Deloraine was appointed its General Manager.

The main objective was to endow this Laboratory with sufficient resources to make it a center of research intended not only to supply associated French companies with automatic switching techniques, but also to constitute, on a broader scale, a central source of technical information in other areas of telecommunications for the ITT companies in Europe.

It is certain that this conception was very advanced for the industrial views of that time, but it proved to be entirely successful, also fitting well in the atmosphere created recently by the progress of the Common Market. To illustrate this character, the name was changed in 1945 to Laboratoire Central de Télécommunications, a company the capital of which is divided among its associated companies in France and in three other countries of the Common Market.

But let us start at the beginning and quickly trace the history of this Laboratory from 1928 to 1939. First of all, the buildings underwent important modifications to adapt them to their new roles; in particular, all the small buildings in the courtyard were removed.

The terms of the rotary contract of 1926 between the French Posts, Telegraphs, and Telephones (PTT) and Le Matériel Téléphonique foresaw the transfer to Paris of a group of experts in telephone switching. These experts were to come from the personnel of the Bell Telephone Manufacturing Company of Antwerp, since this company was the very cradle of the rotary system.

The first contributions of the Laboratory were the work of this group of switching experts from Antwerp, led by the man who was always considered to be the Father of Rotary, Gerald Deakin. His main collaborators, whose names make up a part of the history of automatic switching, were: Polinkowsky, Hatton, Schreiber, Damoiseau, and Van Mierlo. This group brought indispensable support to the study and construction of the first rotary *7A1* exchange of Paris, Carnot [1, 2], which was cut over in 1928. Moreover, during the years that followed, new versions of rotary (*7A2* and *7D*) were studied and perfected. These found their applications abroad. Later, a system based on experience with them and adapted to French requirements was developed in France by LMT.

The first *7A2* rotary exchange went into service at Bucharest in 1933. While retaining the broad outline of the *7A1,* it provided numerous improvements in technology and in operational facilities [3].

The *7D* rotary system was equally well adapted to rural areas and to large exchanges, and included most of the modern features devised for economical operation and reduced staff [4].

Therefore, from the very beginning, the Laboratory contributed importantly in the studies related to automatic telephone switching. However, another division of the Laboratory was working on advanced techniques in radio and in transmission over cables and wires.

In 1928, radio techniques seemed to be developing in two major directions: toward medium-wave high-power transmitters intended particularly for radio broadcasting and toward short-wave links for long-distance telephone or telegraph communication. Work was undertaken in these two fields. In 1931, a 120-kilowatt radio broadcast station [5] was installed in Prague, and a short-wave telephone link was put in service between Madrid and Buenos Aires over a distance of 10 300 kilometers (6400 miles) [6]. Both of these achievements represented technical records at that time.

However, the number of possible radio links on medium and short waves quickly proved insufficient to satisfy the requirements, and more-revolutionary possibilities were therefore considered. It seemed possible to find the answer in the use of higher frequencies.

Although wavelengths of the order of 1 meter (300 megahertz) were still unused, it was decided to take a long step to test the possibilities offered by much-shorter wavelengths. It was decided to make equipment for working on a wavelength of 17 centimeters (1765 megahertz), to take advantage of the directive properties obtainable with a paraboloidal reflector of acceptable dimensions that would concentrate a narrow beam onto an identical paraboloidal reflector at the other end of the link. This was the starting point for the development of microwave links. A demonstration across the English Channel in 1931 [7, 8] was followed by the cutover 1 year later of a telephone and telegraph link between a French and an English airport [9]. The aerials in Figure 2 of the St. Inglevert terminal show that the external appearance of a station of this type has not changed much in the course of the past 34 years.

It was easy even in 1931 to imagine the possibilities of long-distance communication by ultra-short waves, using a number of repeaters. Such a project connecting Paris and London by ultra-short-wave links with repeaters spaced by about 50 kilometers (31 miles) was described.

We note in passing that the chief author of this work, A. G. Clavier, described an observation, the importance of which had been missed at the time, that during the trials leading to the demonstration across the Channel in 1931, ships crossing the radio beam where it skimmed the surface of the Channel affected the propagation between the ends of the circuit; this effect also varied according to the dimensions of the ships. It was therefore possible by this means to detect the passage of ships across the beam and to judge their size.

R. L. Smith-Rose, who was then Director of the National Physical Laboratory of Great Britian, wrote later on [10] that by adding the facility of determining distances to a radio projector such as that used in this demonstration the basic principles of modern radar would have been satisfied.

A logical observation was presented after these trials that advantage should be taken of the considerable bandwidth available at these frequencies to introduce multiple-channel transmission systems.

In view of the difficulties then met in obtaining the necessary linearity in the circuit elements, attention was directed to substantially lower frequencies. This resulted in the realization, in 1932, of the first commercial 4-meter (75-megahertz) multiplex link with 9 telephone channels, which was put in service between Belfast, Northern Ireland. and Stranraer, Scotland, across the North Channel [11].

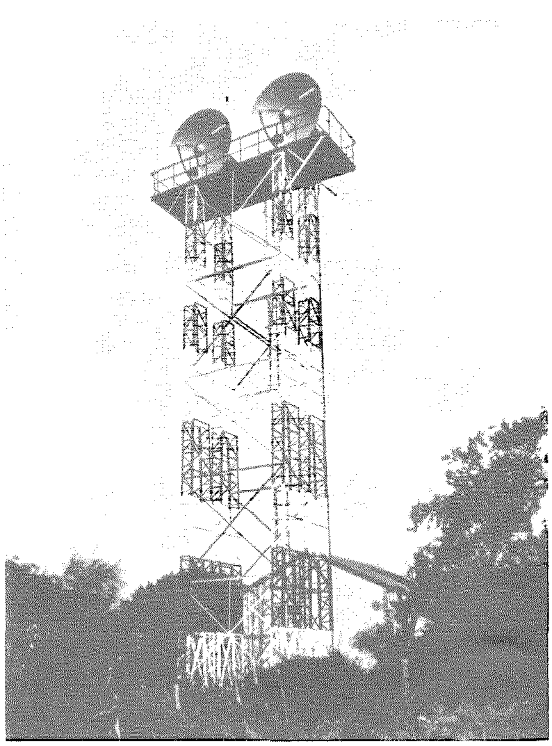

Figure 2—Antennas of the cross-channel microwave link demonstrated in 1931.

Attention continued to be concentrated on long-distance short-wave telephone links even though the transmission quality obtained over most of them left much to be desired, mainly because of radio propagation irregularities.

The basic amplitude-modulated carrier wave with its two sidebands was then exclusively used on short-wave links. A. H. Reeves improved the single-sideband method invented by J. R. Carson, in order to apply it to short-wave links. The problem was to generate a new carrier wave at the receive end, the frequency of which would stay within a few hertz of the carrier that had been suppressed at the transmit end. Mr. Reeves invented the now-classic method of quasi-synchronization [12, 13] and demonstrated it conclusively in transmissions between Paris and Madrid. Later this method was adopted for all long-distance short-wave telephone links.

Having experienced, before the invention of feedback by H. S. Black, the difficulties met in the frequency multiplexing of telephone links due to intermodulation, the engineers at the Laboratory came to think that time multiplexing might possibly have advantages over frequency multiplexing. This was an established technique in telegraphy but it had not been applied in telephony for many reasons, the principal objection being that it was thought necessary to be very economical as regards bandwidth.

Trials were made by first taking a series of samples of the amplitude of speech currents for each of several channels and then transmitting from each channel sequentially in the form of interleaved pulses. It was soon realized that this solution was not very advantageous, as most of the linearity problems remained. The first major improvement was to use pulses of constant amplitude and variable width, the latter corresponding to the amplitude of the sample. This quickly led to suppression of the body of the pulse, as the only significant parts were the beginning and the end of each pulse, and finally to retaining only the beginning of the pulse. Thus in 1938, pulse-time modulation, called both PTM and PPM, was invented [14]. Although this method was widely applied, it remained clear that the transmission quality in a PTM system was still easily influenced by many factors, such as phase distortion and noise, which could change the shape of pulses or displace them in time, producing crosstalk between telephone channels.

Mr. Reeves then introduced the method that was later to become increasingly important. He understood that one had to revert to the telegraph concept, that is, to use identical pulses of constant amplitude and equally spaced, in groups that formed a code of the telegraph type.

He then stated the three basic principles: sampling of the waveform, quantization of the measured amplitude values according to an integer scale, and coding of these numbers in binary form. The inverse operations took place at the other end of the system [15].

In this way the known advantages of telegraph codes were obtained, in particular the possibility of using pulse-regenerating repeaters, eliminating to a large extent the cumulative distortion effects in links using repeaters, which effects are inevitable in the other systems. Today this method is called pulse-code modulation (PCM) and has been widely applied in both civil and military fields.

As the general interest taken in broadcasting and transmission of television signals was of growing importance, the Laboratory made a series of demonstrations between the Avenue de Breteuil and the Champs Élysées. In 1937 after designing the necessary electron tubes, it built and installed on the Eiffel Tower a 30-kilowatt transmitter, then the most-powerful television transmitter in operation [16].

At this time, a series of studies were undertaken on the conditions to be satisfied by coaxial cables for the transmission of speech and television signals [17]. The importance of uniform cable impedance was brought to light. Equipment was built for television transmission over coaxial cables by a method employing a carrier wave and a partly suppressed (vestigial) sideband.

However, as the political horizon was then darkening, the activities of the Laboratory were oriented more and more toward military problems.

In the years preceding the war, H. G. Busignies, now Technical Director of ITT, designed several radio compasses and direction finders for sea and air navigation. One of them, the so-called instantaneous-reading radio direction finder (Figure 3), the study of which was originally requested by the French Navy, was built in the United States and used by the American Navy on a large scale. It became of exceptional importance in winning the war against submarines through the long-distance detection of their positions.

Technical knowledge acquired with the Eiffel Tower television transmitter was applied in 1939 toward the realization of a high-power radar system. This model radar operated on 6 meters (50 megahertz) and had a peak power of 400 kilowatts. Installed on the Mediterranean coast, it correctly detected enemy aircraft over Toulon in 1940.

During this research two important inventions were made, one by P. Gloess of the panoramic radar indicator, later called the plan-position indicator (PPI) [18], and the other by Mr. Busignies for the elimination of fixed-target radar echoes [19], known since then as the moving-target indicator (MTI).

After the 1940 armistice, the Laboratory staff was divided into 3 groups of engineers. One of these, comprising Messrs. Deloraine, Busignies, Chevigny, and Labin managed to reach the United States. A second large number of engineers was regrouped in Lyons in unoccupied France. The third group stayed in or came back to Paris.

The 4 engineers who reached the United States created with the sponsorship of ITT a research group in the military field that was the starting point of Federal Telecommunication Laboratories of Nutley, New Jersey.

The group in Lyons continued studies of ultra-short-wave transmission, direction finding, electromagnetic detection, and pulse systems, with

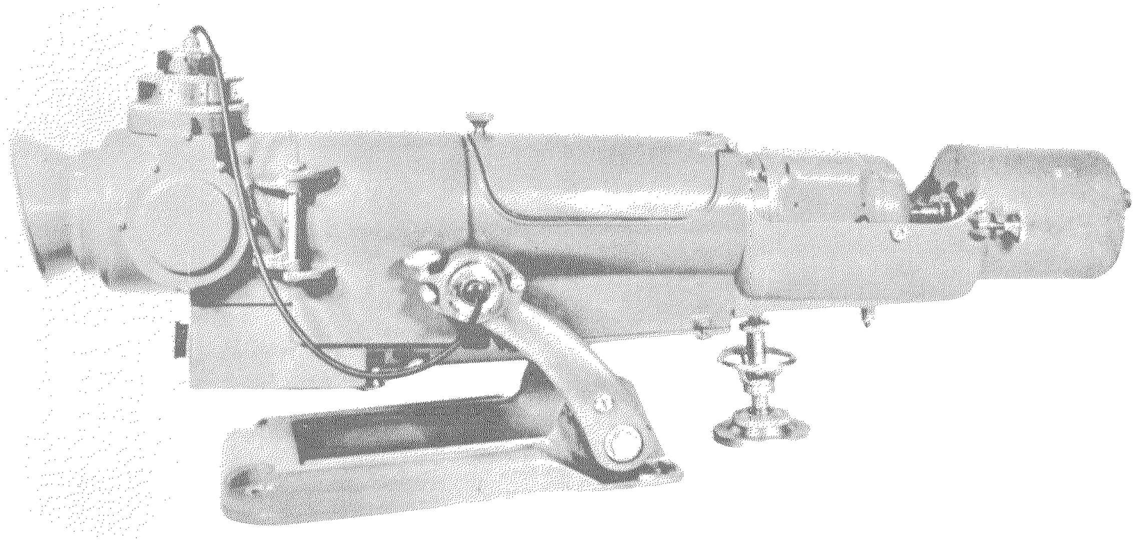

Figure 3—Instantaneous-reading high-frequency radio direction finder known as Huff-Duff during the war.

the object of being ready to resume their work immediately after the war. During this period a radar system operating on 2 meters (150 megahertz) with a peak power of 30 kilowatts was installed on the cruiser *Algérie*. All these personnel were quickly regrouped in 1944 and gave immediate assistance to the Allies, thus earning the Excellence emblem awarded by the United States.

After the war the time had come to think again about telephones, particularly since the impression was spreading in research groups that switching systems could take advantage of the newer techniques, and the term "electronic switching" was beginning to be heard more and more.

It seemed clear that electronic devices capable of switching speech would probably be very expensive compared with metal contacts. We therefore recognized from the very beginning that to justify the cost of electronic switching it would be necessary to take advantage of the high speed of the electronic elements compared with that of relays or electromechanical switches. Thus the early proposals made by Mr. Deloraine in 1945 [20] and others made later by several of his associates concerned exclusively electronic switching systems. The system described employed time-division electronic controls that acted on a speech network consisting of multiplex highways.

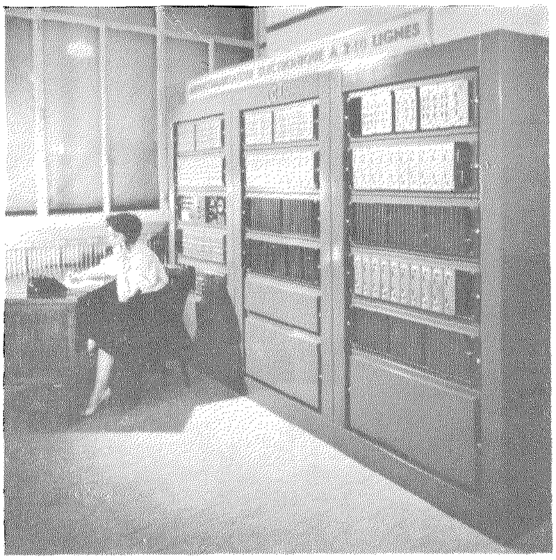

Figure 4—Electronic private automatic branch exchange of 240 lines at the Laboratoire Central de Télécommunications.

A first breadboard model was followed by a demonstration model in 1952, consisting of a 100-line exchange in which a multiplex speech network was switched by a common-control unit incorporating cyclical scanning of lines, memories, and test and control circuits.

However, the available components were still poorly adapted to the requirements, and the vacuum tubes, gas tubes, and diodes used were soon to be replaced by more-appropriate components.

These models created active competition among researchers and a great number of proposals regarding the principles themselves were presented, several of which were basic.

The work done in this field continued at a fast pace. After new system studies, attention was directed again toward "spatial" switching methods, in which the speech network uses a separate path for each communication. The French Navy became interested, and the Laboratory designed a 20-line electronic exchange to fulfill the particular specifications of the Navy. The first equipment [21], which satisfied all the conditions imposed, was soon followed by a second one. Meanwhile, an automatic exchange using the same principles was demonstrated at the Brussels World's Fair in 1959 [22]; the telephone sets used push-button selection.

The work of Bell Telephone Laboratories having drawn attention to the merits of gas tubes as electronic crosspoints in a spatial system, an automatic exchange serving 240 lines was designed, constructed, and cut over (Figure 4) in our own Laboratory in 1960 [23, 24]. This electronic automatic telephone exchange has handled the internal calls of the Laboratory since that time. It is probably the first equipment of this type in regular operation.

This automatic exchange incorporates a common-control circuit, which handles calls simultaneously by time division. For the first time, these circuits included only semiconductor elements, magnetic memories, and gas tubes in the speech circuit. An automatic fault-detecting and -locating device facilitates maintenance and makes it possible to locate with precision all the causes of difficulty or of error in its operation.

The original concept of a speech circuit with electronic crosspoints working in time multiplex was not abandoned and, by a fortunate synthesis, in 1958 the researchers proposed a new and fundamental plan in which the same time division and pulse coding could be applied both within and between switching points [25]. This type of network, in which the same techniques are applied to transmission and to switching, is now generally known under the name of integrated telephone network.

The French military services became very interested in this work and the first model of a pulse integrated network constructed in the Laboratory, with financial help from the Army, has been used for tests and demonstrations since 1962.

This model, which can handle 5000 lines, included all the essential elements for coding and decoding as well as for establishing and switching calls. For transmission it used methods that avoided the necessity of having strict time synchronization within the whole network.

After reactivating the Laboratory in Paris in 1945, the work undertaken in Lyons was continued and oriented mainly toward the problem of eliminating the radar echoes from stationary targets for which Mr. Busignies had proposed a solution in 1940. This work drew the attention of the Centre National d'Études des Télécommunications (CNET), then of the Army and the Air Force and, starting in 1945, further studies have been financed by these organizations. In 1951, LCT supplied equipment for eliminating stationary echoes that was adaptable to most existing radars. In 1953, it built the first model of a ground surveillance radar, the performance of which was considered exceptional. It was then manufactured in quantity. These ground surveillance radars [26] now equip the French Army and several equipments have been bought by the German and American armed forces. (Figure 5.)

The knowledge acquired during these studies subsequently found new applications which are now under study.

Outside these two fields, the Laboratory had also studied various applications of electronics and digital techniques. Most of these studies were carried on for the French armed forces.

2. Present Status

The problems posed as to what studies should be undertaken in the Laboratory, the proportion of advanced research to development resulting from established techniques, and the stage at which equipment under study should leave the Laboratory to be transferred to factories, have been repeatedly examined but a valid answer for all cases has never been found.

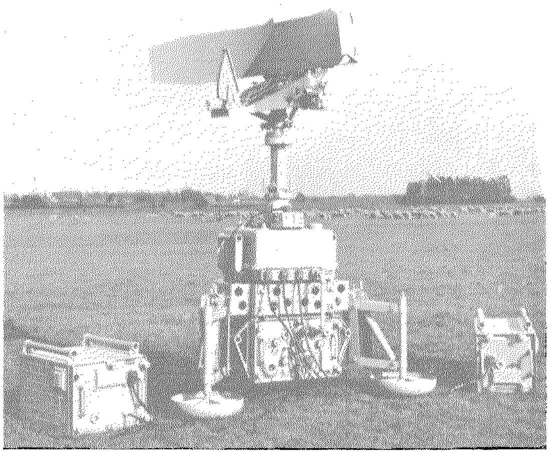

Figure 5—Ground surveillance radar.

In research, regardless of the size of the laboratory, it is sufficient to have a small number of talented inventors to guide its activity to fruitful fields. Basic inventions are few by nature and only appear when favorable conditions are combined. Some of these conditions depend on the management staff of the laboratories, which must devote its attention to making the best use of men of exceptional originality and to offer them working conditions that give them the maximum chance of success.

When these basic inventions are made and management has recognized their value, a long and tedious study is still necessary to show that they can lead to equipment suitable for commercial use and then to prototypes from which factories can undertake the necessary manufacturing development, followed by profitable production under existing economic conditions.

The complexity of modern equipment, and the severity of the conditions under which many equipments are required to work without failure, oblige laboratories to devote more and more of their budgets to programs of adaptation and redesign, which are often longer and more costly then expected.

LCT has found that equipments that have proved successful are usually those for which the basic ideas were conceived early and for which studies were carried out up to the construction of prototypes, which could be thoroughly tested under normal operating conditions and then modified as necessary.

The management of the Laboratory must find the balance between basic research requiring an inventive activity on the one hand and the application of existing knowledge on the other hand. The organization of the Laboratoire Central de Télécommunications includes these two types of activity in proportions considered to give the best results for the tasks assigned to it.

3. Research

The research department has concentrated its efforts for several years in 3 main fields.

(A) The generation of coherent light, especially ruby and gas lasers.

(B) The study of magnetic thin films with a view to the construction of large-capacity fast-access memories.

(C) The study of new electronic component applications.

The research department maintains continual contact with universities and state laboratories where certain basic work is carried out. The close contact with these establishments active in basic research is necessary to guide the first applications of new discoveries. It is profitable to both parties and gives our researchers the advantage of supplementing the information normally obtained from published documentation. An even-closer and more-constant cooperation is offered our research department by some university professors and researchers who serve as consultants to us.

Even though it is not desirable to give, at the start, a particular direction to any basic research, we have tried to direct the studies related to the generation of coherent light toward applications to telecommunications and target location. The enormous bandwidth available and the possibility of concentrating coherent light into a very-narrow beam gives rise to the possibility, on the one hand, of multiplying the number of communication channels on the same carrier and, on the other hand, of increasing the precision of electromagnetic detection systems. Work was undertaken simultaneously on the study of the laser effect in two mediums, crystals and gases.

Studies of the laser effect in crystals rapidly led to the reproduction, in March 1961, for the first time in Europe, of the ruby laser invented by Maiman, and then, in 1962, of the construction of a liquid-nitrogen-cooled ruby laser supplying pulses of coherent light having an energy of 200 joules. The latter laser was capable, after focusing, of piercing a hole 50 microns (0.002 inch) in diameter in a steel plate 3 millimeters (0.1 inch) thick. These equipments were the basis for the study and the construction, by the radar department, of an instantaneous range finder. Within the framework of these studies, research was also undertaken to find and to make new crystals that could exhibit the laser effect.

The gas laser offered the possibility of producing a continuous beam of coherent light and could therefore lead more easily to applications as a carrier in transmission systems. This research began in 1961, and by early 1962 the first helium-neon laser was in operation in the Laboratory. Others followed and, in 1963, a high-precision interferometer 8 meters (26 feet) long was built for research into new transitions in gas mixtures. Associated with this equipment, which is shown in Figure 6, are a wide-band optical spectrograph, a prism spectrograph covering the range from ultraviolet to far infrared, and a lattice spectrograph having a precision of some tenths of an angstrom unit, all for use in the measurement of wavelengths.

With this equipment new transitions were discovered, several of which were reported in the *Compte Rendus de l'Académie des Sciences.*

The coherent-light generators developed by the research department are used for work on the modulation of light, which constitutes the second stage in the use of lasers in transmission systems. For this purpose, a complete cryogenic equipment having means for repurifying helium has been put at the disposal of the researchers. Moreover high-powered ruby lasers are used for the study of nonlinear phenomena in solids. Since such phenomena can be used to good advantage for carrying out frequency conversions, this work is also applicable to transmission systems in which the carrier is a beam of coherent light.

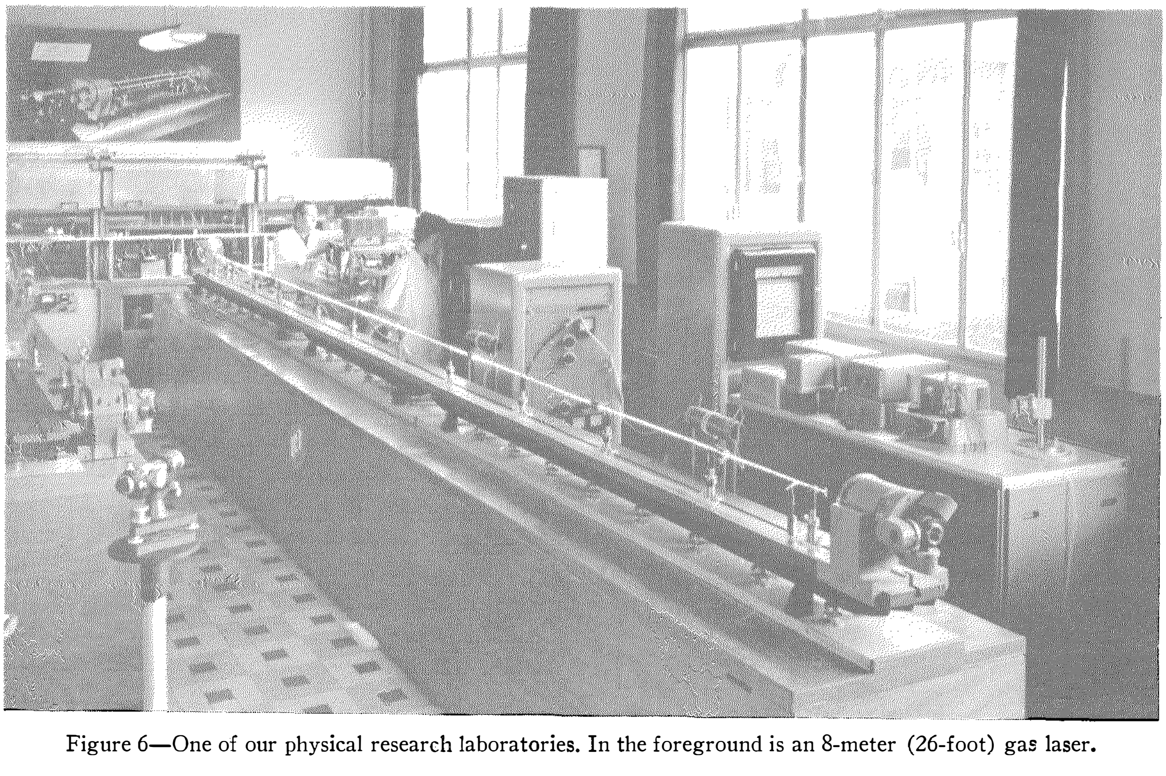

Figure 6—One of our physical research laboratories. In the foreground is an 8-meter (26-foot) gas laser.

The rapid development of information-processing systems, which are the basis not only of large electronic computers but also of modern radar and telephone systems, dictated the study of fast-access large-capacity memories–several million bits. The department of physical research undertook the study of magnetic–thin-film memories in 1961.

Equipped with modern apparatus such as the bell jars shown in Figure 7 in which a very-high vacuum is maintained, experimental basic elements of ultra-fast memories are made for examination by the department in charge of testing. Complex apparatus and special test equipment are indispensable. Two vacuum evaporation installations and one ultra-vacuum evaporation installation permit reaching a pressure as low as 10^{-10} millimeter of mercury. The researchers use a large number of associated measuring equipments, including an electron microscope, equipment for analysis by X-ray fluorescence, and a radio-crystallographic installation with a recording goniometer.

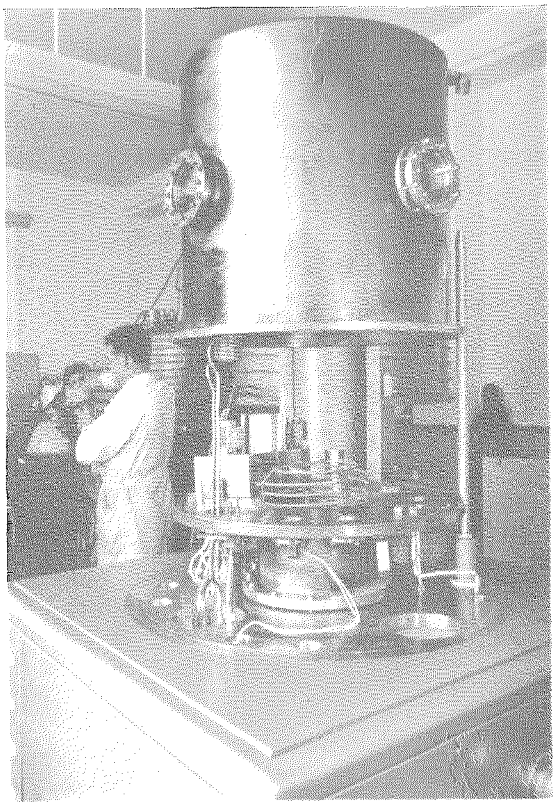

Figure 7—Ultra-high-vacuum bell jar inside which are deposited the thin magnetic films used in ultra-fast memories.

In the course of their work, the researchers designed and constructed an apparatus that we call an "astrometer," which permits instantaneous measurement of the qualities of a magnetic thin film. A curve in the shape of an astroid is shown on an oscilloscope screen and characterizes the change of state of the magnetic material with respect to the direction and the intensity of the magnetic field applied to it. This apparatus illustrates one of the aspects of basic research in which the actual difficulty of a problem is complicated by the need to invent and construct measuring apparatus.

The research department also devotes part of its activity to the study of new electronic components such as tunnel diodes, especially with a view toward using them in ultra-fast memories. The memories constructed are placed at the disposal of the department responsible for studying systems, which integrates them into equipments such as electronic telephone exchanges. Operation and test of these systems produce information that may direct later research into useful fields.

4. Telephony

The ITT companies associated with Laboratoire Central de Télécommunications, in particular Le Matériel Téléphonique and Compagnie Générale de Constructions Téléphoniques in France, devote a great part of their activity to the study, manufacture, installation, and cutover of telephone exchanges. The Laboratory therefore devotes particular effort to this field. After its first work, which culminated in 1956 in prototypes of electronic automatic exchanges, studies continued both on semi-electronic systems with centralized control and on fully electronic switching systems integrated into the transmission network.

The role of the Laboratory is to study the existing telecommunication networks and the trends for the future. It stands to reason that attention should be focused on those parts of the network that are least developed and that, for the most part, represent proportionately large investment and maintenance costs. A view of one of the electronic switching laboratories is shown in Figure 8.

Within this area, increased efficiency is sought for the connections that handle exceptionally low traffic, either between the subscribers' telephone sets and their central offices or between exchanges. These considerations have led to the study of network configurations and to the determination of the characteristics and the size of the most-economical switching exchanges. The general organization of these exchanges develops from these studies, and there is a marked tendency to centralize the control elements while dispersing the switching elements. The study of these control systems requires considerable attention because of the complexity of the problems and the multiplicity of possible solutions.

Modern concepts depend on electronics to solve these problems, yet as a first solution the switching network continues to use relays and switches with metallic contacts. These systems are generally called semi-electronic.

