SPECIFICATION OF ATOMIC FREQUENCY STANDARDS FOR MILITARY AND SPACE APPLICATIONS

J. White, F. Danzy, E. Powers
U.S. Naval Research Laboratory (NRL)
4555 Overlook Avenue, S.W.
Washington, D.C. 20375–5000

Abstract

This paper provides a detailed review of a typical specification for a cesium clock to be used in an orbiting satellite. Area of the specifications to be discussed include the use of military standards and other government documents as references, performance criteria, electrical and mechanical interface details, parts selection, quality assurance standards, and reliability requirements. The relationship between the specifications, the statement of work, and test procedures will also be discussed.

I INTRODUCTION

Specifying an atomic clock for use in a space environment requires an understanding of the requirements and environment not just in the sense of timekeeping or frequency stability, but also of the highly specialized conditions required to be met for flight. In space applications, the ability of the clock to survive and keep stable time over a number of environments at a very high reliability is usually at least as important as exactly how stable it is. For example, since it is not generally practical to recover a failed clock to repair it, satellite systems may carry several clocks just to assure that there will be an operating clock available throughout the expected mission. Similarly, the vibration levels encountered during a rocket launch are much more severe than a laboratory clock would ever see. The transition from an existing laboratory or commercial device requires a broad understanding of what is to be expected from the clock and under what conditions it must provide that performance.

The approach to be presented in this paper defines the steps that are necessary to specify a space clock. Not all performance parameters will be covered, but attention will be given to those that are unique to high precision clocks and also to items that have been found to be especially troublesome. In addition, there are a number of applicable documents and standards available which can be cited in clock specifications. Reliability is another key area where experience has shown difficulties due to the low volume production of space clocks and the uniqueness of atomic resonator packages. Finally, there is the question of what parameters need to be tested and to what extent it is practical to test them to verify that the delivered item really has the desired characteristics. Our experience has been that performance, reliability and acceptance criteria are the principal areas which must be given consideration when developing clock specifications. Figure 1 depicts the relationship of the areas we feel had the greatest influence in the development of the specifications. Table I provides a listing of the military handbooks and specifications we found to be particularly helpful when developing specifications for atomic clocks intended for space applications. We recommend that one become at least familiar with these documents when developing specifications for a militarized clock system. It should be pointed out that table I is not intended to be all inclusive, other applicable documents may be required including program specific reliability/quality documentation which could have been added to this list.

II PERFORMANCE

Frequency standards performance specifications must be realistic and based on an appreciation of the operating environment. For a given technology one can not expect to achieve the level of performance with space hardware as one can get with a laboratory instrument of the same technology. Normally sacrifices in performance must be made in order to reduce the clock's sensitivities to the operational profile of the space mission. The base line performance requirements are generally a derivative of a laboratory instruments capability tailored to conform with the host system's operational and environmental requirements. Typically a performance hierarchy is established with adjustments being made as the clock design become better defined. The following is a listing which illustrates the starting order we used in establishing performance requirements.

Baseline Performance

- Long and Short Term Stability
- Accuracy
- Settability
- Phase Noise
- Spectral Purity

Environment

- Thermal
- Radiation
- Magnetic

Interface

- Output Signal Characteristics
- Diagnostic Monitors
- Electromagnetic Interference and Compatibility
- Telemetry Commands
- Power (turn–on and nominal)
- Warm–up time

It should be emphasized that a lower–order performance requirement can influence a higher–order requirement. That is one might have to sacrifice on the settability requirements because of the spacecraft telemetry capability. Stability or accuracy requirements may have to be reduced due to the thermal or magnetic environment of the spacecraft. Our experience has been the higher the order the more likely requirements sacrifices will be made. If the effort is structured to include a full development program, prototype, engineering and pre–production models, fewer performance sacrifices will be experienced in the end product. It can not be stressed to strongly that the more effort devoted to the engineering and pre–production stages the more likely one is to achieve the desired higher order performance goals. The clocks developed by NRL with the more comprehensive efforts in the engineering development stages have resulted in better demonstrated performance.

