GPS CLOCK TECHNOLOGY AND THE NAVY PTTI PROGRAMS AT THE U.S. NAVAL RESEARCH LABORATORY

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ABSTRACT

For many years, the Naval Research Laboratory (NRL) has been improving the Navy's capability in space systems for navigation and precise timing, frequently in conjunction with the U.S. Naval Observatory. We will briefly summarize NRL's work from tracking the earliest satellites through our part in developing the Global Positioning System (GPS).

Currently, the GPS Clock Technology Program at NRL includes research into the design of atomic clocks for space and terrestrial use, technical management of contractual efforts to build space clocks for use on GPS spacecraft and the GPS Master Control Stations, operation of a sophisticated clock test facility, design of a remote timing station for the GPS Colorado Springs Operations Center, and coordination on timing related functions of the GPS user equipment.

NRL is also involved in support of PTTI applications in other Navy programs. A brief summary of these will be included.

NRL EARLY HISTORY

The strong interest of NRL in position and time determination considerably predates the launching of the first man-made satellites. The Laboratory had been active in developing clocks and timing systems for the U.S. Naval Observatory (USNO) and had been working on new radio-navigation and time-dissemination systems using all parts of the radio spectrum. These radio systems suffered from the limitations. Lower frequencies that could be transmitted over long distances were affected by the ionosphere, and higher frequencies were limited to line-of-sight. The new satellite capabilities overcame these limitations and offered new opportunities to improve both time and position accuracy. Systems of improved accuracy could then be realized that could provide worldwide coverage. New system concepts and technology for navigation and time dissemination were needed.

Satellite Tracking

The MINITRACK system that was developed in the late 1950's for the NRL Vanguard Satellite Program used the signals emitted by Sputnik and later satellites to determine their positions and orbits. This pioneering tracking system led to the concept of tracking non-radiating, or non-cooperative, satellites by signals reflected off of them. An experiment using a transmitter in Fort Monmouth, N.J. and MINITRACK receivers demonstrated the concept, and from this experiment a larger and more elaborate system was developed by NRL. This system became known as the Naval Space Surveillance System (NAVSPASUR), which was commissioned as an operational command in 1961. It is still in active use as a major component of the North American Aerospace Defense Command (NORAD) and is becoming the alternate Space Defense Computational Facility.

The system concept of NAVSPASUR is that of a continuous-wave, bistatic radar. A high powered transmitter generates a large fan beam of energy, commonly called the "Fence", which orbiting objects reflect back to separate receiving stations. The receiving stations use large arrays of antennas as an interferometer to determine the angle and angle rates of arrival from the reflected signals. From observations at several stations, the position of the target satellite can be determined, and the orbit can be determined after multiple penetrations. This rather simple concept led to a highly reliable system which could detect virtually any satellite which came within the transmitter's illuminated field.

Even though NAVSPASUR performs the functions of detection and satellite orbit determination very well, there are limitations on coverage and time required to determine an orbit with the "Fence" approach. NRL experiments into ways of improving the system included the idea of transmitting ranging signals as well as the primary CW signal, so that not only could the angles be measured, but the distance to the target satellite as well. A parallel "Fence" with a ranging capability was built by NRL in the mid-1960's to measure system performance experimentally and to check feasibility of early orbit determination.

The concept of ranging as an aid to tracking satellites led to the inverse idea of ranging from satellites. This concept became known as the TIMATION concept. The TIMATION project was begun at NRL in 1964 to explore the idea of providing both accurate position and precise time to passive terrestrial observers. ("Passive" is used in the sense that the user listens to the satellite broadcasts and does not emit any signals). This technique required precise spaceborne clocks that could be regularly updated by a master clock on the ground to keep multiple satellites in synchronization. The satellite clocks would be linked to the user's receiving equipment by ranging signals broadcast by the satellites and from the received data the users could measure the difference between the user's clock and that in the satellite. A program to improve the satellite quartz crystal clock's performance was performed during the 1960's in cooperation with Frequency Electronics Incorporated. The TIMATION project's program of experimental satellites, ground tracking and control systems, and experimental receivers were used in experiments into accurate time synchronization and positioning throughout the world. Others at NRL, not directly connected with TIMATION who had designed much of the timing equipment used by the U.S. Naval Observatory (USNO), were developing techniques for making precise clock comparisons via communication satellites using pseudo-random-noise (PRN) ranging techniques. Because of their expertise in precise timing and the facilities that they had developed, they were also active in atomic clock investigations.

NAVSTAR GPS ORIGINS

In 1968, the Joint Chiefs of Staff (JCS) issued new requirements for a worldwide capability to locate military forces worldwide very precisely. These requirements and the capabilities beginning to be offered by space technology through such projects as TIMATION led to the establishment of a DoD Executive Steering Group to examine the different satellite navigation projects and proposals then under way and to determine the best way to satisfy these new requirements. The most stringent of the JCS Navigation Requirements were for aircraft navigation and that became the driving parameter.