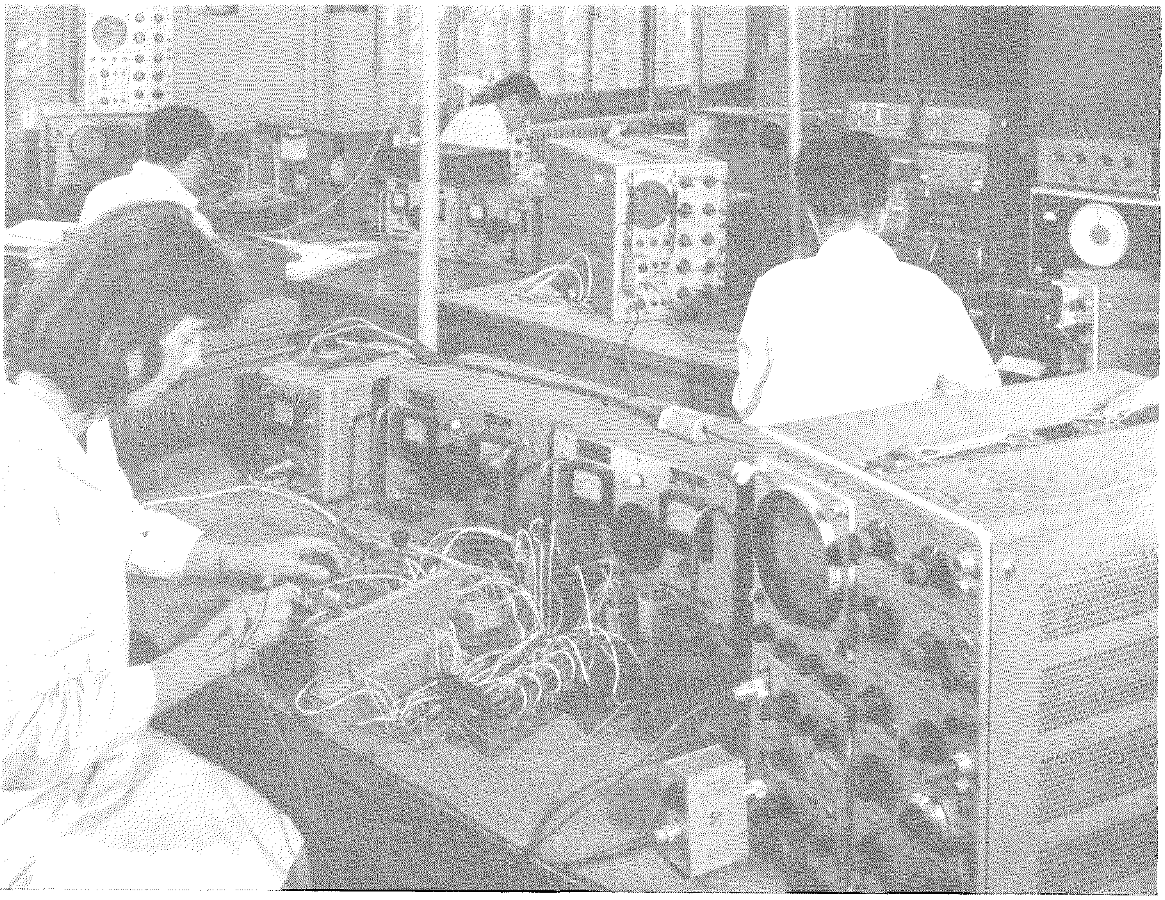

Figure 8—One of the electronic switching laboratories.

These studies can only be carried on successfully in close cooperation with engineers who have experience with existing switching systems as well as in the requirements of telephone operating. These qualifications are found in ITT associated companies and, in particular, in those close to the Laboratory, namely LMT and CGCT.

A more-advanced solution consists of visualizing a telephone network in which the transmission and switching methods are closely related, the aim being to multiplex communications on the lines and also inside the exchanges. Concentrators are used to decrease the length and cost of the lines serving a single telephone set.

In line with this plan, further study of an integrated telephone network proposed originally by E. Touraton in 1958 has been made. In such a network the speech currents are transformed into pulse-code modulation for transmission from a concentrator to the exchange, inside the exchange, and between exchanges.

The problems posed by pulse coding and decoding of speech have been studied to determine the optimum conditions between cost and faithful reproduction of speech. Following the construction in 1962 of the previously mentioned experimental automatic exchange capable of accommodating 5000 incoming lines, an integrated telephone network is under study for military applications in which the services specified by the users are more extensive and more complex than in public exchanges.

Besides these studies on the design of future telephone exchanges, theoretical studies are in progress on the basic problems of operating reliability. The necessity for equipments having hundreds of thousands of parts to operate indefinitely without failure presents a problem that is most important and most difficult to solve. General solutions are devised that guide the engineers in their choice among the various systems, this choice becoming increasingly critical as the complexity of the equipment increases.

5. Radar

The radar department at LCT has specialized in electromagnetic detection systems making use of the doppler effect. While developing ground surveillance radars, the department has also concentrated on digital processing of the radar information and on the study of applying the laser developments made by the research department to electromagnetic detection and to range finding.

Various solid-state military equipments adapted to battlefield surveillance are under study. Although radar signals are usually processed by analog methods, our studies have led to the development of digital methods of information processing. Fast coders having high precision and fast memories of large capacity have made possible the application of digital techniques to improve radar performance. Taking advantage of the experience acquired in these areas by other departments of the Laboratory, the radar department has applied these techniques to various types of radars. These studies indicate potential applications to industrial fields.

As soon as the first ruby lasers became available, the radar department considered the possibility of using these generators in instantaneous range finders. A prototype was completed at the end of 1962. The Army then became interested in the problem and work is now underway for an operational prototype to meet military requirements.

6. Electronics

A separate department is active in the study and construction of electronic devices concerning, primarily, computers and similar equipments. It also studies problems of outer space and has built several prototypes for the French space program.

Moreover, the electronics department is in charge of general studies in the area of air navigation. It benefits from the experience acquired by ITT, which includes the Tacan system among its more-spectacular achievements.

7. Component Testing

A centralized group for testing components performs quality control on certain components, notably semiconductors, capacitors, and microcircuits. The data obtained are used by LCT and by the other ITT companies. They serve especially as a basis for studies on reliability of systems, the ultimate purpose of which is to mitigate the effects of inevitable failures of components.

Extensive installations for automatic testing of components are in service in the Laboratory. Besides the conventional equipment used to test components in various environmental conditions, special automatic machines are used to test capacitors and semiconductors. Figure 9 shows ovens that perform tests of long duration at high temperatures and make it possible to process large numbers of components simultaneously.

8. Vacuum Tubes

In collaboration with the French Atomic Energy Commission, the vacuum-tube department has studied and now produces a complete range of Geiger-Müller counter tubes and of thermal neutron counter tubes. The present studies are directed toward improving the characteristics of the tubes under extreme temperature conditions. A recently developed counter tube has been adopted for radiation detection equipment destined for the French Army.

Besides counter tubes, this department also manufactures, under license from Sperry Rand Corporation, the power klystron used in the Tacan ground beacons. Moreover, the vacuum-tube department continues to manufacture the power tubes for all LMT radio transmitters in service.

Even though it constitutes an accessory activity

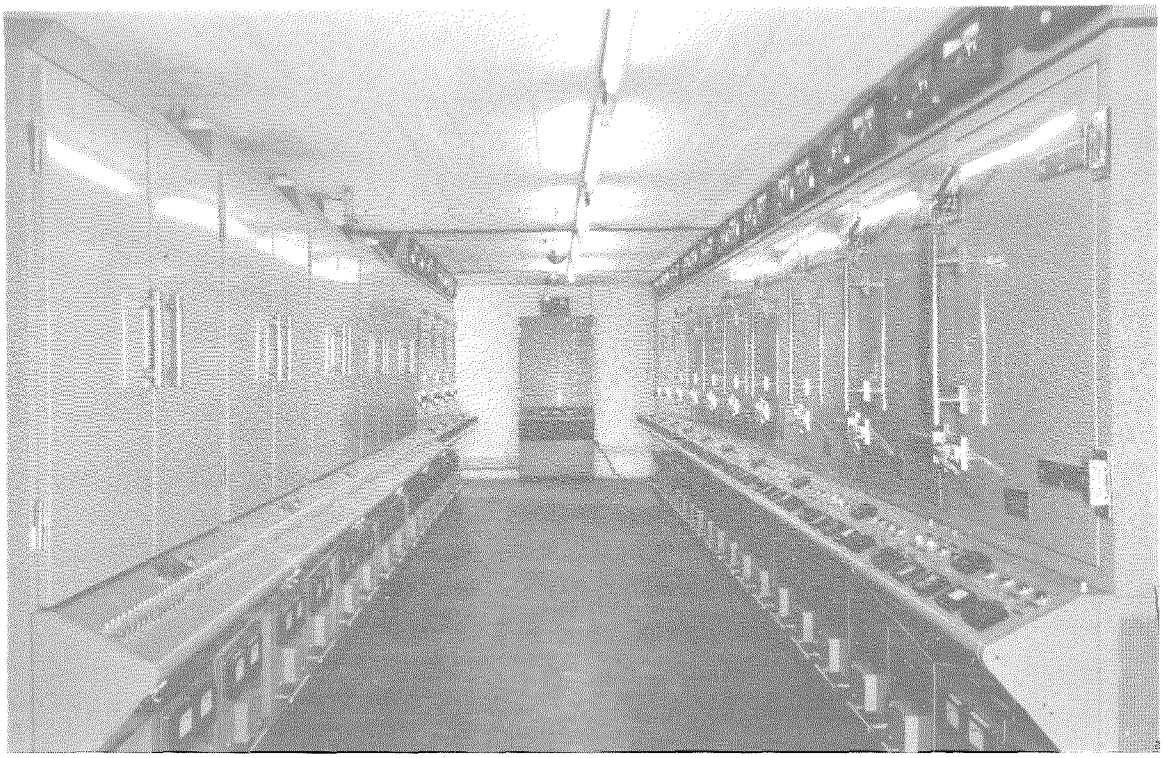

Figure 9—In this room 19 temperature-stabilized ovens are used to test components in extreme environmental conditions.

for the Laboratory, the vacuum-tube department has extensive material for the study and manufacture of modern vacuum tubes and, especially, continuous hydrogen ovens for making high-quality seals.

9. Miscellaneous Services

Like any similar organization, the Laboratoire Central de Télécommunications has miscellaneous services, the role of which is either to aid the researchers or to relieve them of certain work.

The Technical Documentation Service puts 3500 books and 350 technical reviews at the disposal of the researchers. In addition, a large-capacity electronic computer is at the disposal of the technical services.

The general principle that has been adopted is to provide engineers with every facility to permit them to save time and effort and thus increase their effectiveness.

10. In Conclusion

Even though it is located in the center of Paris, the Laboratoire Central de Télécommunications occupies about 15 000 square meters (160 000 square feet) of floor space. It employs more than 800 people, about 400 of whom are engineers and technicians. Selective recruiting has made it possible to assemble personnel who are highly qualified both for research and for the design and construction of prototypes. At the present time it is under the chairmanship of G. Goudet and the management of H. Tanter. The Laboratory attests to its international status in the composition of its Board of Directors, in which are represented the principal European Companies associated with ITT as well as eminent French personalities.

11. References

1. G. Pocholle, "La transformation du réseau téléphonique de Paris en automatique," *La Technique Moderne,* volume 19, page 13; 1 July 1927.

2. G. Deakin, "The Rotary Automatic Telephone Introduced Into Paris," *Electrical Communication,* volume 7, number 2, pages 95–125; October 1928.

3. L. Schreiber and W. Hatton, "7-A2 Rotary Automatic Telephone System," Part I: *Electrical Communication,* volume 11, number 4, pages 179–196; April 1933. Part II: *Electrical Communication,* volume 12, number 1, pages 43–50; July 1933. Part III: *Electrical Communication,* volume 12, number 2, pages 128–136; October 1933.

4. W. Hatton and J. Kruithof, "The 7-D Rotary Automatic Telephone System," *Electrical Communication,* volume 13, number 4, pages 311–347; April 1935.

5. D. B. Mirk, "The Prague High-Power Broadcasting Equipment," *Electrical Communication,* volume 10, number 3, pages 106–130; January 1932.

6. G. H. Gray and N. K. Fairbank, "Madrid–Buenos Aires Radio Link and Its Wire Connections," *Electrical Communication,* volume 8, number 4, pages 208–212; February 1930.

7. "Micro-ray Radio," *Electrical Communication,* volume 10, number 1, pages 20–21; July 1931.

8. A. G. Clavier, "Production and Utilization of Micro-Rays," *Electrical Communication,* volume 12, number 1, pages 3–11; July 1933.

9. A. G. Clavier and L. C. Gallant, "The Anglo-French Micro-Ray Link Between Lympne and St. Inglevert," *Electrical Communication,* volume 12, number 3, pages 222–228; January 1934.

10. R. L. Smith-Rose, "Radio Location—Basic Principles," *Wireless World,* pages 34–37, February 1945.

11. D. B. Mirk, "The Belfast-Stranraer 9-Circuit Ultra-Short Wave Radio Telephone System," *The Post Office Electrical Engineers' Journal,* volume 31, Part 1, pages 33–40; April 1938.

12. A. H. Reeves, "The Single Side-band System Applied to Short Wavelengths," *Electrical Communication,* volume 10, number 1, pages 3–19; July 1931.

13. E. M. Deloraine, "La transmission radiotéléphonique à ondes courtes à bande latérale unique et autres systèmes," *Bulletin de la Société Française des Électriciens,* volume 3, number 27, pages 300–316; March 1933.

14. French patents 833 929 and 49 159; 18 June 1937.

15. French patent 852 183; 3 October 1938.

16. S. Mallein and G. Rabuteau, "The Eiffel Tower Television Transmitter," *Electrical Communication,* volume 17, number 4, pages 382–397; April 1939.

17. A. G. Clavier and V. Altovsky, "Recherches expérimentales sur la propagation des ondes électromagnétiques dans les guides cylindriques," *Revue Générale d'Électricité,* volume 45, pages 697–706; 21 May 1939. Also volume 45, pages 731–743; 22 June 1939.

18. French patent 837 278; 2 October 1937. United States patent 2 807 016.

19. French patent 932 930; 2 March 1941. United States patent 2 570 203.

20. French patent 930 641.

21. G. Dumousseau, "Fully Electronic 20-Line Automatic Telephone Exchange," *Electrical Communication,* volume 34, number 2, pages 92–101; June 1957.

22. "Electronic 20-Line Private Automatic Telephone Exchange," *Electrical Communication,* volume 35, number 2, page 75; 1958.

23. Prince Louis De Broglie, "Introduction of Electronics in Telephone Switching," *Electrical Communication,* volume 36, number 3, pages 159–161; 1960.

24. G. Goudet, "200-Line Fully Electronic Telephone Switchboard," *Electrical Communication,* volume 36, number 3, pages 162–179; 1960.

25. French patent 1 212 984; 21 October 1958.

26. G. van den Broek d'Obrenan, "Le radar SDS, radar de surveillance destiné à la détection des objectifs mobiles au sol," *L'Onde Électrique,* volume 44, number 451, pages 1032–1036; October 1964.

Hervé Tanter was born at Trouville-sur-Mer (Calvados) France, on 18 December 1919. He graduated from École Polytechnique in 1942 and from École Supérieure d'Électricité in 1943.

He joined Le Matériel Téléphonique in Lyons in 1943 and was transferred to Paris in 1946. During that time he was particularly active in radiogoniometry. Appointed Head of the Radar Group in 1949 and of the Radio Department in 1953, he devoted much time to the development of military radars.

Mr. Tanter was appointed Administrative Director of Laboratoire Central de Télécommunications in 1959 and General Manager in 1963.

Pierre Grandry was born at Aulnay-sur-Mauldre (Seine-et-Oise) France, on 21 February 1924. He received the license es-Sciences in 1947.

In 1948, he joined the Patent Department of Le Matériel Téléphonique. Since 1956, he is in charge of the Patent Department of the Laboratoire Central de Télécommunications.

System Engineering: Its Approach and Operations*

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ITT Europe Inc.; Brussels, Belgium

> "In general, we mean by any concept nothing more than a set of operations. The concept is synonymous with the corresponding set of operations."
>
> P. W. Bridgman
> The Logic of Modern Physics
> Macmillan; 1927

1. Introduction

The practice of system engineering was thrust into prominence in the last two decades by multimillion and indeed thousand-million dollar projects—amongst which SAGE (**S**emi**A**utomatic **G**round **E**nvironment) holds something of a legendary place. These projects were conceived, launched, and rapidly brought into operation, creating impacts far beyond their immediate boundaries.

In war and peace big projects like railway networks, industrial plants, bridges, and skyscrapers have been dependent on engineering for as long as there have been engineers. The contemporary drama of such systems arises from their unslacking growth in size, complexity, and rate of development to the point where they defy imagination and challenge the organizing prowess of men. They portend vast economic and social reorientations, influence on employment and unemployment, and perhaps the endowment or disinheritance of future generations.

Computers, communication satellites, and atomic bombs do not come in small easily manageable packages. Bigness is accompanied by complexity and frequently by disorder. Complexity arises out of the heterogeneous composition of systems and the bewildering diversity of interacting disciplines, resources, and skills they employ—economic, social, legal, technical, and mathematical, to list some. The disorder, inherent in complex structures, thrives in varying degree and with varying endurance. It generates intense pressures and impatience for organization, especially from those sectors that are penalized more by the disorder than they are benefited by the organization. Not surprisingly, but unfortunately, the rate at which ramified communication, information processing, transportation, and automation systems were developed in the last decade has accented the negative fallout of such operations. This included the incompatibilities of mass-procured new equipment, financial crises borne of errors in cost estimation, and operational stresses at the undertrained-man—complex-machine interfaces. In the turmoil the calling of system engineer was hastily improvised, and the respondents were hurled into the interdisciplinary gaps.

Inevitably then, the system engineering scene is one of ferment, boiling with advocacy of a great variety of panaceas, methodological partisanship (which can be quite bigoted and narrow on occasion), vigorous debate, and on occasion conflict and confusion.

As of today there appears to be no integrated course of study (under- or post-graduate) in system engineering, and no degrees are conferred. There is no institute or association that governs, promotes, or disciplines practitioners in the field. Although thousands of scientific journals are published, not one appears to be devoted to the subject. In recent years at least a dozen books have appeared with some version of system engineering in the title. There was little if any common denominator in their contents except perhaps for a studied avoidance of a definition of the subject. The profession is not explicitly recognized or certified but its ranks are thought to number in the hundreds and perhaps thousands, and the Sunday New York Times regularly carries advertisements

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* Expanded transcript of a talk given at the System Engineering Symposium sponsored by the North Jersey Chapter of the Professional Technical Group on Communications Systems, Institute of Electrical and Electronics Engineers, Paramus, New Jersey; 21 April 1964.

listing seemingly remunerative vacancies. There is some reason to conclude that, as of now, system engineers are self appointed!

Casting around for some clue to this elusive nonentity recently—as I have for perhaps a decade—I came on an announcement and program for a System Engineering Symposium. Scanning its list of sessions, I noted the following titles at random:

Changing Perspectives of Business
Process Control in Cement Production
Data-Acquisition Equipment
Computer-Controlled Factory for Making a Small Electrical Part
Computer-Controlled Warehouse System
Prototype Testing in System Engineering
Integrated Freight-Handling System
Integrated Microcircuits in Industrial Systems

Note that one could delete the words "System" or "System Engineering" from these titles without loss relevancy. (Parenthetically, the same observation might even be made about system engineers. One might ask, "Are they not simply engineers—and are not all engineers system engineers?")

Using the legendary blind Hindu method of imperfect induction, I arrived at this synthesis!

"System engineering is computers coupled with control; but also cement; small electrical parts; very-small electrical parts, to wit, microcircuits; with a pinch of integrated business perspectives."

In the same vein and with some gain in generality, system engineering could be described as anything we can prefix, suffix, or intermix with the word "system." As for reduction to practice and a real embodiment, I would be at a loss to explain why we could not cite the proverbial mousetrap, provided it is relabeled "An Integrated Computer-Controlled System for the Preservation of Man-Rodent Equilibrium." After all, is there an engineer so reactionary as to dispute the ability of a computer to outwit the mice that have outwitted men for a million years and survived?

While these remarks are obviously not serious, I think that they are to some degree descriptive of the state of concepts in system engineering. There certainly are a host of questions for which ready and unembarrassing answers are not easy to find. For example, one might echo John R. Pierce [1] and ask, are system engineers useful? If *system* engineer makes sense, then why not *system* doctor, *system* lawyer, and for that matter system anybody? One intuitively couples system with order and organization. Is it then possible that, unlike doctors and lawyers, the two groups who appear to be most vocally concerned with systems, namely engineers and politicians, have proliferated so much disorder and disorganization that it was necessary to designate from their midst some members to catch up on housekeeping, and that the designation was dignified under the title of system engineering?

Business, cement, factories, warehouses, and small electrical parts have been around for a long time. System engineers are doing something with and to all of these. I think that what they are doing is important and exciting. Their efforts are not uniformly successful, their methods not always defensibly scientific, and they are constantly complaining about the inadequacy of available tools that they stretch to their elastic limits; but the consequences are increasingly more fruitful and coherent. There is refreshing evidence that they are bringing a rationale into areas where prejudice, chance, and even quackery prevailed. What they are doing is probably best introduced by something called the "system approach."

2. System Approach

There is no system with a capital *S*. System is a measure of correspondence between a set of criteria and their artifact. What may be a system relative to one frame of reference or criteria may or may not be a system relative to another. Dynamically, system is a measure of covariance between an artifact and its criteria.

The system approach designates one of the two currents in a dichotomy that has plagued only one species—the intelligent man—homo sapiens. System, order, and organization are, so far as one can observe, not arrived at in nature by what we shall shortly define as the system approach. The approach of nature and, to a larger and more-important extent than he may profess, of man is to act, do, invent, and create—without a plan, goal, or objective fully aforethought. The sequel to this approach embraces many variations of the "fox and rabbit" theme: Foxes proliferate, consume rabbits, until there are too-few rabbits to sustain foxes, then foxes starve off, fewer rabbits are hastened to their untimely demise, and rabbits proliferate. The process stabilizes at a point of equilibrium between foxes and rabbits, as well as between rabbits and grass—and an order or system emerges.

Adam Smith's concept of the marketplace and free enterprise can also be caricatured in these terms. Men invent, produce, and market products. The sales of a product grow until the marketplace is saturated, then some businesses dissolve while others stabilize. In evolutionary theory the process is rationalized a little further in terms of the law of survival of the fittest. Certainly, in technology, much of the historic process has been due to the random unscheduled invention of gadgets, gimmicks, and push-button contrivances, which fought their way into the marketplace, flourished, endured, or disappeared and were forgotten. By a somewhat blind process of statistical turmoil, all this myriad of people and things seek and find states of equilibrium, order, system, and organization. This is a shakedown process that does not often function as smoothly as an engine controlled by a precise governor. To the contrary, equilibrium and order are frequently achieved by the indelicate recourse of "eating rabbits and starving foxes."

While men have ordered and systematized within the context of this statistical process—and on occasion passionately defended it as *the* method—they have with equal dedication postulated the possibility of purpose and plan, intelligently and even omnisciently imposed or imposable from above. The faith of man in the existence or realizability of self-consistent, orderly, harmonious, and good plans, which could be imposed on the multivariables of the world and displace the brutality of the competitive survival of the fittest, has survived uncounted failures and disillusionments. Systems of different scope in various domains have been tirelessly invented, tried, and imposed—sometimes imposed and made compatible and self-consistent by the not-so-gentle ministrations of edict, sledgehammer, brainwashing, and gas chambers.

It is a datum of observation that men will tolerate the free jostling of the statistical pursuit of equilibrium to a point and no further. Societies demand at a certain point that the law of survival of the fittest, or strongest man, or best-advertised device be complemented by some intelligent order and goal orientation.

The approach from the particular to the general (component approach) and the approach from the general to the particular (system approach) are not mutually exclusive. The overwhelming dominance of one or the other can be exceedingly dangerous to products, people, as well as to societies. They must thrive on mutual complementation.

The system approach (and we need not engage in pedantic rivalry with Webster and Oxford over the definition of the word "approach") is the approach to the part from the context of the whole, the approach to man from the context of society, the approach to the cell from the context of the organ, the approach to a switching center from the context of the communication network.

What then is the whole and what the part? Our preoccupation with structures that are big notwithstanding, there is nothing in the system approach that is scale sensitive. As an example, in spectra such as the biological, technical, and military, given in Table 1, it is not

TABLE 1

Comparable Levels for 3 Spectra

Level		Biological	Technical	Military
1	complex	society	automated industrial economy	United States Department of Defense
2	network	nation	common carrier	United States Army
3	"set"	family	radio relay	corps
4	subsystem	female	receiver	division
5	unit	heart	amplifier	battalion
6	component	cell	transistor	enlisted man
7	physical process	protein chemistry	solid-state physics	military training

really material whether the level under consideration is 1, 2, 3, or 7—or anyplace else in a spectrum that extends indefinitely above and below the intervals selected for attention.

Confining our attention to the technical column of the table, the component approach to a radio receiver would proceed upward through discovery, invention, and design from as low a level as solid-state physics (the discovery of semiconduction and the invention of the transistor). That approach produces devices and offers them to users. In its "purest" sense, it is governed less by specified demand than by innovation, ingenuity, curiosity, and whatever else motivates discoverers and inventors. Many, perhaps most, of the technical devices we now regard as necessary were the product of relatively unreined and nongoal-oriented curiosity, sometimes initiated by boredom and confinement. Not till they were thrust out into the industrial and economic world did they carve out a point of equilibrium in the overall order and become necessities.

The system approach to the same receiver, in a communications network, could begin with perhaps a microwave relay, the transmitter with which the receiver had to work, the number of channels it would have to carry, the permissible weight, and the pressure and temperature ranges over which it would have to operate. The system approach to the receiver establishes for the designer interface and performance specifications derived from consideration of its balanced place relative to the next higher level or whole of which the receiver is to be a part.

I recall an example once used in this connection. Consider a man and his ear, it went. If man were a product of technology and the Component Approach, it might well have happened, if the maker of ears were a large organization with a forceful ear-promotion department, that man would have been constructed with an ear from head to foot and having the diameter of a tuba.

The answer to "Why not system doctor?" is probably obvious at this point. The adjective would be redundant. The general practitioner is a guardian of the whole, first and foremost. He is a diagnostician who proceeds from "Something is wrong with me, doctor," to the part at fault, and then refers the problem to the specialist (surgeon, neurologist, endocrinologist, et cetera). By contrast, in engineering it is the specialist or "component" man (electrical, chemical, electronic, et cetera, engineer) who became the predominant practitioner—until the conflict between the disparate parts reached the point requiring the rebirth of the "whole"—the system engineer.

3. Arithmetic of Synthesis

It is desirable, in a subject so vulnerable to semantic equivocation as system development, to use language that is less ambiguous than the literary. Mathematics furnishes such a language. Not only is it less ambiguous, but standards being what they are, a paper for engineers would be undignified if it were not at least a little mathematical!

Let us then call the "part" (a black box) G and the whole U. U may be the whole universe or only the adjacent contiguous strip of the universe. The interactions between U and G (they are interactions since everything is dynamic of one rate of change or other) must consist of those that act from U to G (call them F) and those that act from G to U (call them H).

F may be a signal from an antenna, G a linear amplifier, H an amplified version of F. But F could also be a fillet of beef, H hamburger, and G a very-nonlinear grinder.

If the system approach is used to arrive at the part G from the whole U, it would derive G from a statement of the inputs F and outputs H.

Now since by definition

$$H = F\,G \qquad (1)$$

where H is the response, F is the excitation, and G is the system, then $G = H/F$, if we define the system in the "admittance" sense, or $G^{-1} = F/H$, if we define the system in the "impedance" sense.

The operation of solving for G, given H and F, is called synthesis in circuit theory.

It is important to remember at this stage that there is a very-severe simplification in the preceding arithmetic. Such simplifications may be permissible and indeed necessary to make the problem analytically tractable at one level of system engineering, but may make the tool inept at another level. Mathematical oversimplifications are probably the leading source of system engineering embarrassments.

H is almost always a complex function not only of a particular excitation F and facility G, but of P (pressure), T (temperature), C (cost), W (weight), M (maintenance), et cetera. That is to say

$$H = f\,(F, G, P, T, C, W, M, \ldots).$$

We usually assume, with more or less validity, that P, T, C, W, M, et cetera, can be kept fixed, and that the equation has the form $H = FG + f\,(G, P, T, C, W, M, \ldots)$ where F appears in multiplicative association only with G.

We then deal with the partial derivative

$$\partial H/\partial F = G_1.$$

We may or may not subsequently take into account variations in other parameters.

The system developer (and our use of the word developer will become apparent shortly) therefore sets out to devise a system G the performance of which satisfies $\partial H/\partial F$.

The first dilemma of synthesis, the system approach and system engineering, appears immediately. There are almost always no unique solutions to equation (1), $G = H/F$. There may be several ways in which to realize a G satisfying the partial objective. For a very-simple example, suppose that F were a step function $U(t)$ and H a delta function $\delta(t)$ (neither of them "ideal," since there is no practical road to "ideal" objectives). At least two systems G can be configured to satisfy H/F, namely a resistance-capacitance or a resistance-inductance network.

While the ensuing argument in terms of a system as simple as a differentiator may be trivial, it becomes quite crucial if the system and choices are more complex and involve scarce resources.

Which of the possible solutions will the system engineer take? One of the major claims of the system approach is that of objectivity. Obviously if the system engineer, in our trivial case, happens to be also a producer of resistance-capacitance differentiator networks, he may well choose that solution in preference to resistance-inductance differentiator networks produced by X. He is then not only not objective but potentially vulnerable to charges of conflict of interest.

There is, of course, a way out of the dilemma. Indeed the dilemma is frequently caused by none other than the system engineer himself. Having written (1) as a partial differential, holding all other variables fixed, he may later have conveniently forgotten that the variables he fixed may indeed be variable. If there are N possible solutions to G, that is, if G has N degrees of freedom, it is necessary to have at least N equations or constraints.

Thus $\partial H/\partial T$ may have a solution G_2, and $\partial H/\partial M$ a solution G_3. It may well be that only one of the N alternatives satisfies $\partial H/\partial F$ and $\partial H/\partial T$, for example a resistance-inductance as against a resistance-capacitance network.

In general, therefore, because he proceeds from the whole (which includes not only F but cost, temperature, maintainability, pressure, transportability, et cetera) and because he is required to find unique, thus objective solutions, the system designer is likely to suboptimize relative to a much-wider number of objectives and over a greater space than the inventor-researcher, who proceeds from the part to a whole and lets the whole adapt to the part. If the latter produces a temperature-sensitive television set and his buyers are anxious to see certain programs, they will "change the whole," stabilize the temperature in the room and see the programs—for that matter, they will alter and restabilize their habits of living. In a like case the system engineer would be discharged for incompetence.

