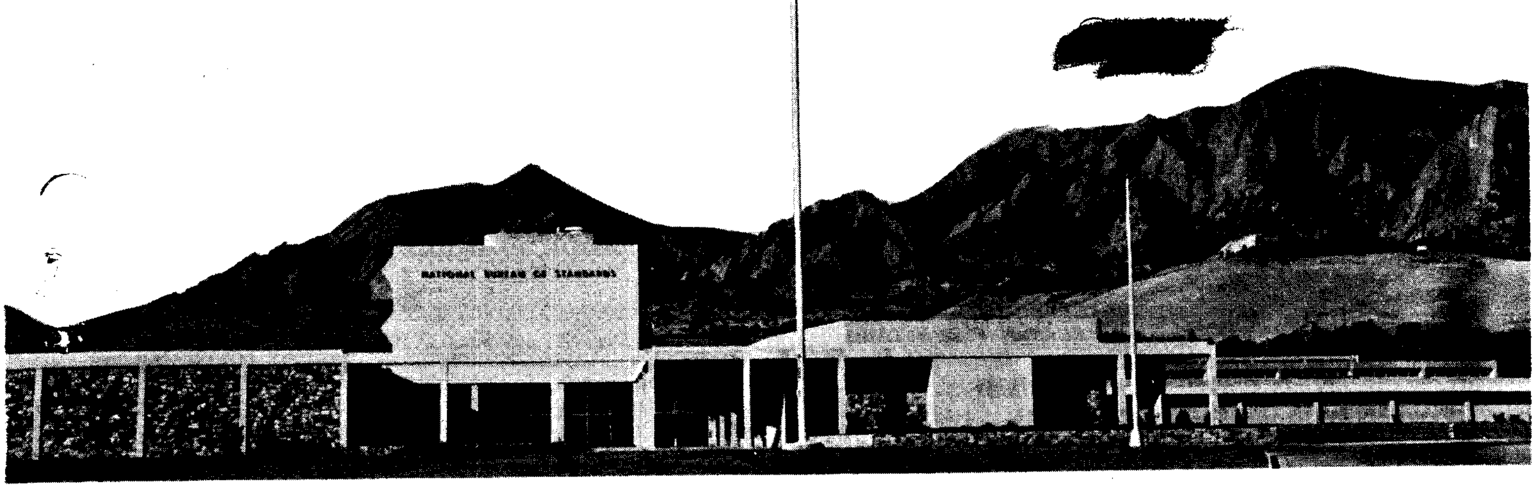


NBS REPORT

10 735

# SPACEBORNE CLOCK SYSTEM:
## Some Alternatives for a Proposed NASA Experiment

Roger E. Beehler
Coordinator, Steering Committee for
GEOS Timing Experiment
Time and Frequency Division
National Bureau of Standards
Boulder, Colorado 80302

NBS

November 1971
Final Report Prepared for:
National Aeronautics & Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

**U. S. DEPARTMENT OF COMMERCE**
**NATIONAL BUREAU OF STANDARDS**
**Institute for Basic Standards**
**Boulder, Colorado 80302**

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.
[2] Part of the Center for Radiation Research.
[3] Located at Boulder, Colorado 80302.

# NATIONAL BUREAU OF STANDARDS REPORT

**NBS PROJECT** 27300-2730101

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SPACEBORNE CLOCK SYSTEM:
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U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

16. Abstract (contd.)

commercial supplier, contracting to the Applied Physics Lab of Johns Hopkins University, a cooperative program with the Department of Defense, and use of an existing spaceborne rubidium standard developed for NASA-MSFC.

# PREFACE

The objective of this report is to evaluate various alternatives for achieving five goals stated by NASA-GSFC: (1) the improvement of international time and frequency comparisons, (2) the improvement of precise one-way Doppler tracking techniques, (3) the study of satellite one-way ranging techniques, (4) the performance of certain relativistic experiments, and (5) the development of new atomic frequency standards technology. In addition to NASA's proposed solution of developing a special on-board atomic clock for this purpose, other alternatives are considered including the use of existing terrestrial and satellite time dissemination systems, the use of other satellite techniques not requiring an on-board clock, and the use of a satellite-borne atomic clock already developed for another NASA program. Technical inputs to this study were provided by an ad-hoc Technical Steering Committee appointed by NASA-GSFC, by knowledgeable commercial representatives, by the existing scientific literature in the time and frequency field, by commercial data and specifications on various types of existing frequency standards, and by wide experience at the National Bureau of Standards with various standards and dissemination techniques.

With regard to NASA's stated goal of improving international time and frequency dissemination, it was concluded that several existing techniques and systems--including both terrestrial and satellite methods--hold promise for achieving the stated objectives. Some of these are likely to be less expensive and more reliable than the satellite-borne clock solution. Of the satellite methods considered the use of a ground-based atomic standard transmitting to a transponder on board a geostationary spacecraft appears to offer many advantages relative to the on-board clock approach originally proposed for the timing experiment.

The other four NASA goals can probably be achieved <u>at the stated accuracy levels</u> only by using a spaceborne atomic standard. Based on an analysis of such factors as presently-achieved performance of commercial and non-commercial atomic standards of various types, constraints imposed by the spacecraft environment, and various physical characteristics of the contenders, it was concluded that cesium or rubidium standards offer the best compromise for the experiment as proposed by NASA-GSFC. It is recommended that before any expensive development effort is initiated for such a standard, serious consideration should be given to the use of an already existing rubidium standard developed by NASA-MSFC for the Apollo Applications Program and to the possibility of joining with interested units in the Department of Defense in a coordinated, joint development effort.

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## 1. INTRODUCTION AND GENERAL BACKGROUND

During early 1968 Goddard Space Flight Center initiated a contract with the Time and Frequency Division of the National Bureau of Standards to study various alternatives for an atomic frequency standard and clock system compatible with a spacecraft environment. Originally, the intent was to develop specifications for an atomic standard suitable for use as a source of precise frequency and time signals specifically in connection with the GEOS series of geodetic satellites. During later stages of the study, however, as future planning for GEOS-C, D, and beyond remained rather uncertain, and as possible applications for ultra-stable satellite timing signals were suggested in areas other than geodesy, restrictions to particular satellites or satellite programs were removed.

To provide the primary source of technical information, a Steering Committee for the GEOS Timing Experiment was established consisting originally of the following representatives:

(a) Mr. James D. Rosenberg
Geodetic Satellites Program Manager
National Aeronautics and Space Administration
Washington, D. C.

(b) Mr. Roger Beehler
Steering Committee Coordinator
Time and Frequency Division
National Bureau of Standards
Boulder, Colorado

(c) Mr. Carl Hagge
Smithsonian Institution Astrophysical Laboratory
Cambridge, Massachusetts

(d) Captain Robert Paulson
Guidance and Control Division
Space and Missile Systems Organization
USAF
Los Angeles, California

(e) Dr. Friedrick H. Reder
Exploratory Research Division C
Institute for Exploratory Research
U. S. Army Electronics Command
Fort Monmouth, New Jersey

(f) Mr. Arthur Shapiro
Aerospace Corp
Los Angeles, California

(g) Dr. Richard L. Sydnor
Jet Propulsion Laboratory
Pasadena, California

(h) Dr. George C. Weiffenbach
The Johns Hopkins University
Applied Physics Laboratory
Silver Spring, Maryland
Presently with Smithsonian Astrophysical Lab
Cambridge, Massachusetts

(i) Dr. R. Glenn Hall
Time Services Division
U. S. Naval Observatory
Washington, D. C.

(j) Mr. John H. Berbert
Goddard Space Flight Center
Greenbelt, Maryland

(k) Mr. Arthur F. Block
Goddard Space Flight Center
Greenbelt, Maryland

(l) Mr. Andrew R. Chi, Chairman
Goddard Space Flight Center
Greenbelt, Maryland

(m) Dr. Bodo Kruger
Goddard Space Flight Center
Greenbelt, Maryland

(n) Mr. Straton Laios
Goddard Space Flight Center
Greenbelt, Maryland

(o) Mr. Francis J. Lerch
Goddard Space Flight Center
Greenbelt, Maryland

(p) Dr. Fouad G. Major
Goddard Space Flight Center
Greenbelt, Maryland

(q) Mr. Thomas E. McGunigal
Goddard Space Flight Center
Greenbelt, Maryland

The committee was chaired by Mr. A. R. Chi of NASA GSFC with the NBS contractor, Mr. R. Beehler, acting as coordinator. Technical information was also obtained from a variety of other sources, including knowledgable commercial representatives, published specifications for commercial frequency standards, extensive experience with various types and models of quartz oscillators and atomic standards at the National Bureau of Standards, and the existing scientific literature pertinent to the time and frequency field.

During the course of this study NASA GSFC also awarded a supplementary contract to the Applied Physics Lab of Johns Hopkins University to cover an analysis of possible modulation techniques and other aspects of the electronics systems required to transfer the inherently stable signals characteristic of the atomic standard itself from the satellite to the users on the ground. A report of this investigation, including many detailed conclusions gained from APL's previous work in satellite timing systems sponsored by the U. S. Navy and NASA, was completed in October, 1969 [1].

The Technical Steering Committee met in April, 1968 and January, 1969 in Washington, D. C. In addition, information and opinions were exchanged by means of correspondence, telephone calls, and one trip by the coordinator to visit several committee members and commercial labs for more detailed discussions. As the study proceeded it became increasingly apparent that the basic question of what type and design of atomic standard should be selected could not be intelligently answered until much broader considerations, such as the general justification for developing <u>any</u> kind of spacecraft atomic clock system, the needs for improved timing capabilities, alternative solutions to any existing timing problems, etc., were dealt with.

Because of the importance of these broader considerations in the choice of a possible atomic standard for spacecraft applications, this report will discuss some of these aspects first before dealing with the more specific question of what type of standard is "best". Section 2 of the report discusses some possible needs and applications for improved time dissemination services without regard to the particular dissemination techniques that might be employed. In Section 3 various alternatives and techniques, including the use of satellites, are considered as possible solutions for existing and projected timing needs. Included are discussions of the various <u>satellite</u> techniques available and the pros and cons of active vs. passive systems, stationary vs. orbiting satellites, one-way vs. two-way techniques, and quartz vs. atomic on-board oscillators. The fourth section then proceeds to an analysis of the various types of atomic standards that are reasonable candidates for spacecraft applications, assuming certain constraints imposed by the satellite environment. Also, assuming that a decision <u>is</u> made to develop a spacecraft atomic clock system, some alternative approaches are considered for developing the necessary atomic standard.

A clear concensus of the Technical Steering Committee on many of the questions discussed was impossible to discern. This was probably due in part to the wide range of differences in background, experiences, and objectives of the committee members and their institutions and in part to a general uncertainty about NASA's program objectives and operating constraints in this area (at least during the early stages of this study). Conclusions stated in this report, therefore, except where specifically identified as a committee viewpoint, should generally be regarded as the coordinator's opinion, based on his filtering of a great variety of technical information input from many sources.

## 2. SOME NEEDS FOR IMPROVED TIME DISSEMINATION

### 2.1 Introduction

As various aspects of time and frequency technology — such as frequency sources, dissemination techniques, and measurement methods — have made rapid progress during recent years, a trend seems to have developed toward making use of time and frequency technology to solve problems in other unrelated fields. The emergence of the time-and-frequency-based aircraft collision avoidance system now undergoing evaluation and the development of time-synchronized communication systems provide two examples of this trend. But at the same time that this advanced time and frequency technology is being so successfully applied to solving important problems in a variety of fields, the mere availability of atomic standards and improved dissemination systems is making it possible for system designers to plan even more refined and demanding applications for time and frequency technology, which in turn generate more demanding requirements of the time and frequency equipment and dissemination systems.

This interrelated development of time and frequency needs and capabilities has produced a situation at present, and likely continuing into the foreseeable future, in which at least some needs seem to exist that require improved time and frequency standards and/or dissemination techniques. These required improvements may take many forms — for example, in terms of accuracy, precision, coverage area, equipment cost and/or complexity, operator skill required, reliability, percent of time available, security, and so forth. Generally, needs for improved timing capabilities can be classified according to whether Universal Time — i.e., earth position — is required or whether only synchronization is needed. Applications in which earth position is important, such as satellite tracking, geodesy, and celestial navigation, depend on some form of Universal Time while most other applications require only that local time be synchronized with some other arbitrary time reference.

As an aid in discussing more specifically some of those applications that might benefit from improved timing capabilities, we can somewhat arbitrarily categorize each application as having needs for low, intermediate, or high accuracy timing. Low accuracy will refer to timing needs less stringent than 1 ms, intermediate accuracy to requirements in the 1 ms - 50$\mu$s range, and high accuracy to the better-than-50$\mu$s range. Several difficulties quickly become apparent in any such attempt to identify and classify needs for timing information. First, because of the great diversity of time and frequency users and applications and because, in many cases, users do not have to identify themselves in order to gain access to the timing information (anyone with a proper receiver can receive WWV, for example), it becomes most difficult to obtain an accurate measure of who is using various time and frequency dissemination services. A further contributing factor to this user identification problem is a seeming reluctance on the part of some users to admit using a service for fear that they will be asked to help pay for it. Secondly, even when needs are expressed, it is often hard to evaluate how realistic the stated requirement is. Different users, of course, tend to include varying amounts of safety factor in their stated requirements and it is rare that enough information about such assumptions is included to enable an "outsider" to make a meaningful independent judgement. Finally, a related problem arises from the military classification procedure — that is, military timing needs are often stated to exist or are at least strongly implied, but efforts to evaluate these requirements are frustrated because most details of the application are classified. In spite of these limitations, however, the following is an attempt to categorize some of the applications for time and frequency technology and, in some cases, to indicate some specific needs for improved services or equipment.

### 2.2 Some Needs and Applications for Improved Time and Frequency

#### a. Low-accuracy Range (less stringent than 1 ms)

(1) Some applications

(a) General public needs for time (e.g., time-of-day services)
(b) Most industrial applications
(c) Electric power companies for power flow coordination
(d) Amateur radio users
(e) Small boat owners (navigation)
(f) Commercial shipping (navigation)
(g) Airlines
(h) Radio and television stations
(i) Coarse time for resolution of ambiguities in more precise systems and applications
(j) Time base for seismographic monitoring
(k) Some missile and satellite tracking applications
(l) Time base for some astronomical observations

(2) Some needed improvements

(a) Reduction of interference for existing services such as WWVB
(b) More availability of time information — e.g., less sensitivity to propagation disturbances

(c) Better geographical coverage — e.g., for small boat owners along East Coast
(d) More convenient time codes and formats for automatic data handling — e.g., in remote seismic sensing stations
(e) Simpler, cheaper receiving equipment
(f) User cost more directly related to needed accuracy.

b. Intermediate-accuracy Range (1 ms - 50μs)

(1) Some applications

(a) World mapping studies (AFCRL)
(b) Instrumentation development
(c) Satellite tracking — e.g., Apollo, STADAN, Air Force Satellite Control System
(d) Some seismic monitoring (AEC)
(e) Geodetic studies (U.S. Coast & Geodetic Survey)
(f) Fundamental propagation studies
(g) Communication systems
(h) Rocket measurements
(i) General timing support for a variety of DOD activities — e.g., Air Defense Command Space Surveilance Facilities

(2) Some needed improvements

(a) Better geographical coverage — e.g., so that expensive portable clock trips do not have to be used for moderate-precision needs
(b) Simpler, cheaper receivers
(c) More continuous availability of suitable broadcast signals
(d) User cost more directly related to needed accuracy
(e) Continuous availability of day/hr/min/sec coded information.

c. High-accuracy Range (better than 50μs)

(1) Some applications

(a) Some industrial standards labs
(b) National and international timekeeping centers — e.g., NBS, USNO, BIH (International Time Bureau, Paris)
(c) Special-purpose timekeeping centers — e.g., APL, NASA GSFC, DOD Time-Reference Stations, JPL (Goldstone)
(d) Synchronized communications systems
(e) Long-baseline-interferometry measurements
(f) Laser-ranging systems
(g) U. S. Air Force one-way ranging applications
(h) Stationkeeping systems
(i) Aircraft collision avoidance systems
(j) General aircraft traffic control techniques
(k) Satellite navigation systems

(l) Relativity experiments
(m) Car locator system (Rand Corp)
(n) U. S. Air Force ICNI system
(o) Automatic landing systems
(p) Some projected space tracking applications — e.g., Apollo (10-50μs)
(q) Identification function by knowing scheduled transmission and arrival times
(r) More accurate synchronizations for reducing the number of portable clock trips
(s) Unspecified, classified DOD applications for better-than-1μs timing
(t) Reduction of TV co-channel interference via carrier frequency stabilization
(u) TV network operations.

(2) Some needed improvements

(a) Better geographical coverage
(b) Better coordination among existing facilities and systems
(c) Simpler dissemination and receiving techniques so as to place fewer technical demands on semi-skilled users in the field
(d) Higher reliability of available services
(e) More continuous availability of precise timing information
(f) Continued efforts to develop higher precision and higher accuracy techniques and systems as required for the continuing improvement of the many applications depending on advanced time – e.g., advanced station-keeping techniques
(g) More consideration of economic costs and benefits both for existing systems and proposed new services
(h) More efficient use of the electromagnetic spectrum
(i) Development of cheaper, smaller atomic clocks (especially desired by DOD agencies, such as USAEC, Ft. Monmouth, N. J.).

### 2.3 NASA's Role in Meeting These Needs

During the early stages of the Technical Steering Committee's deliberations concerning NASA's proposed development of a modified atomic frequency standard for on-board spacecraft applications, a number of questions arose related to which time and frequency needs and applications were considered to be the primary justifications for the proposed satellite experiment. A large portion of the Committee's time was spent in considering the potential impact of the proposed satellite timing system on many of the application areas listed above. Most of the committee members seemed to agree that:

a. NASA should use its available expertise and resources to contribute to the solution of timing problems in some of the above areas which relate directly to NASA program objectives — e.g., satellite tracking.

b. For applications, such as one-way ranging, where the proposed NASA timing experiment might contribute strongly to other agencies' programs (e.g., the Air Force in this case of the one-way ranging application), NASA should actively seek to cooperate with the appropriate related organizations.

c. Any such NASA satellite experiment to provide improved timing should be designed primarily for the state-of-the-art user, although several committee members also felt that a dual-precision-level approach was desirable, in which both moderately-precise and highly-precise timing information would be made available.

d. Although the proposed timing experiment was being considered for a particular geodetic satellite, GEOS-C, the primary justification was <u>not</u> to provide improved geodetic measurements. Information from APL personnel and other sources, though somewhat contradictory, seemed to suggest that timing improvements beyond about 100μs would not have significant impact upon the overall accuracy of most geodetic measurements.

e. NASA should not attempt to provide a "timing service" to large numbers of users but rather should emphasize experimental studies of state-of-the-art techniques.

f. Before attempting to make choices concerning which type of atomic standard should be developed for the proposed satellite experiment, NASA should first decide on a definitive set of objectives for the experiment, including statements of which timing needs are being attacked, and secondly should also consider other possible techniques for satisfying those needs.