III RELIABILITY

Reliability requirements are generally based on the level of risk acceptable to meet mission requirements. If it is an economically reflyable mission, reliability requirements can be somewhat relaxed. But if it is a high priority, minimum risk mission reliability requirements can be quite stringent. The effort to develop clocks for the GPS program would be a good example of a program with a minimum risk mission requirement. If the mission requires a highly reliable clock and the manufacturer doesn't have extensive experience in building space qualified clocks for efforts which requiring high reliability you can expect to experience considerable difficulty. Unfortunately our experience has shown there is a flip side to this coin. Sometimes a manufacturer with space hardware experience has established in–house production procedures based on what was considered acceptable for other programs. When this is the case, one might experience difficulty in introducing program specific reliability and quality program requirements. Specifications should include requirements for the manufacturer to provide a detailed reliability/quality program plan, even for an engineering development effort. We feel that at a minimum the program plans should include the items listed below in order their of priority:

- Parts, Materials and Processing program
- Vendor Performance Requirements
- Workmanship Standards
- Configuration Management
- Documentation Control
- Test Procedures
- Test system configurations

The hierarchy of this list should be modified as the program progresses. Test plans/procedures and documentation control will eventually become the more critical. Reliability requirements must be address at the very beginning of the effort. Attempts to introduce reliability practices after the baseline design has been established is one mistake one does not want to make. If the host system has stringent piece part quality requirements, specifications should clearly reflect these requirements in any effort above the level of prototype. If reliability predictions are to be required, the ground rules for performing the predictions should be clearly stated in the specifications. Mechanical reliability is an area often taken for granted in the early design stages. An attitude frequently encountered was "I can always make it strong enough to survive the launch environment". Our experience has been obtaining the mechanical reliability which meets the launch, shock and vibration environment, was one of the hardest to achieve and generally this requirement has zero room for sacrifice. As an aside one can expect to become familiar with DOD–STD–480 (waivers and deviations) the degree will depend on (a) experience of the manufacturer, (b) specification clarity/detail, and (c) adequacy of development effort.

IV ACCEPTANCE CRITERIA

Qualification requirements are generally used as the base line for the acceptance criteria. The qualifications requirements are generated from the host system operating environment and system specified performance and survivability requirements. Requirements imposed by military standards influence the acceptance criteria, but one must recognize that atomic clock technology is some what unique to space applications and tailoring of some of the requirements imposed by military standards is necessary. Verification that a given design will meet or exceed the minimum acceptance criteria can only be accomplished from the results obtained through the qualification and acceptance testing programs. Design analysis and predictions will only give a reasonable estimate of product performance. The decision to fly a candidate unit will be based solely on the test results. It is therefore very important that the qualification and acceptance test plans be carefully thought out to insure the data you get from testing will provide the information you really need to know. To insure that the data packages contained the right information the qualification and acceptance test plans are made part of our specifications. The test plans include the basic format for data presentation, but variations to accommodate a manufacturer's data collection schemes may be acceptable. The following is a list of some of the areas we consider to require special attention in the specifications:

(1) Ambient or Thermal Vacuum Environment
(2) Magnetic field
(3) EMI/EMC
(4) Cyclic or Incremental Profiles
(5) Testing Sequence

Figure 2 is an example of what can result when test plans are not spelled out in detail. The manufacturer's initial estimate of the unit's temperature coefficient was base on figure 2a. To verify the unit's temperature coefficient the test was repeated at NRL with smaller temperature steps, the results are shown in figure 2b. Operationally the unit's nominal base plate temperature would be in the range from 20 to 35 degrees celsius. In this range the unit exhibited a temperature coefficient of approximately $+1.55 \times 10^{-13}$ per degrees celsius, significantly greater than the manufacturer's initial estimate of 4.0×10^{-15} per degree celsius. The task of developing the test procedures was left to the manufacturer, but approval was required prior to their being instituted. The test procedures submitted by the manufacturer for approval should include schematics of test system configurations. Additionally pictorial drawings illustrating test article position and orientation should be included. The test data required by the specifications does not have to be limited to the qualification or acceptance test results obtained from the clock system. Specifications might include data requirements for subassemblies, especially parametric measurements made on the physic package. This information can be used to measure product variability.