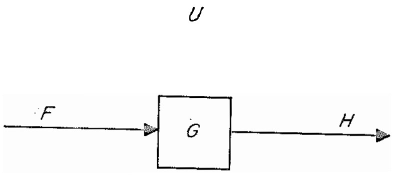

Figure 1—Interactions between part G and whole U.

In the lexicon of system engineering, the factor H/F is not frequently referred to by its parts F (system excitation) and H (system response). Another term has come into fairly general use. That term is "requirement." In common with most words, it has been the subject of tyrannical confusion. If, however, we remember, at least for the present, that requirement r means specifically $r = \partial H/\partial F$, we can avoid a good deal of semantic equivocation.

The models we have used thus far are obviously "little." A black box such as the one shown in Figure 1 could be a receiver lodged between an antenna and a multiplex equipment. Two- and four-terminal boxes do not begin to represent the complexity of the sort of structures with which we tend to associate system engineers.

Bigness means that a part interacts not with just one or two other parts of a whole, but with many other parts, a great many in some cases. When this occurs, the system does not have a simple input side and an output side. It may have many sides each with many inputs and outputs, and interactions may not be dimensionally homogeneous. The inputs may be steel, paint, plastic, and labor, and the outputs cars, aircraft, and missiles. Such "systems" cannot even be denigrated by being called boxes, black or otherwise. They are not just-a-little but

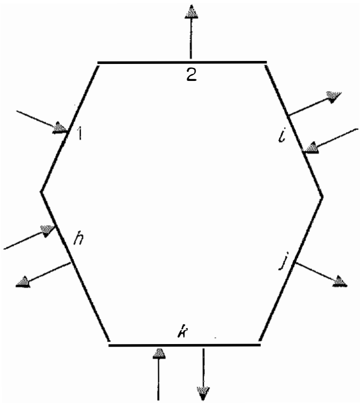

Figure 2—Interactions in large systems.

infinitely more complex than differentiating circuits.

An introductory look at large systems will serve as a means of viewing some of the man-sized operations of system engineering.

We can start by putting more sides on the box of Figure 1. The lines of Figure 2 again represent originating or terminating interactions in the sense of the arrows. The closed boundary formed by the sides cuts across the set of all interactions.

Since the problem is now much-more cumbersome, we must consolidate some of our notation. With each interaction incident on a port i, there is an interaction excident from port j. This could be denoted by H_j/F_i. Since we have established a new term R for this ratio, we can call $H_j/F_i \equiv R_{ij}$.

We also need a higher-level algebra. A bigger tool is available to us in matrix algebra.

The new requirement $|R|$ can be represented in tabular form by listing the ports in the column and row titles of a table as we do in road maps. We have made a few entries in the spaces of Figure 3. All the spaces, except those on the principal diagonal, are occupied by positive nonzero numbers. The spaces on the principal diagonal represent self-interactions, that is to say processes that go on inside the black box. They are the domain of the component approach. They are not the domain of the system planner, except if he is chartered to proceed to the next level. In the latter case, he would expand r_{ii} into a new submatrix of interactions $|R_{ii}|$.

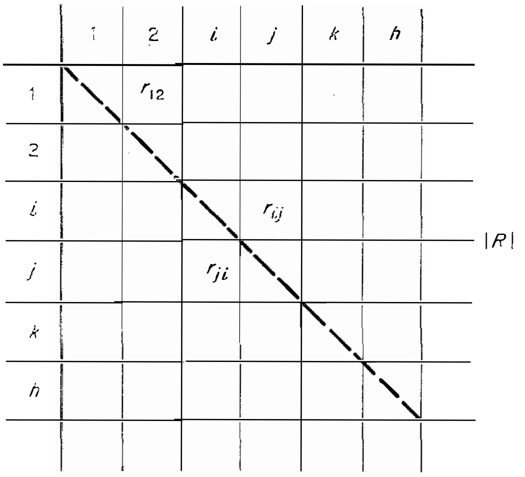

Figure 3—Interaction matrix.

The matrix $|R|$ is a statement of requirement. Each r_{ij} is a complex-valued set. Depending on the system, r_{ij} may be the movement of mail, passengers, telephone calls, automobiles, freight, or sewage between originating points i and terminating points j. Suppose it is mail. The mail consists of offered pieces or letters (F_a) to be responded to (H_a) by delivery in a dry, readable, unfolded condition, in a time not exceeding τ_a, with a confidence of 0.999, and an average cost not exceeding $0.03 per piece. The pieces are to be packed in mailbags (F_b) and delivered in a time τ_b that is less than τ_a. These bags are packed in trucks . . . well—you can see the multilevel probabilistic terms in which the r_{ij} are specified.

4. Procedural Dilemmas

Given $|R|$, a system engineer is expected to be able to design or synthesize a national postal system G (or transportation or pipeline system) in a smooth, sophisticated, scientific, objective exhibition of deductive logic. In general, he frequently cannot even begin the task for at least two reasons.

(A) $|R|$ is not given in any of the senses an engineer attaches to the words "given," "specified," or "defined." If the system is big with a multitude of terminals, there may not be any centralized intelligence that knows what the requirement is. In the mail example, an exhaustive census of the entire mail-using public could cost so much in dollars and time that, when it was completed, no money would be left for building a postal system. It could also be too late, because writing habits might have changed under the impact of inexpensive telephony. More important, users do not precisely know their requirement for a service or a product until they have been offered it. Then the requirement becomes a function of what they already have. The paradox is this: The system engineer cannot achieve a system approach until the requirements for the system have been specified. The potential beneficiary of the system cannot specify his requirements until he has had an opportunity to use and judge the system. The problem is reminiscent of the puzzle of primacy—was it the chicken?—was it the egg? We thus have a classic operational-research problem. In general, large-scale systems take 3 to 10 years to bring into being. Thus, the requirement at issue is not today's or yesterday's—for a system built to satisfy those requirements will be obsolete before it is completed. It is the predictable future demand that must be satisfied.

A familiar large-scale requirements-gathering operation, sponsored by industry, is called market research. The United States consumer industry will spend 200 million dollars on it in 1964. This is an effort to ascertain what the consumer requires of the consumer-products industry. It is interesting to note that the same industry will spend about 15 billion dollars on advertising, that is to say, on telling the user what he ought to require!

(B) The second constraint is a mixed blessing. The positive part of the mix is that it partly resolves the impasse of **(A)** in the following manner. Generally, the system engineer's assignment does not call for the free synthesis of a system $|G|$ to respond to requirements $|R|$. In big structures there is almost always some facility $|G'|$, however inadequate, already in existence. The system-engineering assignment is thus not inventing "out of the clear blue," but one of developing a system from an existing status to one that more-nearly responds to the requirements.

This situation partly solves one problem and creates another. It helps solve the chicken-and-egg impasse raised in **(A)**. The user does have a system to help judge his discomforts and desires for improvements. If the rate of a user's change in demand X is a function of what is already provided for him, the situation can be expressed in the form of $\mathrm{d}X/\mathrm{d}t = KX$.

The solution for such equations involves the exponential e^{gt}. Given additional data such as the level q of ultimate demand L already fulfilled, a solution takes the form of

$$q(t) = \frac{L}{1 + k\mathrm{e}^{-gt}} \qquad (2)$$

the famous crutch of most growth analysts [2–4]. It is, incidentally, by means of exponential arguments of this tenor that intercontinental traffic engineers arrive at rules of thumb like the one that says: Given a new improved facility, utilization will expand by 75 percent in a short time and then recover its long-term rate of growth of 7 percent per annum.

There are, of course, various other avenues of attack and the system engineer's portfolio of them is growing rapidly.

There are risks with exponential extrapolations, and they increase with the distance into the future that they probe. For instance, the sign of g in the exponential can change from positive to negative, resulting in catastrophic miscalculation and bankruptcy. Moreover, extrapolations do not furnish an answer to the problem of estimating future requirements for something that does not now exist. In this situation, the system approach can run out of steam. The system approach requires the component approach—the approach of the inventor—motivated by motives unspecified, oriented by goals unknown, producing perhaps a carbonated caffeine brew and creating an international institution from the demand for a product called Coke.

Teamwork, complementation, and conflict between the system engineer and the operator-user on the one hand, and between the former and the inventor-researcher on the other, are inescapable at the "requirements" and "component" interfaces, respectively. The interfaces at which boundary lines are fixed must be defined for each undertaking. Above or outward is the boundary line at which the system engineer can expect to be "given" a set of requirements; below or inward is the boundary line at which he is to release performance specifications for the procurement of component parts.

Many of the difficulties of system engineers arise from lack of attention to such definition. The sort of graceless dialogue that arises as a consequence may sound like the following.

System Engineer: "The reason progress could not be made is your failure to provide the necessary requirement inputs."

Client: "If I knew my requirements, I would not need a system engineer."

or . . .

Client: "I think that you are involving yourself in internal policy questions in the name of requirements."

System Engineer: "In order to establish your requirements, I have no alternative but to pursue my line of research wherever it leads."

et cetera . . .

At the lower boundary, it is also necessary to avoid over-specification of component-part performance requirements, so as to enable the supplier to exercise the maximum freedom and ingenuity. It can happen that, in the name of objectivity and the system approach, the system engineer straitjackets the "part" developer and thus brings a stultifying end to progress. A system engineer can become a die-hard conservative, and he can establish constraints motivated by his aversion to change rather than by any objective derivation from requirements.

It deserves reiterating that a pure system engineering approach is not viable, that requirements and the system are fashioned by the inventive productivity of the component approach [5], and that the latter is also spurred and oriented in its creativity by the system planner. The two approaches are proper and important disciplines of the larger one of engineering.

5. System Development

The usual presence of an existing facility $|G'|$, as a point of departure, has a dominant place in structuring the operations of system engineers. For a demand r_{ij} there may be a facility g_{ikj}. If r_{ij} is a demand for a facility to support car traffic from i's place (John Smith's garage) to g (downtown New York City), then g_{ikj} may be a road g_{ik} from his garage to the expressway toll gate, and an expressway g_{kj} from the toll gate to j.

We have two matrixes now—a matrix of facility $|G'|$ and a matrix of demand $|R|$. The business of evolving a development plan for $|G'|$ may go through the following steps.

(A) Programing $|R|$ on $|G'|$ and finding that no feasible solutions exist, or finding that a linear program is inapplicable to a nonlinear process and changing to dynamic programing—a discipline still in its infancy.

(B) Making an "intuitive" change in $|G'|$ and programing $|R|$ on modified $|G''|$—hit-and-miss style. If the test modification is a new warehouse or a transatlantic cable, it cannot be mocked up in a laboratory. Thus simulation is resorted to.

(C) If all this fails, going back to $|R|$ to analyze it for structure or pattern, and comparing $|G'|$ and $|R|$ structurally [6].

(D) Taking account of the dynamics of $|R|$ and devising an adaptable $|G|$. This means control, and control means communications, "switches," and computers.

These processes and operations of system development, and thus system engineering, can at best only be catalogued in a paper. A comprehensible treatment of the subject requires the space of a book.

6. Concluding Observations

Before concluding, I would like to return to "Requirements" and Table 1.

Because the requirement at a given level (for example, for the receiver in the technical column) may not be given or specifiable by the client, the system engineer may be asked to analyze the microwave relay of which the receiver is to be a part, and thus derive the requirements or performance specifications for the receiver.

At the subsystem level it turns out that a microwave relay does not exist and, to derive the performance specification for the receiver, it is necessary to derive the performance specification (requirements) for the microwave relay by analyzing the network of which the relay is a part.

It turns out that the network is known to be inadequate, and the microwave relay it will require should be derived from a development plan for the future network.

You can see how the system engineer, having advocated the system approach, can now become a victim of it. He is inexorably driven up the ladder, or—to be 3-dimensional—outward in space! In the above example, before he is aware of what has happened, he has become embroiled in the national industrial structure (of which common-carrier communications are a component) and its economic, social, and political currents.

When he has floated up to this level, he is still in systems but possibly not in engineering systems. He could find himself pontificating on matters involving war, peace, psychological effects of automation, and the neurotic proclivities of decision makers. These can be fields in which his skills, qualifications, and credentials have little or no relevancy. He may be flouting his system engineering (or operations research) mantle before those who are much-less scientific and less systematic (in his view), but much-better qualified [7, 8].

It is simply not true that an inventor of a bomb is thereby an authority on peace negotiations, any more than a dental mechanic is an authority on the endocrinal effects of fluoride. Too often have disciplines oversold themselves as panaceas, impoverishing their reputations and losing the faith of the public in consequence. This does not deny the right of an engineer to be interested in subjects beyond the technical level; it does suggest that he pose there as a layman, or else that he learn the disciplines.

System engineering is moving through a very-promising and exciting phase of its development. There are some of the usual polemics associated with any subject that cannot avoid philosophic ingredients. There are enough evangelistic partisans who hold that their "Method," their "Book," their "Revelation" is the only pure, inspired, authoritative method, book, or revelation, and that every other is false and impure. These are the unavoidable skirmishes on the road to important developments. The system approach is necessary and viable as a complement of what I have called here the component approach—in engineering as well as in business, science, and government. Insulated within itself, the system approach can stultify progress. Similarly placed, the component approach can generate chaos.

On the positive side, it is my opinion that many of the basic conceptual discoveries have been made. Frameworks exist in information theory and communication engineering; in control theory and practice; in mathematical disciplines of programing, gaming, modeling, statistics, and group theory; in the metric practices of economists and psychologists; and even in the market-research sector of the sales and advertising industries. These well-supported and frequently large-scale attacks have been moving from different quarters, and it may well be that they will coalesce into an integrated science and practice of system engineering in this decade.

If bigotry does not prevail, we may witness from the system engineering community a fresh and constructive approach to many problems in which "seat-of-the-pants" approaches are demonstrably unacceptable. The system engineering approach is needed to solve the problems in transportation, urban planning, banking, information management, and in a host of other big, complex, disorderly areas that characterize our increasingly interdependent world.

7. References

1. J. R. Pierce, "The Paper Dragon," *Physics Today,* volume 16, number 8, pages 45–50; August 1963.

2. E. R. Dewey and E. F. Dakin, "Cycles, the Science of Prediction," Henry Holt and Company, Toronto, Canada; 1947.

3. A. D. Hall, "A Methodology for Systems Engineering," D. Van Nostrand Company, Princeton, New Jersey; 1962: Chapter 6.

4. F. Baade, "The Race to the Year 2000," Doubleday & Company, Toronto, Canada; 1962.

5. P. F. Drucker, "The Big Power of Little Ideas," *Harvard Business Review,* volume 42, number 3, page 6; June 1964.

6. J. W. Halina, "The Structure of Interactions—an Exploratory Study of the Organization of Networks," *Transactions of Professional Technical Group on Communications Systems,* Institute of Electrical and Electronics Engineers, volume CS-11, number 4, pages 394–402; December 1963.

7. Colonel F. X. Kane, "Security is Too Important to be Left to Computers," *Fortune,* volume 69, number 4, page 146; April 1964.

8. Sir Solly Zuckerman, "Judgment and Control in Modern Warfare," *Foreign Affairs,* volume 40, number 2, pages 196–212; January 1962.

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Modulation and Coding

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1. Introduction

Both data transmission and pulse-code modulation are essentially intended for transmitting digits or code elements. The data bits are exactly the same in each case. Although data transmission is merely an improvement, however considerable, on telegraphy, the same is not true of pulse-code modulation for it represents a radical modification from the classic analog transmission systems used in telephony, television, and telemetry.

In the analog systems, which presently dominate our telecommunications networks, the signals are modulated continuously by variations in amplitude, frequency, or phase. One undesirable property of these types of modulation is that noise and distortion are superposed on the signal and cannot be removed.

In transmission systems using pulse-code modulation, the forms that the signals can take are few. It is therefore easily conceivable that if the noise and distortion levels do not exceed certain limits, it is theoretically possible to completely eliminate them from the received signals.

Other properties of pulse-code modulation have been demonstrated in a previous article [1].

One of the aims of the present paper is to show how it is possible to facilitate the regeneration operation (the quasi-ideal reconstitution of the message being transmitted) by modifying the structure of the information before transmission. But first certain frequently used terms will be defined so that their meanings are clear.

2. Terminology

2.1 Binary Information and Pulse-Code Modulation

The adjectives "binary," "ternary," et cetera, identify without ambiguity numbering systems of base 2, base 3, et cetera. In the same way, there is no danger in attaching these adjectives to the noun "information." Unfortunately, it is not the same for modulation systems because some call binary modulation a type of modulation used to transmit binary information, while others call it a type of modulation in which the signal transmitted can take 1 of 2 possible forms. There are now systems in which 3 possible forms of the signal are used to transmit binary information.

Consequently, we shall reserve binary, ternary, et cetera, to the numbering systems and to the types of information discussed, whereas we shall speak of "number of levels" to specify the types of pulse-code modulation.

2.2 Digits, Code Elements, and Coded Pulses

Most people have elementary notions of "number" and of "digit." Nevertheless, the expression "binary digit" is commonly used instead of "code element." Now, if the significance of a digit is complete as soon as its value and its row in the number to which it belongs are known, it is not the same for the code element. For example, the last element of a reflected binary code (also known as Gray code or cyclical code) takes on significance only from the moment that all other elements of the code are known.

At other times, it is possible for a code element to be modified without the code itself losing significance; this is the case in autocorrective codes.

The origin of this confusion can be explained by the fact that the same symbols are used for binary digits as for the elements of a code.

The coded pulses are the shapes of the signals that carry the information during transmission. However, two (or more) types of coded pulses may correspond to one type of data to be transmitted.

2.3 Measurement, Coding, and Translation

The transmission of information using pulse-code modulation is generally preceded by certain fundamental operations, such as sampling the value to be transmitted, measuring this sample, and, lastly, the pulse-code modulation itself.

Sampling is of interest, as far as this paper is concerned, only because it suggests a certain division, generally uniform, of the time allotted to the transmission. Moreover, it is possible to envisage certain types of coded transmission without sampling.

The measurement of the value to be transmitted (or of its sample) is a precisely defined operation but it can take particular forms, especially in the cases that interest us.

On the other hand, coding is an operation to which have been attributed meanings as numerous as they are vague. It can be said that coding is an operation to translate a message with a view to giving it certain properties. If we accept this definition, then changing the base of a numbering system constitutes one class of coding.

Enciphering, which is intended to ensure or to increase the secrecy of the transmission of a message, constitutes another class of coding.

The conversion of a code without redundancy to a redundant code is a new class of coding intended most often either to increase the degree of reliability of the transmission or to permit detection, location, and even correction of errors.

In the latter case, the number of elements of the new code is greater than that of the original code, whereas the number of different symbols used remains, generally, invariable.

Lastly, the coding may have to ensure only that the transmitted signal has certain spectral properties, with a view toward facilitating its transmission. We shall give the most attention to this aspect.

Another definition of coding that often confuses us is associated with measurement. A characteristic example is the shaft encoder using the reflected binary code. Such an element permits the value of the rotation angle of the shaft to be directly translated into a reflected binary code without passing through the intermediate pure binary number that measures this angle. Likewise, in the transmitting part of the pulse-code-modulation multiplex telephone transmission equipment *Mk 1* developed by Standard Telecommunication Laboratories, the amplitude of the voice sample converts directly into the unit disparity code (disparity being the difference between the number of ones and zeroes).

To avoid confusion we shall reserve the word "coder' to mean the device that converts the characteristic value to be transmitted (amplitude, duration, frequency, et cetera) into a code or into a number.

The operation that converts from the number, or from the code supplied by the coder, to another code will be called translation.

3. Transmission Using Pulse-Code Modulation

The form of the electrical signals at the output of the coders or other terminal equipment is not necessarily the most appropriate for transmission. At this stage of the diffusion or exchange of information, we find two fundamental problems—transmission reliability and economy.

3.1 TRANSMISSION RELIABILITY

The coders generally supply the information to be transmitted in the form of coded pulses. Extremely few configurations of these elementary signals are possible, most often only two or three. Actually, the main reliability factor and the appeal of this type of transmission reside in the fact that the number of possible configurations being very small, it is relatively easy to distinguish between them. This remains true even if, in the name of economy, the configurations of the signals actually transmitted are more numerous than those of the signals supplied by the coders. The other means for increasing the transmission reliability generally result from the introduction of redundancy into the message, from the repetition of the message, or from the simultaneous transmission of the signal by different means. Moreover, these last means are not necessarily proper to the types of transmission studied here.

3.2 TRANSMISSION ECONOMY

In the interest of simplification, we shall limit the following study to the case of the synchronous transmission of serial-type binary information over special lines. Multiplex telephone transmission using pulse-code modulation on multiple-pair cables is one particularly interesting example.

Two important difficulties must be solved: the use of a very-poor transmission medium, and the necessity to maintain as exact synchronism as possible during the transmission of the message. These two difficulties are encountered several times in succession during the same transmission.

3.2.1 *Very-Poor Transmission Medium*

The cables that must be used form the infrastructure of the present telephone network, mainly of the local network. These cables have been studied for transmitting voice-frequency currents over some tens of kilometers.

The rate of information we wish to obtain is about 2 megabits per second.

It appears immediately that crosstalk due to the transmission over this medium of rather-high frequencies constitutes a serious obstacle. It is the same for the propagation characteristics and their variations.

One consequence of the inadequacy of the transmission medium is the necessity to frequently regenerate the signals. This regeneration is possible only because of the use of coded pulses and it is done in devices that we shall call repeaters.

3.2.2 *Necessity for Strict Synchronism*

The transmission of binary information of the serial type implies the transmission of synchronization information. In the example chosen, this aspect is fundamental since the synchronism must be restored before regeneration can take place within each repeater. Actually, the information represented by a coded pulse depends most often on two factors: the configuration of this pulse, and its position with respect to a regular frame that divides the transmission time into equal periods. This frame can be virtual, but it is indispensable to be able to reconstitute it.

Several means have been envisaged to obtain synchronism. We have thought, in some cases, of transmitting the synchronization signal via a channel parallel to the one carrying the coded pulses.

We have also considered superposing the two signals at the transmitting end and separating them in the repeaters. All these methods are too expensive and consequently are not used.

The usual method of obtaining the synchronization signal at the present time consists of directly processing the coded pulses received.

Section 4 examines the different devices used to this end, as well as the relations that exist between the form of the transmitted signals and the structure of the repeaters.

4. Regeneration of the Coded Pulses

Before giving details of the regenerating methods used, the different types of pulse-code modulation used and the functions that the repeaters must fulfil will be described.

4.1 TYPES OF PULSE-CODE MODULATION

4.1.1 *Nonreturn to Zero*

The oldest type of pulse-code modulation is on-off or nonreturn-to-zero modulation (see Figure 1*A*). This is a two-level modulation. If there is no restriction on the code employed, the difficulty of extracting the synchronization signal during the transmission of a long series of identical symbols is evident. This also applies to the transmission of the direct-current component. On the other hand, nonreturn-to-zero modulation is of interest because it provides economy of bandwidth.

4.1.2 *2-Phase*

The difficulty in extracting the synchronization signal can be solved by giving a transition to the signal during each cycle. Then the information resides in the direction of this transition. The waveforms in Figure 1*B* correspond to the same code as the waveforms obtained by nonreturn-to-zero modulation. It is also a two-level modulation.

In addition to the transition advantage, 2-phase modulation permits transmission of the direct-current component to be avoided. On the other hand, it requires a bandwidth practically double that required for nonreturn-to-zero modulation.

4.1.3 *Unipolar*

Unipolar two-level modulation (Figure 1*C*) is of interest only because of the simplicity of the repeaters used. It permits particularly easy extraction of the synchronization signal. Nevertheless, it has drawbacks in required bandwidth, transmission of the direct-current component, and variations of the synchronization signal, that often make it unacceptable.

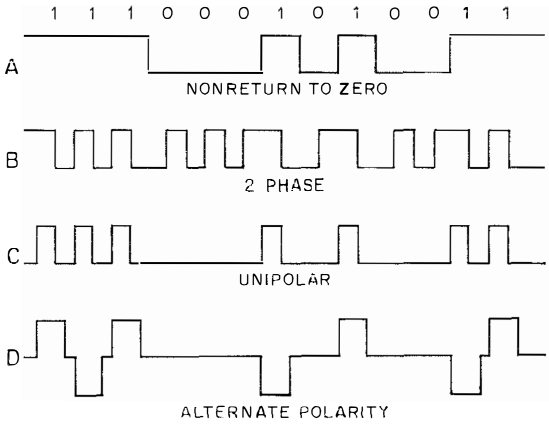

Figure 1—Types of pulse-code modulation.

4.1.4 *Alternate Polarity*

Alternate-polarity modulation uses three levels (Figure 1*D*). One information element is represented by the middle level, while the other, depending on the parity of its row, is represented by pulses of identical shape but alternate polarity.

The advantages of alternate-polarity modulation with regard to the transmission of the direct-current component and the required bandwidth are evident. The level of the synchronization signal varies with the density of the pulses of the same polarity transmitted. On the other hand, it can be shown that most of the energy for the synchronization signal comes from a frequency band about half the frequency of the synchronization signal. This is an appreciable advantage in protection against crosstalk.

4.2 REPEATER FUNCTIONS

The repeaters must eliminate spurious signals that are superposed on the pulse signal and also must normalize this signal in phase, amplitude, and shape.

Furthermore, repeaters must be supplied with power from the transmission line itself and provide the necessary means to localize breakdowns.

To accomplish these tasks, the repeater comprises the following units.

(A) Input and output transformers.

(B) An equalizer and amplifier, which compensate for variations of line characteristics with respect to frequency, and which raise the received signal to an adequate level for processing.

(C) Devices to extract the synchronization, eliminate spurious signals, retime the pulse signals, normalize their amplitude, and reshape them.

(D) A loop mechanism to localize breakdowns.

Repeater complexity (and therefore the cost) depends largely on the characteristics of the transmission medium and on the spectral properties of the transmitted signal. Only the spectral properties can be conveniently changed and therefore are of the greatest importance in achieving quality synchronization.

4.3 SYNCHRONIZATION METHODS

We have already discarded the direct transmission of the synchronization signal because of high cost. The indirect methods can be either of the phase-locking or of the filtering types. Repeaters using a phase-locked oscillator (sinusoidal or otherwise) give excellent results. They are, however, less-frequently employed than the other methods because they are more expensive. Filtering is used in the majority of cases, and the spectral properties of the random signals received are most important. These spectral properties have led us to study various ways of modifying the structure of the transmitted signals to produce most-favorable results.

4.3.1 *Simple Filtering*

Filtering is by far the simplest method. The output signal of the amplifier is merely sent, possibly cleared by peak-clipping of certain troublesome components, through a narrow-band filter tuned to the synchronization frequency. The spectrum of the received signal possesses a line at this frequency. Among the types of modulation mentioned, only unipolar is suitable, if the code is almost complete.

Bennett [2] has shown that the signal formed by a group of such random pulses has a periodic average.

If f_r is the synchronization frequency, that is, the maximum frequency of the transmitted information, if d is the density of the pulses, and if the shape of a pulse is described by the function $g(t)$, its Fourier transform is

$$G(f) = \int_{-\infty}^{+\infty} g(t) \exp(-2\pi jft)dt \qquad (1)$$

and the component at frequency f_r of the signal formed by the group of pulses has for its amplitude

$$d \cdot f_r \cdot G(f_r).$$

It can be shown that the level of the synchronization signal varies with respect to the density of the pulses. It is much-more serious that the phase shift of the synchronization signal varies with respect to the input signal, depending on the shape and particularly on the density of the pulses.

This phenomenon is even-more troublesome if certain restrictions are not enforced for the codes, as they can be formed by a great number of elements.

For example, if an 8-unit code is used and if the combination *00000000* is excluded, the phase-shift is capable of reaching 1 radian! The interaction between the structure of the transmitted codes and the ease of restoring synchronism in the repeaters is apparent.

The difficulties encountered in the development of the repeaters have naturally led to research into simple methods of modifying the structure of the codes, to bring the variations of the synchronization signal within tolerable limits.

The property of this structure that interests us here is the reduction of the density variation of the pulses representing the code elements. This means that it will be possible to use only a part of the 2^n combinations permitted by a code with n binary elements. The Bell Telephone Laboratories have already taken a timid step in this direction by excluding the combination *0* from the group of 256 possibilities given by the 8-unit code of their *T1* system [3, 4].

A pseudoternary code with zero disparity has been proposed by Neu [5]. In this code the ternary digits *0* and *2* are replaced by the binary doublets *01* and *10,* and the digit *1* is replaced by the doublets *00* or *11* depending on the parity of its row. Such a code possesses the interesting property of using practically the same number of zeroes and of ones, no matter what message is transmitted.

The equipments *Mk 1* and *Mk 2* of Standard Telecommunication Laboratories [6] use a code with unit disparity. In *Mk 2,* 4 or 5 elements are always present among the 9 permitted positions.

4.3.2 *Filtering and Nonlinear Processing of the Coded Pulses*

The method described in Section 4.3.1 offers the advantage of simplicity. Nevertheless, its use may be prohibited for various reasons, such as the bandwidth available or the level of crosstalk.

Spectral analysis of the signals obtained by means of nonreturn-to-zero, 2-phase, and alternate-polarity modulations shows that they do not give a line at the synchronization frequency. This is particularly obvious if infinite sequences of *1* are chosen for nonreturn-to-zero and alternate-polarity modulations and *01* sequences for 2-phase modulation. It therefore becomes necessary to process the signals before filtering.

One of the simplest operations that produces the desired line is rectification, which can on occasion be associated with peak-clipping. This is the method commonly employed. Here again the level and phase of the synchronization signal, obtained at the output of the filter that follows the rectifier, may vary depending on the type of modulation used and on the configuration of the codes. From this point of view, 2-phase modulation is most favorable because its variations are practically independent of the configuration of the codes. However, the required bandwidth is almost always the reason this type of modulation is rejected.