## 2.4 NASA GSFC's Stated Objectives for the Satellite Timing Experiment

In response to these initial committee discussions NASA GSFC then prepared a more detailed proposal and justification for the experiment. Five application areas were identified as being the primary beneficiaries of the proposed satellite experiment:

a. <u>International Comparison of Frequency and Time</u>. The objective here is to use simultaneous measurements of the satellite time signal in terms of the local clocks at two remote sites to obtain a time comparison of the two local clocks to within 0.1μs. This, of course, assumes that the differential propagation delay is known to this degree. Such comparisons would be useful to national and international timekeeping centers, satellite tracking stations, long-baseline-interferometry stations, and to ground stations in the proposed aircraft-collision-avoidance system (ACAS).

b. Precise One-Way-Doppler Tracking. Differing opinions seem to exist on the possibility of reducing errors in the one-way Doppler tracking technique by use of an on-board atomic standard to generate the appropriate frequencies. Since a new frequency parameter is normally fitted to the Doppler tracking data on each satellite pass for each receiving station, the primary frequency fluctuations of interest are those that occur during a single pass ( $\approx 10$ minutes). For this averaging period, the stability of a typical commercial atomic standard may not be better than that of a good quartz oscillator; for longer periods where the atomic standard's stability is superior, the Doppler measurement uncertainties are not very sensitive to oscillator instabilities. Even if the relatively short-term stability over about 10 minutes can be improved (by using an improved oscillator — atomic or quartz), there is some disagreement about any resulting reduction in the overall Doppler measurement errors [2]. APL personnel did indicate to the Technical Steering Committee at one point that an improved stability of $1 \times 10^{-12}$ during a single pass would reduce one error component by a factor of five, but no estimate was given of the resulting effect on the overall measurement uncertainty. A further point was made that the improved long-term stability expected from an atomic standard might make it unnecessary to fit a new frequency for each pass, resulting in at least an operational simplification of the Doppler measurement procedure. Further documentation is needed in this area to pinpoint more exactly what the main error contributions are for this measurement technique.

c. One-way Ranging . The objective in this case is to evaluate the one-way ranging technique, in which range is determined from the measured one-way propagation time between the satellite and the receiving station. Clearly, the satellite and receiving station clocks must be synchronized (or at least the time difference must be accurately known). A significant advantage of this technique is the large reduction in the number of necessary transmissions among a network of N participating stations needing range separation information relative to a two-way radar beacon transponding approach. A further advantage for some military applications is that users can function in a passive role without needing to identify themselves or their positions. The Air Force is interested in this technique for the Navigation Satellite (NAVSAT) program at a level providing slant range to 30 m [3], requiring time synchronizations to be maintained to within 0.1μs. Advanced Army avionics applications also rely heavily on this technique; one stated requirement calls for a stationkeeping capability between aircraft to ± 3 m, or a synchronization capability to ± 10 ns over a period of a few hours [4]. Non-military applications include spacecraft tracking and aspects of one proposed civilian aircraft collision avoidance system (the time and frequency approach) [5].

d. Precision Relativistic Time Study. Provision of a highly-stable frequency standard on an orbiting rocket or satellite and the comparison of these transmissions with similar standards on the ground over a sufficient period of time allows the measurement of certain relativistic effects. For near earth orbits relatively long-term stabilities of a few parts in $10^{12}$ or better are needed, but the stability requirements are more relaxed for wider ranging orbits. A spacecraft-borne hydrogen maser system is being developed at the Smithsonian Astrophysical Observatory by Dr. R.F.C. Vessot for a proposed satellite or rocket gravitational red-shift experiment, but plans are still somewhat uncertain at this time [6].

e. Development of New Technology in the Form of a Spaceborne Atomic Clock System. As time and frequency technology is applied in more and more areas, and as these applications require more stringent performance from the frequency and time sources, the role of atomic clocks will almost certainly continue to grow in future years. In recognition of this trend several committee members felt strongly that every effort should be made to encourage the development of smaller, cheaper, lighter, lower-power, more reliable atomic standards for both military and civilian future applications. The satellite timing experiment being proposed at this time by NASA is seen as one approach toward encouraging this development for other later applications.

## 2.5 Possible Impact Areas for Improved Time Dissemination

The possible impact areas covered by these proposed NASA objectives for the satellite timing experiment clearly cross many organizational and agency lines. Although the goals dealing with Doppler tracking and one-way ranging are of primary concern to NASA and some DOD elements, the objective of synchronizing ground stations over large areas to within 0.1μs is of interest to a much larger segment of users — for example, standards laboratories (national and international); aircraft collision avoidance system ground stations; state-of-the-art industrial laboratories and standards groups; remote monitoring stations for various government and university projects, such as seismic-event monitors and geodetic units (though not needing timing to 0.1μs); satellite and missile tracking facilities, both military and civilian; long-baseline interferometry sites; navigation stations over large areas such as those in the Omega and Loran-C systems; and a large number of miscellaneous civilian users of less-precise timing, provided the satellite signals are also designed for this class of user.

Before proceeding on to a discussion of how the proposed satellite-borne clock system might be implemented most efficiently, it might be worth considering first some alternative ways in which at least some of NASA's experimental objectives could be met using other techniques and/or facilities. Hopefully, this information to be provided in the next section of this report will give some useful perspective for NASA's eventual decision on whether to undertake this experiment.

# 3. SOME ALTERNATIVES FOR MEETING NASA'S OBJECTIVES

## 3.1 Introduction

For purposes of discussion in this chapter the experimental objectives referred to previously can be broken down into one rather general goal and four more specific ones. The general goal is to provide improved time dissemination over wide geographical areas at an accuracy level of $0.1\mu s$ for state-of-the-art users and concurrently at a lower-accuracy level (perhaps $100\mu s$) for less sophisticated users. The more specific goals of the experiment are (1) to evaluate the one-way ranging technique, (2) to improve the one-way Doppler tracking technique, (3) to perform relativity tests, and (4) to develop a spacecraft-compatible atomic clock system which will be smaller, lighter, less power-consuming, cheaper, and more reliable than commercial units presently available.

The first part of this chapter will include discussions of a variety of time dissemination techniques that might contribute solutions to some of the timing goals identified by NASA and mentioned in the previous chapter. While the several forms of satellite dissemination techniques described here will obviously be of most interest to NASA, other possible alternatives — such as VLF, LF, portable clock, aircraft flyover, and television methods — are also included for completeness and for comparative purposes. Following the discussion of the various alternatives, an attempt will be made to concisely summarize and compare the pros and cons for each time dissemination system, so that the particular proposed satellite technique employing an on-board atomic clock can be evaluated relative to other possible approaches.

This chapter will then conclude with some comments on possible alternative approaches for achieving the more specific experimental objectives outlined by NASA — i.e., evaluation of the one-way ranging technique, improvement of one-way Doppler tracking, performance of relativity tests, and development of a spacecraft-compatible atomic frequency standard.

## 3.2 Some Possible Alternatives For Improved Time Dissemination

Improvements in time dissemination may take a variety of forms. For example, one part of NASA's stated objective for the proposed satellite experiment calls for time dissemination to $0.1\mu s$; representing, in most cases, an improvement over existing capabilities in terms of higher accuracy. For almost all applications of very precise timing the term accuracy will refer to accuracy of <u>synchronization</u> as contrasted with the accurate transfer of actual date (or time-of-day) information relative to some chosen time scale. Another aspect of the timing objective calls for concurrent improved time dissemination in the 10-100μs range. In this case, since dissemination to this accuracy has already been shown to be technically feasible and practical, the "improvement" desired may include such factors as disseminating the 10-100μs time over larger geographical areas, doing it more reliably, providing the timing information during a larger portion of each 24-hour period, encouraging the development of cheaper and simpler user instrumentation, and reducing the operator skill required to use the timing information. All these factors will be considered in the following discussions of alternative methods that might provide improved time dissemination in accordance with NASA's objectives.

### a. VLF Techniques

The well-known, favorable propagation characteristics of VLF transmissions, in terms of high phase stability and low attenuation over very long reception paths, have resulted in an increasing use of VLF services of such organizations as the U. S. National Bureau of Standards, the U. S. Navy and various similar international organizations for many low-and-moderate accuracy timing applications throughout the world. In a typical case a local clock might be set initially by means of a portable clock carried to the particular location and then tracked and calibrated by maintaining a continuous phase comparison between the local clock and a suitable VLF transmission. Even in the face of various propagation problems, such as the familiar duirnal variations, it has been amply demonstrated that with sufficient care local timing can be maintained to within a few microseconds by using VLF techniques. Fifty-microseconds timing from VLF is fairly routine over wide areas and under varying conditions [7-11]. If one must use calculated values for the propagation path delay in a particular application, however, rather than measured values (e.g., via a portable clock comparison) or simply an assumption that the delay remains constant, local timing uncertainties will be significantly larger — perhaps, 10-50μs at best.

The planned full-implementation of the VLF Omega Navigation System by late 1972 should provide a greatly improved time-and-frequency capability for users in the 1-50μs range on a nearly world-wide basis [12-13]. Though basically a navigation system, Omega also offers the following significant advantages for time and frequency applications:

(1) Eight closely-synchronized, 10-kW VLF stations will provide reliable, world-wide VLF transmissions, so that any user can depend on being able to receive useful signals from 3-5 separate stations.

(2) Each station will generate its transmitted frequencies from a concensus of four commercial cesium beam standards, thus assuring high reliability and extremely good stability.

(3) Each station will transmit three time-multiplexed navigation frequencies (10.2, 11.3, and 13.6 kHz) and probably two additional characteristic frequencies in the 10-14 kHz band. Since the phases of all frequencies transmitted are carefully synchronized, the opportunity exists to use the multiple-VLF-carrier technique, such as practiced with the NBS WWVL two-and-three-frequency transmissions near 20 kHz, to reduce the basic timing ambiguities inherent in the VLF technique by permitting identification of a specific cycle of the carrier.

(4) The Omega System includes provisions for internal system monitoring of the various stations' transmitted frequencies and periodic correction of each stations transmissions to an overall system mean.

(5) The system mean can be adjusted on a more infrequent basis to agree to an accepted reference time scale.

(6) Recent proposals have been made to include a day/hours/minutes low-bit-rate time code in the Omega format, using the two unique frequencies assigned to each station [14]. Though not needed specifically for the navigation function, the time code — when used together with more precise timing information derived from the various difference frequencies available and ultimately from the RF carrier phase itself — would provide complete self-contained time-of-day information from days to microseconds on a global basis. Recommendations for implementing such a timing service using Omega facilities are presently being considered by members of an Omega Precise Time and Time Interval Advisory Group, including NBS, USNO, and other interested agencies, which is advisory to the Omega Project Office.

(7) When fully operational, the Omega system will be civilian-directed by the Department of Transportation with operation of the non-U. S. stations under the control of the particular foreign country hosting each station. It is expected that this operational setup will contribute to the permanency of the Omega service and make frequent changes in format, etc.

unlikely. Equipment manufacturers should therefore be less hesitant to develop proper receivers and other instrumentation for use with Omega than for other systems that are more subject to frequent modification.

Measurement techniques for either time or navigation use are similar, being phase measurements of VLF carriers. For navigation use, they consist of phase comparisons of frequencies broadcasted from pairs of transmitters whose geographical locations are accurately known and do not require a synchronized local clock. For timing use the measurement consists of a phase comparison between frequencies broadcasted from one transmitter and local clock frequencies. The important limitations on the accuracy of these measurements are those due to radio propagation. These consist of propagation media fluctuations (multiplicative noise, and atmospheric, or additive noise). Atmospheric noise can be decreased somewhat by longer averaging times in the measurement, but essentially nothing can be done about propagation media fluctuations except to design the system around them.

Phase stabilities of the VLF carriers themselves, due to propagation media fluctuations, are of the order of a few microseconds, giving potential time synchronization uncertainties (or corresponding position uncertainties) of this order — provided that the propagation delay is also known this well. Such measurements as mentioned here are, of course, ambiguous with the period of the particular frequency used. For example, a measurement on a 10 kHz carrier will be ambiguous to 100μs, and other techniques must be used to resolve this problem. In order to reduce such ambiguities, lower frequencies (longer periods) are needed with stabilities which permit them to be used for identifying a specific cycle of the carrier. As already suggested, these lower frequencies can be obtained by taking differences between the various Omega carrier frequencies.

The lowest difference frequency presently provided for the Omega navigation function is a little over 1 kHz (11.33 - 10.2 kHz), resulting in timing ambiguities of about 880μs. This means that in order to make use of Omega transmissions to set his clock correctly to a few microseconds, the user first must know his time to better than one-half this ambiguity, or 440μs. Ideally, one would like to use lower frequencies from the Omega format itself to get this needed accuracy of 440μs or better. The next lower frequency now available from Omega is approximately one pulse per second from the envelope. [For more details of the Omega format see references [13] and [14]. ] In the operational system these pulses could have a rise time as long as 33 ms, corresponding to an antenna bandwidth of 10 Hz. These pulse rise times are too slow to use in a practical system to identify time to the needed 440μs. One proposed solution calls for assigning the two additional unique frequencies characteristic of each Omega station such that a difference frequency results that will allow one of its cycles to be identified by the envelope pulses. Then the zero crossing of this identified cycle would be capable of identifying a particular cycle of the ≈1 kHz difference frequency. Presently, NBS and the USNO have agreed to recommend assigning unique frequencies such that a difference frequency of 250 Hz results, which should allow resolution of the various timing ambiguities mentioned. As pointed out previously, the further addition of a day/hour/minute time code to the format would then make timing available all the way from days to a few microseconds.

Once fully operational, then, the Omega system potentially offers a significantly improved time dissemination system in the low or moderate accuracy range. System coverage will be worldwide with very high reliability. Receiver costs, where timing is needed but not the navigation function, should prove to be in the moderate category. This cost, which initially may be a few thousand dollars, should decrease as use of the Omega system expands, creating larger economic markets. Finally, it should be noted that while Omega will likely have strong impact within the low-and-moderate-accuracy application areas, any timing needs for sub-microsecond accuracy will remain beyond the capabilities of this VLF system.

### b. LF Techniques

Compared to VLF, radio frequencies in the LF range also tend to propagate with very high phase stability, but over much shorter distances (higher attenuation). Measured phase stabilities in the groundwave mode for distances up to about 1500 km over land have been reported in some cases to be better than 1μs with similar results for 3000 km propagation paths over seawater [15-16]. Other more recent studies, however, indicate that propagation variations of up to 3μs can be experienced over land paths featuring rough and/or inhomogeneous terrain [17]. For longer distances the amplitude of the skywave component becomes significant, producing mutual interference in the received signal and a deterioration in the measured stability to perhaps 50μs. LF techniques then may possess capabilities for sub-microsecond timing over rather limited ranges and types of terrain and for moderate-accuracy timing over much longer distances – perhaps out to 10,000 km.

Two LF services, which in many cases may provide solutions to moderate-to-high-accuracy timing needs, are the NBS 60 kHz broadcast from WWVB in Fort Collins, Colorado and the 100 kHz transmissions from the Loran C navigation system. The useful service area of WWVB is limited primarily to the continental United States. In addition to providing phase-stable signals referenced to the NBS Frequency Standard and its associated time scale systems in Boulder, Colorado, WWVB transmits a BCD time code giving day/hour/minute/second information which can be easily decoded and digitally-displayed using commercially available receivers. Additional information concerning the service is available in the annual NBS Special Publication 236, "NBS Frequency and Time Broadcast Services".

The Loran C system, like Omega, is primarily a navigation system which provides hyperbolic lines of position by utilizing closely-synchronized transmissions from groups of geographically separated (by 480-800 km) stations [15]. The system is operated by the U. S. Coast Guard, but its timing aspects are closely referenced to the UTC(ISNO) time scale. At present the Loran C network consists of some 33 stations, grouped into eight chains — each with one master station and two or more synchronized slave stations. The various chains are spread throughout the world, but cover only selected areas due to the more limited propagation range at this frequency.

Synchronization of the various stations within a given Loran C chain is generally held to within 0.1-0.2μs by operating a monitoring station within the coverage area of each station and by using carefully-evaluated path delay data for each monitor station-to-transmitting station path. In addition, by using periodic portable clock comparisons between the USNO and at least some of the monitor stations, five of the Loran C chains are now synchronized to the UTC(USNO) time scale to within a stated tolerance of about $\pm$ 25μs.

The Loran C transmissions achieve their sub-microsecond timing capability by using a pulsed modulation format which enables the user to separate the more stable groundwave portion of the received signal from the skywave. In addition, the pulse-coded format is designed to permit the separation of different Loran C chains and the identification of individual stations within a single chain. Each station transmits groups of pulses at precisely known times relative to the master and other slaves in the chain. By visually displaying the received Loran C pulse from a master station on an oscilloscope, a fairly sophisticated user can usually obtain a timing comparison between Loran C and a local clock to within $\pm$ 20μs. To realize the full timing potential of Loran C, however, one needs an automatic receiver which locks on to the proper point of the pulse structure to reduce skywave influences. Even with such receivers it is possible to have errors of one or two cycles, corresponding to 10 or 20μs, but with adequate care results in the sub-microsecond region are possible under ideal conditions.

Synchronization accuracies achievable with Loran C depend on many factors, such as one's ability to calculate or measure path delays and on whether comparisons are made relative to a single station, two stations in the same chain, or two stations in different chains. If station and user locations are known adequately, propagation time delays over all-seawater paths can be calculated to 0.1μs for distance up to 1500 km [18]. Over mixed land and sea paths, however, the calculation is much more difficult and the resulting synchronization inaccuracies may be much larger. An added difficulty in calculating path delays arises from uncertainties in determining absolute receiver delays.

Best synchronization results, of course, are generally obtained when two users can receive signals from a common Loran C station. If two different stations in the same chain are used, an additional error of at least 0.1-0.2μs may result. For synchronizations using received signals from stations in two different Loran C chains, an additional error of at least ± 15μs is possible where both chains are timed by the USNO. Some improvements in these values are possible by using after-the-fact published values for chain errors with respect to the USNO master clock. For untimed chains the errors will, of course, be considerably greater.

Users beyond the normal Loran C groundwave range may still be able to receive useful timing information via the skywave. Uncertainties are larger due to difficulties in determining the exact propagation mode being received and in selecting a particular cycle for reference. Studies have claimed skywave timing accuracies of ± 20μs over 6,000 km paths [19].

Summarizing then, Loran C can perhaps impact favorably on both the sub-microsecond and the more moderate accuracy requirements for improved time dissemination mentioned by NASA. For example, one NASA group has stated that the use of Loran C for timing at Apollo tracking stations should be adequate for all present and future needs (10-50μs) [20]. For moderate-accuracy needs within the continental U. S., WWVB may offer an acceptable solution. However, for the highest accuracy applications only certain selected geographic areas are adequately covered by Loran C and the usual difficulties in calibrating the path delays must be carefully considered. Demands on user skill are rather severe in many application — especially, if the highest quality automatic receivers are not available. User cost for receivers can be rather low ($1000) in strong signal areas or where highest accuracy is not required, but rises to about $10,000 for the more sophisticated automatic equipment. A large plus for the Loran C system is, of course, that it is already fully operational with extensive use of high-quality commercial cesium standards for frequency and time control.

### c. Portable Clock Techniques

Two variations of the basic portable clock technique for solving high-accuracy timing needs have been used successfully — one on an operational basis and the second only on an experimental basis so far. The first technique, usually referred to simply as the "portable clock" technique, consists of the following basic procedure:

(1) First, in the reference laboratory measure (and adjust, if necessary) the frequency and time differences between the portable clock and the reference standard.
(2) Next, transport the operating portable clock as quickly and gently as possible to the local laboratory needing the time transfer.
(3) Next, measure the time difference between the local clock and the portable clock.
(4) Next, as quickly as possible return the portable clock to the reference laboratory and again make frequency and time comparisons with the reference standard.
(5) Finally, using the data obtained, correct the measured portable clock-local clock readings to reflect such things as frequency offset between portable and reference clocks and any other known changes occurring during the trip.

This technique has been employed by Hewlett-Packard Company on several occasions [21] to demonstrate that presently-available atomic clock systems can be transported by a variety of modes all over the world during a period of about a month to synchronize local clocks to within one microsecond or better.

The portable clock technique has been and will probably continue to be used extensively by the Department of Defense to establish and maintain accurate timing at remote sites worldwide in support of various DOD programs, such as satellite tracking. The most extensive portable clock operations are those of the U. S. Naval Observatory and the U. S. Air Force Aerospace Guidance and Metrology Center at Newark Air Force Base, Ohio. Portable clock trips by USNO personnel every 3-6 months have been one of the principal means used by USNO and NBS to maintain coordination between their respective UTC time scales. Since October, 1968 synchronization has been kept to within $\approx \pm 5\ \mu s$ at all times. Comparisons between USNO and NBS using other backup methods, such as VLF and LF monitoring by the two organizations, show excellent long-term agreement with the portable clock results.

Even though quartz crystal oscillators which have documentable stable drift characteristics can be used successfully in some portable clock applications, most portable clock operations today rely on the superior stability of atomic standards — either rubidium or cesium devices. Since many portable clock trips involve changing modes of transportation, changing environmental conditions (e.g., temperatures, mechanical shock, electrical power sources, magnetic fields), and fairly long intervals of time away from "home base", the following are some of the principal attributes of an ideal portable clock for most purposes:

(1) High stability both in long-term (e.g., during the duration of a typical trip — perhaps 1 day – 1 month) and in short-term (during a typical calibration measurement). However, a uniform drift, in principle, need not degrade the results.

(2) Insensitivity to environmental effects such as temperature, pressure, humidity, magnetic fields, electrical supply voltage, and mechanical shock.

(3) High reliability.

(4) Small size and weight consistent with reasonably convenient travel by commercial airline, automobile, etc.