TIMATION Navigation Satellite Program

Navigation and positioning systems up through 1968 were still in the beginnings of space technology. The Navy Navigation Satellite System, or TRANSIT, as it is more commonly known, was developed in the early 1960's and had demonstrated that worldwide accurate navigation was possible from space. With only one satellite, a worldwide capability resulted and with several, positioning could be provided frequently. The TIMATION project originally had an objective of examining means of speeding up and simplifying the positioning capability from space through experiments with passive ranging techniques. However, the passive ranging technique requires an accurate and stable oscillator in the satellite. The TIMATION project concentrated on developing an improved quartz frequency standard for satellites, thereby reducing the error in the passive ranging links, and also on determining the most effective satellite constellation for providing worldwide coverage [1,2,3]. Simplified receiving equipment using a Side Tone Ranging technique and the techniques of celestial navigation could be used for simple and accurate navigation and time determination. The transformation to celestial navigation techniques was described in a paper by Easton [4].

Two experimental satellites were launched during the TIMATION project. The third, which began as TIMATION III before the formation of the NAVSTAR GPS Program, was renamed at launch "Navigation Technology Satellite One (NTS-1)". TIMATION I, the first satellite, was launched in 1967 to perform initial feasibility experiments into passive ranging for positioning and time synchronization. A good quality quartz crystal oscillator was built and space qualified for use in generating a ranging signal. The ranging signal format was called side-tone ranging (STR), but was not actually a modulated signal. The format was a set of continuous wave (CW) subcarrier signals spaced by the tone frequencies desired. Upon combining two CW signals, the beat frequency or tone was phase compared with an identical one generated in the ground receiver, and the phase difference was a direct measure of the tone wavelengths traveled by the signal from the transmitter in the satellite to the receiver. Multiple measurement frequencies were required to resolve the wavelength ambiguities.

The TIMATION I satellite [5,6] was a small, power-limited satellite, launched into a 500 nautical mile polar orbit from the Western Test Range as a secondary payload. It was tracked from several experimental ground stations [7], that were built and operated by NRL, to determine the orbit accurately. The STR signals were transmitted at approximately 400 MHz, which was close to the frequency used by TRANSIT. A variety of experiments were conducted with TIMATION I to investigate the technique with different platforms. Experiments were carried out in navigating small boats, aircraft and trucks by passive ranging to the satellite. In the original experiments only one satellite was needed since instantaneous positioning was not required.

The quartz crystal standard used in TIMATION I [8] was a commercial grade unit rebuilt for space use. In space, the unit exhibited a very low aging rate, which seemed to indicate that the use in space was better than on the ground. Later results from TIMATION II, which contained a specially built quartz unit in an attempt to improve the performance, exhibited poorer in-orbit results. The reason for the difference was explained by the radiation effects on the different crystal units [9]. Identification of the type of radiation at different orbits remained an issue throughout the early NAVSTAR development program.

The second satellite, TIMATION II, was a larger satellite that was designed for continuous operation. It was launched into a 500 nautical mile polar orbit in 1969. It incorporated STR signals with an increased measurement capability and transmitted them at 150 and 400 MHz so that correction for the ionospheric refraction could be made. The specially developed quartz oscillator was to reduce synchronization errors and maintain timing for longer periods. Higher frequency range tones were used to increase the precision of the range measurement, the highest being 1 MHz for a measurement precision of about 30 ns or 10 meters. The experiments with this satellite [10-18] were used in the system studies to generate the concept which would satisfy the JCS requirements.

The third satellite, begun in the TIMATION project, was to add additional improvements and experimentally examine facets of the system concept for both an advanced system and an evolutionary concept to bridge the gap between Transit and the advanced system. One of the most interesting experiments was the inclusion of two experimental rubidium frequency standards.

Through the efforts of the TIMATION Project and the Air Force 621B Project which had developed a sophisticated ranging signal concept, based on PRN techniques, the NAVSTAR Global Positioning System (GPS) Program was formed. The Air Force was designated as the executive service and a Joint Program Office (JPO) was established at what is presently Headquarters Space Division, Air Force System Command. There was strong Navy participation in the development of the system concept and technologies, in particular by NRL.

NAVSTAR SYSTEM CONCEPT

The NAVSTAR GPS system concept, that resulted from DoD Tri-Service coordination, was a navigation satellite system based on passive ranging and therefore system wide time synchronization. The system design was to provide highly accurate navigation and time information to users anywhere in the world (Figure 1). The constellation of satellites will continuously provide a minimum of 4 satellites in view of any user located anywhere in the world. The satellites will be operated by a worldwide network of Monitor Stations (MS) which will track and control the operation of the satellites. One of the principal tasks will be to maintain all the satellites synchronized to a common time. Normal operation of the MS's entails tracking of each satellite and the transmission of these data to the Master Control Station (MCS) for processing. The MCS collects and processes the measurements to produce new estimates of satellite clock, orbital parameters and other necessary information for upload back into the satellites. Each satellite will transmit to the users its position, clock correction terms and other information necessary for the user to navigate accurately.