Nonreturn-to-zero modulation is most unfavorable because, without very-severe restrictions on the possible configurations of the codes, the

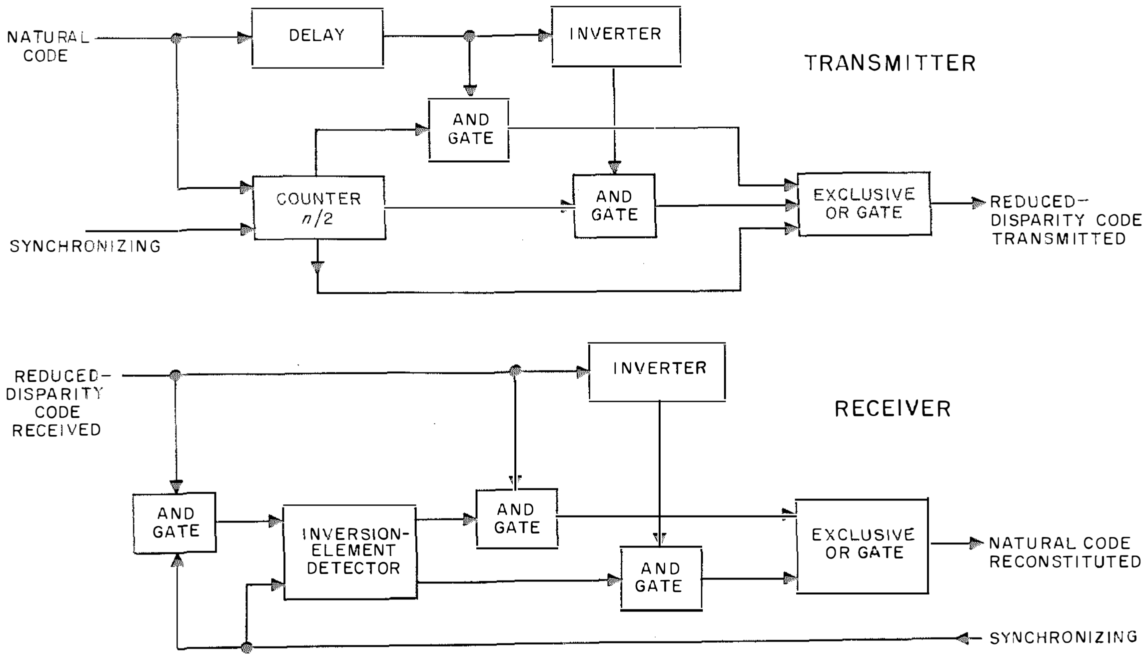

Figure 2—Device for reducing the disparity of the codes.

fluctuations of the synchronization signal are greatest.

Alternate-polarity modulation permits use to be made of the codes with reduced or null disparity, as does unipolar modulation for the simple-filtering diagram.

4.3.3 *Partial Conclusion*

The importance of reducing the disparity of the codes to facilitate transmission with pulse-code modulation became evident very quickly.

A request for a patent concerning a coder designed for this capability was filed in the United States in 1951 by Émile Labin and Pierre Aigrain of Federal Telecommunication Laboratories.

Unfortunately, the greater part of the codes heretofore recommended, inconveniently need a special coder. In addition, it may be necessary to transmit information already in code form either independently or at the same time as the information coming from preceding coders; in this case a relatively complex translator is necessary.

It is with the aim of profiting from the advantages offered by the reduction of the disparity of the codes from the point of view of the facility of transmission and to avoid the use of special coders that the mechanism described hereafter has been conceived.

5. Reduction in Disparity of the Codes

The advantages of reducing the disparity of the codes having been proved by experience as well as theoretically, it would be useful to examine the cost advantages. The problem may be presented in two very-different ways.

(A) Adaptation of a transmission system using pulse-code modulation to tasks for which it was not intended. An example is the use of a line equipped with repeaters intended for multiplex telephone transmission to transmit high-speed data. This is also the case if a system conceived for a transmission medium and given distances is used under much-more-unfavorable conditions than originally foreseen.

(B) Development of a transmission system as versatile as possible at a competitive price.

The solution is a simple equipment that permits a considerable reduction of the disparity of the codes and is suitable for operation with any type of information source.

5.1 DISPARITY-REDUCTION DEVICE

Let us suppose it is necessary to transmit a natural binary code with n elements. Reducing the disparity of the codes transmitted requires that more than n elements be sent. The original code can be transmitted normally if it possesses a number of ones greater than or equal to $n/2$; its binary complement can be transmitted if the number of ones is fewer than $n/2$.

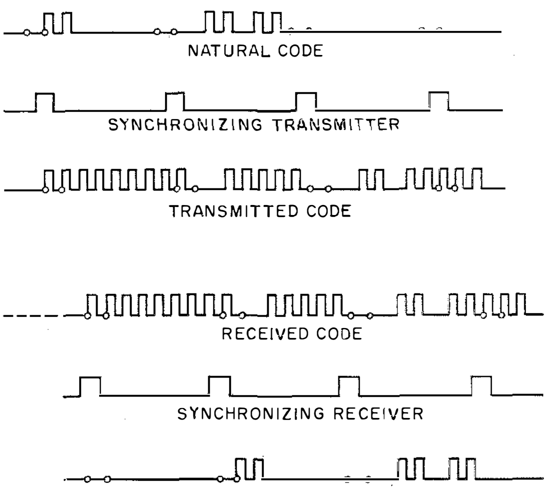

Figure 3—If the natural binary code has $n/2$ marks ($n = 7$ in this figure), it will be transmitted directly, but if not, the elements will be sent inverted as a binary complement. Therefore the first natural code group of 2 marks and 5 spaces appears delayed by 1 group in the transmitted code as 5 marks and 2 spaces. (The mark between the 2 small indicator circles identifies the inverting action.) The next group of 4 marks and 3 spaces is sent with no modification and with no inversion indicator.

A supplementary element indicates whether the natural code or its complement is transmitted.

Figure 2 is the diagram of such an equipment, and Figure 3 gives the corresponding waveforms.

5.2 COMPARISON OF REDUCED-DISPARITY CODES

We have seen that it is illusory to consider the merits of a type of modulation while ignoring the type of code used with it.

Table 1 summarizes the respective advantages of the types of code and modulation foreseen at the present time for multiplex telephone transmission.

Only modulations permitting the use of minimum bandwidths have been retained. It can be shown, however, that using different code lengths than those indicated in the table does not in any way modify the results.

5.3 INFLUENCE OF REDUCED-DISPARITY DEVICE ON THE ENERGY SPECTRUM FOR RANDOM CODES

The energy spectrum of a pulse train representing random codes depends on the form of the pulses and the structure of the codes.

5.3.1 *Unipolar Pulses*

Using the preceding notations, the energy spectrum of a random sequence of unipolar pulses is presented by the function

$$\begin{aligned} P(f) &= d(1-d)f_r|G(f)|^2 \\ &\quad + d^2 f_r^2 |G(f)|^2 a(f) \qquad (2) \end{aligned}$$

$$a(f) = \begin{cases} 1 \text{ if } f = nf_r \\ 0 \text{ if } f \neq nf_r. \end{cases}$$

(A) Natural complete binary code

$$P_1(f) = 0.25 f_r |G(f)|^2 a(f). \qquad (3)$$

(B) $n/2$ disparity code

$$P_2(f) = f_r |G(f)|^2 [0.18 + 0.56 f_r a(f)]. \qquad (4)$$

TABLE 1

CODES AND MODULATION FOR MULTIPLEX TELEPHONE TRANSMISSION

Code[1]	Modulation	Number of Elements	Efficiency of Coding[2]	Variation of Direct-Current Component[3]	Level Variation of Synchronization Signal[4]	Maximum Length of a Sequence[5]
Pure binary (*0* excluded)	Alternate-polarity	8	0.99	0	8/1	14/8
Disparity $n/2$	Alternate-polarity	8	0.87	0	2/1	8/8
Disparity $n/2$ (*0* excluded)	Nonreturn-to-zero	8	0.87	0.75	8/1	14/8
Disparity *1*	Nonreturn-to-zero	9	0.89	0.25	9/1	10/9
Disparity *1*	Alternate-polarity	9	0.89	0	5/4	10/9
Pseudoternary	Nonreturn-to-zero	10	0.76	0	5/2	4/10

[1] The code lengths used are those actually proposed by the authors of the different pulse-code-modulation transmission systems.

[2] The efficiency of the coding is defined as the ratio of the logarithm with base 2 of the number of combinations used to the number of binary elements of the code.

[3] The variation of the direct-current component is the ratio between the maximum increase of this component and its minimum value.

[4] The variation of the synchronization signal is the ratio of its maximum to minimum level. These levels correspond to groups of repetitive codes.

[5] The maximum length of an uninterrupted sequence of identical symbols referred to the number of elements of the code.

It should be noted that the amplitude of the line at the synchronization frequency is more than doubled with respect to the preceding case, while the continuous portion of the spectrum is appreciably reduced.

5.3.2 *Pulses of Alternate Polarity and Same Shape*

The energy spectrum of a random sequence of alternate-polarity pulses is represented by the function

$$Q(f) = 2d(1-d)f_r|G(f)|^2 \cdot \frac{1-\cos 2\pi f/f_r}{1+(2d-1)^2+2(2d-1)\cos 2\pi f/f_r}. \quad (5)$$

The absence of a line at the synchronization frequency will be noted, which implies the impossibility of obtaining this frequency by simple filtering.

(A) Complete natural binary code

$$Q_1(f) = 0.5f_r(1-\cos 2\pi f/f_r)|G(f)|^2. \quad (6)$$

(B) $n/2$ disparity code

$$Q_2(f) = 1.5f_r \frac{1-\cos 2\pi f/f_r}{5+4\cos 2\pi f/f_r}|G(f)|^2. \quad (7)$$

Figure 4 permits comparison of the spectra obtained if the transmitted pulses are sinusoidal. The gain obtained by concentrating energy in the neighborhood of $f_r/2$ to the detriment of frequencies below $f_r/6$ may be noted.

6. Conclusion

We have considered some of the essential problems in transmission when pulse-code modulation is used.

We are particularly interested in systems that operate at high speed and therefore require repeaters. These systems are generally used for multiplex telephone transmission, but they can be used for television as well as for the transmission of numerical (or alphanumerical) information of any origin.

We have primarily shown that an appropriate modification of the structure of the transmitted codes enables the transmission to be improved. This modification generally requires adding a certain redundancy to the message, but it is emphasized that this does not necessarily correspond to a reduction of the maximum output of the channel used.

It is necessary to emphasize the preceding remark because within the next decade the characteristics of transmission systems using pulse-code modulation are likely to be frozen by the various national administrations and by the Comité Consultatif International Télégraphique et Téléphonique.

The system developed by the Laboratoire Central de Télécommunications has been conceived taking these facts into account. It presents the major advantages of great simplicity and flexibility of use. It is inexpensive and highly reliable.

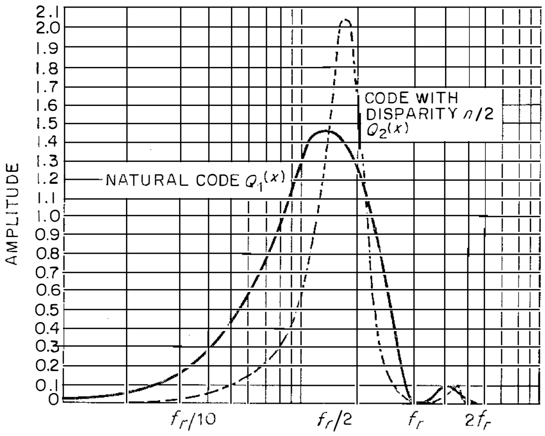

Figure 4—Energy spectrum of a random code train using alternate-polarity pulse modulation.

$$Q_1(x) = \frac{1}{4f_r}\left[\frac{\sin^2 x}{x(1-x^2/\pi^2)}\right]^2$$

$$Q_2(x) = \frac{3}{8f_r}\cdot\frac{1}{5+4\cos 2x}\left[\frac{\sin^2 x}{x(1-x^2/\pi^2)}\right]^2$$

with $x = \pi f/f_r$.

7. Acknowledgments

Permit me here to thank all those who have contributed to this work at Laboratoire Central de Télécommunications, in particular Mr. P. Girard, who had the responsibility of setting up the model and making the associated tests.

8. References

1. P. Mornet, A. Chatelon, and J. Le Corre, "Application of Pulse-Code Modulation to an Integrated Telephone Network," *Electrical Communication,* volume 38, number 1, pages 23–55; 1963.

2. W. R. Bennett, "Statistics of Regenerative Digital Transmission," *Bell System Technical Journal,* volume 37, number 6, pages 1501–1542; November 1958.

3. J. S. Mayo, "A Bipolar Repeater for Pulse Code Modulation Signals," *Bell System Technical Journal,* volume 41, number 1, pages 25–97; 1962.

4. M. R. Aaron, "PCM Transmission in the Exchange Plant," *Bell System Technical Journal,* volume 41, number 1, pages 99–141; 1962.

5. W. Neu, "Some Techniques of Pulse Code Modulation," *Bulletin des Schweizerischen Elektrotechnischen Vereins,* volume 51, number 20, pages 8–17; 8 October 1960.

6. K. W. Cattermole, "Low Disparity Codes and Coding for P.C.M. Transmission Aspects of Communication Networks," presented at I.E.E. Conference, London; February 1964.

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Mr. Chatelon is a member of the Société Française des Électroniciens and of the Institute of Electrical and Electronics Engineers.

Small-Diameter Coaxial Cable Using Moulded-Shell Construction

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1. Introduction

For many years the only internationally-standardized long-distance coaxial cable was the 2·6/9·5-millimetre design recommended by the International Telegraph and Telephone Consultative Committee (CCITT), which has an outer conductor of 0·375-inch (9·5-millimetre) internal diameter. The development and design of this type of cable from 1935 to 1950 was surveyed in an article published in *Electrical Communication* in 1953 [1]. The final version of this type of cable has been in regular production since 1950, and today more than 30 machines of our design and manufacture are installed in 20 cable factories in 14 countries throughout the world.

In recent years, however, a second internationally-standardized long-distance coaxial cable design has gradually developed, made possible by the invention and subsequent exploitation of the transistor. Some information on the origin and early stages in the development of this new cable appeared in *Electrical Communication* in 1959 [2]. When this article was written it was appreciated that the reduced manufacturing and installation costs of transistor amplifiers, together with their low operating voltage and power consumption, tended to modify the balance between repeater and cable costs that had existed previously and had effectively determined the dimensions of the original standard cable design. It was further appreciated that this modification favoured an increase in the number of repeaters and a reduction in cable size, but the exact amount of this reduction and precise construction details had not at that time been agreed on internationally.

2. Early Design of Small Coaxial Core

The cable described in the final sections of the 1959 article had an outer conductor with an internal diameter of 0·163 inch (4·1 millimetres) and used cellular polyethylene as the dielectric material. From 1958 to 1962 we manufactured more than 500 miles (800 kilometres) of this type of core in Great Britain, which was used to provide a total of 180 miles (290 kilometres) of multi-core cable for 10 major contracts. Over the same period, considerably larger quantities of similar cables were made by various European manufacturers operating under license from the International Telephone and Telegraph System.

This type of coaxial core had two advantages over more-recent designs. Firstly, by virtue of its relatively simple construction it was possible for most cable factories to commence manufacture with very-little plant investment, insulation being applied on a conventional polyethylene extruder and the outer coverings being applied on existing coaxial core-forming machinery, suitably modified. Secondly, since no special extrusion tooling was required, dimensional changes could easily be made to meet local conditions and requirements.

One disadvantage was that, for reasons of mechanical stability, the effective permittivity of the cellular polyethylene insulation could not be reduced below about 1·40 using conventional extrusion methods. Even using special techniques, such as vertical extrusion or compounding the expanding agent with high-density polymers, the absolute limit of stability was found to be approximately 1·30. These values contrasted unfavourably with the figure of 1·07 obtained on the standard disc-spaced cable of the 2·6/9·5-millimetre design. International discussion on the standardization of small-diameter coaxial cable designs indicated that the preferred permittivity would be in the range of 1·15 to 1·20, and for such values cellular polyethylene was obviously unsuitable.

It is difficult to maintain a desired dielectric constant in polyethylene expanded by more than

100 per cent. In addition to the difficulty of obtaining raw material having a correct and consistent degree of potential expansion, the extrusion process is extremely heat sensitive and small fluctuations in either internal or external thermal conditions can produce intolerably large impedance variations in the coaxial core. With care, the impedance variations in the 0·163-inch (4·1-millimetre) diameter coaxial core could be maintained within the limits recommended by the International Telegraph and Telephone Consultative Committee for telephony, but it was known that some authorities were anxious to impose television-quality limits on their final design. A notable example was the British Post Office—whose first draft specification, published in 1961, contained impedance regularity limits that were more stringent than those specified at that time by either itself or the International Telegraph and Telephone Consultative Committee for the standard 0·375-inch (9·5-millimetre) design. The reasons for these stringent limits were given in an article [3] published in 1964.

The draft specification also stated that the internal diameter of the outer conductor was to be 0·174 inch (4·4 millimetres). Since this was less than half the size of the standard disc-spaced design, it followed that all dimensional tolerances on the new product would have to be approximately halved to obtain equivalent degrees of electrical uniformity on the two cable designs.

3. Design Basis for New Cable

The reduction of already stringent dimensional tolerances was a major feature in the design of the following component items of the new type small-diameter coaxial cable.

3.1 Centre Conductor

To obtain the specified impedance value a centre-conductor diameter of approximately 0·047 inch (1·2 millimetres) was necessary. Wire of this size is seldom commercially available with a dimensional accuracy of better than ±0·0003 inch (0·0076 millimetre). Such a variation would alone produce impedance changes in a 0·174-inch (4·4-millimetre) cable comparable in magnitude to the total variations permitted from all sources. On the new design a tenfold reduction in this variation was desired, and it was therefore decided to include a wire-drawing operation as part of the manufacturing process.

3.2 Insulation

To comply with the proposed limits for impedance regularity, a moulded insulation was preferred to a directly extruded type, since a moulded product can be manufactured with high precision—a fact demonstrated 20 years ago during the development of the 0·975-inch (25-millimetre) coaxial cable [1, 4]. It was therefore decided to concentrate on the development of a continuously moulded form of insulation. This development is discussed in Section 4.

3.3 Outer Conductor

It was decided to construct the outer conductor from a flat copper tape with corrugated edges [5]. This technique is well established and has been used in the manufacture of 0·375-inch (9·5-millimetre) coaxial cable for many years, but in reducing to 0·174-inch (4·4-millimetre) diameter the dimensions of the raw material became of considerable importance.

The best quality copper tape commercially available locally is manufactured to limits of ±0·0003 inch (0·0076 millimetre) in thickness and ±0·0015 inch (0·038 millimetre) in width. In a 0·174-inch (4·4-millimetre) diameter cable the worst combination of these limits would produce an impedance change having the unacceptable magnitude of 0·7 ohm.

The width variation factor was effectively eliminated by making the size of the final die on the outer-conductor forming tool such that only the minimum width of tape would pass through as a tube unreduced in size, any wider tape being subjected to a small amount of drawing down. Control of the thickness variation factor, on the other hand, presented considerable difficulty. At the suppliers' works the copper ingots are individually rolled to size, so that although there is usually little thickness variation within each of the resulting pads, experience has shown that a similar degree of uniformity does not always exist between two consecutive rollings.

Cables are normally ordered in standard lengths for direct burial in the ground. The copper tape can therefore be ordered in integral multiples of these standard lengths, thus obviating the need for copper tape joints. In the United Kingdom, however, coaxial cables are normally drawn into underground ducts and hence standard lengths are seldom encountered, so that copper tape jointing is economically desirable. Impedance mismatches at these joints can, however, be limited by selecting for jointing copper tapes having compatible physical dimensions.

3.4 SCREENING TAPES

It was realized even before the development of the 0·163-inch (4·1-millimetre) coaxial cable that the conventional screen consisting of two helical steel tapes applied in the same direction was not an efficient arrangement and better crosstalk values would result if one or both screening tapes were applied longitudinally. At that time, however, it was not considered desirable to depart from standard procedures in view of the extensive modifications that would have been necessary to existing machinery. Although very efficient, longitudinal screening tapes are mechanically less satisfactory and it was decided that this form of construction would be best avoided on the new design, since processing from small-diameter bobbins was envisaged.

A study of various alternative constructions indicated that crosstalk would be improved if the two screening tapes were applied in opposite directions, crossing each other at right angles. It was therefore decided to adopt this form of construction for the new cable, and for convenience of machine design it was considered best to apply each tape at an angle of 45 degrees. To obtain continuous contact between the two tapes at cross-over it was necessary to apply the inner tape with a slight gap, whilst to obtain complete screening at cross-over it was equally necessary to apply the outer tape with an overlap.

It is of interest to note that a comprehensive theoretical and practical study of this problem carried out recently in Japan [6] has also concluded that on this size of cable optimum mechanical and electrical results can be obtained if the two steel tapes are applied in opposite directions and cross approximately at right angles.

4. Development of Moulded-Shell Insulating Machine

The primary requirement of the new insulating machine was that it be capable of producing continuous lengths of insulated conductor having high dimensional accuracy. Some form of mechanical moulding process was favoured, but this did not determine the precise form the insulant should take. The final form was evolved by making two separate selections, namely, the method of centre-conductor location and the type of moulding process employed.

4.1 CENTRE-CONDUCTOR LOCATION

Of the many methods for centre-conductor location that were considered, two are worthy of mention. The first used a series of projections formed on the surface of a flat tape [7]. If the tape was bent to form a tube, the projections formed the spokes of a wheel with the centre conductor as the hub. Some exploratory work was performed on this method of construction and small samples were made, but it was felt that the construction had two disadvantages: (*A*) With the tape thickness necessary to produce the desired permittivity, difficulties were anticipated in making a continuous seam in the edges, and (*B*) the spaces between the projections would allow water to penetrate axially along the core. This second point was of relatively minor importance, but some authorities have expressed a wish for resistance to axial water penetration in coaxial cores.

So far, this design has been used at Standard Telephones and Cables only on experimental lengths of 0·087-inch (2·2-millimetre) diameter coaxial cable, but it is of interest to note that a similar form of construction was developed for 0·174-inch (4·4-millimetre) diameter cable by the Nippon Telegraph and Telephone Public Corporation together with three major Japanese cable companies in 1963 [8]. It is now the standard design for this type of cable in Japan.

The second method of centre-conductor location, which was the one adopted, used discs to locate the centre conductor [9]. This overcame the problem of axial water penetration and, due to the particular manufacturing methods that were adopted, also simplified the sealing problem.

4.2 Moulding Process

Numerous schemes for moulding were suggested involving the use of travelling injection moulds, but these were rejected in favour of the pressure moulding of a continuous tape between rollers. The mechanical reliability and potential accuracy of such a method were considered to be greater than could be achieved by using travelling moulds.

It was then necessary to check the calculated dimensional requirements of the moulded insulant. This was done by making small sections of insulant in an injection moulding tool and preparing short lengths of coaxial core by hand. Measurements from these samples enabled the final dimensions of the moulded insulant to be determined.

The final manufacturing sequence can be seen from Figure 1, which shows the various stages in the formation of the fully insulated centre conductor. A plain tape of polyethylene is extruded and, whilst still in a plastic state, is pinched between moulding wheels. These produce the two halves of the final insulant form, supported by a number of intermediate strips that strengthen the entire moulding and provide a reservoir of polyethylene to assist in the moulding process. The complete moulding is then cut in half lengthwise and the excess moulding flash is trimmed from the outside. The two halves are then placed face to face, their facing surfaces are heated to the point of plasticity, the centre conductor is placed between them, and they are pressed together by sealing wheels. The support strips are then removed, leaving the finished product.

4.3 Initial Production

The individual problems encountered in the development of the moulded-shell insulating process were solved with the aid of separate mechanisms, constructed mostly from component parts that were already available. As the development progressed, it became necessary to combine the individual operations to form a working process. This led to the construction of a machine, built by assembling the various experimental mechanisms on a slotted metal framework in the most-convenient manner.

Although the operation of this machine was not simple (it used 8 electric motors, all connected through separate switches), it provided valuable experience and made it possible to avoid many operating problems on the subsequent production machine.

However, since the demand for 0·174-inch (4·4-millimetre) coaxial core developed in advance of production machinery, this mechanically unreliable experimental machine was pressed into full-scale manufacture, producing 280 000 yards (250 kilometres) of insulated conductor before it was finally dismantled.

As soon as it proved possible to manufacture reasonable lengths of insulated conductor, the emphasis passed to achieving and maintaining quality. Inspection of the moulded insulant posed a serious problem, for it was apparent that the average electrical effect of the insulant was far more uniform than was indicated by dimensional measurements of the moulded shell. Attempts were made to acquire some form of capacitance monitoring device having the necessary sensitivity, but when general production commenced no such instrument was available.

The method of inspection finally adopted as a rough indication of the potential permittivity of the insulant was that of weighing a unit length after it had been stripped from its centre wire. This method can only be applied to test samples, and the question of regulating the insulant during a production run remained unsolved. A test programme was therefore instituted in which the various influencing factors in the process were independently adjusted and samples were taken of the resulting moulded shell to determine the effects. The results showed that it was the temperature of the moulding wheels in combination with the speed at which they were running and with the space between them that determined the weight of the moulded-shell insulant. The higher the temperature, the higher the speed, and the smaller the gap between the wheels, the lower would be the weight of the insulant. It was also found that a rapid degradation in moulding quality resulted if any of these factors was altered too far.

A system was therefore established in which control of moulding-wheel temperature was maintained, the machine was run at a fixed speed, and no adjustment of the wheel separation was permitted. Under these conditions the product remained sensibly uniform over each production length and by examination of the test results on sample ends it was possible to adjust the working temperatures to maintain the effective permittivity of the insulant within very-close limits—in fact, to a point where variations in the moulded shell could be ignored as a serious source of impedance variation in the cable.

4.4 Centre Conductor

Attention was next turned to the centre conductor. Production of other forms of coaxial cable had shown that commercially produced copper wire would be unsuitable because of its lack of uniformity. It was decided, therefore, to include a final wire drawing operation as part of the manufacturing process. Because of the comparatively small diameter of this centre conductor, a separate drawing operation proved unsuccessful. Variations in stretch (inevitable in re-reeling the wire at high speeds) manifested themselves as pulse reflections in the electrical testing of the final cable. The drawing operation was therefore included in the machine that produced the moulded insulant. The operation presented no difficulty once the correct form had been established for the drawing die, but because the moulded-shell machine could run efficiently only in continuous production, the problem of changing wire bobbins became of importance.

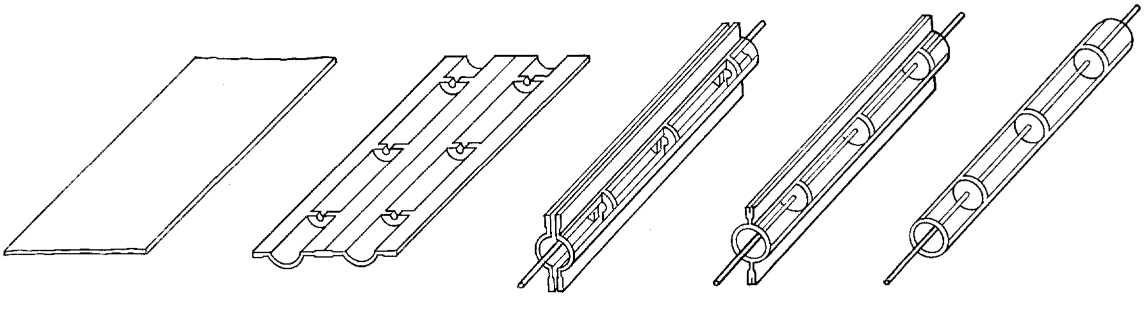


Figure 1—Stages in the production of moulded-shell insulation.

It was essential that the machine be able to produce continuous but variable lengths of insulated conductor from a bobbin of wire the precise length of which was not known. It was therefore decided to provide a means whereby the supply wire could be jointed while the machine was in operation. A wire accumulator was introduced with a storage capacity of 30 yards (27 metres), and a method of welding the centre conductor was devised that produced so little welding flash that no variation in size could be detected in the subsequently drawn wire.

4.5 PRODUCTION MACHINE

The production machine that was subsequently designed incorporated the desirable characteristics of the experimental machine, bringing the previously established production techniques on to a rational basis. The final form of the moulded-shell machine can be seen in Figure 2, which shows a general view of the machine without the control cabinet, which if left in position would obscure much of the machine. To the right is the extruder, which has a barrel 2 inches (50 millimetres) in diameter and uses the normal type of metering screw having a length-to-diameter ratio of 20:1 and a compression ratio of 4:1. The extruder has a simple gravity feed, is equipped with screw-cooling, has a cooled feed section, and is driven by an electronically controlled variable-speed direct-current motor. The wire drawing unit is to the left.

As the moulding process deposits surplus polyethylene in the form of a moulding flash, no speed regulating system is necessary. The drive to the extruder is therefore independent of the functioning of the rest of the machine.

Temperature regulation is, however, very important and good-quality temperature controllers are used on all barrel zones and on the extrusion diehead. A temperature indicator measures the inlet and outlet temperatures of all the cooling water systems.

The tape-moulding unit is situated adjacent to the extruder, and the extrusion die is so positioned that the extruded tape falls on the surface of one of the moulding wheels. The alignment of these wheels can be adjusted so that the extruded tape falls exactly on their axis. The tape

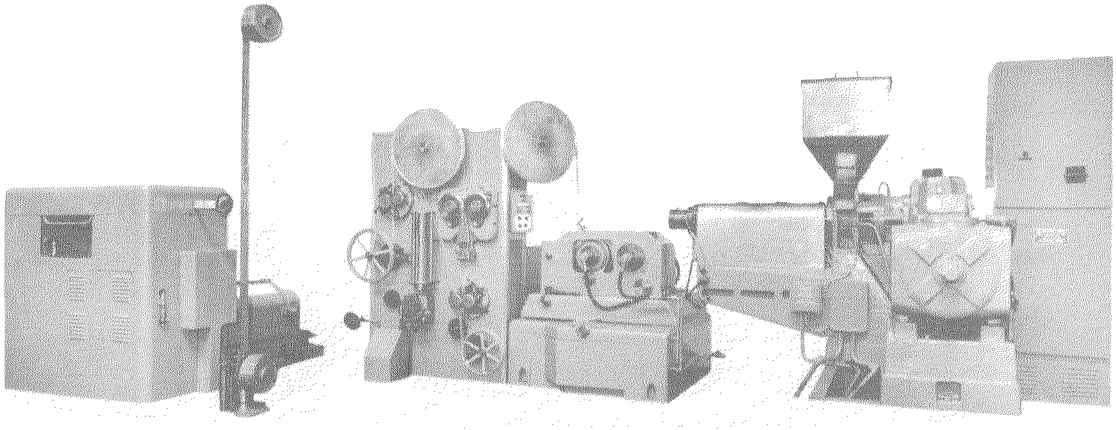


Figure 2—At the right is the polyethylene extruder, the ribbon from which falls on the surface of one of the moulding wheels in the next unit. After moulding, the tape goes to a third unit, where it is sealed round the centre conductor and the excess flash is trimmed. At the far left is the wire supply, wire drawing equipment, and accumulator.

is drawn down between the moulding wheels, adheres to the wheel that is more remote from the extruder, and is finally stripped off by a tape guide after 180 degrees of rotation of this wheel. The separation between the moulding wheels is under micrometer adjustment. Both wheels are water-cooled, and an indication of the degree of cooling is obtained by comparing measurements of input and output water temperatures.