(5) Capability for operation from a wide variety of electrical supply sources.

(6) Provision for conveniently resetting time (and perhaps frequency) outputs with high resolution.

As might be expected, no one device clearly excels in all these categories. Quartz clocks excel in (4) but are especially weak in (1) and (2). Rubidium clocks represent a good compromise in almost all categories, but generally suffer somewhat in long-term stability and must have their frequency adjusted initially against a primary standard. Cesium beam clock systems excel in (1) and (2), are quite satisfactory in terms of (3), (5), and (6), but most versions used to date have serious drawbacks in terms of their relatively large size and weight.

In considering briefly the pros and cons of this basic portable clock technique, it is presently the only proven way of reliably transferring sub-microsecond timing over large distances using commercially-available equipment. Coverage is limited only by transportation requirements. On the negative side the main disadvantage is the large travel and equipment expenses plus salaries for the accompanying personnel. The cost for a month-long trip stopping at several remote sites will obviously cost many thousands of dollars. Additional disadvantages include the limited number of users that can be served, the general inconvenience of the method, and the rather infrequent availability of such a service.

In view of these practical limitations, the basic portable clock technique is clearly a poor way of attempting to meet NASA's objective of providing improved timing to large numbers of users in the moderate accuracy range. However, for more limited application to a small number of specific, sub-microsecond timing problems, the technique should at least be considered and is perhaps capable of providing improved timing in the sense of higher-accuracy synchronization capabilities relative to most other alternative methods.

A second more recent variation of the basic portable clock technique is the so-called "aircraft flyover" technique, so far used only on an experimental basis. This technique, like that previously discussed, involves the physical transporting of a calibrated portable clock from a reference site to the vicinity of the local site needing time synchronization. In the flyover technique, however, the portable clock is merely flown within perhaps 40-80 km of the local site and time comparisons between the portable clock and the local clock are made by either one-way or two-way radio transmission from aircraft to ground.

In one group of experiments involving ground tests of equipment developed for the U. S. Air Force at Newark Air Force Base, Ohio time synchronizations to within 0.1μs were achieved between two stations using two-way L-band transmissions for determining the propagation delay time [22]. Although initial flight tests using this system were unsatisfactory due to interference problems in the Washington, D.C. area, later modifications to the system appear to have eliminated the problem to the extent that ground tests of the modified system produced the results mentioned above. Similar results ($\approx$0.1 μs) are now expected to be observed in flight tests.

Similar experiments in France have been conducted by the Office National d'Études et de Recherches Aérospatiales (ONERA) [23]. In these actual flight tests the following two methods were used to determine propagation time for the aircraft-ground path:

(1) A one-way technique in which the time difference between the aircraft and ground clocks as observed on the ground was measured repeatedly as the plane flew directly over the ground site at a reasonably constant altitude. At the point of minimum observed time difference, which presumably occurs as the plane is directly overhead, the altimeter reading is noted and used to compute a delay time for the aircraft-ground path.

(2) A two-way technique, utilizing concurrent radio transmissions of timing information in both directions. In this case, of course, the aircraft is not required to fly directly over the ground site or to maintain a particularly constant altitude.

The results of these flight tests conducted over the International Time Bureau (BIH) in Paris and the Physikalisch Technische Bundesanstalt (PTB) laboratories in Braunschweig, West Germany demonstrated synchronization accuracies of about 30 ns for the one-way technique and better than 20 ns for the two-way case. Based on these experiments, ONERA believes various national time scales can be correlated to within 50 ns using the flyover technique. Further tests are planned in cooperation with various timekeeping centers in other countries.

Generally, the same comments on pros and cons apply to the flyover method as to the previously-discussed more basic portable clock technique. The flyover method appears to be somewhat more convenient, less arduous, quicker, and even more accurate than the basic portable clock technique, but only after properly instrumented aircraft and ground sites have been established, of course. It is worth noting that properly instrumented aircraft, including on-board atomic standards, may eventually become fairly widely available in conjunction with a large-scale collision avoidance system based on time and frequency technology. In fact, the flyover technique is presently considered by the FAA to be the leading contender for the primary synchronization of the ACAS ground stations.

If NASA Goddard's proposal to develop a smaller, lighter, satellite-borne atomic standard is accepted and carried through to completion, the resulting product might have significant impact on the more extensive use of the portable clock techniques described above. This type of potential "spinoff" from the spacecraft-borne atomic standard development was recognized by several members of the Technical Steering Committee and is considered by at least one committee member to be a strong justification for the proposed development program.

### d. Television Time Dissemination Techniques

The use of existing television network facilities and signal formats for disseminating time and frequency information is a relatively recent development, originating with work in 1967 in Czechoslovakia by J. Tolman and others [24]. Tolman and his colleagues developed a technique in which two timing users, separated by hundreds of kilometers, could synchronize their clocks to within 1 μs by making simultaneous measurements of the time difference between their respective local clock and a particular synchronization pulse in the television picture format as received at each local site. Any difference between the two measurements is equal to the actual difference between the two local clocks being compared plus a (hopefully) constant differential propagation delay time that can be computed or measured by carrying a portable clock, for example. Whether the two local clocks were both receiving broadcasts from one common TV station or from two different stations connected by a microwave relay network, the Czech group found that synchronization to within 1 μs was possible for clock separations up to 870 km.

Expanding upon this work, NBS developed instrumentation using the line-10 sync pulse from Denver TV transmissions to synchronize local clocks at radio station WWV in Fort Collins, Colorado with the atomic time scale system at NBS, Boulder, Colorado. The differential propagation path delay was both computed and measured by portable clock, providing a sufficiently accurate path calibration to be consistent with sub-microsecond clock comparisons. The Boulder and Fort Collins local clocks are still compared routinely using this technique to daily precisions of better than 100 ns.

Further studies of the technique by NBS and the USNO, using the 6400 km microwave network path connecting Denver and Washington, D.C., showed that this microwave path – for all three major television networks – is stable to a few nanoseconds for short periods (minutes) and to at least a few microseconds for periods of several months, except for very occasional larger jumps due to major network reroutings that can be easily detected [25-26]. The observed stability of the 3.58 MHz color subcarrier received in Boulder for periods of several minutes over the networks correspond to a frequency stability of better than $1 \times 10^{-11}$ – about what can be attributed to the controlling rubidium standard at the central network control point in New York City. This technique, using line-10 sync pulses as transmitted over the microwave network, is now in operational use by some Department of Defense components for routine clock comparisons over large distances within the U. S.

Many European groups are also using this basic technique for routine clock comparisons among various European countries. The Eurovision Network and other hookups among these countries are used for this purpose. Recent results show that clock synchronizations within Europe are being accomplished easily and routinely to an accuracy of $0.1 \pm 0.1\,\mu s$ [27] and are at least as good as obtained with portable clocks.

Still more recently, NBS has developed a more elaborate TV time dissemination system in which a time code, giving hours/minutes/seconds/microseconds information is encoded onto one of the lines in the vertical blanking interval of the picture format [25]. An inexpensive decoder, which includes a standard TV set, then decodes and displays the timing information digitally on the TV screen superimposed over the normal picture. The first line of the display gives hours/minutes/seconds referenced to a cesium clock generating the time code at the local TV station or at the network control station in New York City. The second line of the display provides a measurement of the time difference — with a selectable resolution of either 100 ns or 1 ns — between the local user's clock and a time reference generated by the originating cesium clock. The displayed time is automatically self-updating so that interruptions in signal reception do not matter.

This dissemination system has been tested extensively since September, 1969 in the local Denver, Colorado area and more recently, in cooperation with the USNO and NASA, in the Washington, D. C. and Los Angeles areas. Results show that the observed instabilities of the received timing information are only a few nanoseconds over reasonably short time periods and are about what one would expect due just to instabilities in the controlling cesium standard. The USNO has already expressed its desire to have such a TV time dissemination system implemented on an operational basis as soon as possible. Further tests of an improved version of the system are being planned on the national network during October 1971. Eventually, it is likely that the FCC will be asked to formally and permanently allocate a particular line of the TV signal format for time dissemination purposes.

Time dissemination by means of existing television facilities offers many advantages and may prove to be a valid alternative for providing improved timing within the United States to large numbers of users, both in the moderate-accuracy and the highest-accuracy range. User cost is very low, ranging from perhaps $20 for 1-second timing up to perhaps $1000 for the full 1-ns capability. Potential precision is perhaps the highest of any technique being seriously developed, except possibly for a few sophisticated, special-purpose DOD satellite systems. On the negative side, the network timing information may be available in some areas of the U. S. for only a few hours per day and network reroutings may cause occasional problems for high-accuracy users — especially, if only one of the networks is being monitored.

### e. Satellite Timing Techniques

#### (1) Introduction

The use of artifical earth satellites for disseminating time information offers significant advantages over some of the other methods considered in terms of coverage and uncertainties due to the propagation path. It is possible to obtain global coverage, for example, on a once-or-twice-per-day basis from a single polar orbiting satellite or on a continuous basis with three or more geostationary satellites. The propagation path uncertainties are reduced relative to most other techniques, because only a small portion of the total ground→ satellite → ground or satellite→ ground path involves propagation through the ionosphere and atmosphere with their associated perturbing influences. Detailed discussions of propagation effects may be found in [1, 18]. It appears most unlikely that a special satellite could ever be justified solely for time dissemination; however, as more and more satellites are planned and launched in the future for other broader applications, it is quite possible that a time dissemination capability can be included at little extra cost in "piggyback" fashion.

In discussing time dissemination via satellites the various alternative techniques will be classified as one-way relay, two-way relay, or on-board clock according to the following distinctions:

(a) One-way Relay - the satellite functions in a relay mode for transferring radio signals from one ground point to another. The user is passive, having only a "receiving" capability and must therefore determine the path delay for his particular location by calculation from known satellite, transmitter, and receiver locations or by measuring the path delay by some means such as a portable clock calibration.

(b) Two-way Relay - the satellite still functions as a relay, but the user now has both transmit and receive capabilities. In this case an exchange of signals between the two ground sites being synchronized is used to provide a measurement of the path delay which does not require knowledge of either ground site or satellite locations.

(c) On-board Clock - the satellite in this case carries an on-board clock which provides directly the timing signals for transmission. The user will normally operate only in a receive mode with this technique.

Satellite orbits to be considered will be primarily the low-altitude non-synchronous and the geostationary or earth-synchronous types. The geostationary orbits offer advantages in terms of reduced Doppler effects, a relatively constant propagation path length, and the possibility of using fixed-tuned receivers (no Doppler shift of incoming signals) and non-steerable antennas. Disadvantages include a higher signal strength loss due to the much longer propagation path and only partial-earth coverage from a single satellite (although the timing information can be made available continuously over this limited area). The low-altitude orbiting satellite can cover a much larger area — though only periodically — but makes the propagation path determination much more difficult due to the rapidly changing satellite-observer path during a measurement period.

Each of the three basic techniques mentioned will now be discussed in turn, including some of the experimental results obtained to-date in each case.

(2) Discussion of the Three Basic Satellite Techniques

(a) One-way Relay Technique

In using the one-way relay method for synchronizing clocks at two separated sites, station #1 transmits timing information through the satellite transponder to station #2, where the arrival time of a particular time reference marker is measured relative to the station #2 local clock pulse. The measured time delay then consists of the actual difference between the two local clocks plus the total propagation path delay, including the transmitter and receiver equipment delays, the satellite transponder delay, and the propagation delay for the appropriate signal path. Since any uncertainties associated with these various delay components will clearly produce a corresponding uncertainty in the resulting clock synchronization achieved, the accuracy of this method is generally limited by ones' ability to determine the path. Calculation of the propagation time requires knowledge of the

3-dimensional coordinates of both ground stations and the satellite. Information concerning the satellite's position may be included as part of the signal format (as in the case of TRANSIT, for example) or may be obtained from published coordinates of the satellite — either predicted in advance or based on actual tracking data near the date of the synchronization measurement. Equipment delays can be particularly troublesome, both because they are difficult to measure accurately under conditions closely approximating those applying to an actual satellite measurement and because the delays, once calibrated, are subject to various changes with time due to such factors as varying environmental conditions. Equipment delay uncertainties have been quoted from 0.1 μs [28] up to many microseconds.

Begley and Shapiro [28] calculate a total root-sum-square (RSS) uncertainty for the passive, one-way method of 0.35 μs, assuming use of a synchronous Comsat-type satellite with approximately 450 m position errors, survey uncertainties of 30-45 m in the ground station locations, 0.1 μs equipment delay errors, and essentially negligible propagation errors due to the relatively high frequency (2 GHz) assumed. Sperry Gyroscope Company personnel [18], by comparison, estimate the RSS uncertainty for this technique to be 0.9 μs, based on satellite position errors of about 150 m, station survey errors of about 30 m, propagation errors of 0.5 μs (assuming 100-500 MHz frequencies are used), and 0.2 μs uncertainties in knowledge of equipment delays.

Many experiments have been conducted by NBS and other organizations to evaluate this one-way relay technique for time dissemination. The NBS tests have emphasized the use of low-cost equipment (such as taxi cab receivers, for example) and simple operational measurement procedures. In general, because of modest transmitter power and bandwidth available, the side-tone ranging technique has been used, in which successive, coherent audio tones are transmitted rather than pulses. The lowest tone used reduces the ambiguity of the timing information and the highest tone provides adequate resolution. In 1967 the ATS-1 VHF transponder was used by stations at NBS in Boulder, Colorado; Goldstone (California) Venus site; Goldstone STADAN site; and Anchorage, Alaska to transfer time with uncertainties of less than 10 μs for the best available satellite range measurements from NASA and to within 60 μs using range values predicted one week in advance of the time transfer experiment [29]. All participating stations had cesium clocks whose synchronizations were checked by means of two-way satellite time transfers. The major timing uncertainties assigned to these results were ± 2 μs for equipment delays, ± 6 μs for ionospheric effects, ± 5 μs for noise jitter in the measurement process, and $\pm$ 1.5 $\mu s$ for rounding errors in the satellite range values.

More recently, similar experiments have been performed using two U. S. Air Force satellites, TACSAT and LES-6 [30]. The participating stations — including NBS, Newark AFB, Lincoln Labs (Mass.), and several Air Force stellar camera sites in South America — were all synchronized to within $\pm$ 5 $\mu s$ during the various experiments by other techniques such as portable clocks, Loran C, and the television method. Transmitter and receiver locations were known to within $\pm$1 km and the satellite positions were computed from its orbital coordinates. Initial results showed one-way synchronization capabilities using TACSAT of 150 $\mu s$ by using the satellite coordinates anytime within two weeks of their determination. A similar technique with LES-6, using the coordinates determined within twelve hours of the actual time transfer, reduced the time transfer uncertainties to $\pm$ 25 $\mu s$. Since the variabilities in the delay time due to satellite motion (even for these geostationary satellites) were observed to contribute significantly to the overall errors, improved results were expected, and have now been experimentally verified, for a variation of this technique in which satellite range is actually determined from measurements of the timing signals received at three previously synchronized ground stations, rather than by computation from the orbital elements supplied from normal tracking data [31].

Beginning in September 1971, NBS, in cooperation with NASA, initiated an experimental time dissemination service using the ATS-3 geostationary satellite in a one-way relay mode. The format is similar to the present WWV format and is designed to provide timing in the range from 1 second down to 100 microseconds to a large number of unsophisticated users possessing only relatively simple and inexpensive receiving equipment. If the service is found to be useful, a more permanent service may be planned using other satellites, such as those in the Department of Commerce's GOES (environment sensing) program.

In summary, the one-way relay satellite technique offers wide area time dissemination in the 10-100 $\mu s$ range using simple, inexpensive receiving equipment and does not require complex equipment to be located on the satellite. Large numbers of users can be served simultaneously in the one-way mode with either low-altitude orbiting or geostationary satellites. User location can be kept secret, since the user functions in a "receive" mode only. For these conveniences, however, the user must pay the price of having to determine the total propagation path delay, including equipment delays, to whatever accuracy is needed for the time transfer measurements. This requires, among other things, knowledge of the satellite coordinates, which must be updated as necessary to keep these uncertainties at an acceptably-low level.

The one-way relay technique thus would seem to represent a good solution to the particular goal of improving time dissemination over large areas in the moderate precision range. Uncertainties in such aspects as equipment delays and knowledge of the satellite position at the time of a particular measurement would seem to preclude using this method for time transfers in the sub-microsecond region.

(b) Two-way Relay Technique

The basic feature of the two-way relay technique is the addition of transmission from station #2 back to station #1 for the purpose of obtaining a measurement of the actual total propagation path delay through the satellite with very high confidence levels. The specific experimental techniques vary, but in one method each station measures the time difference between its own transmitted pulse and the received pulse from the other station. A second method, which involves a round-trip measurement, requires station #1 to transmit to station #2 which then retransmits the received pulse back to station #1, along with its own timing pulse. For more details of such methods see [28]. In either case, sufficient information is available from the two-way measurements to determine the total path delay without needing to know accurately the locations of either ground station or the satellite providing the following assumptions are valid:

(1) The exchange of signals from $1 \rightarrow 2$ and $2 \rightarrow 1$ occurs either simultaneously or within such a short time that satellite motion in the interim between the two transmissions is negligible. Clearly, this assumption is easier to fulfill for a geostationary satellite than for a low-altitude orbiting one whose position can change very rapidly.

(2) The path is exactly reciprocal. This may not be strictly true in all experiments — for example, different frequencies are subject to slightly different perturbations by the ionosphere.

(3) Transmitter and receiver equipment delays at both stations must be exactly equal or at least accurately known so that corrections for any differences can be applied to the data. Because of the previously-mentioned difficulties in calibrating equipment delays and insuring their stability with time, this assumption is probably the most significant

limitation on the two-way relay method's accuracy — especially in the sub-microsecond range.

Begley and Shapiro [28] estimate an RSS error for this method of time transfer of 0.14 μs, consisting of 0.1 μs uncertainty contributions due to ground and satellite equipment delay errors. A Comsat-type synchronous satellite relay is assumed. The Sperry Gyroscope report [18] also estimates the corresponding uncertainties to be in the 0.1-0.2 μs range for this method.

Several experiments have been conducted which demonstrate the very high synchronization accuracy that can be achieved with the two-way technique. In 1962 the Telstar satellite was used by the U. S. Naval Observatory and the Royal Greenwich Observatory to achieve time transfers across the Atlantic to within at least ± 20 μs [32]. However, most of this uncertainty was attributed to the LF ground links used between the two timekeeping laboratories and the respective satellite communication terminals. Apparently, ± 1 μs time transfers were achieved between the two satellite ground stations without the LF link uncertainties. Measured path delays agreed to within ± 6 μs of the predicted values. The transmission formats employed frequencies of about 4100 MHz and 6400 MHz and used 5 μs pulses for timing markers.

In 1965 two-way time transfers were conducted between Mojave, California and Kashima, Japan using 1700 MHz and 4200 MHz transmissions through the Relay satellite [33]. The format was similar to the Telstar experiment with both 5 μs and 11 μs pulses being used. The results, checked by portable clock trips, purported to show an achieved synchronization accuracy of ±0.1 μs. Later, these results were disputed by some who claimed that 0.1 μs was actually the <u>precision</u> of reading the photographs involved while the actual synchronization <u>accuracy</u> was limited to perhaps ± 1 μs by various systematic errors. Nevertheless, the Relay experiments certainly further verified the potential of the two-way relay method for very high-accuracy time transfers.

In 1967 the ATS-1 and ATS-3 transponders were used in a series of experiments by NBS and other organizations to achieve two-way time transfers over intercontinental distances using more convenient frequencies (≈ 150 MHz) and very much simplified equipment and receiving techniques [29, 34]. Using the successive-audio-tone technique mentioned previously in the discussion of the one-way method, clocks at NBS (Boulder), STADAN (California), and Maui, Hawaii were synchronized to within better than ± 5 μs, as confirmed by portable clock measurements. Another longer-distance synchronization between

Boulder and Pitcairn Island in the Pacific was also successful to within $\pm$ 5 $\mu s$. Other results include 0.5 - 8.4 $\mu s$ closures for successive time synchronizations around a 32,000 km closed loop of stations including two sites in the South Atlantic.

More recently, in 1970, facilities of the Defense Satellite Communications System (DSCS) have been used for two-way time transfers between Maryland and Hawaii accurate to $\approx 0.1\ \mu s$ when multiple exchanges can be averaged [35]. The format in this case was a high speed pseudo-random code.