The navigation performance of the NAVSTAR system is described as the product of the basic ranging error and the Geometric Dilution of Precision (GDOP). The basic ranging error (Figure 2), which has been called the User Range Error (URE), is the combination of uncertainties or errors in the measurement of range between the satellites and the user receiver. The system design is such that each ranging link is considered equivalent and the magnification of errors induced by the geometry of the satellites relative to the user receiver can be expressed as a dimensionless factor known as GDOP. Except for its multiplication of errors, the GDOP factor is not an issue in system technology, since the constellation coverage will not change unless the number or positions of satellites changes. The URE is a combination of the actual range measurement error due to instrumentation, residual ionospheric and tropospheric correction, orbital position and clock errors. The URE is strongly influenced by both clock and orbit errors.

The URE and associated error contributions are illustrated below (actual error contributions are highly dependent upon the equipment used and the phase of deployment).

User Range Error (meters)

Satellite Position	1.5
Satellite Clock Errors	1.5
Atmospheric Delays	2.4 - 5.2
Satellite Equipment Delays	1.0
Multipath	1.2 - 2.7
Receiver Noise and Resolution	1.5
RSS	3.6 - 6.3

The dominant errors appear to be atmospheric delays and multipath. These errors, however, are the limits of the expected errors. The satellite position and clock errors are functions of elapsed time since the last clock update or orbit prediction and represent limiting factors on system performance.

Satellite position errors are induced by the various perturbing forces and the ability to measure and predict satellite trajectory. These errors will accumulate as a time-varying function and are also dependent upon separation of position errors from timing errors. The clock errors also accumulate as a time varying function. These satellite clock errors are dependent upon the interval between the time the clock was updated and the time a user range measurement is taken. The stability of the clock in this interval determines its error contribution since the clock is assumed to be perfectly synchronized at the update. The maximum error growth determines how frequently the satellite clocks must be updated to stay within the system specified error bounds. This maximum error is what is reflected in the URE. Different types of clocks have different characteristics and may strongly affect the operating mode and update interval. Depending on the requirement for accuracy, different clocks can be employed by varying the update interval.

NAVSTAR GPS DEVELOPMENT PROGRAM

The NAVSTAR GPS Development Concept Paper number 133 approved in 1973 called for NRL to continue the technology efforts begun in the TIMATION Project. The system concept uses the same basic technique of passive ranging using precision clocks and a constellation of multiple satellites in circular orbits for worldwide coverage as the TIMATION system concept had proposed [19,20]. The work by NRL was recognized at the establishment of the NAVSTAR Program as vital to the time based system concept.

The Deputy Secretary of Defense Memorandum of 22 Dec 1973 approving the Phase I development of NAVSTAR called for Navy participation with emphasis on the clock developments necessary for the program. A cesium standard development,proposed by NRL, was selected as the most likely satellite clock candidate for meeting the ultimate requirements of the program. In the Phase I concept validation, rubidium standards were proposed by Rockwell International and selected as the units to be used on the first developmental NAVSTAR satellites. The Navy program was defined to demonstrate the feasibility of the system concept by constructing Navigation Technology Satellites and to advance the state of the art in navigation satellite technology. A major requirement was to develop and space qualify cesium standards for later phases of the NAVSTAR program.

Additional direction was provided in the Director of Defense Research and Engineering (DDR&E) memorandum of 19 November 1974, where the Navy was requested to expand the NAVSTAR clock development to include a second, parallel cesium project to be done by an aerospace contractor for use on NTS-2. The memo stated that if either or both of the cesium clocks performed satisfactorily, cesium should be used in any satellites subsequent to the initial six NAVSTARs. Navy was also directed to develop hydrogen maser standards for ground station use and space qualify the units with NTS-3 for subsequent use on NAVSTAR satellites. The Navy Program was designed to meet the requirements of the DDR&E direction.

The NTS-1 satellite, built and operated by NRL (Figure 3), was launched one year after the GPS Program was formally started. Part of its mission was to examine the operation in space of the first two experimental rubidium vapor frequency standards. Late in the construction of the satellite a very small commercial rubidium standard became available from Efratom in Munich, Germany. Several units were purchased and were evaluated for possible experimental use in space. After an evaluation and a flight qualification effort, it was decided to attempt using these devices in the satellite. Two of the commercial units were modified to be remotely operated and to survive the launch environment, and were integrated into the flight electronics [21]). The in-orbit tests of the experimental rubidium units showed that the devices were possible contributors to the operational system [22]. The stability was such that time synchronization could be maintained for hours to good precision. For periods of time up to a day the long term performance of the standard started to exhibit the characteristic drift known to be in these types of standards. Variations in this drift amount to a growing time or frequency uncertainty. This type of drift is not present in cesium standards which became the focus of NRL efforts for advanced spaceborne frequency standards.

Aside from the experimental standards, NTS-1 employed new ranging frequencies. It transmitted at 335 and 1580 MHz and the highest range tone was at 6.4 MHz, for a measurement precision of about 4.7 nanoseconds or 1.5 meters. The satellite was tracked by a worldwide network of stations some operated by NRL and cooperating stations in England and Australia. Experiments into ionospheric and tropospheric refraction effects [23], and other navigation related tests [24] were conducted. The first international experiments in time transfer using this technique were carried out and time synchronizations performed to a few tens of microseconds between NRL and the Royal Greenwich Observatory in England [25,26].

