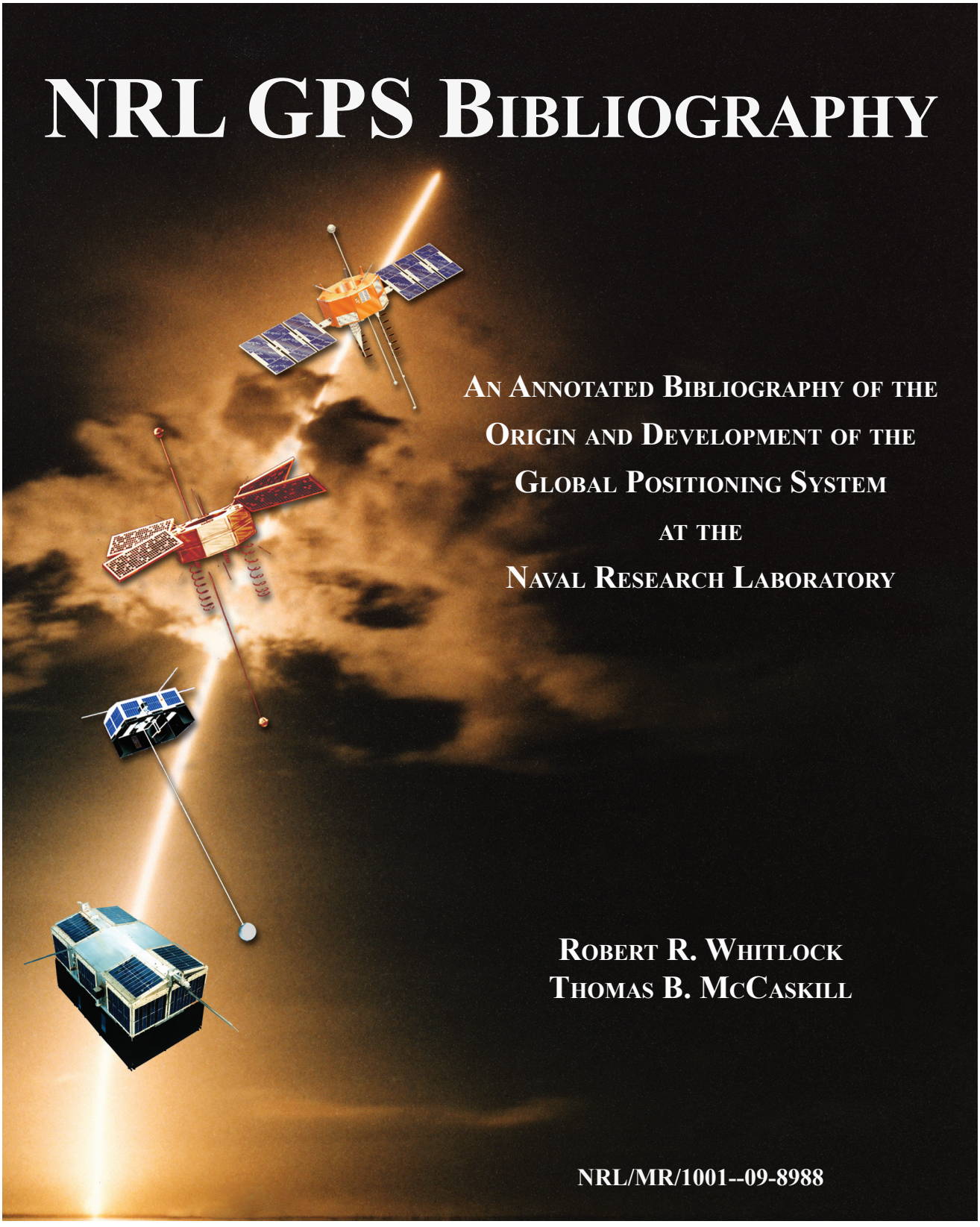
Naval Research Laboratory

Washington, DC 20375-5320

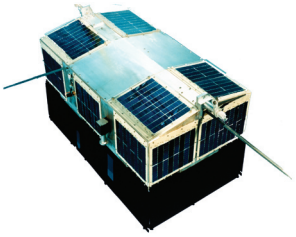
NRL GPS Bibliography



An Annotated Bibliography of the Origin and Development of the Global Positioning System at the Naval Research Laboratory