From the tape-moulding unit the moulded tape passes over a large transfer wheel, then down to the base of the sealing and trimming unit, which is immediately to the left of the moulding unit and is shown at close range in Figure 3. At the bottom right is a speed control wheel that adjusts the speed of the drive for this unit to match that of the moulding unit. Immediately above this speed control wheel is the first trimming unit, which removes the moulding flash and slits the tape into halves. These halves then pass upwards to the sealing heater; the right-hand half is reversed so that the two forms face one another. The two halves pass over the wedge-shaped heating element and the centre conductor passes behind the first trimming cutters and into the centre of the heater. It is then enclosed between the two halves of the moulded shell, which are then sealed together by the sealing wheels. A means of adjusting the coincidence of the two halves of each disc is provided immediately below the sealing heater.

After being sealed, the moulded shell passes over a further transfer wheel at the top of the unit, which serves to measure the length of moulded shell produced, and travels down the left side where the final trimming unit removes the redundant support strips. The completed moulded shell is transferred to the take-up stand via the speed control wheel at the left below the final trimming cutters.

The surplus strips are guided by pins into the top of the reclaiming heater in the centre of the unit. The heated strips are drawn down by the action of the reclaiming unit immediately below the heater. They are compressed together and granulated, the reclaimed granules being deposited in a bin at the foot of the unit.

The large cabinet at the left in Figure 2 houses the wire supply bobbin, wire sizing die, oil tank, oil circulation pump, wire drawing capstan, drive for the take-up stand (including the drive for its traverse), and other ancillary equipment.

Adjacent to the wire drawing and take-up cabinet can be seen the wire accumulator, which stores wire for approximately 3·5 minutes of production time, thus enabling a new bobbin of wire to be joined in while the machine is running. The bottom 6 inches (15 centimetres) of movement on this accumulator is used to provide speed control for the wire drawing capstan.

5. Development of Machine for Forming Outer Conductor

The provision of an outer conductor and metal screening for the 0·174-inch (4·4-millimetre)

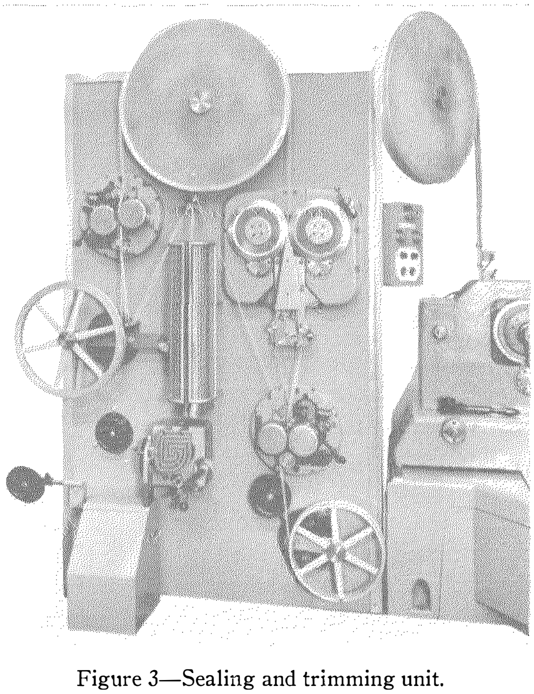


Figure 3—Sealing and trimming unit.

diameter coaxial cable involved no special difficulty, since similar techniques had been used to produce earlier types of coaxial cable. This size of cable, however, introduced one variation to the standard procedure; the two steel screening tapes had to be lapped in alternate directions. The mechanical effects of this were not immediately realized. An old coaxial machine previously used for the production of 0·375-inch (9·5-millimetre) diameter coaxial core was modified to form the copper outer-conductor tube and to apply two screening tapes and two covering papers. This produced core that was electrically satisfactory, and several early contracts were completed using core made on this machine.

5.1 Steel Tapes

When the production model of the moulded-shell insulating machine was brought into use, and the quality of the insulated conductor was thus improved, it became apparent that the application of the steel tapes on the outer-conductor forming machine was causing considerable impedance variations. Experiments showed that because the steel tapes were lapped in alternate directions and consequently were applied individually, their tensions were causing deflection in the formed outer conductor. Since this conductor was supported only by a plain circular die, the copper tube became distorted. Because the tension at which the steel tapes were applied to the core did not remain uniform, the degree of this distortion tended to vary from beginning to end of each pad of steel tape and also from pad to pad and from day to day. The method of supporting the copper tube was therefore modified. The plain circular die was replaced by a device shown in Figure 4. This consisted of a *U*-shaped supporting element for the outer conductor, the steel tape being introduced over the top of the *U*. These devices reduced the degree of deformation caused by the application of steel tapes but, although a much-better cable quality resulted, the level of cable impedance also increased because of the more-circular configuration of the outer conductor.

As the dimensions of the moulding wheels had been established by the time this development took place, the permittivity of the insulant was increased to reduce the impedance of the finished core to an acceptable level.

5.2 Outer Conductor

The outer conductor is formed from a flat copper tape with the edges lightly corrugated to prevent the possibility of overlap during subsequent processing of the cable. It has not been found possible to obtain supplies of copper tape with limits of accuracy better than 0·0006 inch (0·015 millimetre) in thickness and 0·003 inch (0·076 millimetre) in width. These variations have already been outlined in Section 3.3 together with the method used to minimize their effects. It should, however, be pointed out that the drawing down that occurs if tape of the widest permitted size is used produces very-little reduction in thickness, and the maximum improvement in impedance uniformity is thus achieved. The drawing-down operation results in these dies having a shorter life than those used for the production of coaxial core of 0·375-inch (9·5-millimetre) diameter, where drawing down is not necessary.

5.3 Production Machine

Although the modified machine produced satisfactory core as a result of this development work, the throughput speed was much below that of the moulded-shell machine. It was therefore considered desirable to construct an outer-conductor forming machine having a matching production capacity.

The throughput speed demanded that the steel-tape lapping heads should rotate at a speed that made a concentric type of head desirable. Such a head was designed to apply pads of steel tape, each capable of producing 1000 yards (915 metres) of core, without any significant variation in the tension of the steel tape as applied to the core from beginning to end of the pad. This head employed the same tape-application technique as was developed for the modified coaxial machine.

The decision to use concentric lapping heads made it desirable to provide an adequate reserve of tape pads on magazines coaxially placed with respect to the cable. The magazine requirements of the final machine were based on the production of 6 kilometres (3·7 miles) of core for each complete load of the machine, thus permitting the longest normal repeater-section length to be manufactured continuously.

The outer-conductor forming machine can be seen in Figure 5. The right-hand cabinet contains the supply stand for the bobbin of insulated centre conductor, the copper-tape supply unit, and the mechanism for brazing one copper tape to another. The substantially cylindrical part of the machine contains the 4 lapping heads, 2 for steel tapes and 2 for insulating tapes. The portable welder for joining one steel tape to another is in position for welding tape on the second tape head. Beyond the lapping

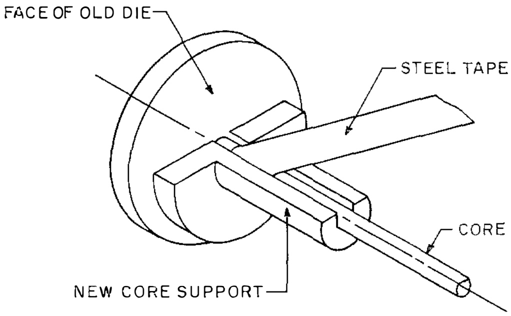


Figure 4—Improved method of core support for steel tape lapping.

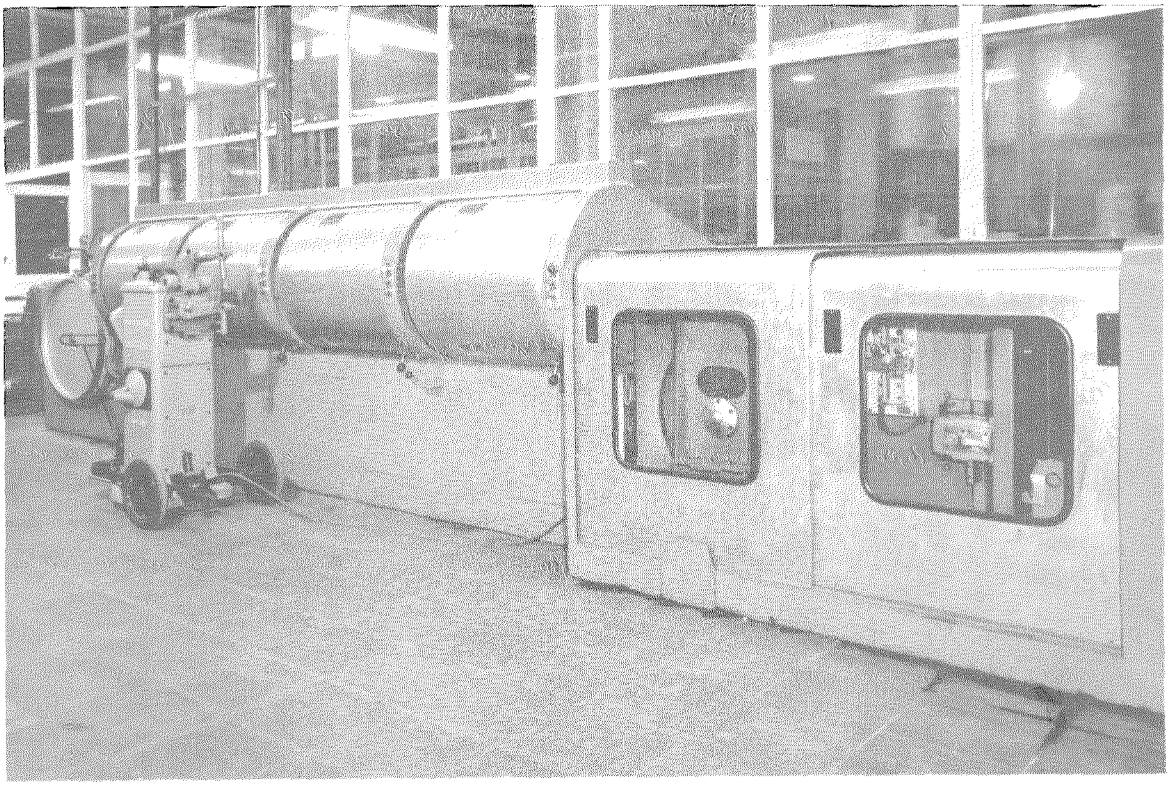


Figure 5—Outer-conductor forming machine.

heads at left can be seen the capstan and take-up stand, which are of conventional construction.

The steel-tape lapping head can be seen in Figure 6; the steel-tape pad is supported on a rotating disc to which is applied the pad-retarding torque. The steel-tape-tension control lever can be seen projecting just beyond the edge of the disc at the bottom of the head. This lever controls the torque applied to the pad. The tape is applied to the core by means of the special tape-applicator nose, which is the large bulbous section projecting from the end of the head spindle. The tape is guided by a groove that is tangential to the core; the tape is persuaded to take a helical form by means of a roller located immediately above it. The core is supported by a *U*-shaped groove, which is provided with different radii to accommodate the core before and after the application of the tape.

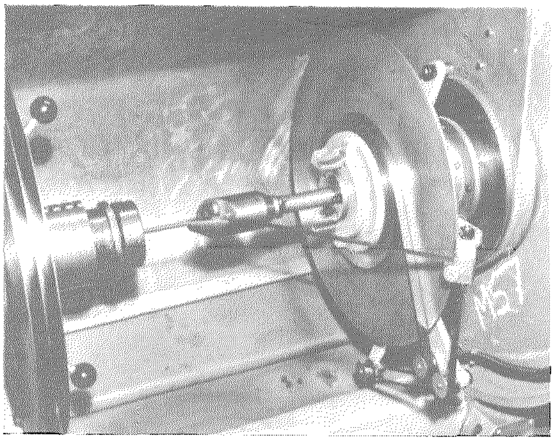


Figure 6—High-speed concentric steel-tape lapping head.

With normal operative care, such a machine in proper mechanical order will manufacture core that contains no impedance irregularities attributable to the machine processes.

6. Test Results

6.1 First Production System

The first long-distance cable system in the United Kingdom using coaxial cable of 0·174-inch (4·4-millimetre) diameter and transistor repeaters was supplied and installed by Standard Telephones and Cables. The cable for this system was made entirely on the prototype machinery described in Sections 4 and 5 in the summer and autumn of 1962, and was installed between Tavistock and Widemouth, England, the following winter. Jointing of the cables and the associated equipment was completed by the summer of 1963, and the system was opened for commercial traffic in October of that year.

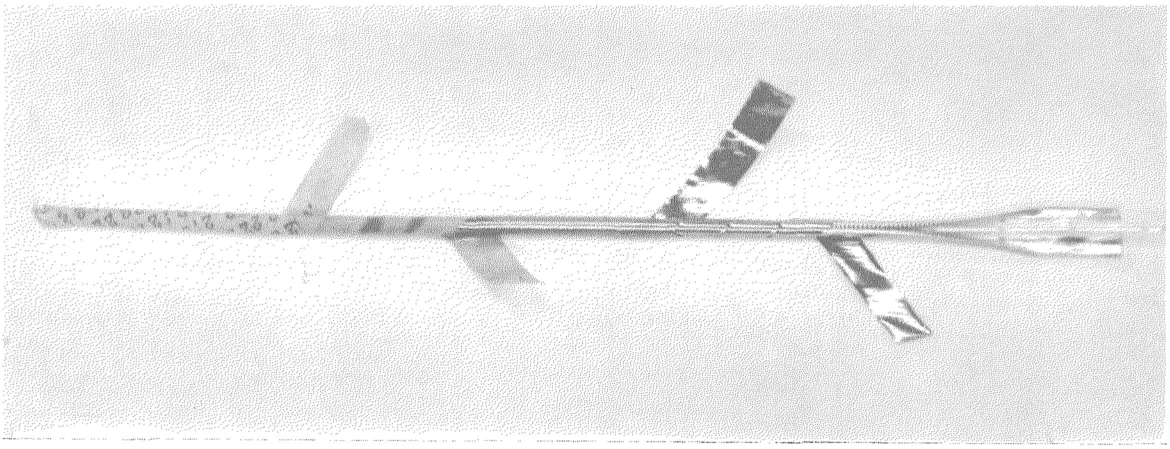


Figure 7—Coaxial core 0·174 inch (4 millimetres) in diameter showing component parts.

The cable route length of 29 miles (47 kilometres) is divided into 7 full repeater sections, each nominally 3·6 miles (5·8 kilometres) in length, with a half section at each end. The transistor repeaters have a nominal gain of 35 decibels at 1300 kilohertz, and the system is designed to carry up to 300 two-way speech circuits at 4-kilohertz spacing over each pair of coaxial cores, working over the line frequency spectrum from 60 to 1300 kilohertz with a line-regulating pilot frequency of 1364 kilohertz. The equipment includes automatic level regulation to compensate for attenuation changes caused by cable temperature variations, gain-control units (regulators) being fitted to alternate repeaters. All repeaters operate from a constant-current non-lethal direct-current source, thus allowing jointing work to be performed without removing power from other coaxial systems in service.

The cable for this system was of 4-core construction with 5 interstitial paper-insulated control pairs (see Figures 7 and 8). The cable core was lead sheathed and polyethylene protected for installation in underground ducts. Most of the cables were approximately 1100 yards (1 kilometre) in length, and approximately 200 lengths of coaxial core were therefore necessary to meet the overall requirements. Although the cable was made on prototype machinery, the electrical results obtained both in the factory and in the field were well within the tentative television-quality limits recommended by the International Telegraph and Telephone Consultative Committee at Geneva in 1962 and by the British Post Office, as shown in Tables 1 and 2.

6.1.1 *Impedance*

Figure 9 plots the impedance of a typical repeater section tested over the frequency spectrum from 0·06 to 7·5 megahertz. The smooth mean impedance at 1 megahertz was 75·0 ohms and the maximum deviation from the smooth mean curve was 0·75 per cent. On the complete contract the maximum recorded value of this deviation was 2·5 per cent.

6.1.2 *Attenuation*

Figure 10 plots the attenuation of a typical repeater section over the frequency spectrum from 0·06 to 7·5 megahertz. Figure 11 plots the same

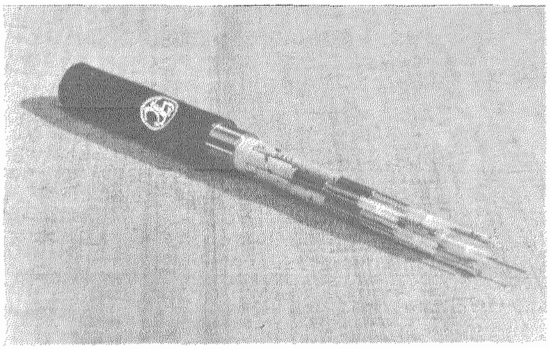


Figure 8—Cable containing 4 coaxial cores and 5 paper-insulated interstitial pairs.

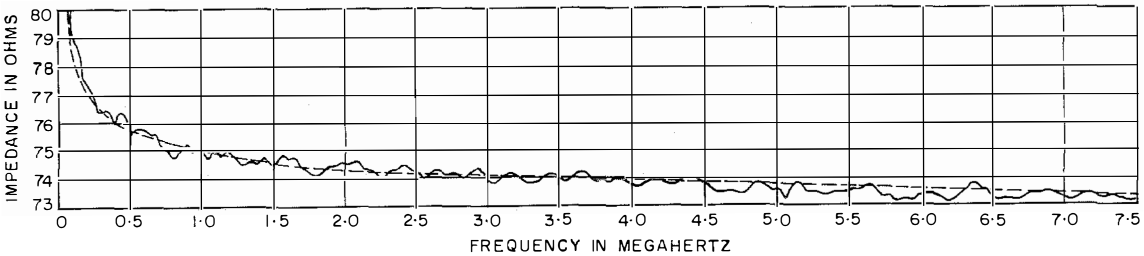


Figure 9—Impedance of a typical repeater section plotted against frequency. The smooth mean value at 1 megahertz is 75·0 ohms. The maximum deviation of 0·75 per cent occurs at 5·1 megahertz.

values in the form $\alpha/F^{1/2}$ versus $F^{1/2}$, (where F is the frequency in megahertz and α is the attenuation in decibels per mile). From Figure 11 it can be shown that the attenuation of the cable at frequencies above 1 megahertz may be approximately represented by the following relationship:

$$\begin{aligned}\alpha &= 8{\cdot}4\,F^{1/2} + 0{\cdot}008F \text{ (decibels per mile)}\\ &= 601\,F^{1/2} + 0{\cdot}6F \text{ (millinepers per kilometre).}\end{aligned}$$

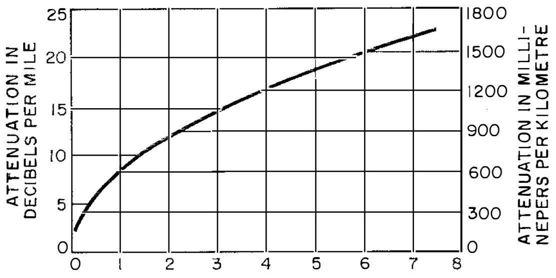


Figure 10—Attenuation at 10 degrees Celsius as a function of frequency for a typical repeater section.

The second term in this expression represents the dielectric loss, from which it can be calculated that the power factor was approximately 0·00005.

6.1.3 *Crosstalk*

Figure 12 shows typical curves for near-end crosstalk attenuation and far-end signal-to-crosstalk ratio on all core combinations over the frequency spectrum from 0·06 to 0·55 megahertz.

TABLE 1

FACTORY TEST RESULTS ON 200 CORE LENGTHS OF TAVISTOCK-WIDEMOUTH CABLE

Quantity	Test Results		British Post Office Limit	International Telegraph and Telephone Consultative Committee Recommendation
	Mean Value	Standard Deviation		
End impedance in ohms at 1 megahertz	75·0	0·15	75·0 ± 0·75 for 100 per cent of cores 75·0 ± 0·50 for 50 per cent of cores	75·0 ± 1·5 (telephony) 75·0 ± 1·0 (television)
Impedance regularity*:				
(A) worst uncorrected	61	2·7	54 minimum	not quoted
(B) average of 3 worst	59	2·3	51 minimum	not quoted
(C) worst corrected	57	2·7	not quoted	minimum 45 (telephony) minimum 48 (television) for 100 per cent of cores minimum 54 (television) for 80 per cent of cores
Mutual capacitance:				
microfarads per mile	0·0784	0·0002	not quoted	
nanofarads per kilometre	48·72	0·12		
Permittivity	1·16	0·003	not quoted	
Ionization extinction voltage in kilovolts	1·45	0·25	0·5 minimum	not quoted

* Internal voltage reflections in decibels below transmitted level when tested with a 0·05-microsecond pulse. The regularity is expressed by:

(*A*) Worst directly-measured internal reflection (not corrected for line attenuation).
(*B*) Average of the 3 worst internal reflections (corrected for line attenuation).
(*C*) Worst internal reflection (corrected for line attenuation).

6.2 Subsequent Manufacture

By the time manufacture of the Tavistock-Widemouth cable was finished, the final production equipment had been commissioned and all subsequent core was made on this machinery. During 1963 and 1964, some 650 miles

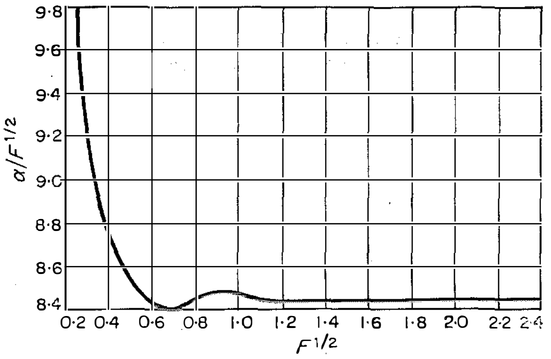


Figure 11—$\alpha/F^{1/2}$ plotted against $F^{1/2}$ for a typical repeater section. α = attenuation in decibels per mile at 10 degrees Celsius and F = frequency in megahertz.

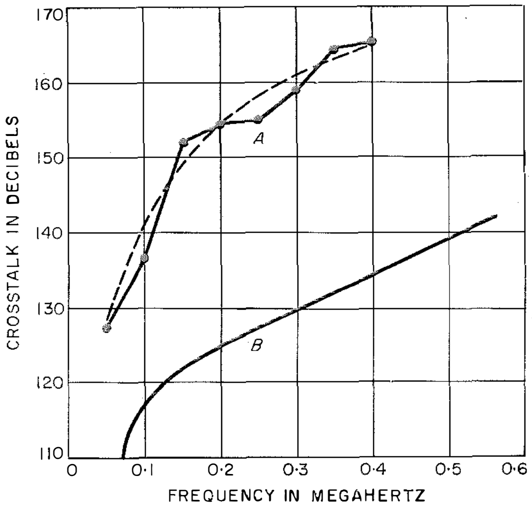
TABLE 2

Field Test Results on 36 Core Lengths of Tavistock-Widemouth Cable

Quantity	Test Results		British Post Office Limit	International Telegraph and Telephone Consultative Committee Recommendation
	Mean Value	Standard Deviation		
End impedance in ohms at 1 megahertz:				
before termination	74·9	0·14		
after termination	74·9	0·10	75·0 ± 0·50	75·0 ± 1·5 (telephony) 75·0 ± 1·0 (television)
Impedance regularity*				
(*A*) worst uncorrected	60·5	2·9	54 minimum	minimum 52 (television)
(*B*) average of 3 worst	58·5	3·4	50 minimum	not quoted
(*C*) worst corrected	55·5	3·4	48 minimum	minimum 42 (telephony) minimum 44 (television)
Attenuation at 1 megahertz corrected to 10 degrees Celsius:				
decibels per mile	8·48	0·02	8·5 ± 0·20	
millinepers per kilometre	607	1·5		610 ± 23
Far-end signal-to-crosstalk ratio in decibels at 60 kilohertz on full repeater sections:				
adjacent combinations	105	1·2	90 minimum (all combinations on 3·6-mile sections)	89 minimum (all combinations on 6-kilometre sections)
diagonal combinations	105	1·6		
Near-end crosstalk attenuation in decibels at 60 kilohertz on full repeater sections:				
adjacent combinations	125	5	95 minimum (all combinations)	not quoted
diagonal combinations	127	4		not quoted

* Internal voltage reflections in decibels below transmitted level when tested with a 0·10- microsecond pulse. The regularity is expressed by:
(*A*) Worst directly measured internal reflection (not corrected for line attenuation).
(*B*) Average of the 3 worst internal reflections (corrected for line attenuation).
(*C*) Worst internal reflection (corrected for line attenuation).

Figure 12—*A* shows typical measured values at 50-kilohertz intervals of near-end crosstalk attenuation, with the probable smooth mean curve in broken lines. *B* shows the far-end signal-to-crosstalk ratio.



(1050 kilometres) of core were manufactured and installed under 6 major contracts. During this same period 280 miles (450 kilometres) of core were shipped to various European countries for further processing, and manufacturing equipment for moulded-shell cable was exported to factories in 3 of these countries.

Notwithstanding the apparent complexity of the process, experience in establishing production units in these factories, one of which had no previous experience in coaxial cable production, has shown that the process is reliable and simple to manage. Satisfactory production is normally expected within 14 days of the installation of the machinery.

Transfer from prototype to production machinery resulted in a noticeable improvement in quality, as shown in Table 3. The prototype test results in this table are those obtained on the 200 core lengths recorded in Table 1. The production results are the averages of the results recorded on the 6 contracts mentioned above, which represent a total of more than 2000 core lengths. From this table it will be seen that the production machinery reduced the spread of end impedances by 20 per cent and improved the internal impedance regularity by approximately 6 decibels (halving the ohmic magnitude of the worst internal variations).

It will also be seen that on the more-recent contracts the mean end impedance value was raised from 75·0 ohms to 75·2 ohms. This change was made to counteract the impedance drop that was found to occur when the cables were drawn into underground ducts. From Tables 1 and 2 it will be seen that this drop was 0·1 ohm on the Tavistock-Widemouth contract. Here, however, installation conditions were good; on certain subsequent contracts increased pulling tensions were experienced and impedance drops of greater magnitude were encountered.

7. International Situation

The development of small-diameter coaxial cable and transmission equipment was not confined to the United Kingdom. Similar evolutionary processes from cellular polyethylene insulated cores of various diameters to low-loss cables meeting the standards of the International Telegraph and Telephone Consultative Committee have been reported from many other countries [10]. The first long-distance all-transistor system employing low-loss small-diameter coaxial cables to be laid in Europe was the Marseille-Toulon cable, which was manufactured and installed by La Société Anonyme des Télécommunications in 1959–1960. This cable employed the so-called balloon type of insulation—a polyethylene version of a form of construction suggested some years earlier to reduce the permittivity of cables insulated with paper or rubber. Special machinery for the construction of this type of coaxial core was developed in France between 1950 and 1960, the first cables being laid during the latter half of this period. These were, however, all short-haul runs (6 to 9 kilometres in length) and did not employ intermediate repeaters. The Marseille-Toulon cable, which—together with the associated manufacturing equipment—has been fully described in the French technical press [11], was used experimentally in 1960 and has carried commercial traffic since 1963.

Currently a number of different forms of low-loss dielectric structure are used for 0·174-inch (4·4-millimetre) diameter coaxial cables made in more than a dozen countries. These fall broadly into the following 3 categories:

(A) Moulded insulations. These comprise the fully moulded forms such as moulded shell and moulded tape, and the semi-moulded forms of which the moulded disc is the best-known example. In this latter form the discs are covered overall with either a lapping or an extrusion of plastic material.

(B) Directly extruded insulations. The early cellular-polyethylene designs were, of course, in this category. Today, however, the only widely used example of this form of insulation is the balloon type.

(C) Lapped string and tape insulations. These use strings of polyethylene or polystyrene, often made in cellular, tubular, or twisted-pair form to reduce permittivity, and tapes of a wide range of plastic materials.

8. Future Trends

The administrations in some countries standardized on a single design in the early stages of development—typical examples from the 3 above categories being Japan (category **A**), France (category **B**), and Italy (category **C**). In other countries a plurality of designs exist—typical examples being Great Britain and Germany, where the administrations currently accept designs from all of the above categories. Further, the specification limits imposed by the various administrations differ considerably. The indications are, however, that as new and improved transmission equipment becomes available these limits will gradually be tightened to allow small-diameter coaxial cables to be exploited more fully.

A 4-megahertz system capable of carrying up to 960 two-way speech circuits at 4-kilohertz spacing over each pair of coaxial cores has already

TABLE 3

COMPARISON OF TEST RESULTS OBTAINED ON FACTORY LENGTHS OF CABLE

Quantity	Test Results			
	Prototype Equipment		Final Production Equipment	
	Mean Value	Standard Deviation	Mean Value	Standard Deviation
End impedance in ohms at 1 megahertz	75·0	0·15	75·2	0·12
Impedance regularity*				
(*A*) worst uncorrected	61	2·7	66	3·6
(*B*) average of 3 worst	59	2·3	66	3·6
(*C*) worst corrected	57	2·7	62·5	3·9
Mutual capacitance:				
microfarads per mile	0·0784	0·0002	0·0781	0·0002
nanofarads per kilometre	48·7	0·12	48·5	0·12
Permittivity	1·16	0·003	1·14	0·003

* Internal voltage reflections in decibels below transmitted level when tested with a 0·05-microsecond pulse. The regularity is expressed by:

(*A*) Worst directly measured internal reflection (not corrected for line attenuation).
(*B*) Average of the 3 worst internal reflections (corrected for line attenuation).
(*C*) Worst internal reflection (corrected for line attenuation).

been designed by Standard Telephones and Cables for exploitation in 1965. The nominal repeater spacing is 2·5 miles (4 kilometres).

Similar developments have also been reported from France, where work commenced in 1964 on an experimental 6-megahertz 1260-channel system with 1·87-mile (3-kilometre) repeater spacing [11.5] between Versailles and Dreux and from Japan, where commercial tests on a 4-megahertz system with 2·5-mile (4-kilometre) repeater spacing were started the same year [8].