Summarizing, there seems little doubt that two-way time transfers via satellite transponder can be used for sub-microsecond synchronizations and thus represents a possible way of improving time dissemination for any applications requiring this level of timing accuracy. The main advantage,, of course, is the capability for essentially eliminating the path delay problems associated with one-way techniques. On the negative side, only a limited number of users can be serviced with the two-way method and the scheduling problem could be formidable. Because each user must transmit information, user cost is relatively high and his position cannot be kept secret. Also, from the military point of view, the two-way satellite relay is somewhat susceptible to jamming and other interference.

(c) On-board Clock Technique

In the on-board-clock satellite technique timing information is transmitted directly from a clock on-board the satellite to the user site on the ground. The satellite clock may include a quartz crystal oscillator or an atomic frequency standard and may operate independently or be synchronized to a reference clock on the ground. To obtain timing information relative to the satellite clock a user must measure the received signal relative to his local clock and then apply a correction for the total satellite $\rightarrow$ ground propagation delay, basically as in the previously-discussed one-way relay method. Two separated ground stations may, of course, compare their local clocks by both receiving the same satellite transmission and correcting for their respective propagation delays. As in the one-way relay case the main limitations tend to be in such factors as knowledge of the satellite and ground station positions and uncertainties in receiver delays.

For a geostationary satellite carrying an on-board clock the satellite position is usually fairly well known; also, any errors in the assumed position of the satellite for two separated ground stations comparing their times tend to be highly correlated, resulting in a reduced contribution to overall inaccuracies in the time comparison. An additional problem for the on-board clock technique is the shift in clock rate due to the relativistic gravitational shift and second-order Doppler effects. For synchronous orbit the gravitational shift is about 50 $\mu$s/day while the second-order Doppler effect is about 4.4 $\mu$s/day [36]. These shifts are constant, however, and can therefore be compensated for.

The low-altitude orbiting clock technique is complicated by the dynamic nature of the received signals. During a typical satellite pass near a receiving station the received frequency will typically undergo Doppler shifts of as much as $25 \times 10^{-6}$, requiring more elaborate dynamic tracking techniques. Usually, about 50 timing measurements of (received signal-local clock) can be obtained for each satellite pass lasting 10-15 minutes. At the point of minimum satellite approach, in-track satellite position errors have little effect on the timing measurements.

Begley and Shapiro [28] estimate the RSS error for the on-board-clock technique to be 0.26 $\mu$s with the main error sources being ground and satellite equipment calibration errors (0.14 $\mu$s each) and ground station location errors (0.16 $\mu$s). This estimate applies to synchronization measurements between ground stations using the same synchronous satellite, where satellite position errors are likely to be highly correlated. The Sperry Gyroscope report [18] estimates the RSS uncertainty at about 0.7 $\mu$s, with the major contributions coming from satellite position errors (0.5 $\mu$s corresponding to a 150 m range error), ground station position errors (0.15 $\mu$s corresponding to 45 m uncertainties), propagation error (0.3 $\mu$s for 200 MHz transmissions), and equipment delay uncertainties (0.2 $\mu$s).

Experimental results using on-board clocks have been obtained from the ANNA, GEOS, DODGE, TRANSIT, and TIMATION satellite programs to date. The first three programs involve geodetic applications while the latter two are navigation oriented. All five have used on-board quartz crystal oscillators to provide timing signals for transmission to ground stations. All except DODGE used low-altitude orbits; DODGE was synchronous. Anna IB was launched in 1962 and provided synchronizations to within 250 $\mu$s. This result was believed limited primarily by ground station equipment and not the on-board clock system. GEOS-A in 1965 and GEOS-B in 1968 provided some improvements by adding a capability for normalizing the satellite clock's 1-minute markers to within $\pm$ 10 $\mu$s of the UT-2 time scale by means of a divider pulse deletion technique controlled from the ground.

By using after-the-fact corrections to the transmitted time signals, NASA's STADAN tracking network stations were able to achieve synchronizations to within $\pm$ 100 $\mu$s with GEOS-A and $\pm$ 40 $\mu$s with GEOS-B. The DODGE (Department of Defense) satellite launched in 1967 was similar to GEOS but allowed 8 $\mu$s synchronization accuracies according to [1].

TRANSIT [37] is a U. S. Navy navigation system which became operational in 1964 and presently uses three polar orbiting satellites to provide navigation fixes each four hours to ships and submarines. Time markers are transmitted each two minutes along with information for calculating the satellite-to-user path delay. Time synchronizations to at least $\pm$ 40 $\mu$s have been achieved so far and some commercial receivers for the TRANSIT signals are now available, though very expensive.

TIMATION is another Navy system and uses two orbiting satellites at present — the most recent being launched in September 1969. A third satellite is in the planning stage. These satellites feature very high quality crystal oscillators with stabilities of a few parts in $10^{12}$ per day [38]. Excellent synchronization accuracies have been claimed but many details are unfortunately classified.

In considering the pros and cons of an on-board clock system for time dissemination it is perhaps most meaningful to consider synchronous and low-altitude orbiting satellites separately.

<u>Synchronous Satellites With On-Board Clock</u>

(a) Advantages
   (1) Signals are available <u>continuously</u> to a large region — three satellites could provide global coverage.
   (2) A large number of users can be serviced simultaneously.
   (3) Users do not need transmitters.
   (4) Dynamic tracking is not necessary.
   (5) Satellite → user distance remains relatively constant.

(b) Disadvantages
   (1) Cannot achieve worldwide coverage from a single satellite.
   (2) Some users will have to receive satellite signals at low elevation angles.
   (3) High launch costs for synchronous altitude.
   (4) Long-distance path from satellite → user requiries either high satellite transmitter power or high-gain receiving antennas.
   (5) Unfavorable radiation environment.

(6) Clock in orbit can't be repaired or modified.
(7) Limited clock life.
(8) High electrical power requirements if atomic standard is used.
(9) High development cost of clock, if atomic.
(10) Difficult to provide for oscillator/clock corrections from ground.

Low-Altitude Orbiting Satellite With On-Board Clock

(a) Advantages
  (1) Can achieve worldwide, though periodic, coverage with one satellite.
  (2) Can serve large number of users and only one user at a time needs to be able to "see" the satellite.
  (3) All users can receive signals at high elevation angles for minimum propagation effects.
  (4) Cheaper launch costs because of relatively small booster rockets required.
  (5) Short line-of-sight range gives favorable signal-to-noise ratio.
  (6) Users do not need transmitters.
(b) Disadvantages
  (1) User must deal with a large dynamic range and correct for Doppler effects.
  (2) Can't use fixed-tuned receivers.
  (3) Signals are available only 10-15 minutes per satellite pass and only a few times per day.
  (4) Clock in orbit can't be repaired or modified.
  (5) Limited clock life.
  (6) High electrical power requirements if atomic standard is used.
  (7) High development cost of clock, if atomic.
  (8) Difficult to provide for oscillator/clock corrections from ground.

(3) The Crystal Oscillator Vs. Atomic Standard Question

In any consideration of a satellite time dissemination system using an on-board clock the complex question of whether to use a quartz crystal oscillator or an atomic frequency standard to provide the basic clock rate must be answered at an early stage. Many factors must be considered carefully, including

(a) do the experimental objectives require an atomic standard level of performance?

(b) is a crystal oscillator adequate in terms of performance if provisions are included for remote frequency and/or time corrections?
(c) prior experience in orbit with both types of standards.
(d) relative sensitivity to satellite environments and launch conditions.
(e) cost considerations.
(f) electrical power required from the satellite.
(g) development time required if not available "off-the-shelf".

It seems evident from the standpoint of cost, complexity, power requirements, and availability that a crystal oscillator should be preferred if at all consistent with the mission objectives. In attempting to decide whether a crystal clock can meet the specific objectives for the proposed NASA satellite experiment, it might be worth reviewing what has been accomplished to date with satellite — borne crystal clocks.

The most extensive recent experience with satellite-borne crystal oscillators that is described in the non-classified literature is probably that of the Naval Research Lab in connection with the previously-mentioned Timation satellite program. Timation I, launched in 1967, used a specially-developed, selected 5 MHz crystal oscillator with a 5th overtone, glass-enclosed crystal in a double proportional control oven [39]. Provisions were included for adjusting the output frequency of the oscillator from the ground in $1 \times 10^{-11}$ steps via a mechanical tuning capacitor. The oscillator frequency showed a change of about $2 \times 10^{-9}$ at launch and then settled down to a long-term performance featured by:

(a) a measured temperature coefficient of $2 \times 10^{-11}/^{\circ}C.$, which was much larger than expected.
(b) a drift rate which decreased more sharply in orbit (to $2 \times 10^{-12}$/day) than that for a similar oscillator maintained on the ground.
(c) a sensitivity to radiation amounting to about $2 \times 10^{-11}$/day.

In September 1969 Timation II was launched with an improved crystal oscillator in terms of having more radiation shielding, a triple proportional oven, a high-resolution frequency adjustment mechanism with a $3.6 \times 10^{-12}$/step capability, and a crystal enclosure with cold-welded seals, high-temperature vacuum bakeout processing, and thermal compression bonded leads [38]. These changes resulted in a much reduced temperature sensitivity of $1\text{-}2 \times 10^{-12}/^{\circ}C.$ in orbit. Radiation effects continued to be a problem. Over a 6-month period in orbit, the oscillator frequency was maintained constant to within $\pm 2 \times 10^{-10}$ most of the time by making about ten frequency adjustments from the ground. Unfortunately, the timing results achieved with this series of satellites have not yet been generally discussed in the open literature. It seems likely, however, that time synchronizations performed by separated ground stations via reception of Timation timing signals within a reasonably short period of perhaps a few hours are limited more by uncertainties in the satellite position as available from the transmission format itself than by the crystal oscillator instability. The accuracy of the transmitted time with respect to an accepted reference time scale is harder to estimate, since inadequate information is available both on possible frequency differences between the corrected satellite oscillator and the reference time scale rate and also with regard to initial synchronization of the satellite time markers with the reference time scale markers. It is clear, however, from the published satellite oscillator stability data discussed above that frequency offsets of at least $2 \times 10^{-10}$ did occur with Timation II, resulting in timing error accumulations of at least 20 μs/day during these periods of maximum offset. However, such errors could be reduced substantially in similar civilian applications by using published after-the-fact corrections to the timing signal.

Time transfer results, using crystal oscillators in other satellite series, such as GEOS, have already been mentioned in a preceeding section of this report. In general, time transfers from satellites to ground in such systems appears to be definitely possible in the 50 μs range and perhaps downward into the 10 μs range with less confidence.

It should be noted that the crystal oscillators used to date in satellite applications are not state-of-the-art oscillators in terms of stability performance, but rather represent a necessary compromise between stability performance and many other considerations such as environmental sensitivity under space flight conditions, size, weight, and electricl power requirements. These compromise, packaged units have achieved an acceleration sensitivity of $1\text{-}4 \times 10^{-9}$/G, operational temperature range of -55°C. to +60°C., 1-second frequency stability of better than $1 \times 10^{-10}$, and daily aging rates of $5 \times 10^{-10}$ all in a package size of less than 650 $cm^3$ and a weight of about 0.45 kg [36]. This reference also states that an improved packaged oscillator was already under development in 1967 with a projected 1-second stability of $< 1 \times 10^{-11}$, a daily aging rate of $< 5 \times 10^{-12}$, and an acceleration sensitivity of $1 \times 10^{-10}$/G.

In view of the significant advancements being achieved with precision laboratory crystal oscillators, it seems likely that the ruggedized, packaged versions may be expected to show corresponding stability improvements in the future. Recent stability measurements of some commercially available and other under-development laboratory oscillators conducted at NBS have documented 1-second stabilities of better than $5 \times 10^{-13}$ and flicker noise levels (usually the most important factor in determining the oscillator's stability for measurement times in the 1-1000 second range) at least 12dB lower than previously-available commercial units [40-41].

In contrast to the crystal oscillator case, essentially no experience is available on the performance of atomic frequency standards in spacecraft applications. Rubidium gas cell standards, in the form of satellite magnetometers, have been launched, however, and apparently have functioned well in orbit. As will be discussed in detail in the next chapter of this report, there is every expectation that a cesium or rubidium standard could be developed which would perform in a timing function essentially the same as these units do now on the ground — that is, with high reliability, high accuracy, and nearly drift-free stability in long term. The advisability of proceeding with such a development program seems to hinge not so much on the technical feasibility, then, but more on whether the advantages gained, primarily in terms of stability, are worth the rather expensive development cost of several hundred thousand dollars.

Some members of the Steering Committee apparently concluded that, <u>if</u> a satellite with an on-board clock is to be used at all, an atomic standard would make more sense than a crystal oscillator for the following reasons:

(a) For time dissemination purposes the atomic standard will require less management from the ground in the form of rate and time corrections to the satellite clock system. However, it was also pointed out that not many corrections are needed for a <u>good</u> crystal oscillator (e.g., the Timation case) and that the corrections are not difficult to achieve even when needed.

(b) For Doppler tracking the data reduction technique may be simplified to some extent if a separate frequency parameter for the satellite oscillator does not have to be extracted from the data for each pass.

The committee did agree that if an atomic standard is used in any satellite, a back-up mode using a crystal oscillator should be designed into the system. Since both cesium and rubidium atomic standards employ a crystal oscillator electronically locked to the atomic resonance, it seems reasonable to provide for decoupling this oscillator from the atomic reference package in the event of problems developing in the cesium beam tube, the rubidium gas cell package, or their associated electronics.

Other members of the committee expressed strong reservations over putting anything as complex as an atomic frequency standard in a satellite environment where repairs or modifications to the system are not possible. If there are any other reasonable alternatives, it is best to leave the complex instrumentation on the ground. This argument against an atomic standard in the satellite does not, of course, necessarily support the idea of a crystal oscillator in the satellite either, but may instead suggest that a transponder technique with a passive satellite will avoid the problem of having <u>any</u> type of standard in the spacecraft.

If one considers the available information on crystal oscillators and atomic standards for possible spacecraft use, along with NASA's stated objectives for this satellite timing experiment as proposed, the following preliminary conclusions seem warranted:

(a) <u>If</u> a decision is first made to use an on-board clock technique, then an atomic standard, rather than a crystal oscillator, should be seriously considered in view of NASA's stated goal of providing improved time dissemination in the sub-microsecond range. Crystal oscillator instabilities, at least for present packaged units, appear to be inadequate for maintenance of sub-microsecond timing — at least, without using very elaborate and time consuming monitoring and correction techniques. It must be realized, however, that even with the improved performance offered by atomic standards, sub-microsecond time dissemination is not possible without adequate knowledge of the propagation delays involved.

(b) Since the use of <u>either</u> an atomic standard or a crystal oscillator on-board a satellite produces significant problems (e.g., frequency instabilities of the crystal oscillator and development cost and complexity for the atomic device), serious consideration should be given to other alternatives for meeting the mission objectives.

## 3.3 A Summary of Pros and Cons For Various Time Dissemination Techniques

Figure 1 is an attempt to compare some of the important aspects of various time dissemination systems and techniques. As is usually

| | ACCURACY FOR DATE TRANSFER OR SYNCHRONIZATION | COVERAGE FOR STATED ACCURACY | RELIABILITY | % OF TIME AVAILABLE | AMBIGUITY | RECEIVER COST FOR STATED ACCURACY | COST PER CALIBRATION | NUMBER OF USERS THAT CAN BE SERVED | OPERATOR SKILL REQUIRED FOR STATED ACCURACY |
|---|---|---|---|---|---|---|---|---|---|
| HF - WWV | 1000 $\mu$s | HEMISPHERE | DEPENDS ON CONDITIONS | | 1 DAY | | | | |
| LF - WWVB (VIA TIME CODE) | 500 $\mu$s | USA | | | 1 YEAR | MODERATE | | USA | |
| LF - LORAN C | 1 $\mu$s | SPECIAL AREAS | | | 50ms | | | SPECIAL AREAS | |
| VLF - OMEGA (VIA PROPOSED TIME CODE) | 10 $\mu$s | WORLD | | | 1 YEAR | MODERATE | | | |
| SATELLITES, ONE-WAY RELAY (STATIONARY) | 10-50 $\mu$s | HEMISPHERE | | STATIONARY | 1 DAY | | | | |
| SATELLITES, TWO-WAY RELAY (STATIONARY) | 1/10 $\mu$s | HEMISPHERE | | | 1 DAY | | | | |
| SATELLITES, ONE-WAY, ON-BOARD CLOCK (ORBITING) | 10-50 $\mu$s | WORLD | | ORBITING | 1 DAY | | | | |
| SATELLITES, ONE-WAY, ON-BOARD CLOCK (STATIONARY) | 10-50 $\mu$s | HEMISPHERE | | STATIONARY | 1 DAY | | | | |
| PORTABLE CLOCKS | 1/10 $\mu$s | LIMITED BY TRANSPORTATION | | AS NEEDED | 1 DAY | NONE | | | |
| AIRCRAFT FLYOVER, TWO-WAY | 20ns | LIMITED BY TRANSPORTATION | | | DEPENDS ON FORMAT | | | | |
| AIRCRAFT FLYOVER, ONE-WAY | 50ns | LIMITED BY TRANSPORTATION | | | DEPENDS ON FORMAT | | | | |
| TV | 1-10 $\mu$s | USA | | | 1 DAY | | | USA | |

GOOD FAIR DEFICIENT

Fig. 1 - A Comparison of Some Time Dissemination Systems

the case in such attempts, some degree of oversimplification and subjective judgement is undoubtedly involved; however, it may prove helpful in summarizing much of the discussion occurring in Section 3.2 of this report.

Some explanatory comments on the terms used in Figure 1 to compare the various techniques follow:

(a) Accuracy - may refer to either how accurately time-of-day (date) information can be transmitted or to how accurately two separated stations can be synchronized using the particular technique. In general, accuracy of date transfer is referred to for all techniques or systems capable of disseminating this kind of information. The numbers given are believed to be realistic for most users. It must be recognized that under either extremely favorable or unfavorable reception conditions, locations, etc., these estimates should be adjusted accordingly. The rather arbitrary breaks between "deficient"-and-"fair" and "fair"-and-"good" accuracies are placed at about 1 ms and 5 μs, respectively. Stated accuracies for the one-way satellite techniques are believed to be rather conservative, reflecting primarily the likely uncertainties in determining the propagation path delay from information generally available to the casual user on a reasonably current basis.

(b) Coverage - a general indication of geographical coverage area in which the technique can be used for the stated accuracy.

(c) Reliability - takes into account such factors as severe dependences on propagation conditions or the placement of critical system components in satellite environments which could result in an interruption of the services provided.

(d) % of Time Available - refers to whether the service is available continuously (good), a portion of each day (fair), or only occasionally by special arrangement (deficient). Irregular interruptions due to such factors as propagation conditions are not included in this category.

(e) Ambiguity - refers to the longest interval of time which can be provided by the particular system or technique without ambiguity. For example, the day/hour/minute/second time code on WWVB provides date information which is unambiguous up to the year. For Omega, it is assumed that a time code (such as proposed by NBS) is available within the format. The ambiguity is generally given as 1 day for the satellite techniques, on the assumption that sufficient bandwidth is available to transmit at least on hour/minute/second time code, if desired.

(f) Receiver Cost - refers to the relative cost of an appropriate receiver and antenna system for using the technique to the stated accuracy. "Deficient" is considered to imply costs greater than a few thousand dollars, "fair" refers to costs in the $1000-$3000 range, and "good" means less that $1000.

(g) Cost per Calibration - a relative judgement taking into account such factors as how often a calibration can be made conveniently and the cost of needed equipment. Portable clocks are downrated on the assumption that the user must in some way pay for part of the rather large travel and equipment costs involved. Downrating is also applied to any technique which allows only infrequent calibrations, since fixed user costs can be spread over relatively few calibrations.

(h) Number of Users That Can Be Served - a relative indication of how many users might be likely to use the technique, assuming a reasonably regular service is available. Keep in mind that some of the techniques described are only experimental as of now. The TV technique is considered to have more potential users than WWVB, even though both cover essentially the continental U. S., because the TV receiver costs are much lower and because WWVB reception is subject to some propagation disturbances and to interference in some areas of the country.

(i) Operator Skill Required For Stated Accuracy - a relative indication of how difficult a measurement is to make in the lab to the stated accuracy. Techniques are rated "good" if the time information can simply be read directly off a measuring instrument, such as a counter or oscilloscope. "Fair" implies that the user must process the data obtained, make multiple measurements, perhaps select particular cycles of the signal (Loran C), or use special receiving techniques (such as Doppler tracking of orbiting satellites). "Deficient" is applied to Omega because of the rather complex procedure and skill required in going from the received envelope to a particular cycle of one of the carriers. Future automatic timing receivers may alleviate this problem, of course.