Robert R. Whitlock
Thomas B. McCaskill

NRL/MR/1001--09-8988



Timation I

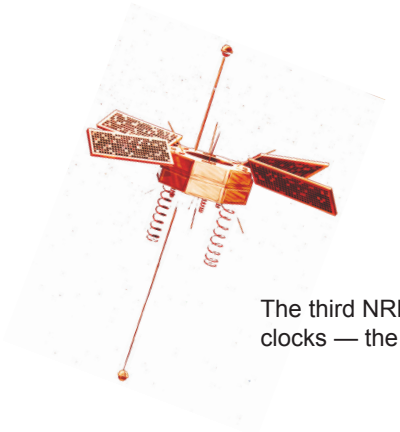
Launched 31 May 1967, 2-hour, circular orbit

Time navigation, a visionary and patented satellite navigation method for passively measuring range from the time of flight of transmitted timing signals, was first demonstrated to Navy and DoD sponsors with the Timation I satellite on 25 October 1967. Now used by the Global Positioning System, time navigation requires synchronism between the onboard clock and a clock at the receiver. For the 1967 demonstration, a graphical range-intercept chart was used to determine the receiver's (navigator's) position and clock offset, using three or more measurements. Position accuracy in subsequent Timation I demonstrations with moving boats, vehicles, and airplanes was on the order of 1/3 nautical mile.

Timation II

Launched 30 September 1969, 2-hour, circular orbit

Positioning accuracy was improved to 33 meters by transmitting the timing signal simultaneously at two frequencies, making possible correction for ionosphere delay. The orbital position of the satellite was determined to 10 meters. Transatlantic satellite time transfer accuracy of better than one microsecond was achieved between the U.S. Naval Observatory in Washington, DC, and the Royal Greenwich Observatory in England.



Timation III (Navigation Technology Satellite – I)

Launched 14 July 1974, 8-hour, circular orbit

The third NRL satellite carried a quartz clock and two digitally controlled rubidium atomic clocks — the first atomic clocks in space. Worldwide time transfer was demonstrated.

Navigation Technology Satellite – II (Timation IV)

Launched 23 June 1977, 12-hour, circular orbit

NTS-II, the first satellite completely designed and built by NRL under GPS Joint Program funding, was the first of a four-satellite constellation configured to demonstrate instantaneous navigation positioning. The effect of relativity on the onboard cesium atomic clocks was measured and corrected so that a GPS receiver on Earth could observe that the rate of GPS time is the same as UTC (Universal Time Coordinated). The clock frequency stability specification of 2 parts per 10^{13} was met. NTS-II was the first operational NAVSTAR GPS Satellite.

NRL GPS BIBLIOGRAPHY

AN ANNOTATED BIBLIOGRAPHY OF THE ORIGIN AND DEVELOPMENT OF THE GLOBAL POSITIONING SYSTEM AT THE NAVAL RESEARCH LABORATORY

ROBERT R. WHITLOCK

AND

THOMAS B. MCCASKILL

June 3, 2009

Approved for public release; distribution is unlimited.

The Naval Research Laboratory was founded on the advice of Thomas Edison, and began operations in 1923. The Laboratory has made many significant scientific and technical contributions to the Navy and to the nation.

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INTRODUCTION

ONE OF THE GREATEST ACCOMPLISHMENTS of the Naval Research Laboratory (NRL) has been the invention and development of the enabling technologies that became the Global Positioning System (GPS). Like another towering NRL achievement in an earlier generation, radar, GPS has transformed warfare while also providing major benefits to civil air transportation. GPS is not only a global navigation aid, it is also the means for precision time and time transfer throughout the world, which has wide ranging and influential impact on communications and commerce; these features are a direct outcome of the technology envisioned and introduced by NRL scientists and engineers.