The second technology satellite built by NRL [27-30], NTS-2, was the first satellite launched which contained all the features that would be employed by the developmental NAVSTAR satellites. These were built by Rockwell International to demonstrate the system concept. NTS-2 contained the first two prototype cesium beam frequency standards to be flown in space to examine the feasibility of using these devices in space and support the development of space technology for the program [31]. In distinction to the rubidium standards flown on NTS-1, the cesium standards in NTS-2 were designed and constructed for space use. An extensive program of flight qualification and design was carried out between NRL and Frequency and Time Systems, Inc., who built the units. The success of these prototypes [32,33] led to the development of the production cesium units currently to be flown on-board the operational NAVSTAR satellites. The performance of the NTS-2 units was a frequency stability of 2 parts in 10 (-13) for one day averages, or a time error of about 20 nanoseconds a day.

The ranging systems on NTS-2 were of two types, the same STR system that was flown on NTS-1, with the addition of a data link for satellite position and other data, and a Pseudorandom Noise Signal Assembly (PRNSA). The PRNSA was provided by the NAVSTAR Program Office so that NTS-2 could be used in the same manner as the Rockwell developmental satellites, which were originally known as Navigation Developmental Satellites (NDS). This permitted NTS-2 to be operated by the GPS control stations in parallel with the stations operated by NRL [34]. A laser retroreflector was also installed on the satellite to provide an independent tracking means of comparing the radio techniques with optical ones for comparison of accuracies. The success of the laser tracking experiments was limited by the ability of the then existing laser tracking network. A major part of the mission of NTS-2 was to measure the capabilities of tracking and accurately predicting the satellite position. In a system such as this which is based on time measurements there is a problem distinguishing time error from position error - particularly the satellite position error.

Since NTS-2 was fully compatible with the GPS Control Segment it was initially used to evaluate the stations, software and systems for the first NAVSTAR satellites, which began to be launched about a year after NTS-2. The first three NAVSTAR satellites contained three rubidium standards on each satellite. NAVSTAR 4 was the first NDS with three rubidium standards and an NRL-provided cesium onboard. From launch of these four satellites through about 1979 considerable problems were encountered in the operation of the rubidium standards, and the NAVSTAR 4 cesium power supply failed after approximately 12 hours of operation. These problems led to a reexamination in 1979 of the space-qualified standards for the program. At this time, NRL was in the design stage of NTS-3. That satellite was to be the test vehicle for the next step in clock technology, the hydrogen maser [35,36]. The techniques for improving orbit prediction would be very important for NTS-3 in separation of the clock and orbital position uncertainties. These two elements are the key factors in the operation of the system for prolonged periods (days to weeks) without update from the ground.

NAVSTAR CLOCK TECHNOLOGY PROGRAM

Subsequent to the Second Defense System Acquisition Review Council (DSARC II) in 1979, which approved operational system deployment, the Navy Program was redirected to its present focus. From the results of the clocks flown in the first phase of the system development, it was recognized that clock technology was crucial to the success of GPS, and that adequate clocks were not available at that time [37].

A joint program into clock technology was established. The JPO in conjunction with their prime contractor Rockwell International was to continue the improvement of the rubidium units built in a joint effort with Efratom of California. They were also pursuing an alternative rubidium development for a second source of spacecraft standards with EG&G. That effort ultimately produced a new design for a space-qualified unit hardened to the GPS radiation requirements. The Navy program was organized into the following key elements:

(1) development of alternate sources of cesium clock technology, including multiple competitive contracts,

(2) hydrogen maser technology development, consisting of in-house work and efforts at recognized centers of maser technology,

(3) development of an aerospace source of hydrogen masers,

(4) establishment of a testing facility where long-term data on flight clocks could be gathered in space simulation to develop a database of performance and reliability, and

(5) establishing means of independently determining the in-orbit performance of these clocks once deployed.

The present program being conducted in accordance with a coordinated clock development plan and memoranda of agreement among NRL, the Space and Naval Warfare Systems Command, and the GPS JPO, embraces the same five main elements.

Cesium Development

As was discussed earlier, the original efforts on developing cesium units for spacecraft for the GPS Program were conducted between NRL and FTS. That effort resulted in the production of units for the developmental NAVSTAR satellites (or Block 1 satellites) currently in orbit and the units to be launched in the initial operational NAVSTAR satellites. That source developed for the program is the sole provider of these types of units. The objective of this effort is to develop alternative sources for possible program use, increase performance where possible, improve reliability, and promote competition.

In this effort, two potential second-source contractors, Frequency Electronics, Incorporated and Kernco, are competitively developing spacecraft cesium clocks. Both contractors are working to identical specifications which call for improved performance beyond that of the clocks in the present development spacecraft, and for a life expectancy of over seven years in space. Reliability of the developed units was a key feature of this effort. To assure compatibility with the spacecraft and the space environment, an interface control document (ICD) has been drawn up between each contractor's unit and the operational, or Block-II, spacecraft. The compatibility of the units with the spacecraft is essential to the final step in qualifying their design and operation in the system, which is actually to launch the units in NAVSTAR satellites for on-orbit verification of their operation. This requirement for in-orbit operation was considered necessary for final verification before operational use. To accomplish the verification, units will be flown in the latter Block 2 satellites.