Many of the techniques discussed are capable of providing timing information at reduced accuracy under greatly different conditions than those stated in the table — for example, to larger coverage areas, serving larger numbers of users, and requiring cheaper and simpler equipment. Other tables, corresponding to Fig. 1, would be necessary for these reduced accuracy situations.

### 3.4 Possible Alternatives For NASA Objectives Other Than Improved Time Dissemination

In addition to improved time dissemination, NASA-GSFC has also stated as goals for the proposed satellite experiment the refinement of the one-way Doppler tracking technique, the evaluation of the one-way ranging technique, the measurement of certain relativistic effects, and the development of new technology in the atomic frequency standards area. Unlike the time dissemination case, as discussed in the previous parts of Section 3, fulfillment of these remaining objectives (except perhaps for the last one) seems to require some type of clock orbiting in a satellite.

In discussions of the one-way Doppler technique before the GEOS-timing Steering Committee, it was not clarified exactly how an improved clock in orbit would improve Doppler tracking, although such implications were made on several occasions. There was little question that an atomic standard in orbit would provide better stability from one satellite pass to the next, but generally this seems to be of only minor consequence. Personnel from APL did state that improved stability during a pass would help reduce at least one component of the overall tracking error — perhaps, by a factor of five. However, it could not be clarified by the committee what effect this would have on the overall tracking error. It should also be noted that the relevant stability of a typical commercial cesium standard during a typical 10-minute pass would be on the order of $\sigma(2, 100\ \text{sec.}) \approx 5 \times 10^{-12}$. (For an explanation of this increasingly-used stability measure, the square root of the Allan variance, see references [42-43]). The corresponding quantity for precision laboratory crystal oscillators is significantly better than this — in fact, as low as a few parts in $10^{13}$ in some cases. While the state-of-the-art in packaged oscillators, suitable for satellite use, is certainly not this good yet, a 100-second stability of $5 \times 10^{-12}$ or better is almost certainly achievable in such a unit, as discussed in Section 4. In conclusion, then, a possible alternative to the Doppler tracking experiment with on-board atomic clock might be to simply develop an improved packaged crystal oscillator.

The one-way ranging technique again requires some sort of on-board clock. If the technique is to be fully exploited, atomic clocks may indeed provide significant advantages in terms of more precise synchronization capability and less frequent needs for resynchronizations.

Suitable alternatives are not apparent, unless relaxed tolerances on the ranging errors are acceptable — a judgement which must be made for each specific proposed application.

The relativistic measurements are most easily and conveniently done by using an orbiting atomic clock. However, such measurement techniques have been proposed before by others, and one should look into the status of these other proposals before becoming committed to this particular proposal. For example, R. F. C. Vessot of the Smithsonian Astrophysical Observatory has already developed a small atomic hydrogen maser for the expressed purpose of use on a satellite in an eccentric synchronous orbit in order to determine the gravitational red shift [6]. A similar experiment is also being considered by ESRO in Europe.

Finally, in regard to the objective of developing new technology in the area of atomic standards, clearly, some sort of atomic standard must be selected. However, advances in terms of smaller size and weight, lower power consumption, better reliability, etc. could be made without involving satellites, if the general justification warranted it.

### 3.5 Conclusions Concerning Possible Alternatives For Achieving NASA's Objectives for the Proposed Experiment

In the view of this author the value of developing an atomic standard for use on a spacecraft depends significantly on the relative importance which NASA attaches to the five main objectives of the experiment. For time dissemination purposes there are many interesting alternatives to the expensive development of a special atomic standard for use on an active satellite. These have been discussed at length in Section 3.2 and summarized in Section 3.3. However, some of the other stated objectives — particularly, the one-way ranging evaluation the relativistic measurements, and the development of new technology — probably would benefit from the suggested active satellite approach. Therefore, the overall advisability of proceeding with the atomic standard development would seem to depend rather critically on the relative importance of the various stated goals from NASA's point of view.

# 4. ALTERNATIVES FOR A SPACECRAFT ATOMIC CLOCK

## 4.1 Introduction

In this chapter the intent is to discuss the more specific question of what type of atomic frequency standard would be most suitable for accomplishing the mission objectives mentioned previously, assuming for the moment that the active satellite technique using an on-board clock is selected by NASA management as the most reasonable way to proceed. Analagous to the earlier part of this report where alternative methods were considered, this chapter will deal with alternative devices for use with one particular satellite technique discussed previously.

During the early stages of this study, including the period up to and including the last meeting of the Steering Committee in January of 1969, it had been assumed that one of the GEOS satellite series would serve as the vehicle for any atomic standard developed as a result of this study. Thus, much of the discussion centered around specific spacecraft constraints on size, weight, and electrical power appropriate only for GEOS satellites. Eventually, however, it was realized that these constraints might be rather artificial if other alternative vehicles, such as the ATS series of applications technology satellites, for example, could also be considered as possible choices for the experimental program proposed. Because of these uncertainties regarding the actual launch and spacecraft vehicles that are realistic candidates for such a program, any discussions of environmental constraints imposed by the satellite will be kept rather general.

A few general comments can be made concerning desirable characteristics of any atomic frequency standard considered seriously for such a spacecraft application:

(a) It must obviously be able to not only survive the launch phase, but also be able to perform within specifications within the spacecraft environment.

(b) It must have size, weight, and electrical power requirements consistent with the particular satellite vehicle used.

(c) It must be sufficiently stable over appropriate time periods to allow completion of the experimental objectives.

(d) It should be reliable, since no possibility exists for repairing a defective standard in orbit and extensive redundancy becomes expensive for such complex devices.

(e) It should contain provisions for ground monitoring of any critical components or subsystems.

(f) Its development cost must be consistent with available resources and the benefits to be realized.
(g) A successful development should not depend on uncertain technological breakthroughs that may produce unacceptable risks in terms of ultimate development cost and/or development time.

### 4.2 Some Constraints Imposed by the Launch and Spacecraft Environments

Ideally, one would like to be able to use already-existing atomic standards, or at least fairly minor modifications of such instruments, in any spacecraft application requiring a highly precise and accurate on-board standard. The resulting economics in terms of both development time and cost would go far in making such a satellite-borne atomic standard project practical and cost effective.

As we will see in more detail later on in this chapter, commercial atomic frequency standards are being developed which can provide near state-of-the-art performance over a wide range of environmental conditions found in typical terrestrial field applications. The question remains, of course, as to whether a launch vehicle and satellite environment introduces significantly more serious constraints on the design and operation of an atomic standard than does a severe terrestrial application. In order to discuss the question further, but without limiting ourselves, in general, to a specific launch vehicle or spacecraft program, consider the following physical and performance characteristics of an atomic standard, which become especially important for a spacecraft application.

#### a. Reliability of the Standard

While this aspect of atomic standard performance is obviously important in almost any application — terrestrial or spaceborne — the consequences of equipment failure in an unmanned spacecraft are clearly more catastrophic than on the ground, where repair facilities, test equipment, spare components or modules, and even complete substitute atomic standards can be arranged to be readily available. Even in view of the generally excellent reliability achieved in present-day commercial atomic standards, one of the prime goals of any program to develop a spaceborne atomic standard must be to provide improved reliability. Adequate improvements in the reliability of the electronics associated with the standard may result simply from modifying present electronic systems to use space-qualified components. Circuit simplifications — although perhaps at some price in terms of reduced convenience and flexibility — can undoubtedly be effected with a resulting further increase in reliability. The beam tube, in the case of a cesium atomic frequency standard, and the optical package, in the case of the rubidium gas-cell standard, contain relatively small numbers of components and should be capable of rather minor redesigns for sufficiently improved reliability. Present commercial cesium beam tubes are already warranted for 3 years and improved versions designed for reliable operation in much more rugged environment over a 5 year period will be available within the next year [44]. The rubidium optical packages have already demonstrated their reliability in space by performing successfully as components of spacecraft-borne magnetometer systems.

In both the cesium and rubidium standard cases, the output frequencies are derived from a slaved crystal oscillator which is electronically locked to the appropriate atomic resonance frequency. During the various discussions within the Technical Steering Committee, it was apparent that most members felt strongly that any atomic standard developed for a spacecraft application should definitely contain provision for remotely opening the electronic servo loop to allow for backup operation of the free-running crystal oscillator in the event of a failure in orbit by the cesium or rubidium atomic resonance device itself. Such a design provision should offer no special problems if done properly.

b. Physical Size and Weight

Limitations imposed on the size and weight of a spacecraft atomic standard will, of course, depend on the particular satellite and launch vehicle used and will be influenced by such factors as the particular physical configuration within the spacecraft and the priority of the spaceborne atomic standard relative to other competing missions for that satellite system. For the GEOS series of geodetic satellites, which during most of the Steering Committee's deliberations appeared to be the most likely candidate for the spaceborne atomic clock experiment, weight was not considered a major problem and the standard's overall volume would be less of a problem than its actual shape. The GEOS spacecraft designers from APL felt that a 30 cm × 20 cm × 15 cm package could probably be accomodated without much trouble but that any larger size requirements would have to await decisions regarding details of future GEOS mission requirements. As will be seen in the next subsection, present-day commercial developments in cesium and rubidium standards suggest that such size restrictions could probably be met without too much difficulty or compromise in performance.

c. Environmental Sensitivity

The sensitivity of the atomic standard to such environmental parameters as temperature, pressure, shock, spacecraft spin, vibration, and magnetic fields must be evaluated with regard to the specific satellite and launch vehicle being used. Not only will these environmental conditions vary greatly from one satellite series to another, but they may also depend significantly on the exact location of the standard within the spacecraft configuration. In GEOS, for example, vibration levels are worst on the outside of the spacecraft package, dropping to less than 7 G's on the inside within the instrument compartment — even during the launch phase. Assuming no severe mechanical resonance problems in the atomic standard package, vibrations at the servo modulation frequency and its harmonics are likely to prove most serious in causing deterioration of the standard's performance and must be carefully evaluated during the testing phases. Severe variations in the spacecraft ambient temperature could also cause unacceptable frequency instability, but at least in GEOS, the temperature control observed of $\pm 3^{\circ}C$ appears to be more than adequate for the performance levels needed in the proposed experiments. Spacecraft spin could be a serious problem for a beam-type atomic device, such as a cesium standard, since for the usual beam geometries employed, certain rotational motions will cause a loss of signal at the beam detector resulting in loss of servo-system lock. For spin-damped satellites like GEOS rotational rates are slow enough to eliminate this type of problem. Even for satellites with higher rotation rates, a different beam geometry can be utilized to minimize this effect as has already been done in at least one commercial version [44]. The actual value of the ambient temperature, in addition to its stability, must be known and considered in the design of the atomic standard, but otherwise should not offer much of a restriction. Since the present leading atomic standard candidates — cesium and rubidium devices — are somewhat sensitive to ambient magnetic fields, care must be exercised in the use of magnetic materials in close proximity to the standard. Again, this should not present too serious a problem, since the magnetic shields routinely employed in both cesium and rubidium standards allow normal operation in ambient fields of several Gauss. GEOS offers a particularly favorable magnetic environment, since some care is exercised to avoid the use of magnetic materials in its construction; ambient magnetic fields of 0.3 Gauss have been achieved in earlier GEOS systems.

d. Provisions For Remote Monitoring

Because of the complexity of an atomic standard, the general lack of experience with such instruments in a space environment, and the rather high level of performance needed to meet some of NASA's objectives for the proposed experiment as discussed previously, it seems essential to provide for close monitoring on the ground of a number of critical parameters of the atomic standard. For a cesium beam standard such things should be capable of being monitored as cesium oven temperature, C-field current; detected beam current; electron multiplier status; mass-analyzer voltage; ionizer supply voltage; beam-tube internal vacuum; control voltage applied to servo oscillator, input supply voltages for various electronics subsystems; output voltages from multiplier chain, oscillator, and certain other subsystems; second-harmonic component level of beam tube output signal; oscillator oven temperatures; radiation levels near the standard; and corresponding status checks of any redundant units or subsystems. For a rubidium gas cell standard the electronics systems are very similar to those used with cesium devices and therefore would require the same sort of ground monitoring. The rubidium atomic resonance package consists of such components as a spectral source of rubidium light, the gas cell itself, a photocell to detect transmitted light intensity, a microwave cavity structure, suitable magnetic shielding, and a C-field structure. Electrical parameters associated with the rubidium lamp source and the operating temperature of the gas cell are two critical monitoring areas within this part of the standard.

Since one of NASA's major objectives in this proposed experiment is to develop and evaluate new technology in the form of a reliable atomic standard that can operate successfully in a spacecraft environment, it is essential that ground monitoring be possible for many more parameters of the system than would be required for future versions. Especially in the event of troubles developing after launch, very detailed monitoring data will be the only hope of pinpointing the difficulties and allowing corrective fixes in future models.

e. Provisions For Remote Adjustments

Certain system parameters will need to be remotely adjustable from the ground in order to insure proper operation of the frequency standard and to provide maximum flexibility for the desired experiments. For example, for either a cesium or rubidium atomic standard, the free-running frequency of the quartz oscillator locked to the atomic resonance must be remotely adjustable to prevent the servo correction signal from exceeding the design limits of the electronic control system as the oscillator frequency ages during the extended duration of the satellite experiment. In the case of a cesium standard it might be desirable to be able to adjust the output beam current to an optimum value through remote control of the oven temperature and the electron multiplier gain (if one is used). The magnetic C-field for either of the two most likely types of atomic standards could be adjustable to provide a fine frequency adjustment and to compensate, if necessary, for any changes in the magnetic shielding characteristics (assuming magnetic shields are used in the final design). The ability to remotely open the servo loop and sweep the oscillator frequency over the atomic resonance pattern while observing the DC output signal would provide a most useful diagnostic tool — especially, in the cesium beam case. Since the most useful signals from the spacecraft atomic standard system will be the timing signals, provision must be available for adjusting the "date" of the transmitted signals with sub-microsecond resolution. Suitable methods have been considered by APL [1]. Clearly, these and any other remote adjustment capabilities that are built into the spacecraft atomic standard system must be properly designed so that they do not introduce undesirable fluctuations in the variable parameters during normal system operation.

f. Electrical Power Requirements

This characteristic of atomic frequency standards appears, in the light of discussions before the Technical Steering Committee, to definitely be the most critical problem for a successful spaceborne atomic clock project — especially, if the GEOS series of satellites is to be used. Until the last meeting of the Committee, information from APL indicated that 10 W of electrical power could probably be made available for an atomic standard on GEOS with a possibility of adding 10 W more by additional solar cell panels. All discussions with commercial suppliers were based on examining the feasibility of developing an atomic standard with a power requirement of 10 W or as near to this as practically and economically possible. During the last committee meeting, however, APL stated that even 10 W (continuous) availability was very uncertain for future GEOS satellites and that this level would require additional solar cell appendages. In view of this situation and the projected electrical power requirements for future atomic standards as discussed in a later sub-section, another satellite series without such severe electrical power supply limitations should be seriously considered if this proposed project is pursued further by NASA.

## 4.3 Possible Types of Atomic Standards For the Proposed Experiment

Since the proposed experiment will presumably involve the development of hardware within the next several years, it seems reasonable to consider only those types of atomic standards for which general feasibility has already been shown. Such a list of contenders might then include cesium and thallium beam devices ; the rubidium gas cell standard ; ammonia, rubidium, and hydrogen masers ; the hydrogen storage beam device; and the methane-stabilized laser. Some comments will be made about each of these, but more detailed discussions can be found in the references listed in each of the following subsections. Details of performance achieved to date and some future projections for the leading contenders will follow later in this section.

a. Cesium and Thallium Beam Standards

The atomic beam magnetic resonance technique, which provides the basis for these standards, has been well documented over a long period in the scientific literature and will not be described in detail here [45]. Practical cesium beam standards have the longest history of any of the atomic standards and have been commercially available since the mid-1950's. The great amount of development effort spent on these cesium standards over the years has produced relatively small, reliable, and rugged devices which are now in common use in a variety of precise frequency and timing applications throughout the world. This type of standard has been selected to provide the internationally-accepted basis for the definition of the unit of time in terms of the cesium resonance frequency. As will become even more clear in the next subsection, the remarkable accuracy and stability performance achieved over rather wide environmental conditions certainly makes it a leading candidate for adaptation to a satellite-borne experiment.

Thallium beam standards, though never commercially produced, have been designed, built, and evaluated independently in several laboratories a few years ago as a similar, but possibly improved, atomic standard using the basic atomic beam technique [46-48]. While the anticipated advantages over cesium associated with thallium's reduced sensitivity to external magnetic fields and simpler atomic spectrum were shown to be realizable, enough other practical operating disadvantages became apparent with the experimental standards built to convince most workers that such devices are not likely to surpass cesium's already impressive accomplishments — at least, by a large enough margin to warrant further extensive development work. Since, even with further development, the potential advantages offered by thallium are not in any of the more critical limiting areas of the spacecraft application — e.g., electrical power requirement, size, reliability — it seems reasonable to exclude the development of a spaceborne thallium standard from further consideration at this time.

b. Rubidium Gas Cell Standard

Development work on a practical rubidium gas cell standard began about 1957, based on the successful use of double resonance, optical pumping, and optical detection techniques in a number of independent laboratories [45]. Commercial versions became available soon thereafter and have been continually improved up to the present time. The rubidium gas cell standard's small size and weight, its outstanding stability performance especially in short and medium term (say, for measurement times of 0.1-10,000 seconds), and its small initial cost (relative to other atomic standards) have resulted in its wide acceptance for many precise timing applications. As in the case of cesium standards, commercial sales to date are in the hundreds of units. The great amount of accumulated experience with rubidium standards and the generally high level of achieved performance make this device a serious candidate for the type of spacecraft application being considered in this NASA program.

c. Ammonia, Rubidium, and Hydrogen Masers

The application of the maser technique to frequency standards has resulted in the development of devices which directly emit stable and accurate atomic or molecular resonance frequencies for external use. The first successful devices of this type used an inversion transition in ammonia to generate frequencies which were stable to a few parts in $10^{12}$ and were reproducible to a few parts in $10^{11}$ [49]. In spite of considerable effort devoted in many laboratories throughout the world toward improving the ammonia maser's potential for practical frequency standard use during the 1950's and early 1960's, it became apparent that other types of atomic standards coming on the scene offered significant advantages over the ammonia maser — especially, in terms of accuracy potential and insensitivity to system parameters and environmental factors. Commercial versions were never produced, although the U. S. S. R. did orbit an ammonia maser a few years ago for certain relativity studies. The results of the experiment have not been widely published, and it now appears that in view of the successful development of other atomic standards, the ammonia maser is out of the picture for the type of experiment being considered here.

The rubidium maser employs a very high output power from the atomic system in order to provide a very high output signal-to-noise ratio and hence a very good short-term stability [50]. While its stability capability for averaging times of say 1 second and shorter is probably as good as or better than any other standard — quartz or atomic — it suffers in longer term from the usual disadvantages of the maser technique, such as strong influences of the cavity on the output frequency. Commercial devices are not yet available, but the rubidium maser is still worthy of consideration for applications requiring very high short-term stability — for example, where improved Doppler tracking might be a primary objective. However, in the case of the present NASA proposal, where long-term timekeeping ability is also a factor for some aspects of the experiment, the rubidium maser cannot be considered a strong contender at this time.

To date, the atomic hydrogen maser, first conceived by Prof. N. Ramsey at Harvard in 1960, has achieved the greatest success of any of the maser devices [51]. It is certainly among the most accurate and most stable of the known atomic standards, as will become more evident later on. Despite its very impressive performance achievements, the hydrogen maser has not attracted much commercial interest — especially in the last few years. Primarily, this is due to the following reasons:

(1) The hydrogen maser tends to be more attractive as a laboratory standard than a portable, field-use device due to its relatively large size, weight, and electrical power requirements and its need for reasonably well-controlled operating environments.
(2) It is more expensive than other atomic standards.
(3) Even though its stability performance is very impressive over a wide range of measurement averaging times, other cheaper and simpler types of standards have now been developed to the point where nearly comparable or superior stability performance is available over both short and very long ( > 1 day) averaging times.
(4) Earlier hopes for improved accuracy capability relative to laboratory cesium standards have not been realized based on the published literature [52]. It is true, however, at the present time that prototype field-operable hydrogen masers show better stability <u>and</u> accuracy than commercial cesium standards developed for field applications (except perhaps for measurements lasting many days or longer).