The broad utility of GPS is widely recognized and appreciated. Less well known is the critical role played by the Naval Research Laboratory in its invention, concept demonstration, operational configuration, inception, and continued development. Perhaps this is in part due to the quiet way the Laboratory goes about pursuing scientific and technical excellence. Although ample documentation on the NRL role in GPS still remains, it is largely in the form of memoranda, technical reports, proceedings from specialized technical conferences, and a relatively few widely published articles. Many of the key technical reports were classified when originally produced, were not declassified until the mid 1990s, and were not disseminated at that time.

The Laboratory has provided a fertile context of broadly based scientific and technical investigation and experience from which strategic innovations could grow. In the areas of electronics, communications, and frequency control, this basis extends all the way back to the founding of the institution in the early 1920s. Research in communication led to advances in transmitters and receivers, and to investigations of the propagation of radio signals. Interest in propagation contributed to an interest in the ionosphere, the upper atmosphere, the edge of space, and the means to investigate these. The Laboratory demonstrated the ability to launch probes to the edge of space, track their location without the need for optical contact, and telemeter and recover data. For the Laboratory, the leap to space was an incremental step – a momentous step, but nonetheless incremental.

The opportunity to take such a step rarely comes easily. NRL researchers did not concentrate solely on advancing their science. They also published explanations of the potential value of the advances they envisioned, and often had to struggle to gain acceptance for their proposals. They were persistent in the face of setbacks.

Perhaps no setback in the history of the Laboratory can match that of the failed attempt to launch a Vanguard satellite on 6 December 1957. The entire country and indeed the world were focused on the event, which provided additional adrenaline to the nation's Sputnik-induced anxiety over the question of preparedness to survive the Cold War. And yet the Vanguard team stayed on task.

Nor, during this stressful time, did they lose their vision for broad national needs. The following February, the designer and builder of the Vanguard satellite, Roger Easton, proposed to the Advanced Research Projects Agency that a major new system be built for the surveillance of space. This system would detect non-radiating satellites overflying the country and determine their orbits. In March 1958, Vanguard I was successfully launched into orbit, where it remains today. In June, the Space Surveillance project was authorized.

Though these events may seem at first glance to have little to do with navigation, they form a continuous thread in the development of GPS by the Laboratory. The thread continues through the Naval Space Surveillance System that arose from Easton's proposal and that remains in operation today. In 1963, an experimental augmentation to the system was funded to add a powerful continuous wave beam that would be transmitted into space from a location in southern Texas. The receiver was located about a hundred miles away from the transmitter. This "electronic fence" performed time-of-flight ranging to determine the flight time of the signal as it propagated from the ground transmitter to the reflecting object in space and on further to the ground receiver. This time-of-flight ranging was performed by adding timing information from a high precision clock to the continuous wave transmitted beam. At the receiver, a synchronized high precision clock provided an absolute time reference for the measurement of the flight time of the received reflected signal. To compensate for drift between the clocks, a third, portable clock was transported between the sites. During the hours that the portable clock was in transport, all three clocks would drift. Drift in the clocks could produce errors in the range measurements. The need to synchronize the clocks of this experimental electronic fence was what prompted Roger Easton to consider placing a precise clock on a satellite that would be visible to transmitter and receiver simultaneously. As he pondered his visionary concept in the coming weeks of 1964, he realized that "clock synchronization could be extended from determining the orbits of satellites to navigation here on Earth."*

Easton's concept of time navigation, or TIMATION, involves passive time-of-flight ranging using precise clocks on board satellites for navigation and time transfer. The Laboratory proved this concept with a series of experimental TIMATION satellites of increasing complexity, calculated satellite constellation geometries, formulated navigation mathematics in four dimensions (three spatial, plus time), defined and assessed measures of error, and performed a succession of navigation and time transfer demonstrations with the TIMATION satellites. Electronic circuitry was designed, built, and tested. Components were subjected to stresses such as temperature, vibration, and radiation. Engineering trades were assessed, and the constraints of available resources and launch opportunities accommodated.