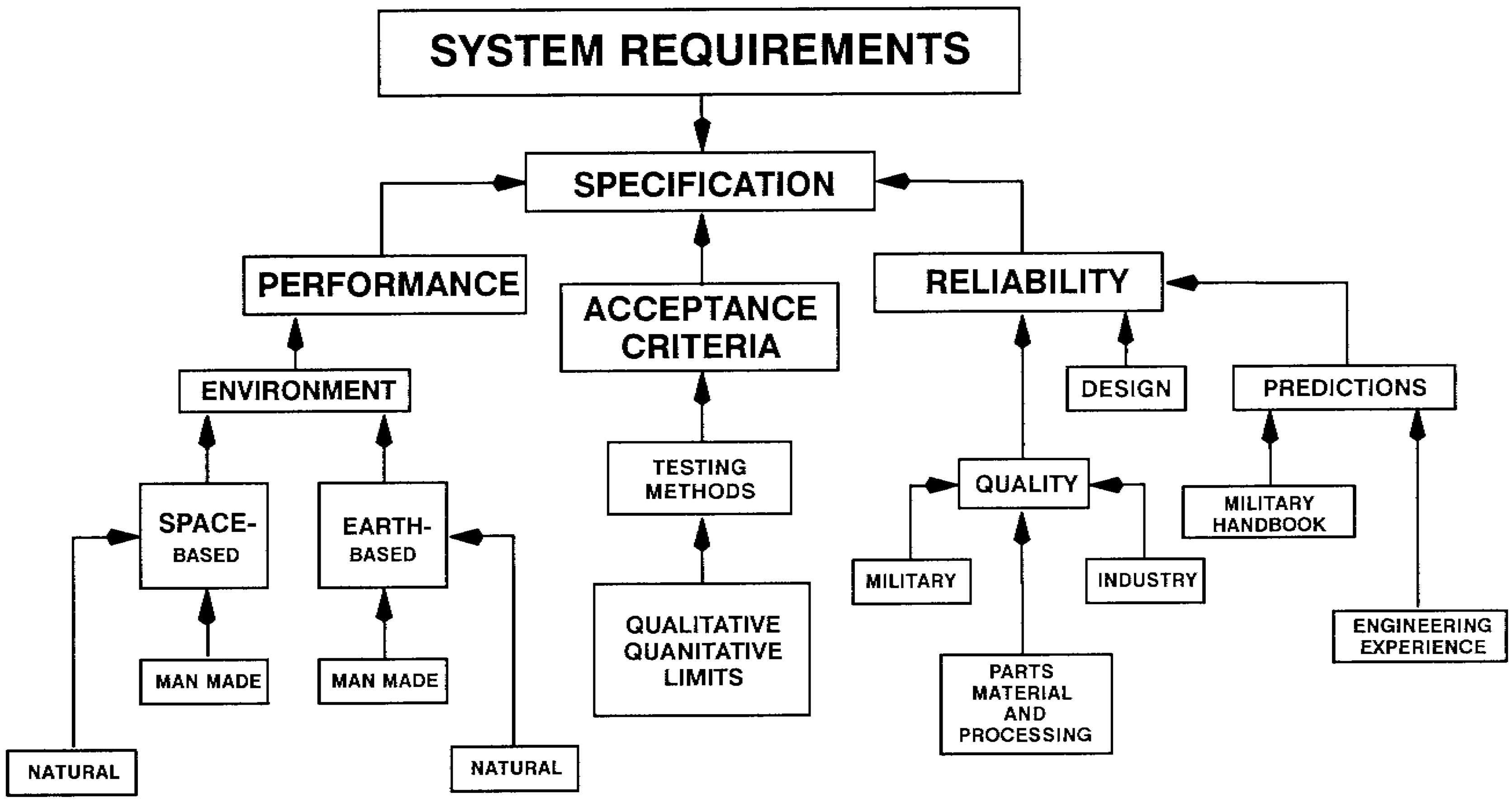
The recommendations for specifications preparations for space qualified atomic frequency standards are base on our experience while developing cesium clock for GPS applications. Areas given special emphasis were done so because of the major difficulties we encountered in achieving these requirements.