Some recent developments, however, lend some encouragement for giving further serious consideration to the hydrogen maser for space applications. First, the Smithsonian Astrophysical Observatory, under contract to NASA, has achieved considerable success in developing a maser specifically designed for a spaceborne experiment involving relativity experiments [6, 53]. A considerable reduction in size, weight, and electrical power requirements has been achieved without sacrificing the maser's excellent stability performance. Secondly, JPL and NASA Goddard have also successfully developed small hydrogen masers designed for field use under conditions existing at sites of NASA's satellite tracking networks [54-55]. The actual performance achieved with these versions is discussed in a later section of this report.

d. Hydrogen Storage Beam Device

This type of standard, as recently proposed by Hellwig of NBS [56], is an attempt to combine most of the virtues of both the cesium beam and hydrogen maser techniques while eliminating at least some of their problems. Potentially, this type of standard may provide both accuracy and stability in the $1 \times 10^{-14}$ region. A preliminary version has been constructed at NBS and used to verify the general feasibility of the technique. Although the technique seems very promising for the future, it appears that the development of a practical, reliable version with a sufficient background of documented experience would require too much time and financial support to merit serious consideration for the present NASA experiments being proposed.

e. Methane-stabilized Laser

As in the previous case, the methane-stabilized laser is a relative newcomer to the atomic standards scene, being developed first by Barger and Hall at NBS in 1969 [57]. In this type of device a laser, acting as a slave oscillator, is electronically frequency-locked to a particular saturated absorption frequency in methane gas. The use of the saturated absorption technique provides a very narrow resonance line whose center frequency is both very stable and very reproducible. Practical devices have already been built which demonstrate better stability over some ranges of averaging time than any other known device — quartz or atomic [58]. In addition it appears that the methane devices may also eventually produce accuracies that are competetive with the best cesium beam standards.

This type of standard is relatively inexpensive, easy-to-build, and compact. One present disadvantage is that the device's output frequency at 88 THz cannot be divided down to the RF region with existing instrumentation. However, it is conceivable that the frequency gap from microwaves up to the methane resonance will be successfully bridged within the next year or so. Thus once again here is a potentially very useful device for future space applications, though probably not within a practical time frame appropriate for this particular experiment due to the frequency gap problem.

4.4 Present Status of the Leading Contenders

a. Introduction

In this section of the report the top atomic contenders from those discussed in the preceeding section and the quartz oscillator are compared with respect to achieved performance and their typical physical characteristics. Based on some of those factors previously discussed the following devices are believed to be the most likely choices for development of a spaceborne version suitable for the experiments outlined by NASA within a 1-3 year time frame:

(1) quartz crystal oscillator
(2) cesium beam standard
(3) rubidium gas cell standard
(4) hydrogen maser standard .

In the following subsections the present status of these devices will be compared first in terms of their physical characteristics, such as size and weight, and then in terms of their performance achievements, such as accuracy, stability, and environmental sensitivity. Data will be given only for versions of these devices which would be reasonably adaptable to spacecraft use with the minimum required development; thus laboratory-type cesium beam standards and laboratory hydrogen masers will be neglected in these comparisons. The comparison data has been collected from a variety of sources, including specification sheets for commercial devices, the existing scientific literature, and information provided by representatives of commercial firms in the frequency standards field. References to specific commercial products by name and model number are avoided.

b. Comparison of Other-than-performance Characteristics

The best potential candidates for spaceborne frequency standard applications are compared in Table 1 with respect to various characteristics that do not include the normal performance indicators. The data for quartz, cesium, rubidium, and hydrogen maser standards is based on actual results achieved and documented to date for existing commercial or specially-built standards.

The information given for quartz oscillators concerning size, volume, weight, and electrical power requirements refers specifically to an oscillator developed under contract for the U. S. Navy's Timation Satellite Program [38-39] and is included here as being representative of the achievements of a quartz oscillator in a similar spaceborne application to the proposed NASA project. The corresponding cesium beam standard data refers to a recently-developed commercial standard designed for small size and weight and dependable operation under severe environmental conditions [44]. Two separate listings are given for rubidium gas cell devices — one which is representative of the status of present commercially-available standards and a second for a version developed under contract from NASA's Manned Space Flight Center specifically for spacecraft use in the Apollo Program [59]. Some of the data given for the latter device reflects design goals and may not have been achieved in full detail in the prototype versions

Table 1 - Comparison of Other-than-performance Characteristics of Some Present Types of Frequency Standards

| Characteristic | Quartz Oscillator | Cesium Beam | Rubidium Gas Cell: Commercial | Rubidium Gas Cell: NASA MSFC | Hydrogen Maser |
|---|---|---|---|---|---|
| Size - cm | 8.9 × 8.9 × 22.9 | 12.7 × 20.3 × 50.8 | 17.8 × 17.8 × 45.7 | 12.7 × 20.3 × 25.4 | 55.9 × 55.9 × 107 |
| - in | 3.5 × 3.5 × 9 | 5 × 8 × 20 | 7 × 7 × 18 | 5 × 8 × 10 | 22 × 22 × 42 |
| Volume - $cm^3$ | 1700 | 14, 200 | 14, 200 | 8500 | $3.3 \times 10^5$ |
| - $ft^3$ | 0.06 | 0.5 | 0.5 | 0.3 | 11.8 |
| Weight - Kg | < 1.8 | 15.9 | 15.4 | 9.1 | 91 |
| - lb. | < 4 | 35 | 34 | 20 | 200 |
| Electrical Power Required - W | 1.5 W | 28 W | 44 W | 20 W | 145 W |
| Relative Cost | 2 (est.) | 12 (est.) | 8 | unknown | 50 |
| Approximate Numbers of Units in Use | Thousands | Hundreds | Hundreds | Prototype only | 25 |
| Number of Years Experience | 40 | 15 | 13 | Prototype only | 10 |

produced thus far. It is shown separately, however, because this device is one of the few atomic standards designed for space applications and because the design goals represent a significant advance relative to existing commercial rubidium standards in terms of size, weight, and electrical power requirements. The hydrogen maser data on size, weight, volume, and electrical power requirements refers to the standard being developed at the Smithsonian Astrophysical Observatory for space applications involving relativity measurements [6, 53].

The data on relative cost, number of units, and experience is rather approximate and is not restricted to a specific model or type of each kind of standard. For example, although thousands of quartz oscillators of various types are in use, clearly only a few of the specific versions for the Timation Program have been produced.

c. Comparison of Performance Characteristics

Table 2 and Figure 2 summarize some of the more relevant performance achievements for the type of standards being considered for the NASA experiment. "Accuracy capability" is an estimate for each device of how large a frequency error may be present in the output frequency with respect to the "ideal" frequency characteristic of a perfectly isolated atom or molecule. Contributions to inaccuracy may consist both of various systematic errors associated with the particular type of standard and the random errors of measurement. In the cesium case, for example, leading contributions are from uncertainties in knowledge about the phase difference between the two ends of the microwave cavity and from effects produced by exciting the atomic resonance with a spectrally-impure RF signal. For hydrogen masers, the largest contribution is due to uncertainties associated with the "wall shift" produced when the hydrogen atoms collide with the walls of the storage bulb. More detailed discussions of the accuracy capability for these standards and the evaluation techniques employed to determine it are included in the previously-cited references appropriate for each type of device.

The stability data, both in Table 2 and the plot of Figure 2, are experimental measures of observed fluctuations in the output frequencies for various measurement averaging times. Whenever possible, the statistical measure quoted is the square root of the Allan variance, $\sigma(N, \tau, T, B)$, for $N = 2$ and $T = \tau$ [42, 43]. The stability data refers to the following specific devices:

(1) Quartz: oscillator developed for Timation Satellite Program

Table 2 - Comparison of Performance Characteristics of Some Present Types of Frequency Standards

| Characteristic | Quartz Oscillator | Cesium Beam | Rubidium Gas Cell: Commercial | Rubidium Gas Cell: NASA MSFC | Hydrogen Maser |
|---|---|---|---|---|---|
| Accuracy Capability | Must be calibrated | $2 \times 10^{-11}$ | Must be calibrated | Must be calibrated | $2 \times 10^{-12}$ |
| Stability | | | | | |
| $\tau$ = 1 second | $3\text{-}4 \times 10^{-12}$ | $5 \times 10^{-11}$ | $5 \times 10^{-12}$ | $\leq 3 \times 10^{-11}$ | $3 \times 10^{-13}$ |
| $\tau$ = 100 seconds | $3\text{-}4 \times 10^{-12}$ | $5 \times 10^{-12}$ | $5 \times 10^{-13}$ | Not specified | $9 \times 10^{-15}$ |
| $\tau$ = 1 day | $1 \times 10^{-11}$ | $< 1 \times 10^{-12}$ | $\approx 2 \times 10^{-12}$ | $< 5 \times 10^{-11}$/year | $9 \times 10^{-15}$ |
| Systematic Drift Rate | $1 \times 10^{-11}$/day | None | $< 1 \times 10^{-11}$/mo. | | None |
| Environmental Sensitivity | | | | | |
| Temperature | $1\text{-}2 \times 10^{-12}/^{\circ}C$ | $< 1 \times 10^{-11}$/-55 to +71°C MIL-E-5400H, Class 1A | $< 4 \times 10^{-11}$/0-50°C | -30° to + 142°F | Not specified |
| Magnetic Field | Not specified | $< 2 \times 10^{-12}$/0-2 Gauss | $< 5 \times 10^{-12}$/1 Gauss | Not specified | Not specified |
| Humidity | $1 \times 10^{-11}$/0-100% | $< 1 \times 10^{-11}$/0-95% at 50°C | 0-95% | 0-100% | Not specified |
| Vibration | $2 \times 10^{-10}$/3 G's in 20-2000 Hz | $< 2 \times 10^{-11}$, MIL-E-5400L, Curve IIA | MIL-STD-167 and MIL-E-5400, Curve 1 with isolators | See [59] | Not specified |
| Shock | $2 \times 10^{-10}$/50 G's for 11 ms | MIL-STD-901C | MIL-T-21200 and MIL-E-5400 (30 G's) | 30 G's for 11 ms | Not specified |
| Radiation | $2 \times 10^{-11}$/rad | Not specified | Not specified | Not specified | Not specified |
| Acceleration | $2 \times 10^{-10}$/15G | Designed for rotation insensitivity | Not specified | 20 G's | Not specified |
| Pressure | $1 \times 10^{-10}$/sea level to $10^{-9}$ mm Hg | Not significant | $< 5 \times 10^{-11}$/0-40,000 ft altitude | 0-200,000 ft altitude | Not specified |

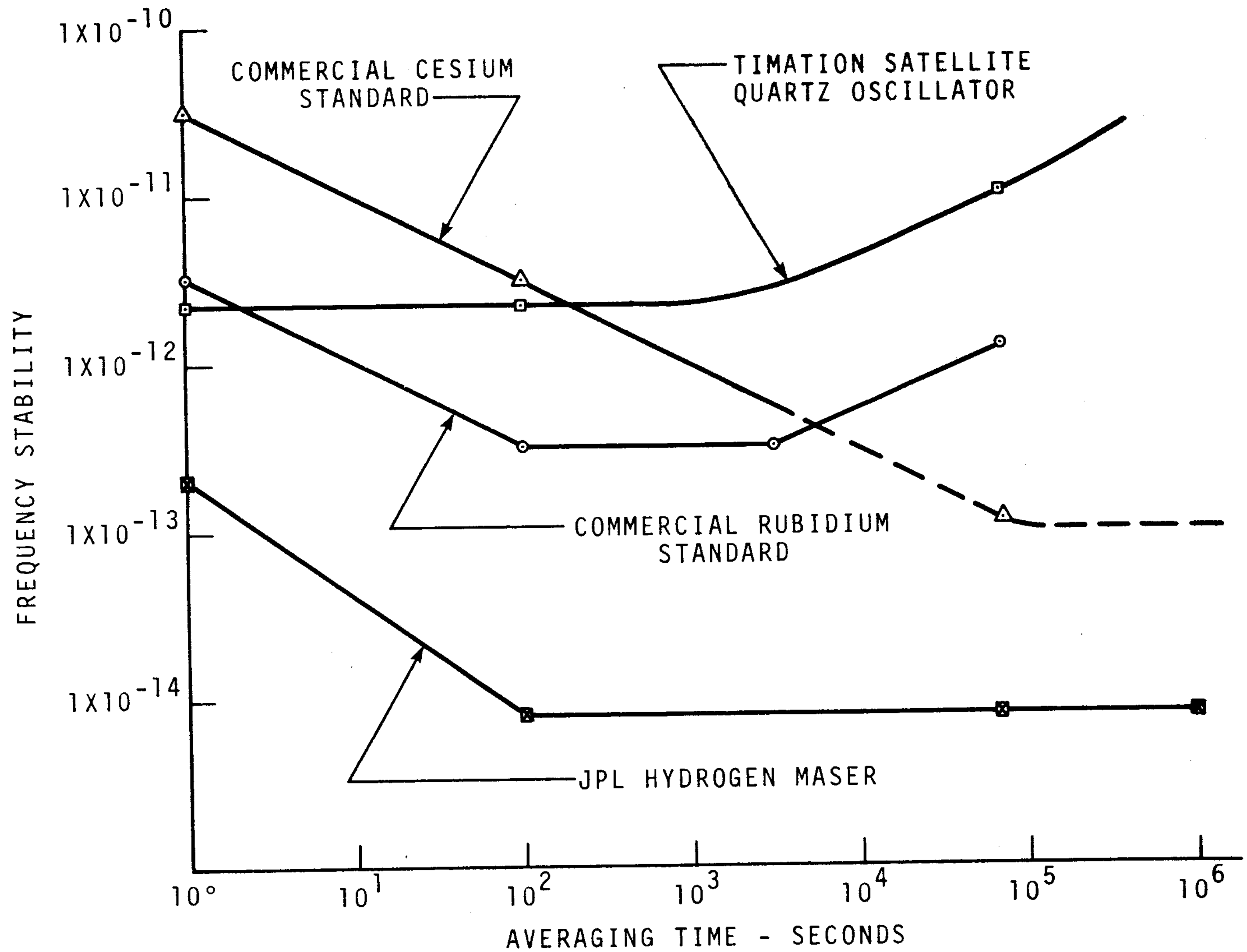


FIG. 2 - FREQUENCY STABILITY DATA FOR VAROUS STANDARDS

(2) Cesium: small commercial standard recently developed for severe-environment applications

(3) Rubidium: several different commercial standards. Complete data is apparently not available on the NASA MSFC unit.

(4) Hydrogen Maser: maser developed by JPL for field use at NASA's Deep Space Network tracking stations.

It should be re-emphasized here that, in some cases at least, better performance data than given here has been observed and scientifically documented. However, this discussion is being confined mainly to those versions of standards which either already exist in space-compatible form or are judged to be reasonably well adapted for space applications.

Environmental data refers to the same specific devices as mentioned above. Adequate data of this type is unfortunately not yet available for the JPL hydrogen maser. The data which is included is taken directly from various publications and manufacturers' data sheets and thus does not appear in a uniform format.

d. Evaluation of Standards Based on the Previous Comparisons

Table 3 is an attempt to evaluate the various possibilities for spacecraft frequency/time standards in terms of their general suitability for the proposed NASA experiment. The somewhat subjective evaluations made in each case have been based on the five main objectives of the experiment as stated by NASA and described in Section 2.4 and on the present status of the several leading contenders as summarized in the previous subsections. Those evaluations requiring some projection of present achievements into the near future are based on (1) information supplied by knowledgeable commercial representatives during presentations to the Technical Steering Committee and during later more informal contacts, and (2) the author's own impressions of progress and trends in the frequency standards field.

The numbered scale of 1-4 used to rate the various standards is interpreted in general terms at the bottom of Table 3. Generally speaking, the lower the number, the more suitable is that particular device for use in the spacecraft experiment proposed. For a few of the rating factors considered, however, some more specific comments are needed concerning the interpretation of the number rating assigned. In the following explanatory notes for each of the rating factors, these comments will be included where necessary, along with the general justification for the detailed ratings for each factor.

Table 3

Evaluation of Possible Standards for Proposed NASA Experiment

| Rating Factor | Quartz | Cesium | Rubidium Gas Cell | Hydrogen Maser |
|---|---|---|---|---|
| Size and Weight | 1 | 2 | 2 | 4 |
| Reliability in Space | 1 | 2 | 2 | 3 |
| Environmental Sensitivity | 4 | 1 | 2 | 2 |
| Electrical Power Required | 1 | 3 | 3 | 4 |
| State of Technological Development | 1 | 2 | 2 | 3 |
| Estimated Development Time/Cost for Spaceborne Version | 1 | 3 | 2 | 3 |
| Suitability for NASA's Specific Experimental Objectives | | | | |
| 1. International Time Comparisons to $<1\ \mu s$ | 4 | 2 | 2 | 1 |
| 2. Improved One-Way Doppler Measurements | 2 | 3 | 2 | 1 |
| 3. One-Way Ranging Measurements | 4 | 1 | 2 | 1 |
| 4. Relativity Experiment | 4 | 1 | 2 | 1 |
| 5. Development of New Technology in Atomic Standards | 4 | 1 | 2 | 2 |

General Interpretation of Ratings (see text for more detail)

1. Most suitable for NASA experiment; little or no further development required.
2. Suitable for use but with some further development required; some objectives may be somewhat compromised.
3. May be suitable for use but extensive further development required; some objectives can't be met at stated desired level.
4. Not considered suitable for NASA experiment.

(1) Size and Weight. The ratings here assume that the timing equipment will probably be only a small portion of the total equipment needed on a typical multipurpose satellite and that size and weight constraints will therefore probably rule out the bulky hydrogen maser. Based on the present status of the various standards it appears quite probable that the cesium and rubidium devices can both be reduced in size and weight to an acceptable level, though never approaching that achieved for the quartz oscillator.

(2) Reliability in Space. Quartz oscillators have already demonstrated their high reliability in space applications. Cesium and rubidium standards are of similar complexity, but clearly must be considered less reliable than the relatively simple quartz oscillator. The maser is rated lower primarily based on some very limited experience with laboratory-type hydrogen maser standards. With a proper amount of development effort, however, it should be possible to achieve acceptable reliability for any of these contenders.

(3) Environmental Sensitivity. The quartz oscillator is considered unacceptable on this count, considering the rather demanding stability requirements imposed by the stated NASA experimental objectives. Even here, though, it might be possible to provide a highly-controlled environment for a quartz oscillator and compensate for its drift rate and other variations sufficiently well by using an elaborate ground monitoring system with adequate frequency and time correctors operated remotely. The evidence indicates cesium standards are somewhat less susceptible to environmental changes than the other atomic devices, though in all cases the differences are not great enough to rule out any of the atomic candidates completely. Based on the rather stable temperature, vibration, magnetic field, and radiation environments achieved in satellites such as the GEOS series, environmental effects should not prove to be limiting in this proposed experiment.

(4) Electrical Power Required. As stated earlier in this report, this factor is one of the more critical ones in selecting a standard for spacecraft use because of the very limited amount of electrical power usually available. The quartz oscillator presents no problem but even the lowest-power cesium and rubidium standards built to date have required 20-50 W of power. Discussions with commercial people in the field suggest that reducing power consumption in a cesium or rubidium standard down to a level of 10 W or lower to be compatible with spacecraft such as the GEOS series will require a major development effort. Accordingly, these devices are rated only "3" on the 1-4 scale.

Since even the SAO sapceborne hydrogen maser still requires 145 W, it seems reasonable to reject this type of standard for use in all but the largest, most elaborate space programs.

(5) State of Technological Development. This factor is closely related to some of the others — particularly, reliability and development time/cost. The ratings given are based primarily on the number of units of each general kind which have been built — ranging from thousands of quartz oscillators down to only tens of hydrogen masers. The assumption is implicitly made that as more units of a particular type are made and evaluated, the reliability of the unit should increase over a period of time, the cost and time needed for a modified version of the device should decrease, and the performance achieved should improve. A rating of "1" here suggests an advanced state of development. No device is rated "4" since all are considered sufficiently well-developed to merit serious consideration for the experiment; the hydrogen storage beam device, on the other hand, would be considered in the "4" category at this point since it does not exist in any form beyond the crude prototype stage.