The development of these cesium units will be continued and the sources supported until the GPS Program will be able to secure competitive contracts for operational units. The long-term performance of the development prototypes in a space environment would be evaluated in a dedicated NRL test facility designed for that purpose.

The program with each of the contractors followed the same phases of development. The projects were arranged in two steps. The first was to develop and build units that were called Engineering Development Models (EDMs). Each contractor built six of these units which are being subjected to space qualification testing and performance evaluation. With the design certified through this testing cycle the contractors are proceeding building Pre-Production Models (PPMs). These PPMs will be fully flight qualified and built with the quality processes necessary for operational hardware.

Hydrogen Maser Technology Development

The original efforts in the NAVSTAR development program for clocks to support improved system performance were toward hydrogen maser units for the ground stations and eventually in spacecraft. Those efforts were based on the active hydrogen maser design developed by the Smithsonian Astrophysical Observatory (SAO). Their results in initiating the VLG series of masers and an experimental Probe unit for NASA, launched in the mid-1970's, provided the feasibility of such devices working in the GPS system. Work with SAO and exploratory efforts with the RCA Research Center and Hughes Research Laboratories (HRL) produced experimental units to investigate the possibility of extremely stable clocks for the GPS system segments.

Development of hydrogen maser clocks for spacecraft (Figure 4) and ground station use is based on the passive maser designs in order to produce spacecraft units comparable in size and weight with the cesium units. The hydrogen maser development is being transitioned to industry to insure early availability of a space-maser clock source which could produce the units in the quantities needed for an operational system. Hughes Research Laboratories was selected for the initial development of the industrial source because of their work in a competitive exploratory development project on maser technology for spacecraft, begun in 1973.

Hydrogen Maser Aerospace Source Development

After initial work to insure that the technology was in hand the actual construction of the developmental units was transferred to the regular production divisions of Hughes. The maser technology development was supported by an active development program in-house at NRL. Four spacecraft development models (Figure 5) were constructed and are still being tested. Considerable technology from that effort and the efforts of other maser technology experts has been transferred to the aerospace developers.

In GPS, the spacecraft clocks are required to operate autonomously between updates from the ground stations. The allowable length of the autonomous period is determined by the stability of the spacecraft clocks and how well they have been characterized by the ground stations. This, in turn, depends upon the stability of the space and ground clocks. It is also interactively coupled with the determination of the satellite's orbital parameters, since the time and position solutions are not completely independent of each other. Superior clocks, therefore, can significantly improve overall system operation.

Improved clocks can also enhance system survivability by extending the allowable autonomous operating periods. The survivability of the system is improved by decreasing or eliminating the continuous dependence of the system on easily destroyed ground stations. With accurately predicted clock and orbit parameters, the satellites could continue to provide a navigation capability whose accuracy would degrade gradually in proportion to the loss of time synchronization. An opponent wishing to disable or degrade the system would be forced into a more costly strategy of attacking satellites instead of ground stations.

Clock Test Facility

The NRL test facility (Figure 6), which now has a number of developmental spacecraft clocks under long-term test, contains a reference clock system composed of five hydrogen masers and a cesium beam standard. In addition, the NRL reference is continuously compared with the USNO Master Clock through a unique system in which both sites monitor a local television station's carrier signal and compare the differences over a dedicated telephone line with a short term noise of about 50 picoseconds. Performance and status data on the clocks under test in space simulation and in bench test, and all environmental conditions are continuously monitored in the test facility. The data are automatically reduced and can be presented in several formats for analysis. For such long-term testing, backup systems for electrical power, data storage, and vital components are required, since a loss of these could invalidate months or years of testing.

On-Orbit Clock Performance Analysis Clock testing is not restricted to the laboratory. The performance of the clocks as used in the orbiting spacecraft is of vital concern, not only to verify the ground tests, but also to determine how the clock should be modeled in the Kalman filter used by the Ground Segment to determine and predict orbits and to determine spacecraft clock time accurately. To this end, NRL conducts a substantial program of on-orbit clock analysis.

The data for these analyses are obtained both from direct measurements of satellite signals made with receivers of NRL and commercial design and from data provided by the control segment and other observers. The Naval Surface Weapons Center provides "best-fit" orbits that are used in conjunction with other data to extract clock performance from the multitude of other variables that affect the measurements in a small, but significant, way.

The results of the analyses indicate that the clocks may perform somewhat better in the space environment than they do in the laboratory. The NRL test facility is being modified to determine which factors are responsible for the difference.

NAVSTAR TIME DISSEMINATION

Although the timing mission of GPS is less well known than the navigation mission, it is an increasingly more important one. Many users already employ the GPS developmental satellites for time dissemination to satisfy operational needs. The number of timing receivers is growing and cost is dropping significantly. New systems are being conceived and developed which will rely on its capability. Communications and intelligence are two areas in which very precise time coordination among units is necessary. In communications, precise time is needed for a number of militarily necessary features. It is useful in synchronizing certain cryptologic systems. In time-division multiple-access systems or steerable systems designed for more efficient use of satellites and other resources, precise time and position are used together to reduce or eliminate unnecessary search or synchronization procedures and vulnerable or inefficient timing transmissions. Modulation schemes, such as pulse-position modulation, in which time of occurrence corresponds with information, can use precise time to great advantage. For anti-jam systems, especially frequency-hopping systems, burst systems or spread-spectrum systems designed for low probability of intercept, precise time is a necessity. Precise time can also be used to advantage in some coherent communications schemes for signal-to-noise enhancement. In the intelligence arena, time coordination among units is needed for emitter location and other purposes. NRL has worked with numerous systems in establishing and achieving their timing requirements.