The anticipated demand for improved cable quality can easily be met by the moulded-shell construction, which gives results well within present specifications. There can therefore be little doubt that this form of construction will play an ever-increasing part in the trunk telecommunication cable systems of the future.

9. References

1. E. Baguley, "Modern Coaxial-Cable Technique in Great Britain," *Electrical Communication,* volume 30, number 3, pages 186–216; 1953.

2. A. W. Montgomery, "Coaxial-Cable Systems: Past and Future," *Electrical Communication,* volume 35, number 4, pages 221–229; 1959.

3. A. F. G. Allan, "Small-Diameter Coaxial-Cable Developments," *Post Office Electrical Engineers' Journal,* volume 57, part 1, pages 1–8; April 1964.

4. H. Stanesby and W. K. Weston, "London-Birmingham Television Cable," *Electrical Communication,* volume 26, number 3, pages 186–200; 1949.

5. British Patent 650 442.

6. H. Kumamaru, "The Crosstalk Characteristics of Coaxial Cables Shielded with Electromagnetically Anisotropic Metallic Layers," paper presented at the 13th Annual Symposium on Technical Progress in Communication Wires and Cables, Atlantic City, New Jersey; 2–4 December 1964.

7. British Patent 988 029.

8. "*CP-4M Tr* Transmission System," Nippon Telegraph and Telephone Public Corporation, Electrical Communication Laboratory, technical publication 13, pages 1–19; September 1964.

9. British Patent 921 232.

10. P. A. Frolov, "Modern Small-Size Coaxial Cables," *Elektrosvyaz,* volume 18, number 6, pages 36–44; June 1964.

11. R. Bélus, G. Fuchs, et al., several articles in *Cables & Transmission,* for example:—
11.1 Number 2, pages 113–131; April 1960.
11.2 Number 4, pages 294–306; October 1960.
11.3 Number 2, pages 160–176; April 1961.
11.4 Number 4, pages 289–303; October 1961.
11.5 Number 2, pages 196–210; April 1964.

Robert Tatman was born in Bromley, Kent, England, in 1927. He obtained a first-class honours degree in electrical engineering from University College, London, in 1947.

After a two-year post-graduate training period —one year at University College and one year at various Standard Telephones and Cables factories—he joined the communication-cable engineering section of the North Woolwich factory, where he is at present engaged in the engineering of coaxial, plastic, and special cables.

Bernard Edwin Ash was born in London in 1924. He served in the Royal Air Force during World War 2, and worked on machine design in a number of industries from 1945 to 1955.

He joined Standard Telephones and Cables in 1956 and designed machines for the Company's overseas interests. He is now concerned with the integrated design of new products and their production processes.

Mr. Ash became an Associate Member of the Institution of Mechanical Engineers in 1954.

Relationship Between Attenuation and Wire-Braid Design for Flexible Radio-Frequency Cables

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1. Introduction

Analysis of European specifications for general-purpose radio-frequency coaxial cables reveals that close limits are given for the electrical properties of the materials employed, the diameter of the centre conductor, the diameter of individual braiding wires, and the overall diameter of the finished cable. In turn these limits give rise to such electrical parameters as characteristic impedance, velocity of propagation, and capacitance. Thus, as far as individual cable designs are concerned, the only variation permitted within specification limits lies in the design of the wire-braided outer conductor.

The design of the wire braid is usually limited by values of 3·0 maximum quoted for lay factor and of 0·70 minimum to 0·95 maximum for filling factor. These values can result in cables that differ widely with respect to attenuation and transfer impedance or cross-talk attenuation. Of equal importance is the fact that a braid must be easy to push back and terminate.

2. Effect of Braid Design on Attenuation

Reference to standard literature for the design of wire-braided cables yields the following equation for that part of the attenuation due to the conductors, assuming that both conductors are of the same material.

$$\alpha_c = \frac{2\cdot 387 \times 10^{-3}(\epsilon\rho f)^{1/2}}{\log_{10}(D/d)}\,\frac{K_s}{d} + \frac{K_b}{D}$$

(decibels per 100 feet) (1)

where

ϵ = dielectric constant
ρ = resistivity of conductors ($1\cdot 724 \times 10^{-6}$ ohm-centimetre for copper)
f = frequency in hertz
K_s = stranding factor of centre conductor (1 for solid, 1·25 for 7-strand)
D = diameter over dielectric in inches
d = diameter of centre conductor in inches ($0\cdot 939d$ for 7-strand)
$K_b = K_l/K_f$ (or braiding factor)
K_l = lay factor
K_f = filling factor.

It will be noted, therefore, that the attenuation is lowest for a small lay factor and high filling factor. However, there is some evidence to show that this is not strictly true at frequencies above 5000 megahertz.

3. Derivation of Lay Factor and Filling Factor

Considering fundamental taping or lapping theory and the wires of the braid applied in one direction only, the diagram of Figure 1 may be drawn.

In Figure 1

θ = angle of application
D = mean diameter of braid
πD = mean pitch circumference
l = length of lay
$(\pi^2D^2 + l^2)^{1/2}$ = length per convolution of 1 wire
x = bandwidth for 100-per-cent fill.

Thus

$$\frac{(l^2 - x^2)^{1/2}}{l} = \frac{x}{\pi D}$$

$$l^2x^2 = \pi^2D^2(l^2 - x^2)$$

$$x^2(l^2 + \pi^2D^2) = \pi^2D^2l^2$$

$$x^2 = \frac{\pi^2D^2l^2}{l^2 + \pi^2D^2} = \frac{\pi^2D^2}{\left(1 + \frac{\pi^2D^2}{l^2}\right)}$$

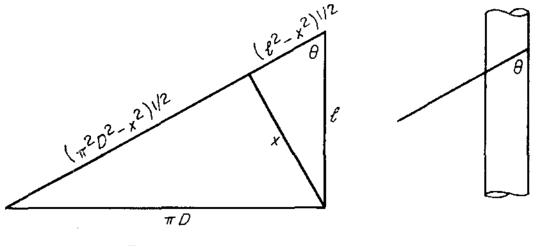

Figure 1—Braiding diagram.

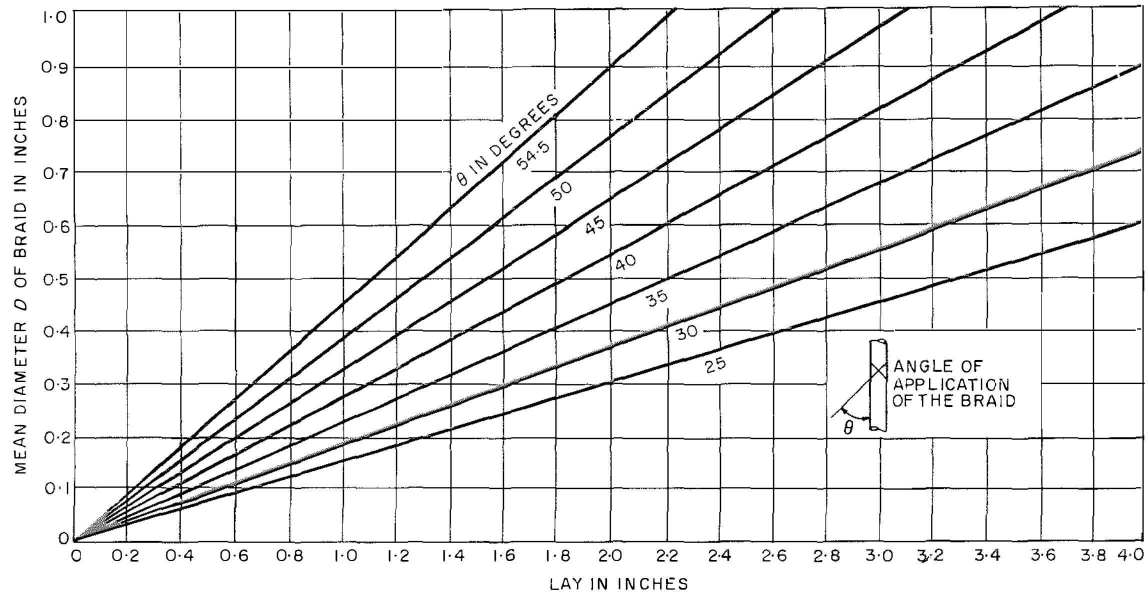

Figure 2—Braiding lay for any mean diameter of braid and angle of application.

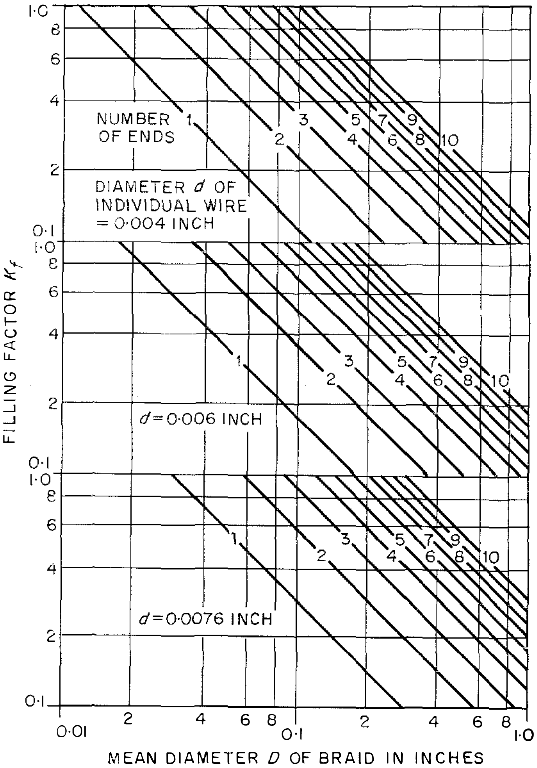

Figure 3—Braiding-design details for flexible radio-frequency cables using 16-spindle braiding machines.

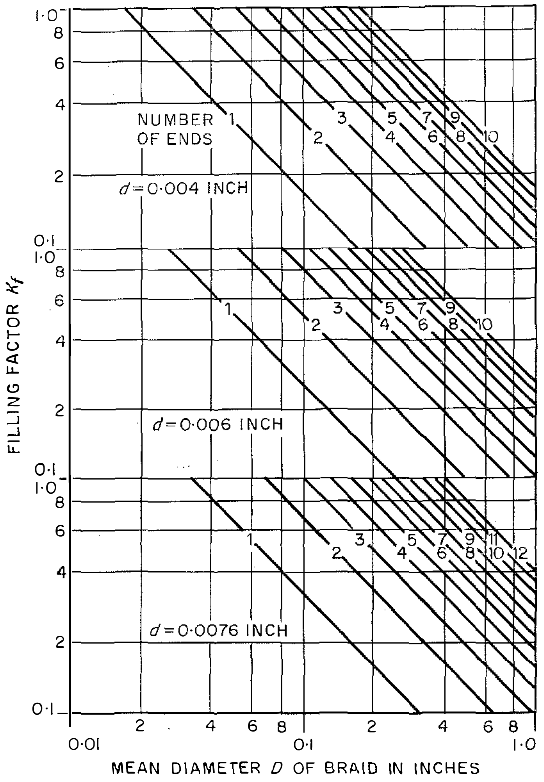

Figure 4—Braiding-design details for flexible radio-frequency cables using 24-spindle braiding machines.

or

$$x = \frac{\pi D}{\left(1 + \frac{\pi^2 D^2}{l^2}\right)^{1/2}}. \qquad (2)$$

Thus the filling factor K_f is defined as the actual bandwidth of wires laid in one direction, divided by the bandwidth of wires laid in one direction for 100-per-cent fill, or

$$K_f = \frac{\text{actual bandwidth} \times \left(1 + \frac{\pi^2 D^2}{l^2}\right)^{1/2}}{\pi D}$$

where

$$\text{actual bandwidth} = \frac{m \times n \times d_w}{2}$$

and

m = total number of spindles applying braid in both directions
n = number of ends of wire per spindle
d_w = diameter of one braiding wire.

Thus

$$K_f = \frac{m \times n \times d_w}{2\pi D}\left(1 + \frac{\pi^2 D^2}{l^2}\right)^{1/2}.$$

The lay factor K_l is defined as

$$K_l = 1 + \frac{\pi^2 D^2}{l^2} = 1 + \tan^2\theta = \sec^2\theta$$

or

$$\sec\theta = K_l^{1/2} \qquad (3)$$

and K_f reduces to

$$\frac{m \times n \times d_w}{2\pi D} \cdot K_l^{1/2}. \qquad (4)$$

4. Choice of Filling Factor and Lay Factor

In general, with regard to cable flexibility and ease of termination, the angle of application of the wire braid should be 30 degrees. This means that $K_l^{1/2} = \sec 30° = 1 \cdot 155$.

In practice the maximum filling factor that can be achieved is $0 \cdot 95$. Thus, transposing both $K_f = 0 \cdot 95$ and $K_l^{1/2} = 1 \cdot 155$ in (4), we have

$$0 \cdot 95 = \frac{m \times n \times d_w}{2\pi D} \times 1 \cdot 155$$

or

$$n = \frac{5 \cdot 16 D}{m d_w}. \qquad (5)$$

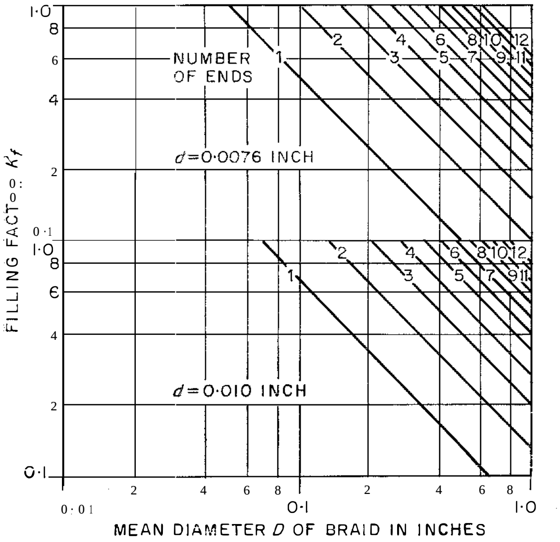

Figure 5—Braiding-design details for flexible radio-frequency cables using 36-spindle braiding machines.

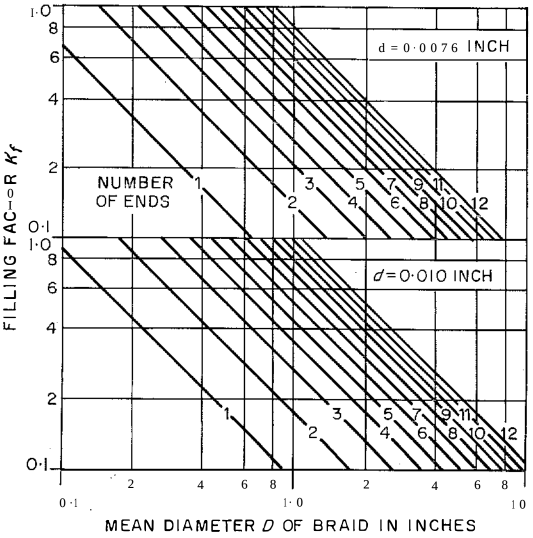

Figure 6—Braiding-design details for flexible radio-frequency cables using 48-spindle braiding machines.

The choice of the number of ends of wire per braiding spindle depends on the number of braiding spindles. Conventional braiding machines are constructed with 16, 24, 36, and 48 spindles, and from a practical viewpoint a length of lay corresponding to an angle of application of between 25 and 30 degrees can normally be obtained.

Figure 2 shows the length of lay plotted against mean braid diameter for any angle of application.

Figures 3 through 6 show the filling factor as a function of the mean diameter of braid for the number of wires required per braiding spindle and for a given braiding machine, assuming that each spindle carries the same number of ends and that the angle of application is 30 degrees.

5. Total Attenuation

The attenuation of a coaxial cable may be divided into two parts: α_c, which is due to the conductors and geometry of the cable, and α_d, which is independent of the size of cable and depends solely on the type of dielectric.

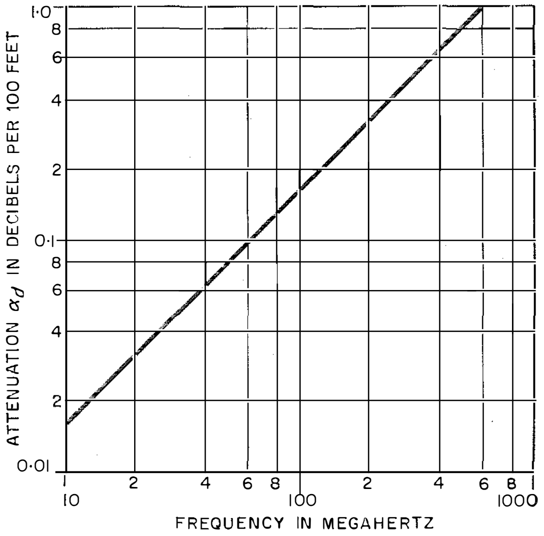

Figure 7—Attenuation α_d due to dielectric plotted as a function of frequency.

The geometry of the cable is normally fixed by either characteristic impedance Z_0 or capacitance C. These parameters are given by

$$Z_0 = \frac{138{\cdot}05 \log_{10} (D/d)}{\epsilon^{1/2}} \text{ (ohms)}$$

$$C = \frac{7 \cdot 365\,\epsilon}{\log_{10} (D/d)} \text{ (picofarads per foot).}$$

The dielectric losses α_d are given by

$$\alpha_d = 2{\cdot}77 \times 10^{-6} \epsilon^{1/2} f \tan \phi \quad \text{(decibels per 100 feet).}$$

From a practical viewpoint $\tan \phi$, the power factor of the dielectric, may be taken as 0·0004 for solid polythene and 0·0005 for cellular polythene. This reduces α_d to the value of $0{\cdot}00166 \times 10^{-6} f$ in decibels per 100 feet, which is shown in Figure 7.

The attenuation α_c due to the conductors can be considered in two parts: α_{c1}, the attenuation due to the centre conductor, and α_{c2}, the attenuation due to the outer conductor.

$$\alpha_{c1} = \frac{2{\cdot}39 \times 10^{-3} (\epsilon \rho f)^{1/2}}{\log_{10} (D/d)} \cdot \frac{1}{d} \quad \text{(decibels per 100 feet)}$$

and

$$\alpha_{c2} = \frac{2{\cdot}39 \times 10^{-3} (\epsilon \rho f)^{1/2}}{\log_{10} (D/d)} \cdot \frac{K_b}{D} \quad \text{(decibels per 100 feet).}$$

For copper conductors these reduce to

$$\alpha_{c1} = \frac{A f^{1/2}}{d}$$

$$\alpha_{c2} = \frac{A f^{1/2}}{d} \cdot K_b.$$

The value of K_b is unity for a plain copper tube as outer conductor, and $A = 0{\cdot}00577 \times 10^{-3}$ for a 75-ohm coaxial cable.

Figure 8 shows variation of attenuation with frequency for 75-ohm coaxial cables, for various diameters of plain copper centre conductors giving α_{c1}, and for various diameters under a plain copper tube as outer conductor giving α_{c2}.

For coaxial cables having other than 75-ohm impedance, the obtained values of attenuation must be multiplied by the factor $75/Z_x$, where Z_x is the impedance of the cable under consideration.

For braided outer conductors, α_{c2} must be multiplied by the factor K_b.

6. Examples

The following examples illustrate the method used to calculate attenuation rapidly at any frequency in the range from 10 to 1000 megahertz.

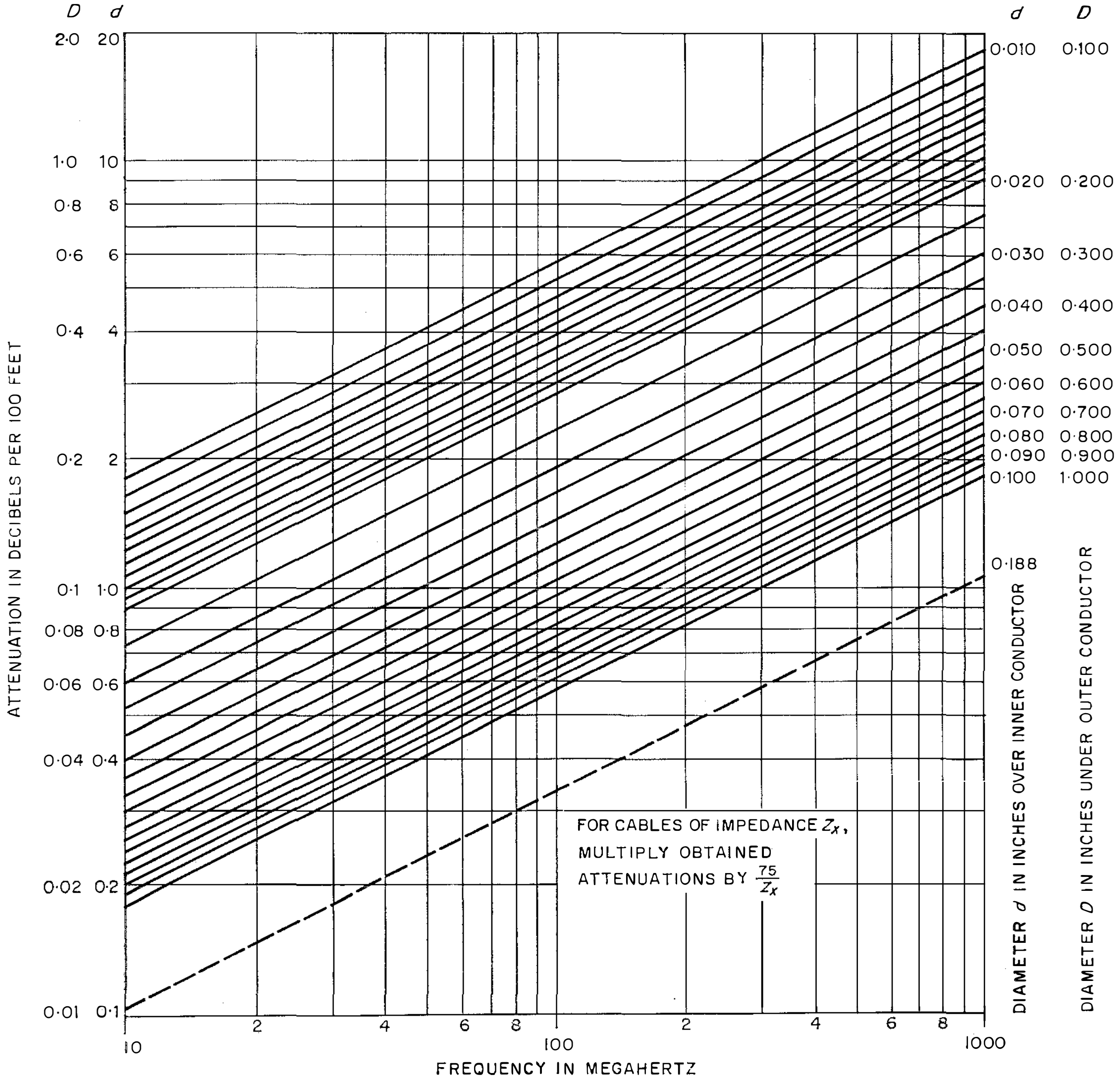

Figure 8—Attenuation due to conductors as a function of frequency for 75-ohm coaxial cables. For the inner conductor (α_{c1}) use scales d and for the outer conductor (α_{c2}) use scales D.

6.1 CASE 1

A 75-ohm polythene-sheathed coaxial cable having a single centre conductor of 0·040-inch plain copper wire, polythene insulated to a diameter of 0·245 inch with a copper outer conductor 0·007 inch thick crimped into a tube with a 0·1-inch overlap.

6.1.1 *Attenuation at 10 Megahertz*

		Decibels Per 100 Feet
α_{c1}	Attenuation due to centre conductor (Figure 8, scales *d*)	0·45
α_{c2}	Attenuation due to outer conductor (Figure 8, scales *D*)	0·073
α_d	Attenuation due to dielectric (Figure 7)	0·016
	Calculated total attenuation	0·54
	Measured total attenuation	0·55

6.2 CASE 2

A 50-ohm polyvinylchloride-sheathed coaxial cable type Uniradio *74* to British Standard *2316* having a single centre conductor of 0·188-inch plain copper wire, polythene insulated to a diameter of 0·680 inch and an outer conductor of braided plain copper wire.

6.2.1 *Braid Design*

From Figure 6, presuming a mean braid diameter of 0·697, the required braid design is given as 48 spindles, 9 ends of 0·0076-inch plain copper wire with a filling factor $K_f = 0{\cdot}87$.

From Figure 2, the braiding lay is given as 3·8 inches at an angle of application of 30 degrees.

The lay factor K_l is thus 1·333 and the braiding factor

$$K_b = \frac{K_l}{K_f} = \frac{1{\cdot}333}{0{\cdot}87} = 1{\cdot}53.$$

6.2.2 *Attenuation at 200 Megahertz*

		Decibels Per 100 Feet
α_{c1}	Attenuation due to centre conductor (Figure 8, scales $d = 0{\cdot}47 \times (75/Z_x))$	0·70
α_{c2}	Attenuation due to outer conductor (Figure 8, scales $D = 0{\cdot}118 \times (75/Z_x) \times 1{\cdot}53)$	0·27
α_d	Attenuation due to dielectric (Figure 7)	0·34
	Calculated total attenuation	1·31
	Measured total attenuation	1·34

For specification purposes it is normal to add 10 per cent to the theoretical value of attenuation. This gives a nominal value of 1·44 decibels per 100 feet for Uniradio *74* at 200 megahertz.

Lyndon R. Spicer was born in Monmouthshire, England, in 1926 and was educated at Newport St. Julian's High School. From 1944 to 1947, he was in the Radio Security Service attached to the Foreign Office.

After joining Standard Telephones and Cables in 1947 he studied telecommunications and for an external degree in physics and mathematics at Newport and Cardiff Technical Colleges.

In 1963 he was appointed a Member of the Order of the British Empire by Her Majesty the Queen for his work on submarine cables for the Admiralty.

Monitor for Color Television

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The introduction of color television affects not only the design of receivers but also the transmitter, transmission links, and, in particular, studio equipment. Most transmitters and transmission links are suitable for handling color-television signals. In the studios, however, color monitors are needed in addition to the existing monochrome monitors. Despite requiring a high degree of flexibility of application, the color monitor should not be larger than the conventional monochrome monitor, it should be easily transportable, and it must fit in racks meeting the German Industrial Standards *DIN 41490* and *DIN 41494* (international 19-inch system).

The color monitor shown in Figure 1 may be used as a picture-modulation monitor or, supplemented by a radio unit, as an ultra-high- and very-high-frequency receiver in laboratories, studios, and transmission systems. It is based on the standards of the International Radio Consultative Committee for 625-line pictures at 25 frames per second with single interlace. Its division into functional units provides for adaptation to National Television System Committee color, the Phase Alternation Line modification of it using a delay line, and the Sequential With Memory systems. It operates from a 220-volt 50-hertz power line, taking 200 volt-amperes.

Except in the horizontal deflection circuits, the monitor uses silicon transistors throughout [1, 2], and therefore has many features applicable to future transistor home television receivers. It contains a rectangular color picture tube with a screen diagonal of 16 inches (41 centimeters) and an aspect ratio of 3:4. It was possible to realize the mechanical design using plug-in techniques in accordance with *DIN 41490* and *DIN 41494* and to meet the electrical requirements of specification *8/10.1* (Monitor *K1.1*) of the A.R.D. (Study Organization of the Broadcasting Corporations of the Federal Republic of Germany) at an ambient temperature between +10 and +50 degrees Celsius.

The *400 KB 22* color picture tube is manufactured by Toshiba Shibaura Electric Company (Tokyo, Japan). Its rectangular screen has usable dimensions of 210 by 280 millimeters (8 by 11 inches) with an aspect ratio of 3:4. The triad of color phosphor dots are at 0.58-millimeter (0.02-inch) spacings. The anode operates at 17.5 kilovolts and 800 microamperes, stabilized.

1. Operation

Figure 2 is the block diagram of the television color monitor. It includes 4 subunits.

1.1 Subunit 1

Subunit 1 essentially comprises the power supply, the decoupling stages, and the signal-processing stages.

1.1.1 *Power Supply*

The power supply produces the electronically stabilized operating voltages, which are independent of each other, for the horizontal-line output stage, the vertical-deflection circuit, the video stages, and the color-subcarrier oscillator, plus a stabilized bias voltage for the control

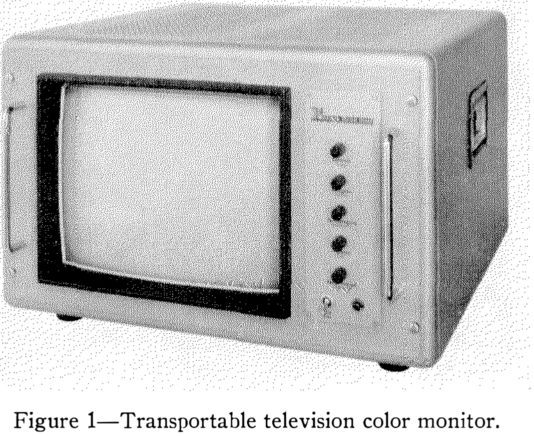

Figure 1—Transportable television color monitor.