(6) Estimated Development Time/Cost for Spaceborne Version. This factor, of course, depends heavily on the existing state of development for each device. The basis for rating the rubidium cell standard slightly better than cesium in this case is that spaceborne versions of the former have already been flown as rubidium magnetometers and have been developed under the NASA MSFC Apollo Applications Program, while the cesium beam developments have been aimed more towards ground and conventional aircraft applications. It should be noted that the ratings here are estimates and are not based on specific proposals or responses from manufacturers. A "1" rating here implies a relatively short, low-cost development program for a spaceborne version, but whether or not the resulting device can meet the performance requirements of the experiments is treated elsewhere as a separate factor to be rated independently.

(7) Suitability for International Time Comparisons. Since NASA's proposed experimental objectives include international timing comparisons to better than $1\,\mu s$, and, assuming that we do not wish to rule out the possibility of laboratories in different geographical areas making time measurements of the satellite signals at times differing by at least several hours, then the inferior long-term stability of a quartz oscillator probably rules it out. The long-term stability of all the atomic devices should be sufficient, although the $\approx 1 \times 10^{-14}$ level demonstrated by the hydrogen maser over periods of hours gives it a

slight edge over the others based on presently-documented performance. It should be cautioned once again, however, that timing comparisons to better than 1 μs via a one-way satellite technique require knowledge of the appropriate path delays to this same level of uncertainty — a difficult task at best.

(8) Suitability for Improved One-way Doppler Measurements. Ratings for this factor are based solely on the demonstrated stability of each type of standard for averaging times of about 1000 seconds, which corresponds roughly to the time for a single satellite pass for a near-earth orbit. As mentioned earlier, there seems to be some question as to just how significant the improvement in the Doppler data will be as a result of improved satellite oscillator stability.

(9) Suitability for One-way Ranging Measurements. These ratings assume that practical, useful one-way ranging experiments require close synchronizations to be maintained for relatively long periods of time — i.e., hours or days. Thus, the long-term stability is a major consideration.

(10) Suitability for Relativity Experiment. Again, for this aspect of the experiment, long-term stability over many days becomes important.

(11) Suitability for Development of New Technology in Atomic Standards. Obviously, a quartz oscillator doesn't meet this objective at all and is therefore rated "4" — i.e., not suitable. The "1" rating for cesium means that a spacecraft version of this device is judged to be a greater contribution to new technology of atomic standards than would be corresponding rubidium or hydrogen maser devices, since space-borne versions of the latter are already under development for other NASA programs.

## 4.5 Conclusions From the Comparisons of Possible Standards For Spacecraft Application

The somewhat arbitrary evaluation of the various standards as presented in Table 3 suggests that cesium or rubidium standards would be the best overall choices for a development effort aimed at satisfying the experimental objectives posed by NASA GSFC. The objectives could probably be met with more certainty by choosing cesium instead of rubidium, although the development time and cost will almost certainly be greater for cesium. In either case the major development problem appears to be obtaining a sufficiently low electrical power consumption, although the magnitude of this task clearly depends on the particular satellite used in the experiment. If a power limit of near

10 W is actually imposed by the mission constraints, then, based on projections made by industry representatives for the next few years, rubidium standards probably offer the better chance for achieving this level of power consumption.

### 4.6 Some Alternative Approaches For Development of a Spaceborne Cesium or Rubidium Standard

a. Contract for Commercial Development

Because of the rather extensive commercial development to date on both cesium and rubidium standards, the further development of a spaceborne version would appear to be well within the present capabilities of several firms. Information supplied by commercial contacts during the performance of this study indicates more commercial interest in the rubidium alternative than in cesium, but no attempt has been made to obtain a complete sampling of potential bidders.

At one point during the Technical Steering Committee's deliberations suggestions were made that it might prove advantageous, in the event cesium or rubidium appeared to be the leading contenders, to prepare separate specifications for a cesium beam tube, a rubidium gas cell optical package, and a set of appropriate electronics which, with slight modification, could be used with either atomic resonance package. Some members of the Committee felt such a procedure would provide maximum flexibility in the later solicitation of bids. In the opinion of the Steering Committee Coordinator, however, a better overall standard is likely to result and with a lower expenditure of time and money if either type of atomic standard is contracted, built, and evaluated as a single, integrated standard, including the atomic resonance package and all associated electronics.

The Appendix consists of tentative procurement specifications for cesium and rubidium devices. All details cannot be included at this time, of course, since the specific spacecraft and launch vehicle to be used for the proposed experiment are not known. Once this information is available, these basic preliminary specifications could perhaps be enlarged upon and used for eventual procurement actions.

b. Contract for Development by Applied Physics Lab (APL)

APL has expressed an interest in developing a rubidium standard suitable for this experiment by combining a commercially-available rubidium optical package with an electronics package designed and built by APL personnel. In this approach APL would make use of its extensive experience with space-qualified electronic components obtained through its involvement in several U. S. Navy Navigation Satellite programs. The design of the servo system and frequency multiplier circuits would follow closely that used in present state-of-the-art rubidium standards, but would be modified as necessary to use the space-qualified components. APL has apparently verified that it can purchase the needed optical package from existing manufacturers. A proposal for such a development program was submitted by APL to NASA GSFC.

c. Use of Rubidium Standard Developed for NASA MSFC

As previously mentioned, NASA's Manned Spaceflight Center in Houston has contracted for the development of a spaceborne rubidium standard for use as a central frequency and timing reference aboard later manned space flights of long duration (up to several years) [59]. In prototype units frequency stabilities have been achieved that are only slightly worse than good commercial versions but which are relatively constant over very wide environmental limits. Electrical power consumption is about 20 W at 25°C.

If the experiment being considered in this report is eventually funded by NASA, it would seem wise to seriously consider making use of this design (and perhaps even the hardware, if available) already existing within the NASA organization and for which well over one-half million dollars has already been invested. Since the MSFC rubidium standard was designed with somewhat different constraints in mind because of the different intended application, some modifications would undoubtedly be necessary. In particular, it may — depending on the spacecraft used — be necessary to reduce the 20 watt power consumption somewhat.

d. Cooperative Development Program With Dept. of Defense

The Technical Steering Committee has included representatives from DOD. Their input, together with published information on various DOD satellite programs being proposed, shows that DOD also has strong interests in the development of improved atomic frequency standards — especially with regard to such factors as size, weight, reliability, power requirements, and environmental sensitivity. Some possibilities may exist for a joint development program which could eliminate unnecessary duplication of effort and higher-than-necessary costs.

## 4.7 Technical Steering Committee Views on Alternatives for a Spacecraft Clock

After hearing from commercial representatives the present status and future projections regarding various types of frequency standards, the Technical Steering Committee reached a general concensus that either a rubidium standard or a cesium standard would probably satisfy most of the technical requirements for meeting the NASA-generated experimental objectives. No clear concensus was reached as to a preference between these two, although several members seemed to feel that if an expensive development program was going to be undertaken, one might as well go the cesium route at somewhat higher cost and achieve some operational simplifications in the experiment by eliminating the atomic standard's long-term drift.

Most of the committee members did seem to feel that the probability of developing an adequate rubidium cell standard would be higher through a contract to an experienced commercial firm than by supporting a development by APL, where the staff clearly has excellent space-electronics competence but little experience with the design of complete atomic frequency standards of any type.

## 5. CONCLUSION

In the first part of this report an attempt has been made to place the proposed satellite-borne atomic clock experiment into proper perspective by considering it in relation to existing needs for improved time dissemination, some possible alternative means of accomplishing the experimental objectives as set forth by NASA GSFC, and related work being performed or proposed by other interested government agencies. Some of the conclusions reached in this part of the report were that:

(a) Time and frequency technology is playing an increasingly-important role in a wide range of systems and activities.

(b) Real needs do exist for improved time and frequency dissemination for many applications, but the needed improvements are not confined only to accuracy and precision. They may also involve wider geographical coverage, greater reliability, lower-cost user options, and accessibility to more users.

(c) Many techniques and systems do exist or are planned which potentially can result in improved time dissemination; the more promising include the VLF Omega Navigation System, the LF Loran C Navigation System, the proposed NBS television time and frequency dissemination system; portable clock techniques including aircraft flyover, and several different satellite methods and systems.

(d) Considering only various satellite techniques for time dissemination, the use of a ground-based clock transmitting to a wide geographical area via a satellite-borne transponder offers significant advantages over a more complex satellite-borne clock system.

(e) If the achievement of all five of NASA GSFC's objectives to the stated accuracy levels is desired by NASA, a satellite-borne atomic clock appears to be the only reasonable alternative.

(f) If some of the stated accuracy goals — e.g., international time dissemination to 0.1 $\mu$s, were relaxed somewhat, the experiment could likely be conducted at much lower cost and on a shorter time scale by using a satellite-borne <u>quartz</u> clock.

(g) If the proposed experiment is undertaken, considerable effort should be devoted to cooperating and coordinating with other interested civilian and military agencies so as to avoid unnecessary duplication of effort.

In the remaining portion of the report the much more specific question of what type of satellite-borne frequency and time standard would be optimum for the proposed experiment was considered. For purposes of this part of the discussion the assumption was thus made that NASA has already decided to employ some sort of standard on board the spacecraft. Constraints on the type of standard used imposed by the spacecraft environment were examined, but specific conclusions were difficult to reach since the particular spacecraft series to be employed for this experiment is unknown at this time. Finally, eight different forms of atomic frequency standards and one particular version of a space-compatible quartz crystal oscillator were compared and evaluated for the proposed experiment. The major conclusions were that:

(a) The major constraint imposed by the spacecraft environment is on the level of electrical power available to the standard.
(b) The size and weight of atomic standards, except in the case of the hydrogen maser, does not appear to present major problems.
(c) A major development effort will be needed for any of the atomic contenders in order to reduce the power consumption down to the vicinity of 10 W, as required for GEOS spacecraft.
(d) The quartz oscillator offers many advantages over the atomic standards in terms of size, weight, power requirements, reliability, and development time/cost, but cannot realistically meet the stated performance objectives of the experiment.
(e) Thallium beam, ammonia maser, rubidium maser, hydrogen storage and methane-stabilized laser standards are unlikely candidates for purposes of this experiment.
(f) Either a cesium beam standard or a rubidium gas cell standard offers the best possibility for achieving the stated experimental objectives at a reasonable cost and within a time frame of not more than a few years.
(g) No clear concensus exists on which of these two choices should be preferred.
(h) The best approach to developing a suitable cesium beam device is by contract to an experienced commercial source.
(i) If a rubidium standard is selected, serious consideration should be given to using the already-developed version funded by NASA MSFC for the Apollo Program.

(j) Since experience in the building of complete atomic frequency standards is considered almost essential in the development of a reliable space-borne unit, a commercial contract for a complete rubidium standard package is to be preferred to the separate development of the atomic resonance package and the required electronics by different groups.

## REFERENCES


[1] E. F. Osborne, "Global timing systems of nanosecond accuracy using satellite references," Technical Memorandum TG-1086, Johns Hopkins University, Applied Physics Lab (October 1969).

[2] Final report for analytical study of the need of frequency and time, ITT Federal Labs, Nutley, N. J., for NASA GSFC Contract NAS 5-9715 (1965).

[3] A. H. Shapiro and H. F. Marx, "A navigation satellite system concept using one-way range measurements," paper presented for the 22nd annual meeting of the Institute of Navigation (June 1966).

[4] T. C. Viars, "Application of precise time-frequency technology in multifunction systems," Proc. 23rd Annual Symposium on Frequency Control, pp. 8-13 (1969).

[5] R. E. Perkinson, "Time-frequency technology in system development," Proc. 24th Annual Symposium on Frequency Control, pp. 315-321 (1970).

[6] R. F. C. Vessot, M. W. Levine, and M. R. Baker, "The design of an atomic hydrogen maser system for satellite experiments," Proc. 21st Annual Symposium on Frequency Control, pp. 512-542 (1967).

[7] W. Markowitz, "Time and frequency measurement, atomic and astronomical," Frequency Technology, Vol. 7, No. 1, pp. 13-18 (January 1969).

[8] B. E. Blair, J. L. Jespersen, and G. Kamas, "VLF precision timekeeping potential," Progress in Radio Science 1966-1969, Part I, (Proc. 16th Gen. Assembly of URSI, Comm. 1, Ottawa, Canada, August 18-29, 1969), C. E. White, Ed. (in press).

[9] J. Wright, "Multiple frequency VLF timing," Tracor On Frequency, Vol. 1, No. 3, pp. 1-5 (May 1969).

[10] A. R. Chi and S. N. Witt, "Time synchronization of remote clocks using dual VLF transmissions," Proc. 20th Annual Symposium on Frequency Control, pp. 588-611 (1966).

[11] L. Fey and C. H. Looney, Jr., "A dual frequency VLF timing system," IEEE Trans. on Instr. and Meas., Vol. IM-15, No. 4, pp. 190-195 (December 1966).

[12] W. Palmer, "The Omega Navigation System as a source of frequency and time," Proc. 24th Annual Symposium on Frequency Control, pp. 345-360 (1970).

[13] E. R. Swanson, "Omega VLF timing," Proc. 25th Annual Symposium on Frequency Control, pp. 159-166 (1971).

[14] L. Fey, "Time dissemination capabilities using the Omega system," Proc. 25th Annual Symposium on Frequency Control, pp. 167-170 (1971).

[15] P. E. Pakos, "Use of the Loran-C System for time and frequency dissemination," Proc. 23rd Annual Symposium on Frequency Control, pp. 236-247 (1969).

[16] L. D. Shapiro, "Time synchronization from Loran-C," IEEE Spectrum (March 1968).

[17] B. Wieder, "Use of Loran-C over land," Proc. 25th Annual Symposium on Frequency Control, pp. 171-178 (1971).

[18] "Study of methods for synchronizing remotely-located clocks," Sperry Gyroscope Company report prepared for NASA Contract CR-738 (March 1967).

[19] L. D. Shapiro, "Loran-C sky-wave delay measurements," IEEE Trans. on Instr. and Meas., Vol. IM-17, No. 4, pp. 366-372 (December 1968).

[20] F. L. Stetina and S. Z. Zufall, "Loran-C, a time synchronization technique," NASA GSFC Report No. X-832-69-514 (September 1969).

[21] L. N. Bodily and R. C. Hyatt, "Flying clock comparisons extended to East Europe, Africa, and Australia," Hewlett-Packard Journal, Vol. 19, No. 4, pp. 12-20 (December 1967).

[22] M. D. Lay and D. T. Davis, "A simple airborne system for calibration of remote precision clocks," Frequency Technology, Vol. 7, No. 12, pp. 13-22 (December 1969).

[23] J. Besson, "Comparison of national time standards by simple overflight," IEEE Trans. on Instr. and Meas., Vol. IM-19, No. 4, pp. 227-232 (November 1970).

[24] J. Tolman, V. Ptacek, A. Soucek, and R. Stecher, "Microsecond clock comparison by means of TV synchronizing pulses," IEEE Trans. on Instr. and Meas., Vol. IM-16, pp. 247-254 (September 1967).

[25] D. D. Davis, J. L. Jespersen, and G. Kamas, "The use of television signals for time and frequency dissemination," Proc. IEEE (Letters), Vol. 58, No. 6, pp. 931-933 (June 1970).

[26] D. D. Davis, B. E. Blair, and J. F. Barnaba, "Long-term continental U. S. timing system via television networks," IEEE Spectrum, Vol. 8, No. 8, pp. 41-52 (August 1971).

[27] P. Parcelier, "Time synchronization by television," IEEE Trans. on Instr. and Meas., Vol. IM-19, No. 4, pp. 233-238 (November 1970).

[28] W. W. Begley and A. H. Shapiro, "Aspects of precision timing systems," Aerospace Corporation Report No. TOR-0066(5306)-2 prepared for Space and Missile Systems Organization, U. S. Air Force under Contract No. F04701-69-C-0066 (October 1969).

[29] L. E. Gatterer, P. W. Bottone, and A. H. Morgan, "Worldwide clock synchronization using a synchronous satellite," IEEE Trans. on Instr. and Meas., Vol. IM-17, No. 4, pp. 372-378 (December 1968).

[30] D. W. Hanson and W. F. Hamilton, "One-way time synchronization via geostationary satellites at UHF," IEEE Trans. on Instr. and Meas., Vol. IM-20, No. 3, pp. 147-153 (August 1971).

[31] D. W. Hanson and W. F. Hamilton, "Clock synchronization from satellite tracking," IEEE Trans. on Aerospace and Electronic Systems, Vol. AES-7, No. 5 (September 1971).

[32] J. McA. Steele et al., "Telstar time synchronization," IEEE Trans. on Instr. and Meas., Vol. IM-13, pp. 164-170 (December 1964).

[33] W. Markowitz et al., "Clock synchronization via Relay II satellite," IEEE Trans. on Instr. and Meas., Vol. IM-15, No. 4, pp. 177-184 (December 1966).

[34] J. L. Jespersen, G. Kamas, L. E. Gatterer, and P. F. MacDoran, "Satellite VHF transponder time synchronization," Proc. IEEE, Vol. 56, No. 7, pp. 1202-1206 (July 1968).

[35] J. A. Murray, D. L. Pritt, L. W. Blocker, W. E. Leavitt, W. D. Goring and P. M. Hooten, "Time transfer by Defense Communications Satellite," Proc. 25th Annual Symposium on Frequency Control, pp. 186-193 (1971).

[36] "Analysis of an advanced time-frequency national air space system concept - Vol. 2," final report on FAA contract No. FA67WA-1712 prepared by Autonetics, North American Rockwell (August 1969).

[37] L. J. Rueger, "One-way time dissemination from low altitude satellits," Proc. 25th Annual Symposium on Frequency Control, pp. 179-185 (1971).

[38] R. Easton, C. Bartholomew, and J. Bowman, "A second satellite oscillator experiment," Proc. 24th Annual Symposium on Frequency Control, pp. 322-324 (1970).

[39] M. Block, J. Ho, I. Math, and J. Teitelbaum, "A low-power remotely-controlled satellite frequency standard," Proc. 21st Annual Symposium on Frequency Control, pp. 331-344 (1967).

[40] D. Halford, "Frequency stability of quality quartz crystal oscillators: performance and some critical applications," Proc. of the Colloque International de Chronometrie, Paris, September 1969, Serie A, pp. A-11-1 to A-11-3.

[41] H. Brandenberger, F. Hadorn, D. Halford, and J. Shoaf, "High quality quartz crystal oscillators; frequency domain and time domain stability," Proc. 25th Annual Symposium on Frequency Control, pp. 226-230 (1971).

[42] D. Allan, "Statistics of atomic frequency standards," Proc. IEEE, Vol. 54, pp. 221-230 (February 1966).

[43] J. Barnes et al., "Characterization of frequency stability," IEEE Trans. on Instr. and Meas., Vol. IM-20, No. 2, pp. 105-120 (May 1971).

[44] R. Hyatt, D. Throne, L. S. Cutler, J. H. Holloway, and L. F. Mueller, "Performance of newly developed cesium beam tubes and standards," Proc. 25th Annual Symposium on Frequency Control, pp. 313-324 (1971).

[45] R. Beehler, "A historical review of atomic frequency standards," Proc. IEEE, Vol. 55, No. 6, pp. 792-805 (June 1967).

[46] R. Beehler, and D. Glaze, "Evaluation of a thallium atomic beam frequency standard at the National Bureau of Standards," IEEE Trans. on Instr. and Meas., Vol. IM-15, Nos. 1 and 2, pp. 55-58 (March-June 1966).

[47] J. Bonanomi, "A thallium beam frequency standard," IRE Trans. on Instr., Vol. I-11, pp. 212-215 (December 1962).

[48] R. Lacey, "A thallium atomic beam tube for frequency control," Proc. 20th Annual Symposium on Frequency Control, pp. 416-423 (1966).

[49] J. Barnes, D. Allan, and A. Wainwright, "The ammonia beam maser as a standard of frequency," IRE Trans. on Instr., Vol. I-11, Nos. 3 and 4, pp. 231-238 (December 1962).

[50] P. Davidovits and R. Novick, "The optically pumped rubidium maser," Proc. IEEE, Vol. 54, No. 2, pp. 155-170 (February 1966).

[51] H. Goldenberg, D. Kleppner, and N. Ramsey, "Atomic hydrogen maser," Phys. Rev. Lett., Vol. 5, pp. 361-362 (October 1960).

[52] H. Hellwig, "Areas of promise for the development of future primary frequency standards," Metrologia, Vol. 6, No. 4, pp. 118-126 (October 1970).