Inter-operation within or among time-dependent systems requires each unit to know time accurately with respect to a common reference. However, for reasons of security or survivability, the dissemination of the reference may be required to be made through means external to the system. For DoD systems, the common reference is Coordinated Universal Time (UTC), maintained by the USNO Master Clock. GPS is considered the primary means of time dissemination, because of its ability to serve passive users, its continuous worldwide coverage, its built-in survivability, its accuracy, and its simultaneous position solution that is often needed by precisely timed systems [38,39]

To implement the USNO time-dissemination requirement, NRL is active in improving the link between USNO and the GPS Control Segment and in the design of a standardized GPS timing interface for the user systems. In addition to developing hydrogen masers for the GPS Control Segment clock system NRL is also responsible for development of improved atomic clocks for the USNO Master Clock. The USNO Master Clock, which now employs an ensemble of cesium and hydrogen maser clocks, is now testing a new stored mercury ion clock developed by Hewlett-Packard under an NRL contract. The clock system being built by NRL for the Control Segment will contain provisions for better coordination with the USNO Master Clock. NRL is also working on a USNO substation to be located at the Consolidated Space Operations Center that would serve other time-dependent systems.

Standardization of the GPS timing interface is very important. Because of the DoD requirement for a common timing reference, many precisely timed systems will be affected. The effect is compounded by the current development of a new military standard for communications systems timing and synchronization, which is also developing a standardized timing interface. NRL is contributing substantially in both standardization efforts.

In addition to the work with the space and control segments of GPS, NRL has been requested by the JPO to help in defining performance parameters of the GPS user equipment and in testing the equipment. The work includes an analysis of the whole GPS system in various user operating scenarios to establish reasonable and attainable performance limits and testing the receiver in various environments, including the relatively benign conditions encountered by a large segment of fixed or low-dynamics users and in more severe environments of mobile users.

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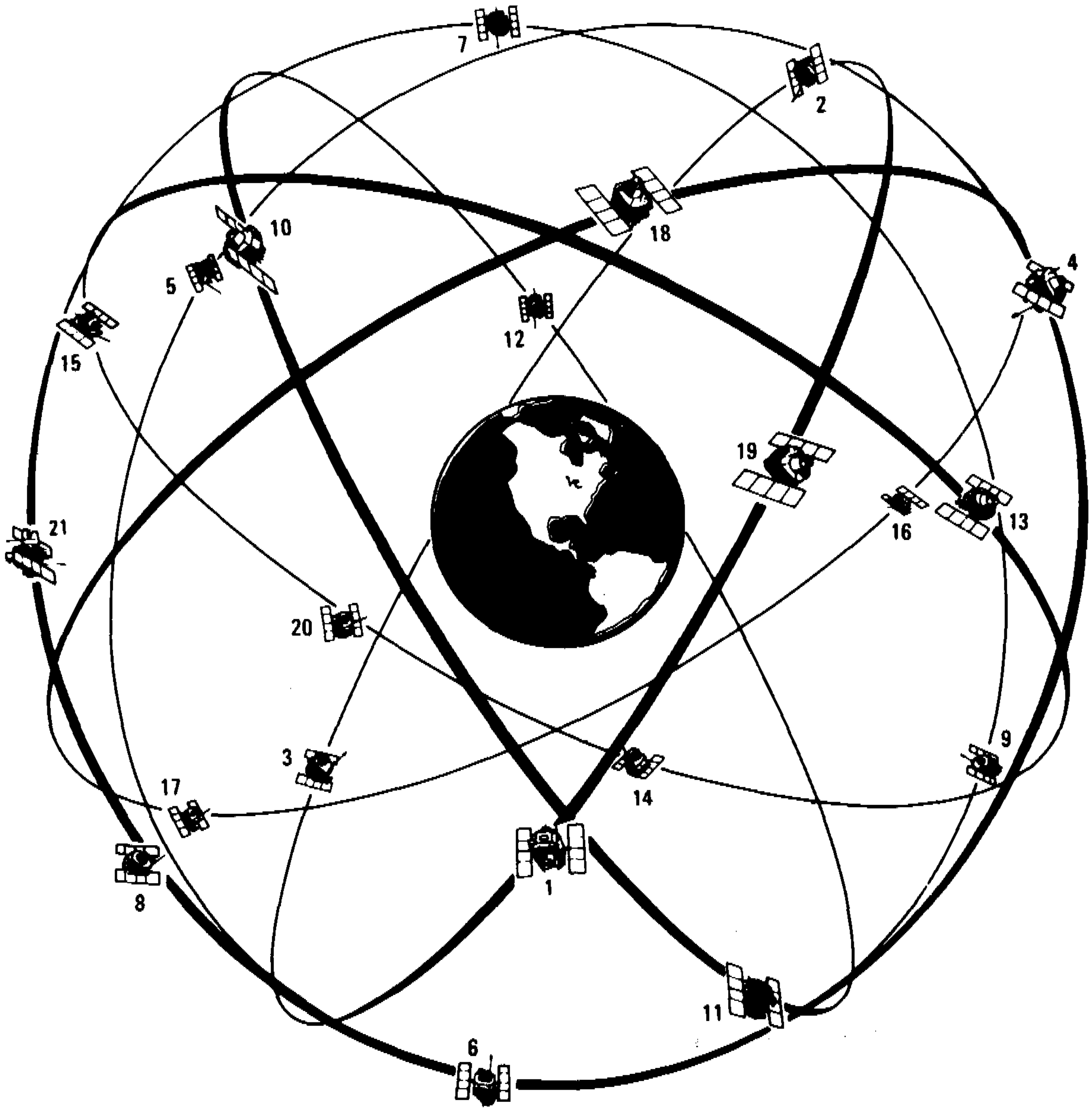