TABLE I

Typical Reference Documents Encountered

(1)	DOD–HDBK–248	Guide for Application and Tailoring of Requirements for Defense Material Acquisitions
(2)	DOD–HDBK–343	Design, Construction, and Testing Requirements for One of a Kind Space Equipment
(3)	DOD–HDBK–344	Environmental Stress Screening(ESS) of Electronic Equipment
(4)	MIL–STD–461	Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference
(5)	DOD–STD–480	Configuration Control–Engineering Changes, Deviations and Wavers
(6)	MIL–STD–490	Specification Practices
(7)	MIL–STD–781	Reliability Design Qualification and Production Acceptance Test: Exponential Distribution
(8)	MIL–STD–785	Reliability Program for System and Equipment Development and Production
(9)	MIL–STD–1540	Test Requirements for Space Vehicle
(10)	MIL–STD–1541	Electromagnetic Compatibility Requirements for Space System
(11)	MIL–STD–1543	Reliability Program Requirements for Space and Missile System
(12)	MIL–STD–1546	Part, Materials, and Processes Standardization, Control and Management Program for Spacecraft and Launch vehicles
(13)	MIL–STD–1546	Part, Materials, and Processes for Space and Launch Vehicles, Technical Requirements for
(14)	DOD–E–8983C	Electronic Equipment, Aerospace, Extended Space Environment
(15)	MIL–Q–9858	Quality Program Requirements
(16)	MIL–F–28811a(EC)	Frequency Standard, Cesium Beam Tube
(17)	FED–STD–209	Clean Room and Work Station Requirements, Controlled Environment

FIGURE 1


SYSTEM REQUIREMENTS
SPECIFICATION
PERFORMANCE
ACCEPTANCE CRITERIA
RELIABILITY
ENVIRONMENT
DESIGN
PREDICTIONS
TESTING METHODS
SPACE-BASED
EARTH-BASED
QUALITY
MILITARY HANDBOOK
MILITARY
INDUSTRY
QUALITATIVE QUANITATIVE LIMITS
MAN MADE
MAN MADE
ENGINEERING EXPERIENCE
PARTS MATERIAL AND PROCESSING
NATURAL
NATURAL