[53] M. Baker, M. Levine, L. Mueller, and R. Vessot, "Progress in the development of hydrogen masers," Proc. 22nd Annual Symposium on Frequency Control, pp. 605-620 (1968).

[54] C. Finnie, R. Sydnor, and A. Sward, "Hydrogen maser frequency standard," Proc. 25th Annual Symposium on Frequency Control, pp. 348-351 (1971).

[55] H. Peters, T. McGunigal and E. Johnson, "Atomic hydrogen standards for NASA tracking stations," Proc. 23rd Annual Symposium on Frequency Control, pp. 297-304 (1969).

[56] H. Hellwig, "The hydrogen storage beam tube — a proposal for a new frequency standard," Metrologia, Vol. 6, No. 2, pp. 56-60 (April 1970).

[57] R. Barger and J. Hall, "Pressure shift and broadening of methane line at 3.39 μ studied by laser-saturated molecular absorption," Phys. Rev. Lett., Vol. 22, No. 1, pp. 4-8 (January 6, 1969).

[58] H. Hellwig, National Bureau of Standards - private communication.

[59] "Atomic time and frequency reference system," Final report - Part I prepared for NASA Manned Space Center under Contract No. NAS9-5425 (January 1966-November 1967).

# APPENDIX

Basic specification as of January 1969. Minor Revisions November 1971.

## Tentative Specification for Cesium Beam Frequency Standard for Spacecraft Application

1. SCOPE

This specification describes requirements for the development of a small cesium beam frequency standard which could serve as a source of stable frequencies and timing signals for several applications on a GEOS spacecraft. Portions of the specification will, of course, have to be changed appropriately if a different spacecraft is selected.

2. APPLICABLE DOCUMENTS

2.1 SPECIFICATIONS. GSFC Document S-320-D-3: Environmental Test Specification for Spacecraft and Components Using Launch Environments Dictated by Delta Launch Vehicles.

3. REQUIREMENTS

3.1 GENERAL DESCRIPTION. The cesium beam frequency standard described herein may be used in a GEOS spacecraft as a source of frequencies stable to within a few parts in $10^{12}$ per day and timing signals stable to a few tenths of a microsecond per day. Timing signals will be kept in close coincidence with the UTC time scale and will be transmitted to various ground stations for use in high precision geodetic measurements and for both moderate and high precision clock comparisons. The complete frequency standard will consist of a cesium beam tube to serve as an atomic frequency reference and an electronics system for electronically locking the frequency of a quartz crystal oscillator to the appropriate resonance frequency of atomic cesium-133. The quartz oscillator used will be of sufficiently high quality that, in the event of troubles developing in the cesium beam tube, the oscillator can be decoupled from the atomic resonance device and be used in a free-running mode with results which are at least as good as those achieved in previous GEOS missions employing quartz oscillator sources of frequency and timing signals. Primary goals in the development of this unit will be high reliability, small volume, low electrical power consumption, and performance characteristics at least comparable to present commercial cesium standards.

The necessary electronics systems will make use of current microcircuit technology to the maximum extent possible consistent with the above-mentioned goals.

3.2 CONFIGURATION. The cesium beam frequency standard configuration must be compatible with space limitations imposed by the requirement to mount the unit within the library compartment of the present GEOS spacecraft configuration without major changes to the GEOS structure. This places a 25 cm limitation on the maximum dimension of the package. The complete standard should not exceed 6550 $cm^3$ (400 $in.^3$) in overall volume.

3.3 RESPONSIBILITIES. Not applicable.

3.4 DESIGN STUDIES. As necessary to meet performance requirements.

3.5 STRUCTURAL REQUIREMENTS. As stated in 3.2 the cesium standard will be mounted within the GEOS spacecraft library compartment. The available space limits the maximum package volume to about 6550 $cm^3$ with a 25 cm $\times$ 20 cm $\times$ 12.7 cm configuration being a desirable design goal. The overall weight is not as critical as the electrical power requirement, but a total weight of less than 11.4 kg is desirable.

3.6 ELECTRICAL AND ELECTRONIC REQUIREMENTS. The cesium standard will be powered from the GEOS Main Power Supply, which is severely limited in the amount of available power. Accordingly, the design goal for the amount of electrical power required by the overall cesium standard shall be less than 10 W for operation anywhere within the expected ambient temperature range of 4° C. - 21° C.

3.6.1 Quartz crystal oscillator. The quartz crystal oscillator, which under normal operating conditions will be locked to the cesium resonance, shall serve as a backup source of stable frequency and time signals in case of failure of the cesium beam tube. An output frequency at a nominal value of 5 MHz - $50 \times 10^{-6}$ shall be derivable from the free-running oscillator or oscillator/synthesizer combination.

3.6.2 Provision for open-loop operation. Provision shall be made for opening or closing the feedback control loop by ground command in order to permit operation of the quartz crystal oscillator independently of the cesium beam tube as desired.

3.6.3 Oscillator sweep mode. Provision shall be made for sweeping the oscillator frequency over a sufficiently wide range by ground command to enable acquisition of the cesium resonance peak by the feedback control system. Once operating in a normal, locked mode the system should automatically initiate oscillator sweeping and automatic relocking of the oscillator to the cesium resonance peak if an interruption of locked operation occurs for any reason.

3.6.4 Locking to proper resonance peak. During the automatic acquisition procedure the system must be capable of sensing and locking to the central peak of the multi-peaked Ramsey resonance pattern.

3.7 MEASURING DEVICES. No special requirements.

3.8 CONTROLS. The following electrical signals shall be telemetered to the ground to serve as checks on the proper operation of the cesium beam frequency standard system.

3.8.1 Cesium beam current. This shall serve as a general measure of the level of the detected cesium beam and particularly as an indicator of when the oscillator frequency corresponds to the central peak of the Ramsey resonance pattern.

3.8.2 C-field current. Changes in this current can cause appreciable shifts in the operating frequency of the cesium beam tube.

3.8.3 Cesium oven control voltage. Monitoring of this voltage and the oven temperature will enable the temperature control circuit for the cesium oven to be checked. Changes in oven temperature should be examined for correlation with any observed variations in cesium beam current.

3.8.4 Cesium oven temperature.

3.8.5 Oscillator control voltage. This is a measure of how much frequency correction is being applied to the quartz oscillator by the feedback electronics loop to maintain locking to the atomic resonance. Since this correction voltage must be kept within certain limits for proper operation, it will be necessary to provide a means of adjusting the free-running oscillator frequency from the ground in order that these limits are never exceeded.

3.9 MODELS. One prototype standard, meeting the general performance requirements, shall be developed and delivered to GSFC. In addition three units shall be supplied meeting all requirements of this specification. These will be used for design qualification and flight acceptance tests and the third for a backup unit.

3.10 RELIABILITY AND REDUNDANCY. Reliable operation of the frequency standard for at least one year and preferably three years in the spacecraft environment is a primary goal of this development. Improvements over presently existing commercial versions--particularly in regard to the electronics--will be necessary.

3.11 PROTECTIVE COATINGS. No special requirements.

3.12 GENERAL PERFORMANCE REQUIREMENTS.

3.12.1 Accuracy. The absolute frequency of the cesium standard shall be within $\pm 5 \times 10^{-12}$ of the nominal value specified when measured relative to an accepted standard, such as the NBS Frequency Standard, Boulder, Colorado.

3.12.2 Long-term stability. Long-term stability for purposes of this specification will be defined as the standard deviation of daily frequency measurements over a period of one year as expressed by the square root of the Allan variance $\sigma(2, \tau, T, B)$ [42, 43]. Each daily measurement should be based on sufficient data to provide a measurement precision of $1 \times 10^{-12}$ or better. The long-term stability requirement for the cesium beam standard shall be $5 \times 10^{-12}$ for operation in the spacecraft environment for a minimum period of one year. Performance data on long-term stability should consist of at least 30 days' measurements.

3.12.3 Short-term stability. Short-term stability for purposes of this specification will be defined as the standard deviation of 1000-second averages, based on a sample of at least 100 consecutive measurements as expressed by the square root of the Allan variance $\sigma(2, \tau, T, B)$. The short-term stability requirement for the cesium beam standard shall be $2 \times 10^{-12}$ when operating under GEOS spacecraft conditions and for a minimum period of one year.

3.12.4 Cesium beam tube figure of merit. The figure of merit for the beam tube used in this cesium standard, defined as the signal-to-noise ratio divided by the resonance linewidth, shall be 1.3 or greater. The noise current is to be measured at the modulation frequency in a $\frac{1}{4}$-Hz bandwidth. The signal current shall be considered as the peak-to-valley amplitude of the central Ramsey pattern peak.

3.12.5 Reliability. The cesium standard shall operate within these specifications for a minimum of one year with three years being a desired design goal.

3.12.6 Operation in "oscillator-only" mode. Under operating conditions with the feedback loop open so that the quartz crystal oscillator is not being stabilized by the atomic resonance, the following stability requirements apply:

(a) Long-term stability. The frequency drift rate from day to day shall not exceed $\pm 2 \times 10^{-10}$.

(b) Short-term stability. As defined in 3.12.3 the short-term stability requirement shall be $2 \times 10^{-11}$.

3.13 ENVIRONMENTAL REQUIREMENTS. The cesium standard shall operate within the specifications listed in 3.12 when subjected to the environmental conditions, either singly or any combination thereof, as described in GSFC Document S-320-D-3, "General Environmental Test Specification for Spacecraft and Components Using Launch Environments Dictated by Delta Launch Vehicles," except as indicated above.

3.13.1 Leak testing of beam tube. Separate leak testing of the cesium beam tube portion of the cesium standard is not required during the design qualification and flight acceptance testing programs since the operational performance requirements for the standard cannot be met unless the vacuum within the beam tube is sufficiently good.

3.13.2 Vibration. Under normal operating conditions in the locked mode the acceptable stability performance levels while being subjected to vibration frequencies at the modulation frequency employed in the frequency stabilization loop or the second harmonic of the modulation frequency shall be ten times worse than those specified in 3.12.3.

3.13.3 Ambient temperature range. The ambient temperature range is expected to be limited to $4^{\circ}$C to $21^{\circ}$C within the library compartment location of the cesium standard.

3.13.4 Ambient magnetic fields. The cesium standard shall operate within the performance specifications of 3.12 during and after being subjected to ambient DC magnetic fields of up to $2 \times 10^{-4}$ T (2 Gauss) in any direction without the necessity of demagnetizing the beam tube magnetic shields.

3.13.5 Operation during launch phase. All electrical power shall be applied to the cesium standard during launch, but normal locked operation is not required during this phase.

3.14 ELECTRICAL POWER CONSUMPTION. The complete cesium standard shall not require more than 10 W electrical power over an ambient temperature range of $4^{\circ}$C to $21^{\circ}$C.

4. SAMPLING, INSPECTION, AND TEST PROCEDURES

4.1 SAMPLING. See 3.9 for sampling requirements.

4.2 INSPECTION. Not applicable.

4.3 TEST PROCEDURES. As described in GSFC Document S-320-D-3.

5. PREPARATION FOR DELIVERY

Reasonable care should be used in packaging, handling, and shipment of all units to GSFC to insure that the standard is not subjected to extremely high temperatures, large ambient magnetic fields, or severe shocks.

Basic specification as of
January 1969. Minor
revisions November 1971.

## Specification for Rubidium Gas Cell Frequency Standard for Spacecraft Application

1. SCOPE

This specification describes requirements for the development of a small rubidium gas cell frequency standard which will serve as a source of stable frequencies and timing signals for several applications on a GEOS spacecraft. Portions of this specification will, of course, have to be changed appropriately if a different spacecraft is selected.

2. APPLICABLE DOCUMENTS

2.1 SPECIFICATIONS. GSFC Document S-320-D-3: Environmental Test Specification for Spacecraft and Components Using Launch Environments Dictated by Delta Launch Vehicles.

3. REQUIREMENTS

3.1 GENERAL DESCRIPTION. The rubidium gas cell frequency standard described herein may be used in a GEOS spacecraft as a source of frequencies stable to within a few parts in $10^{12}$ per day and timing signals stable to a few tenths of a microsecond per day. Timing signals will be kept in close coincidence with the UTC time scale and will be transmitted to various ground stations for use in high precision geodetic measurements and for both moderate and high precision clock comparisons. The complete frequency standard will consist of a rubidium optical package to serve as an atomic frequency reference and an electronics system for electronically locking the frequency of a quartz crystal oscillator to the appropriate resonance frequency of atomic rubidium-87. The quartz oscillator used will be of sufficiently high quality that, in the event of troubles developing in the rubidium optical package, the oscillator can be decoupled from the atomic resonance device and be used in a free-running mode with results which are at least as good as those achieved in previous GEOS missions employing quartz oscillator sources of frequency and timing signals. Primary goals in the development of this unit will be high reliability, small volume, low electrical power consumption, and performance characteristics at least comparable to present commercial rubidium standards. The necessary electronics systems will make use of current microcircuit technology to the maximum extent possible consistent with the above-mentioned goals.

3.2 CONFIGURATION. The rubidium frequency standard configuration must be compatible with space limitations imposed by the requirement to mount the unit within the library compartment of the present GEOS spacecraft configuration without major changes to the GEOS structure. This places a 25 cm limitation on the maximum dimension of the package. The complete standard should not exceed 6550 $cm^3$ (400 $in.^3$) in overall volume.

3.3 RESPONSIBILITIES. Not applicable.

3.4 DESIGN STUDIES. As necessary to meet performance requirements.

3.5 STRUCTURAL REQUIREMENTS. As stated in 3.2 the rubidium standard will be mounted within the GEOS spacecraft library compartment. The available space limits the maximum package volume to about 6550 $cm^3$ with a 25 cm $\times$ 20 cm $\times$ 12.7 cm configuration being a desirable design goal. The overall weight is not as critical as the electrical power requirement, but a total weight of less than 11.4 kg is desirable.

3.6 ELECTRICAL AND ELECTRONIC REQUIREMENTS. The rubidium standard will be powered from the GEOS Main Power Supply, which is severely limited in the amount of available power. Accordingly the design goal for the amount of electrical power required by the overall rubidium standard shall be less than 10 W for operation any where within the expected ambient temperature range of $4^\circ$ C to $21^\circ$ C.

3.6.1 Quartz crystal oscillator. The quartz crystal oscillator, which under normal operation conditions will be locked to the rubidium resonance, shall serve as a backup source of stable frequency and time signals in case of failure of the rubidium optical package. An output frequency at a nominal value of 5 MHz - $50 \times 10^{-6}$ shall be derivable from the free-running oscillator or oscillator/synthesizer combination.

3.6.2 Provision for open-loop operation. Provision shall be made for opening or closing the feedback control loop by ground command in order to permit operation of the quartz crystal oscillator independently of the rubidium optical package as desired.

3.6.3 Oscillator sweep mode. Provision shall be made for sweeping the oscillator frequency over a sufficiently wide range by ground command to enable acquisition of the rubidium resonance peak by the feedback control system. Once operating in a normal, locked mode the system should automatically initiate oscillator sweeping and automatic re-locking of the oscillator to the rubidium resonance peak if an interruption of locked operation occurs for any reason.

3.7 MEASURING DEVICES. No special requirements.

3.8 CONTROLS. The following electrical signals shall be telemetered to the ground to serve as checks on the proper operation of the rubidium frequency standard system.

3.8.1 Transmitted light intensity. A suitable measure of transmitted light intensity through the rubidium reference cell, such as the photocell current, shall be telemetered to the ground as an indication of the amplitude of the rubidium resonance and indirectly as an indication of the frequency of the quartz crystal oscillator exciting the atomic resonance.

3.8.2 DC magnetic field. Changes in the current producing the uniform DC magnetic field used in the region of the rubidium reference cell can cause appreciable shifts in the operating frequency of the rubidium optical package.

3.8.3 Temperature indications. Signals serving as measures of the temperatures at which various components of the optical package are being controlled by the electronic circuitry should be telemetered to the ground as general checks on the proper operation of the standard.

3.8.4 Oscillator control voltage. This is a measure of how much frequency correction is being applied to the quartz oscillator by the feedback electronics loop to maintain locking to the atomic resonance. Since this correction voltage must be kept within certain limits for proper operation, it will be necessary to provide a means of adjusting the free-running oscillator frequency from the ground in order that these limits are never exceeded.

3.9 MODELS. One prototype standard, meeting the general performance requirements, shall be developed and delivered to GSFC. In addition, three units shall be supplied meeting all requirements of this specification. These will be used for design qualification and flight acceptance tests and the third for a backup unit.

3.10 RELIABILITY AND REDUNDANCY. Reliable operation of the frequency standard for at least one year and preferably three years in the spacecraft environment is a primary goal of this development. Improvements over presently existing commercial versions--particularly in regard to the electronics--will be necessary.

3.11 PROTECTIVE COATINGS. No special requirements.

## 3.12 GENERAL PERFORMANCE REQUIREMENTS

3.12.1 Absolute frequency. The absolute frequency of the rubidium standard shall be within $\pm 5 \times 10^{-12}$ of the nominal value specified when measured relative to an accepted standard, such as the NBS Frequency Standard, Boulder, Colorado.

3.12.2 Long-term stability. Long-term stability for purposes of this specification will be defined as the standard deviation of daily frequency measurements over a period of one year as expressed by the square root of the Allan variance $\sigma(2, \tau, T, B)$ [42, 43]. Each daily measurement should be based on sufficient data to provide a measurement precision of $1 \times 10^{-12}$ or better. The long-term stability requirement for the rubidium standard shall be $5 \times 10^{-11}$ for operation in the spacecraft environment for a minimum period of one year. Performance data on long-term stability should consist of at least 30 days' measurements.

3.12.3 Short-term stability. Short-term stability for purposes of this specification will be defined as the standard deviation of 1000-second averages, based on a sample of at least 100 consecutive measurements as expressed by the square root of the Allan variance $\sigma(2, \tau, T, B)$. The short-term stability requirement for the rubidium standard shall be $2 \times 10^{-12}$ when operating under GEOS spacecraft conditions and for a minimum period of one year.

3.12.4 Reliability. The rubidium standard shall operate within these specifications for a minimum of one year with three years being a desired design goal.

3.12.5 Operation in "oscillator-only" mode. Under operating conditions with the feedback loop open so that the quartz crystal oscillator is not being stabilized by the atomic resonance, the following stability requirements apply:

(a) Long-term stability. The frequency drift rate from day to day shall not exceed $\pm 2 \times 10^{-10}$.

(b) Short-term stability. As defined in 3.12.3 the short-term stability requirements shall be $2 \times 10^{-11}$.

3.13 ENVIRONMENTAL REQUIREMENTS. The rubidium standard shall operate within the specifications listed in 3.12 when subjected to the environmental conditions, either singly or any combination thereof, as described in GSFC Document S-320-D-3, "General Environmental Test Specification for Spacecraft and Components Using Launch Environments Dictated by Delta Launch Vehicles," except as indicated below.

3.13.1 Vibration. Under normal operating conditions in the locked mode the acceptable stability performance levels while being subjected to vibration frequencies at the modulation frequency employed in the frequency stabilization loop or the second harmonic of the modulation frequency shall be ten times worse than those specified in 3.12.3.

3.13.2 Ambient temperature range. The ambient temperature range is expected to be limited to $4^{\circ}C$ to $21^{\circ}C$ within the library compartment location of the rubidium standard.

3.13.3 Ambient magnetic fields. The rubidium standard shall operate within the performance specifications of 3.12 during and after being subjected to ambient DC magnetic fields of up to $2 \times 10^{-4}$ T in any direction without the necessity of demagnetizing the optical package magnetic shields.

3.13.4 Operation during launch phase. All electrical power shall be applied to the rubidium standard during launch, but normal locked operation is not required during this phase.

3.14 ELECTRICAL POWER CONSUMPTION. The complete rubidium standard shall not require more than 10 W electrical power over an ambient temperature range of $4^{\circ}C$ to $21^{\circ}C$.

4. SAMPLING, INSPECTION, AND TEST PROCEDURES

4.1 SAMPLING. See 3.9 for sampling requirements.

4.2 INSPECTION. Not applicable.

4.3 TEST PROCEDURES. As described in GSFC Document S-320-D-3.

5. PREPARATION FOR DELIVERY

Reasonable care should be used in packaging, handling, and shipment of all units to GSFC to insure that the standard is not subjected to extremely high temperatures, large ambient magnetic fields, or severe shocks.

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