Figure 1. Navstar operational constellation.

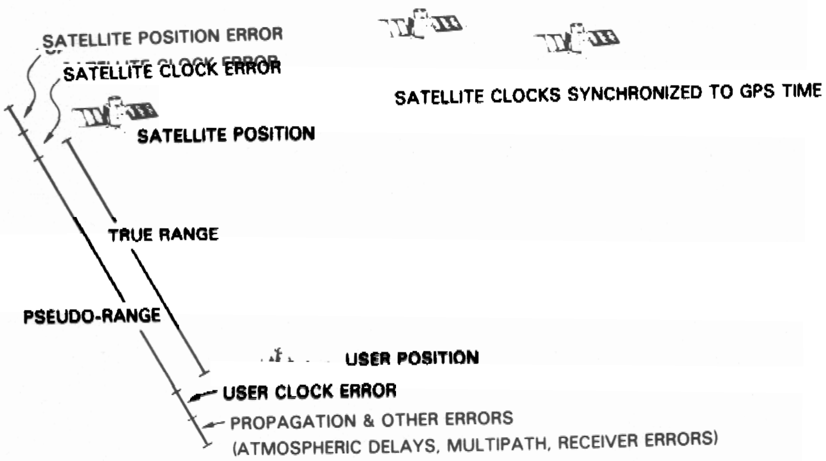

Figure 2. Error contributions in GPS ranging

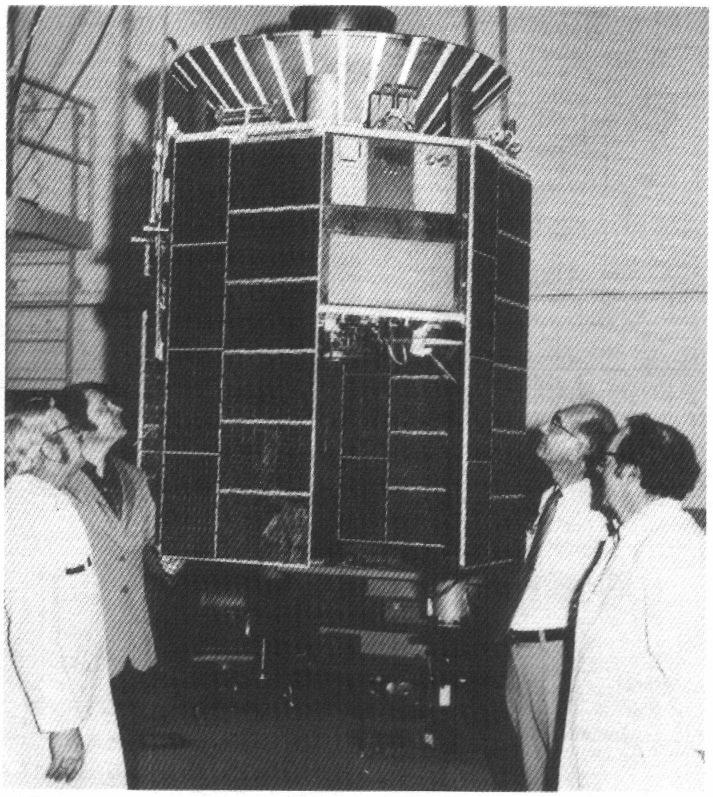

Figure 3. NTS-1 spacecraft ready to be integrated with launch rocket.