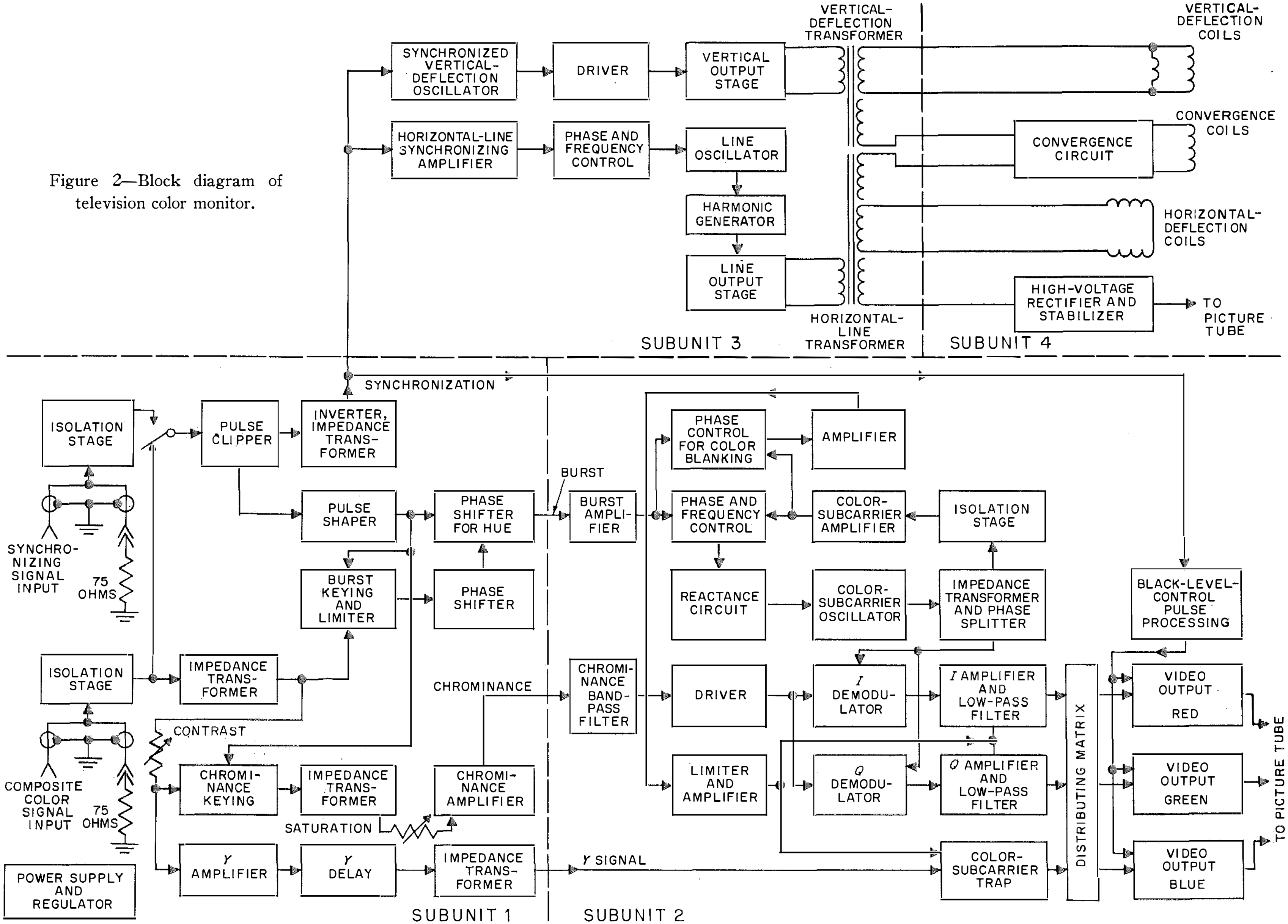

Figure 2—Block diagram of television color monitor.

grids of the picture tube and operating voltages for the amplifiers.

1.1.2 *Decoupling Stages*

The monitor operates optionally with composite color signals and internal synchronization or with blanked color signals and external synchronization. In either case the monitor circuits are decoupled from the input circuit by isolation stages.

The input composite color signal should be +1 volt peak-to-peak ±50 percent. The blanked color signal should be +0.7 volt peak-to-peak ±50 percent. The input impedance is 60 to 150 ohms and the return loss is 24 decibels up to 7 megahertz. The synchronizing signal should be −4 volts peak-to-peak ±50 percent into an impedance of 60 to 150 ohms. The return loss is 24 decibels up to 7 megahertz.

Output signals from the I and Q channels are +1.4 volts peak-to-peak maximum and are adjusted by the contrast and saturation controls. The circuit impedances are both 75 ohms.

1.1.3 *Signal-Processing Stages*

The isolation stages are followed by a 2-stage pulse clipper with inverter stage and impedance transformer. Connected to this is a pulse-shaping circuit, which delivers a pulse for burst keying and chrominance-signal interruption during horizontal blanking. Hence the entire back porch is available for keyed black-level control at constant level.

At the burst-channel input (color-subcarrier synchronizing signal) a limiter keeps the burst amplitude constant at a set value between 30 and 150 percent of nominal with a maximum phase change of ±1 degree. The limiter is followed by an amplitude-independent phase shifter for nominal phase adjustment. The reference phase or hue can be adjusted from the front panel by ±35 degrees.

Contrast and saturation are continuously adjustable from the front panel. The maximum saturation and the maximum contrast are about 200 percent of the nominal amplitude. No measurable phase errors occur over the entire range of adjustment.

Up to 5 megahertz the luminance system is within +3 decibels of the amplitude at 1.5 megahertz, decreasing slightly above 5 megahertz for monochrome operation. With a rectangular-wave test signal at 250 kilohertz and a rise time of 100 nanoseconds, the overshoot does not exceed 3 and 6 percent for monochrome and color, respectively. The tilt of pulse tops is 3 percent at 50 hertz and 1 percent at 15 kilohertz. Linearity is at least 0.95.

The brightness or Y channel incorporates an 860-nanosecond delay line. Up to 6 megahertz the amplitude variation is less than ±0.5 decibel.

1.2 SUBUNIT 2

Subunit 2 consists of the color-subcarrier oscillator with its synchronization and blanking controls, the chrominance demodulators with I and Q output amplifiers, the distributing matrix, and the video output stages with black-level control.

1.2.1 *Color-Subcarrier Oscillator, Synchronization, and Blanking*

The color-subcarrier oscillator is crystal controlled and is synchronized by automatic phase and frequency control [3]. At ±100 hertz off tune, the maximum phase deviation is ±3 degrees. A second, detuned phase-control circuit produces the switching voltage for color blanking. With the oscillator synchronized a rectified voltage results; with the oscillator unsynchronized, the absence of this rectified voltage blocks the chrominance channels and disconnects a color-subcarrier trap in the Y channel to make the full bandwidth of this channel available in monochrome.

1.2.2 *Chrominance Demodulators*

A chrominance band-pass filter is followed by a driver and two ring demodulators, demodulating to *I* and *Q*. The ring demodulators provide a relatively high demodulation efficiency at a linearity ≥ 0.95 and hence a good signal-to-noise ratio. The chroma circuits are switched in or out automatically without moving contacts. Lattice-type demodulators are used. The *I* channel has a pass band up to 1.5 megahertz and the *Q* channel goes up to 0.5 megahertz, both being linear to within 1.5 decibels. The linearity factors (measured between composite color signal input and the lead to the picture-tube cathode) are therefore 0.95. The differential phase error does not exceed ±0.5 degree. For vector and level measurements, the *I* and *Q* signals are available for termination into 75 ohms at coaxial jacks on the rear of the equipment.

1.2.3 *Distributing Matrix*

The distributing matrix consists of a passive resistance network succeeded by emitter followers, which isolate the subsequent stages from stray signals.

1.2.4 *Video Output Stages and Black-Level Control*

The 3 amplifier chains for the red, green, and blue signals are identical, hence only one channel need be described. The black level is maintained at the base of the driver transistor for the power transistor by keying the back porch. Each cathode of the color picture tube is connected via an emitter follower, which helps to reduce the crosstalk between channels because of the capacitance of the parallel picture-tube leads and helps to diminish the capacitance load of the collector-end equalizer circuit. The cost to correct linear distortion can be kept small by keeping overshoot very low. The overshoot occurring in the video output stages (measured at 250 kilohertz with a rectangular wave having a rise time of 100 nanoseconds) is ±1.5 percent. Nonlinear distortion could be kept small without the use of special correction means.

1.3 SUBUNIT 3

Subunit 3 provides for both vertical and horizontal deflection including synchronization of the horizontal-line oscillator.

Deflection synchronization may be either for single-channel operation with composite color signal or for dual-channel operation with blanked composite signal and separate synchronizing signal. Direct synchronization is employed for vertical deflection and phase, and frequency control of a sine-wave oscillator is used for horizontal-line deflection. The beam current is blanked for both retrace intervals. Color-subcarrier synchronization is by phase and frequency control of a crystal oscillator.

1.3.1 *Horizontal-Line Oscillator and Synchronization*

The synchronization signal from the pulse clipper and the retrace pulses from the horizontal-line transformer produce an automatic-frequency-control voltage that is adjusted in phase and frequency [4, 5] to control a sine-wave oscillator. The oscillator is followed by a harmonic generator, the output signal then being amplified in the line output stage to drive the horizontal-deflection coils.

1.3.2 *Horizontal-Line Output*

Horizontal-deflection current is provided through the horizontal-line transformer to the deflection coils. The line output stage is equipped with a *6JE6* vacuum tube and a *6DW4* booster diode.

Since the operating voltage is electronically stabilized in the power section, the only function of the picture width control in the line output stage is to compensate for tube ageing, temperature effects on picture width, and related focus-voltage variations. The adjustable focus voltage is derived from the horizontal-line transformer via a silicon rectifier. The horizontal-line transformer also supplies the anode voltage of 17.5 kilovolts. The rectifier is a *3A3* tube diode.

A linearity control permits operator adjustment of horizontal linearity. For horizontal picture centering the direct current flowing through one of the horizontal-deflection coils can be adjusted, which produces a corresponding displacement of the picture approximately 2 centimeters (0.8 inch) to the left or right.

1.3.3 *Vertical Deflection*

The vertical-deflection circuit contains 3 silicon planar transistors. A blocking oscillator adjustable within ±5 hertz of the nominal frequency is synchronized by pulses from the pulse clipper in subunit 1. Overall linearity, linearity at the beginning of the scan, and deflection amplitude can be adjusted by means of trimmer capacitors. The operating point of the blocking oscillator can be set from the front panel to control synchronization of the vertical-deflection system. The vertical picture centering is similar to the horizontal centering.

1.4 SUBUNIT 4

Subunit 4 comprises the high-voltage rectifier and stabilizer, the convergence circuit, and the picture tube.

1.4.1 *High-Voltage Stabilization*

The 17.5-kilovolt anode supply is stabilized by maintaining the load constant at 800 microamperes. The voltage is thus unaffected by the relatively minor variations in the beam currents flowing at each instant through the picture tube. In this way linearity distortion and unwanted variations dependent on beam currents are prevented. The difference current between 800 microamperes and the particular beam current goes to a high-voltage triode controlled by a nuvistor. The regulating voltage is derived from the high-voltage output via a voltage divider. The mean differential internal resistance of the high-voltage source is 250 kilohms.

1.4.2 *Convergence Circuit and Pincushion Correction*

The convergence circuit is arranged on the main chassis so that the image can be observed during adjustment of the tuning resistors and coils. The required alternating voltages are supplied by the horizontal-line transformer and the vertical-deflection circuit. Here also silicon planar transistors are employed as active elements, ensuring the required high stability in operation. The static convergence is coarsely adjusted by means of permanent magnets that are fastened to the tube neck; fine adjustment is by changing the magnetizing current through the convergence coils.

Vertical pincushion distortion is corrected by superimposing a parabolic component of the line frequency on the vertical-deflection current. Correction in the horizontal direction is not necessary.

1.4.3 *Picture Tube*

The monitor is equipped with a rectangular color picture tube type *400 KB 22* with a 16-inch (41-centimeter) screen diagonal and 70-degree deflection. The tube screen is truly rectangular in shape with a 3:4 aspect ratio so that there is no loss of picture content. Use of the conventional round tube would entail considerable loss of picture at the corners as shown in Figure 3. The color-triad center-point spacing of 0.58 millimeter (0.02 inch) assures satisfactory resolution. The sharpness distribution over the screen area is so uniform that dynamic focusing can be dispensed with. Except for the high voltage, the technical data for this tube differ only insignificantly from those of the well-known type *21 FBP 22.*

2. Mechanical Design

The picture tube and subunits are arranged on a drawer-type chassis (Figure 4), which is identical both for rack and for cabinet mounting.

Figure 3—Comparison of picture tubes. The *400 KB 22* picture tube fills the outer rectangular frame whereas an equivalent conventional round tube covers only the encircled area.

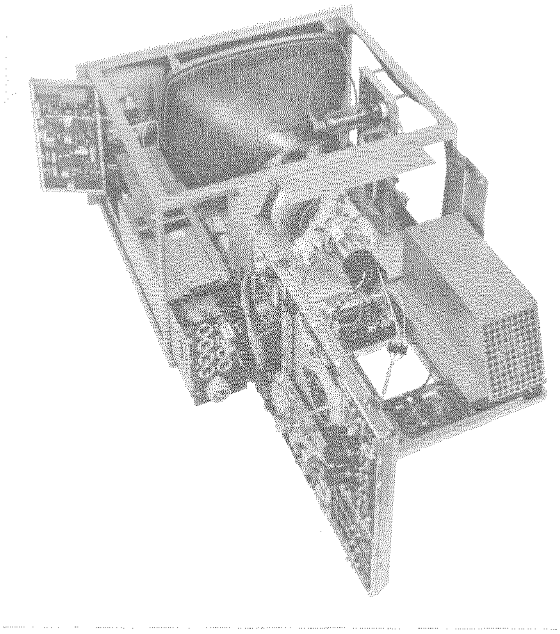

Figure 4—Chassis with panels in extended positions for servicing.

The cabinet model is 334 by 513 by 535 millimeters (13 by 20 by 21 inches) and it may also be mounted in an international (19-inch) rack. It weighs 43 kilograms (95 pounds).

2.1 SUBUNIT 1

The power supply is designed as a plug-in unit. The decoupling stages for the composite color and synchronizing signal inputs are mounted on a plug-in printed-circuit board. The signal-processing stages are arranged on two printed-circuit boards fitted to a hinged frame.

2.2 SUBUNIT 2

The panel hinged to the rear of the chassis, and shown swung out in Figure 4, contains the printed-circuit boards for the color-subcarrier oscillator, the chrominance demodulators (Figure 5), the distributing matrix, and the video output stages.

2.3 SUBUNIT 3

Subunit 3 is also located on the rear of the chassis and mounts all the deflection circuits.

2.4 SUBUNIT 4

Subunit 4 comprises the chassis proper with the picture tube and the high-voltage-rectifier, stabilization, and convergence units.

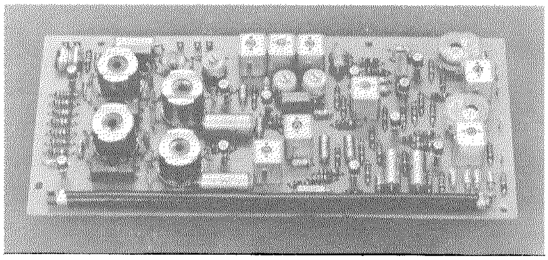

Figure 5—Printed-circuit board mounting chrominance demodulator.

3. References

1. H. Renner and G. Liebscher, "Technologie und Eigenschaften von Si-Planar- und Si-Epitaxial-Planartransistoren," *SEL-Nachrichten,* volume 11, number 1, pages 36-40; 1963.

2. G. Liebscher, "Lebensdaueruntersuchungen an Silizium-Planar-Transistoren," *Radio Mentor,* volume 30, number 5, pages 385–388; 1964.

3. G.-G. Gassmann, "Phasen- und Frequenzvergleichsschaltungen für Fernseher," Presented at 11th Annual Meeting of Fernsehtechnische Gesellschaft; 1963.

4. G.-G. Gassmann, "Neue Phasen- und Frequenzvergleichsschaltungen," *Archiv der Elektrischen Uebertragung,* volume 15, number 8, pages 359–376; 1961.

5. G.-G. Gassmann, "Phasen- und Frequenzvergleichsschaltungen für Fernseher," *Radio Mentor,* volume 27, number 12, pages 1027–1030; 1961.

Rolf Deubert was born in Grünstadt, Germany, on 25 April 1936. He studied telecommunications at the Technische Hochschule of Stuttgart, graduating in 1962 as a Diplom-Ingenieur.

He joined Standard Elektrik Lorenz in 1962 and is now in charge of a group in the Department for Special Developments of the Consumer Electronics Division.

Armin Rappold was born in Heidenheim, Germany, on 9 December 1912. He graduated as a Diplom-Ingenieur in 1936 from the Technische Hochschule of Aachen.

In 1936 he joined C. Lorenz, now Standard Elektrik Lorenz, where he worked on television development as well as radar and radio-link systems. He is now head of the Department for Special Development in the Consumer Electronics Division, working primarily on commercial applications of black-and-white and color television.

Infrared and the Nimbus High-Resolution Radiometer*

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1. Introduction

Infrared radiation was discovered in 1800 by Sir William Herschel [1], who detected it in the solar spectrum. The prism and sensitive thermometer he used formed the first infrared detection system. The later realization that infrared and visible light were made up of transverse electromagnetic waves established a basis for a theoretical treatment of infrared sources. A full understanding of infrared emission, however, had to wait for the introduction of the quantum theory by Planck [2] in 1906. Development of infrared detectors more sensitive than Herschel's thermometer began with the invention of the thermopile by Mellon [3] in 1833, and intensified with the discovery and study of infrared photoconductive and photovoltaic effects by Case [4] and others beginning in 1917.

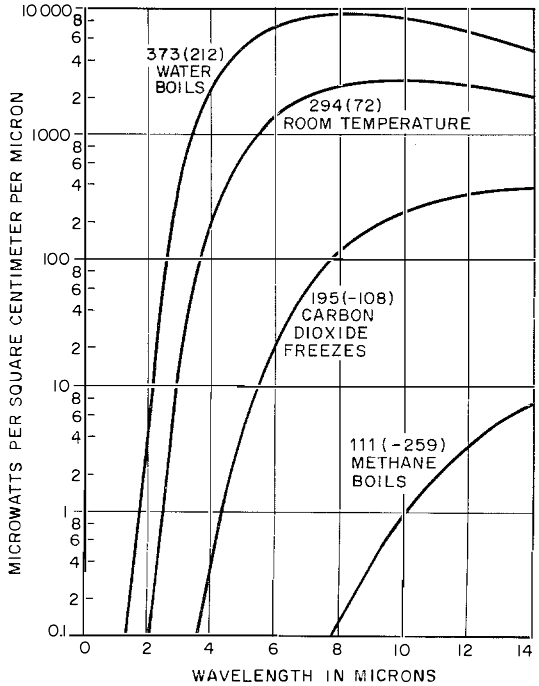

Figure 1—Wavelength distribution of blackbody emission. The numbers on the curves are in degrees Kelvin (fahrenheit).

Today a wide range of infrared optical materials and detectors are available. With our greater understanding of the nature of infrared sources and the properties of the earth's atmosphere, the ingredients are available for the design and construction of many types of infrared detection systems. One that is most useful and interesting is the high-resolution infrared radiometer [5, 6] developed by us for the National Aeronautics and Space Administration, Goddard Space Flight Center. This instrument was designed for the Nimbus meteorological satellite to produce nighttime infrared pictures of the earth and its cloud cover. Combined with the daytime television pictures, it provides 24-hour mapping of the earth's cloud formation. In addition, the radiometer indicates the temperature of the cloud tops and, indirectly, their altitudes.

A brief review of the fundamentals of infrared is given in Section 2 to establish the basis for the design of the radiometer. Its operation is then outlined and its performance illustrated by infrared weather pictures taken from the Nimbus *1* spacecraft.

2. Fundamentals of Infrared [7–13]

The infrared region of the electromagnetic spectrum lies between the visible and the submillimeter microwave regions. The visible region encompasses wavelengths between about 0.4 and 0.7 micron (1 micron = 10^{-4} centimeter) or frequencies between 750 and 450 terahertz (tera = 10^{12}). The microwave region lies at wavelengths longer than about 100 microns (frequencies below 3 terahertz). The

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* The high-resolution infrared radiometer was developed for the Nimbus weather satellite under sponsorship of the National Aeronautics and Space Administration.

familiar very-high-frequency band of television contains wavelengths between 10^6 and 10^7 microns (300 to 30 megahertz).

The utility of the infrared region lies in the fact that all objects with a temperature above absolute zero emit electromagnetic radiation and that for ordinary earth temperatures most of this radiation is contained in the infrared. Many infrared sources of interest are approximately blackbody sources. A blackbody absorbs all the radiation incident on it and has the maximum emission for a source in thermal equilibrium at any temperature. The total power in watts per unit area radiated by a blackbody is given by

$$F(T) = \sigma T^4$$

where T is the absolute temperature of the source in degrees Kelvin and σ is a constant. This is known as Stefan's law and σ as Stefan's constant, which has a value of 5.6686×10^{-8} watts per square meter per degree^4. At room temperature, about 300 degrees Kelvin, a blackbody 1 square meter in area radiates a total power of 460 watts.

The distribution of blackbody radiation with wavelength is given by Planck's law, which states that the power emitted per unit area between wavelengths λ and $\lambda + d\lambda$ is

$$F_\lambda(T, \lambda)d\lambda = \frac{2\pi hc^2}{\lambda^5} \frac{d\lambda}{(e^{ch/\lambda kT} - 1)}$$

where c is the speed of light, k is Boltzmann's constant, and h is Planck's constant of action. The derivation of this equation introduced the quantum hypothesis, namely that radiant energy of frequency c/λ is not emitted continuously but in bundles or "quanta" of amount hc/λ. The wavelength distribution of blackbody emission for several familiar temperatures is shown in Figure 1.

The atmosphere of the earth does not transmit radiation equally at all infrared wavelengths. Selective absorption by water vapor and carbon dioxide, and to a much-smaller extent by other constituents, produces wavelength regions of high and low transmittance, as shown in Figure 2. To detect sources of infrared radiation through the earth's atmosphere, the wavelength region of sensitivity must be limited to one or more of the regions of high transmittance, called "windows."

The radiation transmitted through the earth's atmosphere from an object or scene of interest

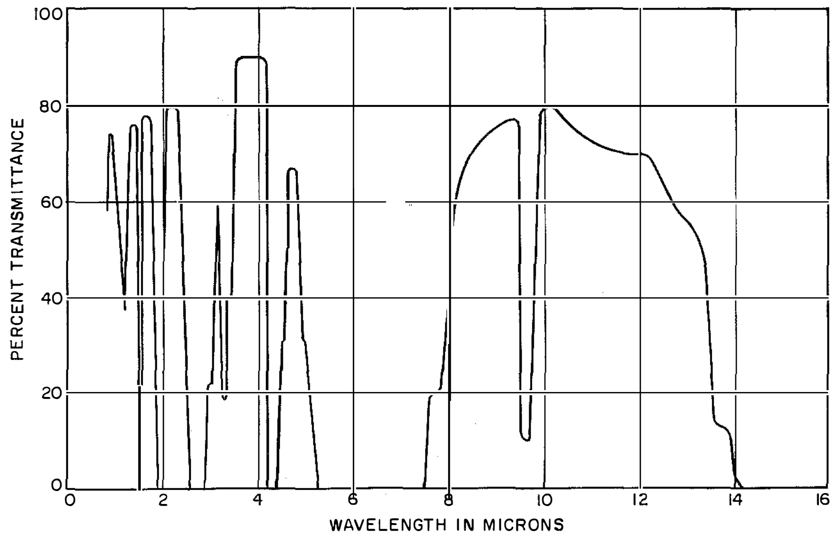

Figure 2—Smoothed vertical transmission curve of the earth's atmosphere.

must be received by a detector sensitive to radiation in the infrared region of the spectrum. In general, the detectors of infrared are classified according to the means of detection as thermal or photo detectors. Thermal detectors sense infrared radiation by changes in their properties with the temperature rise produced by the incident radiation. Such detectors have approximately equal sensitivity throughout the infrared region, ordinarily operate at room temperature, and are relatively slow in responding to changes in incident radiation. In photodetectors the quanta of incident radiation directly excite charge carriers (for example electrons). These detectors have sensitivities that vary with wavelength, require cooling to detect longer wavelengths, and are relatively fast in responding to changes in incident radiation. The essential difference between a photodetector and a thermal detector is that the former, in principle, counts the number of effective quanta (energy units) of radiation absorbed, whereas the response of the latter depends on the total energy absorbed.

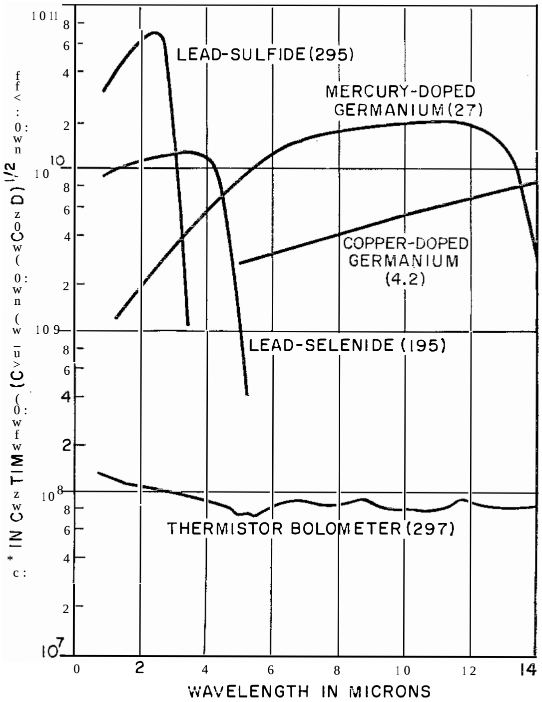

Figure 3—Sensitivity of several infrared detectors. All curves are for a radiation chopping frequency of 1000 cycles per second except the thermistor bolometer, which is for 10 cycles per second. The numbers in parentheses are in degrees Kelvin.

For photodetectors, only quanta having an energy greater than a certain value E_0 (or a wavelength shorter than hc/E_0) are effective; the detectors ignore the quanta of less energy (longer wavelength). As the infrared energy decreases (wavelength increases) the temperature at which a photodetector must be used decreases. If the maximum wavelength to be detected is λ_o, then a photodetector must be used whose E_o value is such that $E_o < hc/\lambda_o$. The required photodetector temperature T_d decreases as λ_o increases such that $\lambda_o T_d$ or T_d/E_o is approximately a constant.

The wavelength sensitivity and temperature of several infrared detectors are shown in Figure 3. The sensitivities are given in terms of D^*, the signal-to-noise ratio from a detector of 1 square centimeter sensitive area in a 1-cycle-per-second electrical bandwidth when 1 watt of power is incident on the detector [14]. Larger values of D^* therefore denote greater sensitivity. The thermistor bolometer is an example of a thermal detector; the others are photodetectors.

3. High-Resolution Infrared Radiometer

The Nimbus vehicle is an earth-oriented satellite that operates in a near-polar orbit. The high-resolution infrared radiometer is mounted on the bottom of the spacecraft. It scans the earth in narrow strips at right angles to satellite motion to produce infrared maps of the earth and its cloud formations. The radiometer is designed for nighttime operation but is also capable of producing daytime pictures. The daytime measurements do not indicate temperatures, however, because of the added reflected solar radiation.

The radiometer operates in the window in the earth's atmosphere located between 3.4 and 4.2

microns in wavelength (see Figure 2). It is designed to detect blackbody radiation from sources in the temperature range from about 210 to 330 degrees Kelvin (−80 to +140 degrees fahrenheit). The minimum detectable temperature difference is 1 degree Kelvin for a source at 260 degrees Kelvin. A lead-selenide photodetector (see Figure 3) is used to sense the infrared signal. This detector is a photoconductor; the absorbed quanta excite charge carriers to the conduction band of the lead-selenide, increasing its electrical conductivity. To detect blackbody radiation from sources in the desired temperature range, a photoconductor operating in the 3.4-to-4.2-micron region must be cooled to about 200 degrees Kelvin (−95 degrees fahrenheit). This is accomplished in the radiometer by radiantly coupling the lead-selenide detector to cold space to obtain an operating temperature of about 195 degrees Kelvin (−105 degrees fahrenheit). Space has an equivalent temperature of about 4 degrees Kelvin or −452 degrees fahrenheit.

A sketch of the radiometer optical system is presented in Figure 4. The scanning mirror rotates about the optic axis to provide coverage perpendicular to the orbital path of the satellite. Coverage in the other direction is provided by the forward motion of the satellite itself. Radiation from a cloud or earth source is collected by the scanning mirror and reflected to the primary telescope, which focuses the radiant signals onto a rotating chopper. The chopper modulates the signal for low-noise stable alternating-current amplification of the detector signal. The modulated signal is then relayed by a pair of back-to-back telescopes to the surface of the radiantly cooled lead-selenide cell. The filter between the relay mirrors limits the wavelength region of sensitivity to the 3.4-to-4.2-micron atmospheric window. The electrical output from the radiometer is stored on magnetic tape in the satellite and is telemetered to the ground on command from the acquisition station. The information is then relayed to the weather data center in Washington, District of Columbia, for use in global weather predictions.

Photographs of the Nimbus radiometer are shown in Figures 5 and 6. The white collars are sunshields to exclude solar radiation from the radiometer during spacecraft sunrise and sunset. The scan mirror can be seen in Figure 5 between the sunshields. The cylindrical cap at the front contains the motor that drives the scan mirror and chopper. The complete radiometer weighs 11.3 pounds (5.1 kilograms) and consumes 4 watts of power.

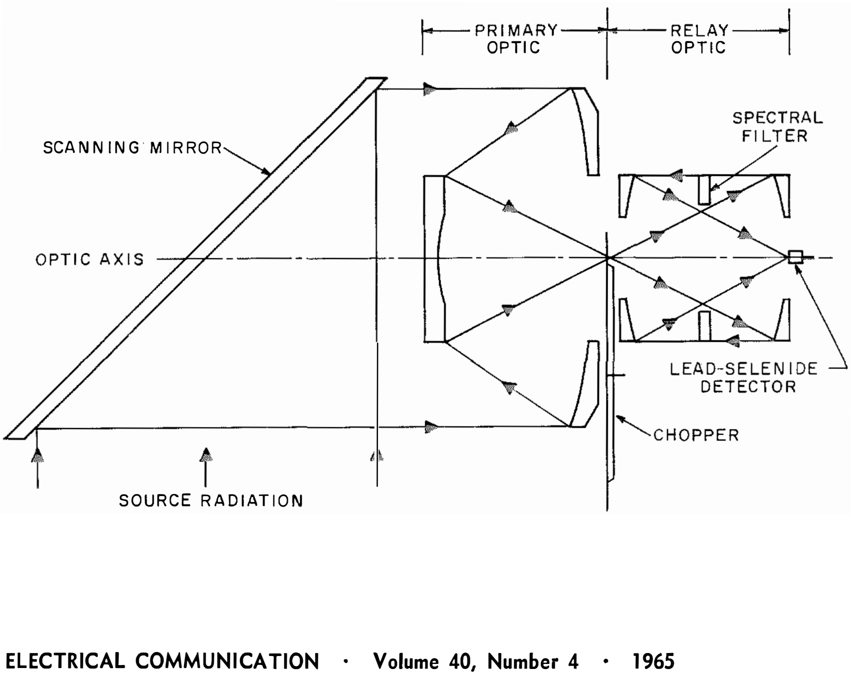

Figure 4—Optical system of the high-resolution infrared radiometer.