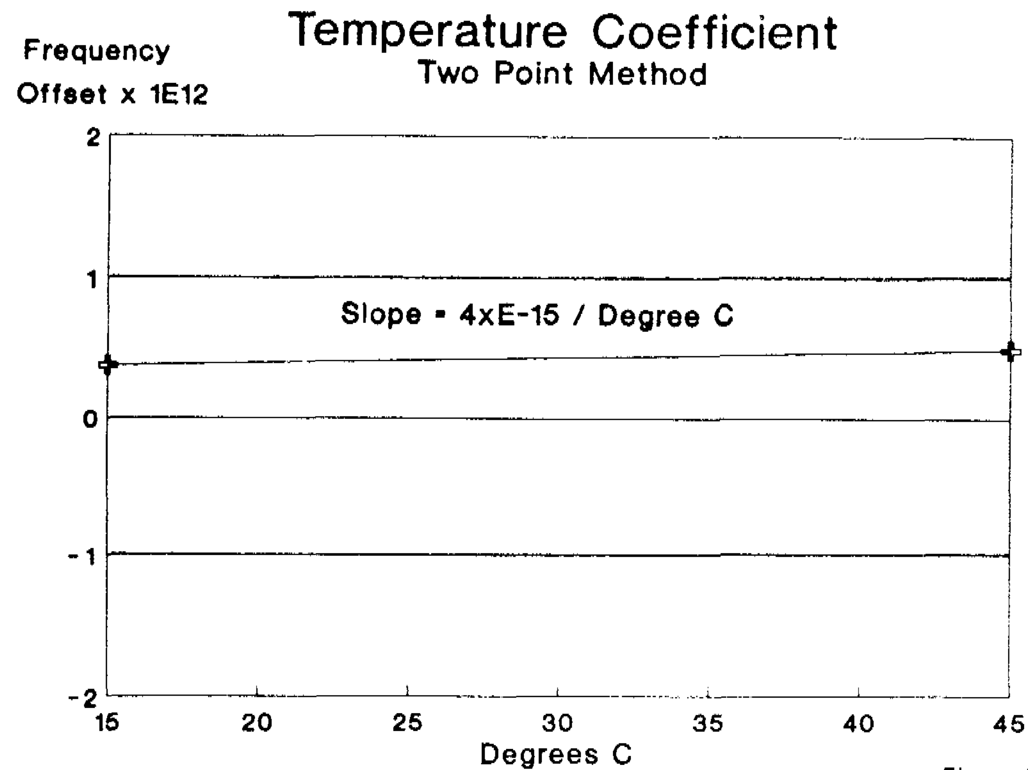


Figure 2A

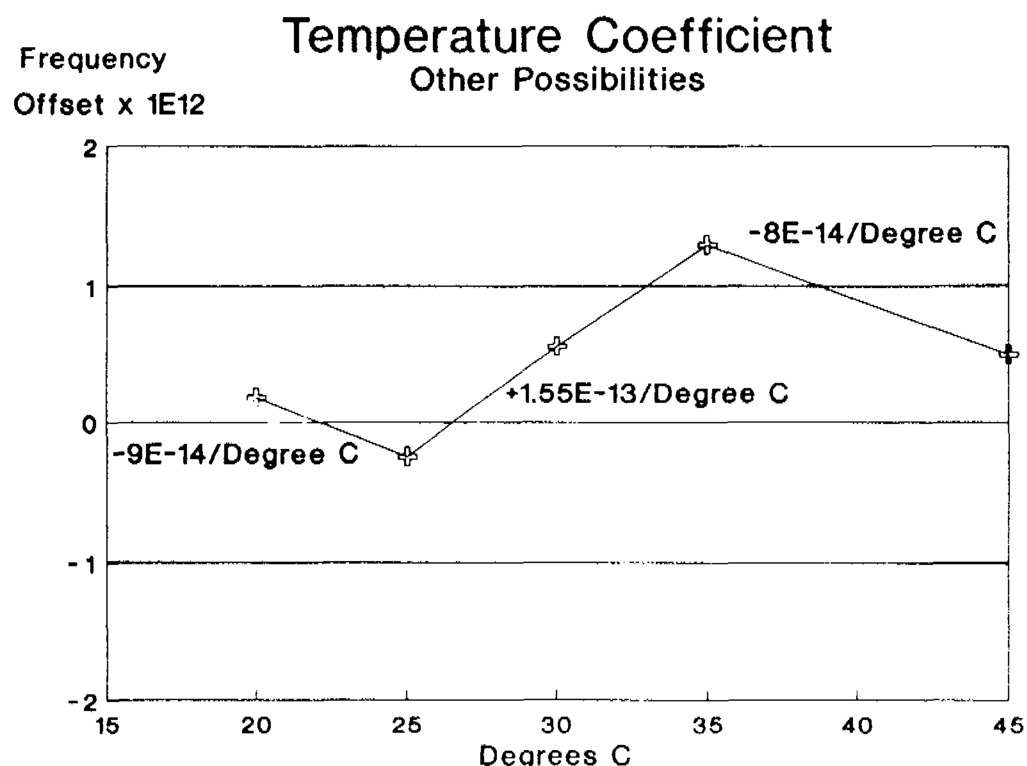


Figure 2B