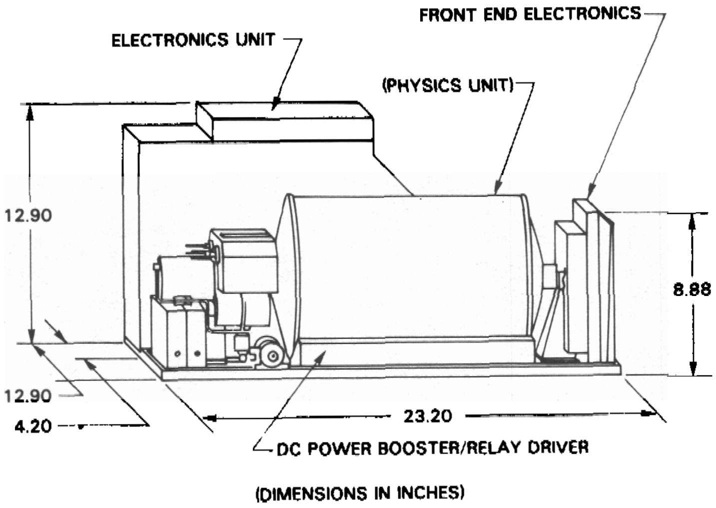

Figure 4. Spaceborne hydrogen maser design.

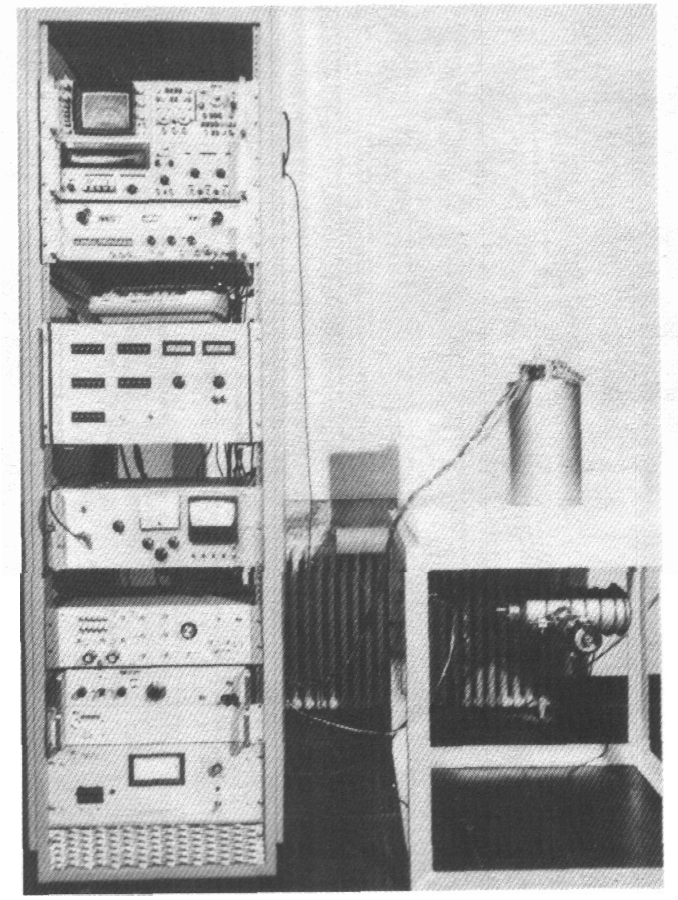

Figure 5. NRL passive hydrogen maser on test stand.

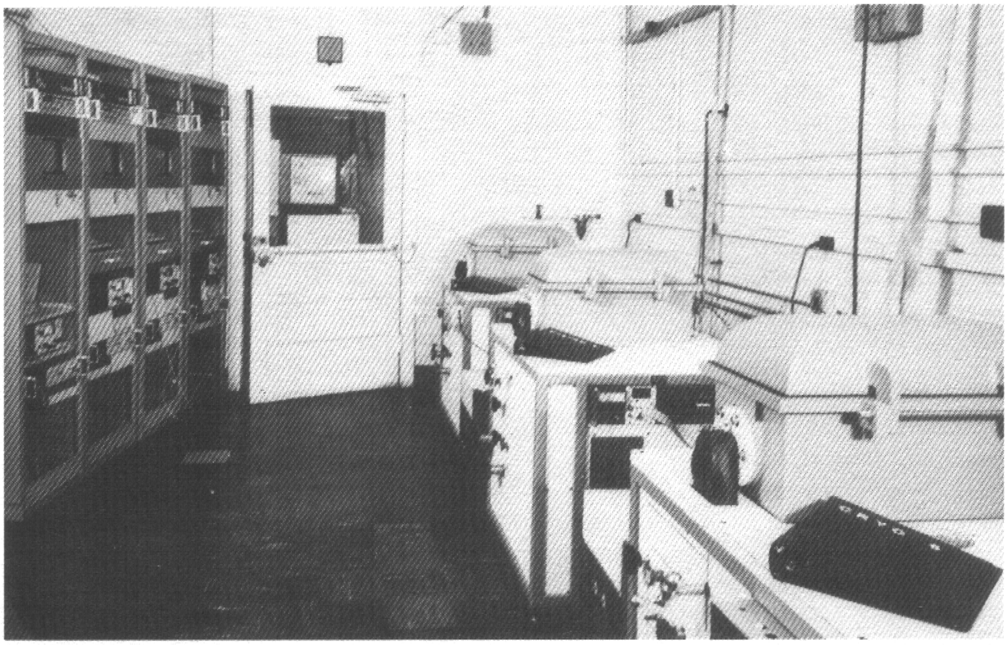

Figure 6. Part of NRL Space Clock Test Facility. Cesium clocks are tested in thermal vacuum chambers (right) that are automatically controlled by the units at left.