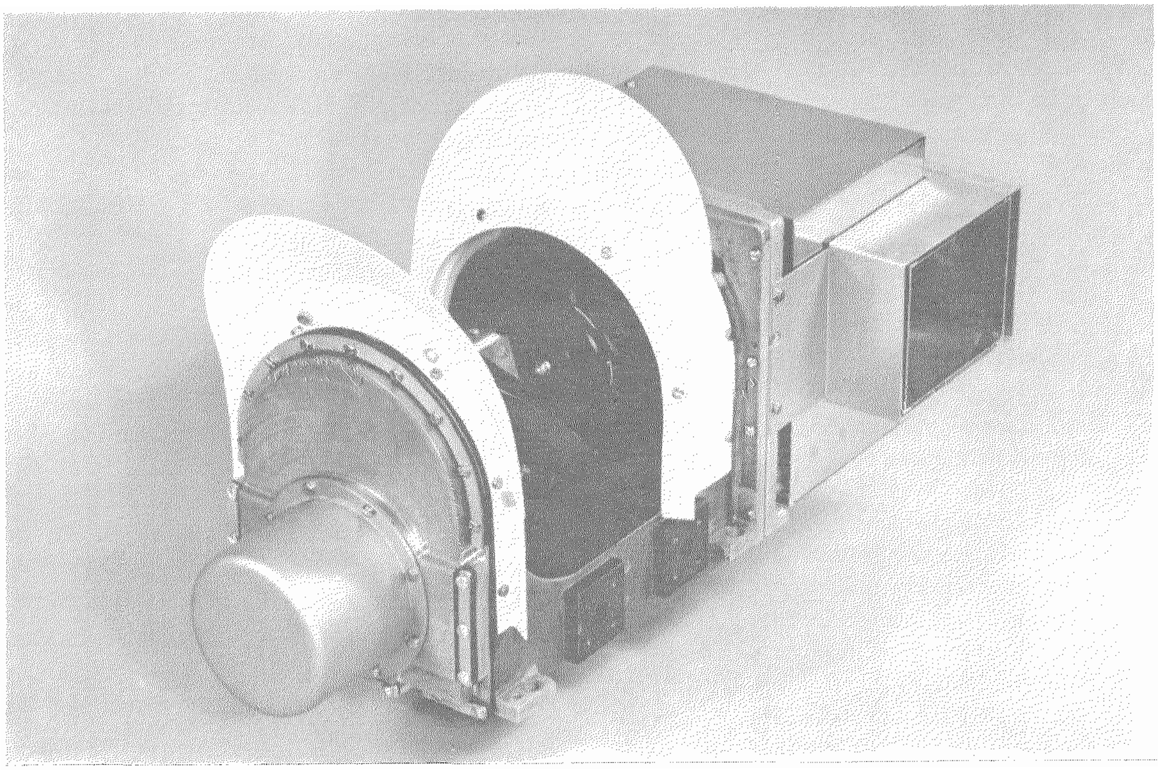

Figure 5—Nimbus high-resolution infrared radiometer.

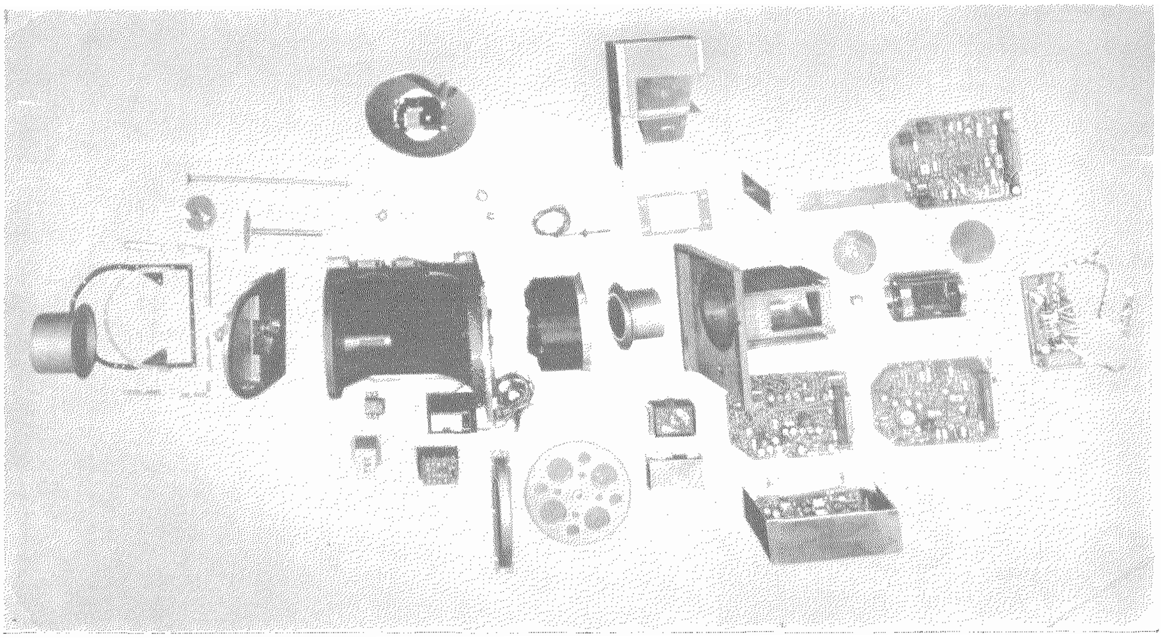

Figure 6—Disassembled radiometer.

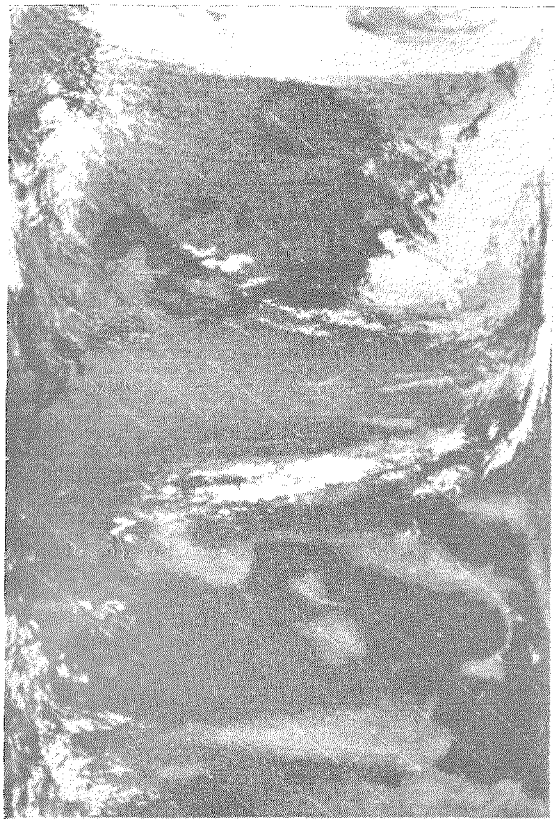

Figure 7—Nimbus radiometer photograph of Europe.

Figure 8—Nimbus radiometer strip map of the Caspian Sea and the east coast of Africa.

The performance of the radiometer is illustrated by the nighttime infrared pictures shown in Figures 7, 8, and 9, which were taken from the Nimbus *1* spacecraft. Although these figures are degraded considerably in photographic reproduction, clouds of high, medium, and low altitudes as well as land and water boundaries are readily visible. In addition, the film limits the intensity scale (shades of gray) to a factor of 10 less than that contained in the recorded infrared analog data.

Figure 7 covers most of Europe and a small portion of northern Africa. This picture was taken near midnight on 12 September 1964. The boot of Italy, Denmark, and the Scandinavian peninsula can be seen. The darker shades indicate warmer temperatures. Thus the bodies of water are warmer than the land masses, and the cloud formations over the Alps and northeastern Europe are cold. The lighter shades of gray along the Italian peninsula indicate the Apennine Mountains.

Figure 8 shows a portion of the infrared strip map taken during orbit 37 of Nimbus *1*. The Caspian Sea is near the top of the picture. and the east coast of Africa can be seen in the lower half. Lake Nyasa in Africa is visible because its temperature is higher than that of the surrounding land mass. Several cloud masses with cold, high-altitude tops are prominent near the center of the strip.

Figure 9—Nimbus radiometer photograph of Hurricane Dora and the southeastern United States.

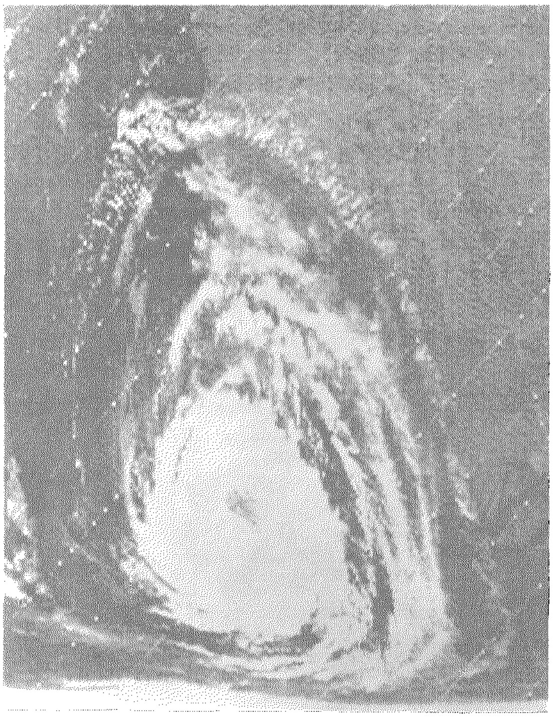

Figure 9 is a picture of Hurricane Dora taken by the radiometer near midnight on 9 September 1964. The eye of the hurricane is clearly visible as the darker region near the center of the white cloud mass. The hurricane was centered off the coast of Florida. Above the storm, at the top right, are Chesapeake Bay and the Potomac and Delaware Rivers. Nimbus weather pictures of Hurricane Dora were of value to meteorologists in studying the storm and its movements.

The photographs demonstrate the ability of an infrared radiometer to map the earth and its cloud formations. The response to scene temperature adds a third dimension to the pictures. High-altitude clouds and land masses appear as lighter shades, indicating lower temperatures and higher altitudes than the darker clouds and land masses.

4. References

1. *Philosophical Transactions of the Royal Society of London;* volume 90, page 284; 1800.

2. "Vorlesungen über die Theorie der Wärmestrahlung," Leipzig, Germany; 1906.

3. *Poggendorff, Annalen der Physik und Chemie,* volume 28, page 371; 1833. Also volume 35, pages 112, 277, and 385; 1835. *Annales de chimie et physique,* (2), volume 60, page 418; 1835.

4. *Physical Review,* volume 9, page 305; 1917.

5. I. L. Goldberg, L. Foshee, W. Nordberg, and C. E. Catoe, "Nimbus High-Resolution Infrared Measurements," paper given at the 3rd Symposium on Remote Sensing of Environment, University of Michigan, 12–14 October 1964.

6. "Nimbus 1 High-Resolution Radiation Data Catalog and User's Manual," Goddard Space Flight Center; 15 January 1965.

7. R. A. Smith, R. E. Jones, and R. F. Chasmar, "The Detection and Measurement of Infrared Radiation," Oxford at the Clarendon Press, London; 1957.

8. P. W. Kruse, L. D. McGlauchlin, and R. B. McQuistan, "Elements of Infrared Technology," John Wiley & Sons, New York; 1962.

9. G. K. T. Conn and D. G. Avery, "Infrared Methods, Principles, and Applications," Academic Press, New York; 1960.

10. M. R. Holter, S. Nudelman, G. H. Suits, W. L. Wolfe, and G. J. Zissis, "Fundamentals of Infrared Technology," Macmillan and Company, New York; 1962.

11. J. A. Jamieson, G. N. Plass, R. H. McFee, R. H. Grube, and R. G. Richards, "Infrared Physics and Engineering," McGraw-Hill Book Company, New York; 1963.

12. *Proceedings of the IRE,* Infrared Issue, volume 47, number 9; September 1959.

13. *Applied Optics,* Infrared Issue, volume 1, number 5; September 1962.

14. R. C. Jones, "Phenomenological Description of the Response and Detecting Ability of Radiation Detectors," *Proceedings of the IRE*, volume 47, number 9, pages 1495–1502; September 1959.

Richard V. Annable was born in Hastings, Michigan, in 1933. He received Bachelor of Engineering and Master of Science degrees, both in physics, from the University of Michigan in 1956 and 1957. In the latter year, he served as a research assistant at the University.

He joined the ITT Farnsworth Electronics Company in 1957 and has worked in the areas of infrared instruments and sensors, photoelectric devices, and geometric optics. He is presently in the Space and Applied Science Department at ITT Industrial Laboratories.

Mr. Annable is a member of Tau Beta Pi and the Optical Society of America.

Kenneth L. DeBrosse was born in Sidney, Ohio, in 1923. In 1944 he received a bachelor's degree cum laude and in 1950 a master's degree in physics and mathematics from Miami University in Ohio, where he served as instructor of physics the following year. From 1944 until 1946 he served in the United States Navy and from 1946 until 1948 he worked in the research department of the Monsanto Chemical Company.

In 1951, he joined the ITT Capehart-Farnsworth Company and has worked on projects concerning special television, infrared components and systems, and scientific instruments. As Manager of the Space and Applied Sciences Department he has been responsible for development of the Nimbus high-resolution infrared radiometer.

Mr. DeBrosse is a member of Phi Beta Kappa and the Optical Society of America.

Howard A. Leiter was born in Mount Gilead, Ohio, in 1918. In 1940 he received a bachelor's degree magna cum laude with honors from Miami University in Ohio, and a master's degree from the University of Illinois in 1942. From 1942 to 1945 he was a staff member of the Radiation Laboratory at Massachusetts Institute of Technology. He then returned to the University of Illinois as a teaching assistant and received a doctorate in physics in 1949.

He joined the Westinghouse Research Laboratories in 1949, where he worked on nuclear physics and infrared projects.

In 1958 he joined ITT Industrial Laboratories, working on infrared detectors and associated cryogenic systems, and currently with photosensitive materials, field-emission microscopy, and low-energy electron diffraction. He served as project manager for the first phase of the Nimbus high-resolution infrared radiometer program.

Dr. Leiter is a member of Phi Beta Kappa, the American Physical Society, and the Optical Society of America.

William H. Wallschlaeger was born in Milwaukee, Wisconsin, on 17 May 1935. He graduated with honors from Michigan State University in 1957, with a Bachelor of Science degree in electrical engineering.

After initial employment with Minneapolis Honeywell, he worked at the A. C. Spark Plug Division of General Motors Corporation, designing ground support equipment for the *WS-315A* (Thor) program.

He joined ITT Industrial Laboratories in 1959 to work on the *AN/AAR-21* Infrared Search-Track Set. Subsequently, he has done electrical design on the Nimbus high-resolution infrared radiometer and is now project manager for that program.

Mr. Wallschlaeger is a member of Eta Kappa Nu and Tau Beta Pi.

United States Patents Issued to International Telephone and Telegraph System; August–October 1964

Between 1 August 1964 and 31 October 1964, the United States Patent Office issued 69 patents to the International System. The names of the inventors, company affiliations, subjects, and patent numbers are listed below.

P. R. Adams and M. Rogoff, ITT Federal Laboratories, Recording System, 3 144 637.

R. T. Adams and G. Raisbeck, ITT Federal Laboratories and Bell Telephone Laboratories, Passive Satellite Repeater System, 3 144 606.

F. R. Arens, General Controls, Adjustable Scale for Manometer, 3 150 524.

G. W. Bain, ITT Laboratories, Combined Plural Carrier Electrostatic Printing and Display System, 3 148 600.

R. Basten, Standard Elektrik Lorenz (Stuttgart), Program-Control Unit Comprising an Index Register, 3 144 550.

F. Buchwald and H. Kudritzki, Standard Elektrik Lorenz (Stuttgart), Pneumatic Tube System for High Carrier Speeds, 3 148 845.

J. R. Clark, ITT Laboratories, Photosensitive Radiant Spot Tracking System, 3 149 235.

R. F. Cleaver and F. G. Cockerill, Standard Telephones and Cables (London), Radio Direction Finding System, 3 149 334.

R. F. Cleaver and F. G. Cockerill, Standard Telephones and Cables (London), Radio Navigation Receiver Arrangement, 3 149 335.

D. K. Coles, ITT Laboratories, Thermionic Converter, 3 144 569.

R. Conway, R. H. Sterns, W. F. Abel, and E. J. Cox, ITT Kellogg, Mounting Structure for Shelves of Switchboard Units, 3 148 311.

R. Dahlberg, Clevite Corporation, Method of Fabricating Laminar Semiconductor Devices, 3 151 007.

E. DeRaedt and H. Verhille, Bell Telephone Manufacturing Company (Antwerp), Registering Circuit, 3 143 723.

W. E. R. Evans and B. W. Kingston, Standard Telephones and Cables (London), Electrolytic Capacitors, 3 143 785.

S. G. Foord and W. E. Simpson, Standard Telecommunication Laboratories (London), Method of Forming a Coaxial Cable, 3 144 369.

E. Ganitta and G. Vogel, Standard Elektrik Lorenz (Stuttgart), Transistorized Telephone Subsets, 3 153 703.

W. L. Garfield, Standard Telephones and Cables (London), Radio Receiver Including a Monitoring Circuit Indicating an Output Upon Input Exceeding Predetermined Frequency, 3 149 243.

G. G. Gassmann, Standard Elektrik Lorenz (Stuttgart), Phase- and Frequency-Comparison Circuit Comprising Two Rectifying Sections, 3 144 612.

R. E. Gitter, ITT Laboratories, Recurring Signalling Condition Detector, 3 144 514.

R. D. Grayson and G. P. Greenamyer, General Controls, Attachment for Controls to a Tank, 3 149 782.

G. E. Griggs, Jennings Radio Manufacturing Corporation, Combined Linear and Rotary Actuator Means for Switch, 3 145 278.

W. Grooteboer, Mix and Genest Werk (Stuttgart), Ferrite Matrix Storage, 3 144 640.

L. B. Haigh and T. W. Tuttle, ITT Laboratories, Pulse Code Signalling Systems, 3 149 203.

G. F. Hardy, Clevite Corporation, Method of Making Diffused Junctions, 3 145 126.

J. S. Hawkins, Jennings Radio Manufacturing Corporation, Three-Phase Vacuum Switch, 3 154 655.

H. F. Herbig, H. G. Whitehead, M. Padalino, G. M. Nonnemacher, and B. McAdams, ITT Laboratories, Sound Monitoring and Recording System, 3 144 519.

J. Hill, Clevite Corporation, Loading Mechanism, 3 152 428.

J. N. Hinde, ITT Bell and Gossett Hydronics, Method of Making Shell and Fin Tube Condenser, 3 153 843.

M. N. Hirsh and P. N. Eisner, ITT Federal Laboratories, Rotation Measuring Device, 3 149 276.

J. L. Holsinger and N. E. Hoag, ITT Industrial Laboratories, Two Gun Storage Tube Utilizing Pulse Circuitry, 3 144 579.

K. Hubner, Clevite Corporation, Semiconductor Device and Method, 3 152 928.

R. A. Hyman and A. D. Thomas, Standard Telephones and Cables (London), Bistable Circuit Comprising a Negative Resistance Device in Combination with a Photo-Voltaic Element, 3 149 311.

K. S. T. Janson, M. V. I. Jeppsson, and K. E. S. Silversjo, Standard Radio & Telefon (Barkarby) and Swedish Posts, Telegraphs, and Telephones, Automatic Error Control Arrangement for Pulse Transmission, 3 145 340.

J. E. Jennings, Jennings Radio Manufacturing Corporation, Vacuum Switch and Actuator Assembly, 3 148 259.

A. E. Karbowiak, Standard Telephones and Cables (London), Manufacture of Long Haul Waveguide, 3 144 072.

H. W. Knau and G. R. Calon, Clevite Corporation, Method of Attaching Leads to Semiconductor Devices, 3 146 514.

W. Lanto, Standard Elektrik Lorenz (Stuttgart), Arrangement for the Turning Over of Flat Dispatch Articles, 3 144 250.

A. G. Latrubesse, Le Matériel Téléphonique (Paris), Manufacture of Molded Articles Carrying Indicia, 3 148 413.

R. T. Lawrence, Standard Telephones and Cables (London), Apparatus for Winding Helical Waveguides, 3 148 722.

A. Lieb, Standard Elektrik Lorenz (Stuttgart), Electroluminescent Voltage Measuring Device, 3 149 281.

J. V. Martens, A. L. M. Fettweis, and C. L. Daems, Bell Telephone Manufacturing Company (Antwerp), Impedance Matched Hybrid Network, 3 143 715.

J. G. McAllan and J. D. Laing, Standard Telephones and Cables (London), Television Signal Receiver Terminal, 3 144 512.

H. A. McIntosh, General Controls, Reset Circuit for Electrical Trip-Out, 3 149 267.

G. Merz and H. Reiner, Mix & Genest Werke (Stuttgart), Ferrite Matrix Storage Device, 3 149 313.

H. H. Naidich, ITT Laboratories, F. M. Radar Display Depicting Velocity and Range, 3 149 326.

R. K. Orthuber, F. F. Hall, and H. Emus, ITT Federal Laboratories, Radiation Source Search System Using an Oscillating Filter, 3 144 562.

A. Pierrot and Y. Lescroel, Lignes Télégraphiques et Téléphoniques (Paris), Magnetic Materials, 3 154 493.

H. Pipping, Clevite Corporation, Lead Wire Connection for Semiconductor Device, 3 150 297.

W. H. P. Pouliart, Bell Telephone Manufacturing Company (Antwerp), Edge Closure Mechanism for a Document Carrier, 3 143 838.

W. A. Ray, General Controls, Flame Detection System Using Oscillating Element, 3 146 822.

W. A. Ray, General Controls, Fluid Pressure Operated Valve Positioner, 3 151 531.

W. A. Ray, General Controls, Heat Motor Operated Valves, 3 151 834.

B. Reidel, Standard Elektrik Lorenz (Stuttgart), Communication Repeater Employing the Pulse-Code Modulation Method and Comprising Fault-Alarm Means, 3 144 605.

Chih-Tang Sah, Clevite Corporation, Four Layer Semiconductor Device, 3 146 135.

W. Shockley, Clevite Corporation, Voltage Regulating Semiconductor Device, 3 154 692.

US Patents to ITT; August–October 1964

W. Sichak, ITT Federal Laboratories, Diversity System, 3 144 647.

F. Steiner, Standard Elektrik Lorenz (Stuttgart), Direction Finder or Omnirange Beacon With Wide-Aperture Antenna System, 3 144 649.

J. W. Steiner, ITT Laboratories, Frequency Generator System, 3 144 623.

W. Suerkemper, Standard Elektrik Lorenz (Stuttgart), Electromagnetic Track Apparatus, Particularly for Axle-Counting Systems in Railway Safety Installations, 3 144 227.

W. Suerkemper and H. Zeeh, Standard Elektrik Lorenz (Stuttgart), Arrangement for Evaluating the Pulses in Railway Axle-Counting Systems, 3 144 225.

E. B. Tidd, ITT Bell and Gossett Hydronics, Air Separator Fitting for Closed Hot Water Heating Systems, 3 147 096.

M. F. Toohig and A. J. Knight, ITT Laboratories, Method of Forming Bowl Shaped Screen for Electron Discharge Tubes, 3 152 384.

F. J. L. Turner, Creed & Company (London), Perforating Apparatus, 3 144 205.

J. P. Van Blarcom, Jr., ITT Bell and Gossett, Marlow Pump Division, Submersible Motor-Pump Unit, 3 153 382.

R. C. Webb, ITT Bell and Gossett Hydronics, Angle Encoding Apparatus, 3 152 324.

A. Weygang, Standard Elektrik Lorenz (Stuttgart), Transistor Switch Utilizing a Control Transistor and Zener Diode, 3 149 239.

D. Wieland, Clevite Corporation, Method of Forming P-N Junctions in Silicon, 3 154 444.

L. R. Woods, International Electronic Research Corporation, Electric Actuated Impact Testing Machine, 3 148 530.

E. P. G. Wright, Standard Telecommunication Laboratories (London), Telegraph Systems, 3 144 634.

Radio Direction Finding System

3 149 334

R. F. Cleaver and F. G. Cockerill

This patent concerns a radio direction finder of the type in which a frequency-modulated signal is derived by a cyclic change in the space path over which the signal is received. To permit the determination of direction by the small frequency deviation produced by practical deviation distances and relatively low cyclic movement, the system provides a fixed antenna as well as the deviating antenna. The two signals are combined and transmitted to a control station where the frequency-discriminated signal is compared with a reference signal related to the cyclic deviation.

Method of Forming a Coaxial Cable

3 144 369

S. G. Foord and W. E. Simpson

This is a method of manufacturing a coaxial cable having expanded plastic insulation, in which partially expanded plastic granules are supplied within the outer coaxial conductor as it is formed. Afterwards, the cable is fed to a heating chamber, which limits expansion of the outer conductor to a uniform diameter and simultaneously causes further expansion of the granules to hold the center conductor in place.

Phase- and Frequency-Comparison Circuit Comprising Two Rectifying Sections

3 144 612

G. G. Gassmann

The phase- and frequency-comparison system described is particularly useful for synchronizing the horizontal-deflection circuit of a television receiver, or for any circuit where sinusoidal oscillating circuits are uneconomical. Pulse or sawtooth waveforms are applied to rectifying sections which when the waves coincide in frequency, deliver a phase-dependent control voltage, and when the frequencies differ, produce a difference-frequency voltage whose polarity depends on the direction of drift.

Manufacture of Long Haul Waveguide

3 144 072

A. E. Karbowiak

This apparatus is for constructing in situ a continuous length of waveguide formed of a closely wound helix. The apparatus consists of a segmented mandrel movable axially on internal ball-races, the segments being separately movable and collapsible at the forward end so they may be removed without disturbing the formed waveguide.

Method of Attaching Leads to Semiconductor Devices

3 146 514

H. W. Knau and G. R. Calon

This is a method of attaching leads to semiconductor devices having junctions alloyed with aluminum or other materials in which rapidly forming oxides impede the making of good electrical contact. According to this method a semiconductor wafer with a plurality of alloyed pellets is first subjected to an etching process to remove the oxide from the alloyed pellets and immediately subjected to an electrodeless nickel plating. The leads are then soldered to the plated alloyed regions and the assembly subjected to etching to remove the plating intermediate to the alloyed surfaces.

Diversity System

3 144 647

W. Sichak

This patent concerns a diversity communication system in which each station is provided with a reflector in the form of a paraboloid of revolution and with an even number of radiant-acting horns spaced symmetrically about the axis of revolution and adjacent to the focus of the reflector. The transmitted signal is supplied to half the horns in phase opposition to that supplied to the other half of the horns, to produce a plurality of divergent beams. The receivers respond individually to the separate beams, and the received outputs are then combined to provide the output signals.

Principal ITT System Products

Communication Equipment and Systems

automatic telephone and telegraph central office switching systems...private telephone and telegraph exchanges—PABX and PAX, electromechanical and electronic...carrier systems: telephone, telegraph, power-line, radio multiplex...long-distance dialing and signaling equipment...automatic message accounting and ticketing equipment...switchboards: manual (local, toll), dial-assistance...test boards and desk...telephones: desk, wall, pay-station, special-environment, field sets...automatic answering and recording equipment...microwave radio systems: line-of-sight, over-the-horizon ...teleprinters and facsimile equipment... broadcast transmitters: AM, FM, TV...studio equipment...point-to-point radio communication...mobile communication: air, ground, marine, portable...closed-circuit television: industrial, aircraft, nuclear radiation...slow-scan television...intercommunication, paging, and public-address systems...submarine cable systems...coaxial cable systems

Data Handling and Transmission

data storage, transmission, display...data-link systems...railway and power control and signaling systems...information-processing and document-handling systems...analog-digital converters...alarm and signaling systems... telemetering

Navigation and Radar

electronic navigation...radar: ground and airborne...simulators: aircraft, radar...antisubmarine warfare systems...distance-measuring and bearing systems: Tacan, DMET, Vortac, Loran...Instrument Landing Systems (ILS) ...air-traffic-control systems...direction finders: aircraft, marine...altimeters—flight systems

Space Equipment and Systems

simulators: missile...missile fuzing, launching, guidance, tracking, recording, and control systems...missile-range control and instrumentation...electronic countermeasures...power systems: ground-support, aircraft, spacecraft, missile...ground and environmental test equipment...programmers, automatic...infrared detection and guidance equipment...global and space communication, control, and data systems ...system management: worldwide, local... ground transportable satellite tracking stations

Commercial/Industrial Equipment and Systems

inverters: static, high-power...power-supply systems...mail-handling systems...pneumatic tube systems...instruments: test, measuring ...oscilloscopes: large-screen, bar-graph...vibration test equipment...pumps: centrifugal, circulating (for domestic and industrial heating)...industrial heating and cooling equipment...automatic controls, valves, instruments, and accessories...nuclear instrumentation

Components and Materials

power rectifiers: selenium, silicon...transistors...diodes: signal, zener, parametric, tunnel ...semiconductor materials: germanium, silicon, gallium arsenide...picture tubes...tubes: receiving, transmitting, rectifier, thyratron, image, storage, microwave, klystron, magnetron, traveling-wave...capacitors: paper, metalized paper, electrolytic, mica, plastic film, tantalum...ferrites...magnetic cores...relays: telephone, industrial, vacuum...switches: telephone (including crossbar), industrial...magnetic counters...magnetic amplifiers and systems...resistors...varistors, thermistors, Silistor devices...quartz crystals...filters: mechanical, quartz, optical...circuits: printed, thin-film, integrated...hermetic seals...photocells, photomultipliers, infrared detectors... antennas...motors: subfractional, fractional, integral...connectors: standard, miniature, microminiature...speakers and turntables

Cable and Wire Products

multiconductor telephone cable...telephone wire: bridle, distribution, drop...switchboard and terminating cable...telephone cords... submarine cable and repeaters...coaxial cable: air and solid dielectric...waveguides...aircraft cable...power cable...domestic cord sets ...fuses and wiring devices...wire, general-purpose

Consumer Products

television and radio receivers...high-fidelity phonographs and equipment...tape recorders ...microphones and loudspeakers...refrigerators and freezers...air conditioners...hearing aids...home intercommunication equipment... electrical housewares

The 25th Anniversary of Pulse-Code Modulation
Laboratoire Central de Télécommunications
System Engineering: Its Approach and Operations
Modulation and Coding
Small-Diameter Coaxial Cable Using Moulded-Shell Construction
Relationship Between Attenuation and Wire-Braid Design for Flexible Radio-Frequency Cables
Monitor for Color Television
Infrared and the Nimbus High-Resolution Radiometer

VOLUME 40 • NUMBER 4 • 1965