The Laboratory's successful program in satellite navigation was initially enabled by a visionary yet practical sponsor in Naval Aviation in the mid 1960s, and the needs of aviation were foundational to its inception. The already existing TRANSIT navigation satellite system was, at that time, deemed sufficient for the Navy's submarine and surface fleet, and also found use in the maritime industry. The ability of the TIMATION method to meet the needs of aviation was also a critical factor in the interdepartmental deliberations that led to the government decision to proceed with a new navigation satellite constellation, now known as the NAVSTAR Global Positioning System.

This bibliography is offered as an aid to those who are interested in better understanding the NRL role in the origins of GPS. Bibliographic citations, primarily of published works, are presented. These are annotated with abstracts, photos, and figures, to facilitate selecting which of the referenced papers to examine more closely. A Timeline is provided to aid in setting the citations in their context of historical development.

Bibliographic Details

The papers are presented in two bibliographic lists, one without abstracts and sorted by date, and the other annotated with abstracts and sorted first by lead author, and then by date.

An electronic collection of scanned copies of the cited entries, with bibliographic database, has been provided to the United States Naval Research Laboratory's Ruth H. Hooker Research Library for reference by researchers. The bibliography was assembled with software designed for bibliographic databasing.

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*Easton, R. L. (2007). Global navigation flies high. Physics World: 2-6.

This bibliography includes papers and reports for which at least one author was an NRL employee or contractor. Documents relating to awards to NRL employees, regardless of authorship, are also included. An attempt was made to gather a complete list of GPS-related NRL publications appearing prior to the 1978 launch of the Block I GPS satellites; however, additional papers continue to surface. NRL papers of later publication date were included as they were encountered.

While the emphasis of this bibliography is on the contribution of the Laboratory, an examination of the GPS-related documentation reveals the magnitude of the visionary scientific and engineering achievements of NRL physicist Roger L. Easton, including contributions to the Vanguard satellite program, the invention and deployment of the Naval Space Surveillance System, and the invention and development of TIMATION as the basis for the Global Positioning System. As early as 1969, Easton described a constellation of his satellites "as a prime possibility for an accurate, all weather, always available, three dimension, U.S. based navigation system."

The list of NRL papers includes papers related to GPS, whether directly related or otherwise. Any known paper on relevant topics such as TIMATION or Navigation Technology Satellites was included, if a copy was available. The two conferences to which the NRL TIMATION team regularly reported their work were the Precise Time and Time Interval (PTTI) meetings and the Institute of Navigation meetings; as available, the tables of contents of these meetings, and those of the IEEE Frequency Control Symposium, were examined for NRL-authored papers, although gaps may remain. The complete set of PTTI proceedings was examined at the Library of the United States Naval Observatory. A visit to the Navy's GPS Library at Point Loma, California, turned up various documents of indirect interest, authored by other organizations dating from 1980 onward, although there was essentially no readily accessible record of NRL's role prior to about 1975; staff at the Library noted that several boxes of older documents had been lost to water damage before they could be catalogued.

Because TIMATION was related to other prior or ongoing work at NRL, additional papers were included if encountered, such as those on the Naval Space Surveillance System and Vanguard. The relationship to communications and electronics work at NRL was not explored. An appreciation for the rich context of space- and electronics-related research at NRL in this time period may be gained from Amato's book *Pushing the Horizon.*

The software used for generating the bibliographic lists does not support special characters, such as Greek letters, mathematical symbols, subscripts or superscripts; as a consequence, adjustments have been made to preserve the meaning in the absence of these typographic features. The authors have placed their primary emphasis on the content of citations, rather than the style, seeking only to make sufficient bibliographic information available to facilitate retrieval of the cited documents.

The annotated list is accompanied with photographs and images of figures extracted from the documents. Due to the sometimes poor quality of available copy and the limitations of publication space, resources and schedule, the usual standards of legibility could not be consistently maintained, despite the investment of significant effort. A few of the figures have been augmented with typed axis labels to aid clarity. While some articles contain no useable figures, others contain quite a few, and figures may appear in multiple publications; as a consequence, a figure may appear on a page other than the page listing the entry of the article in which the figure appeared. The photos and figures are presented for the purpose of visually exhibiting the extent of the represented work, and to lead the reader's interest toward the documents themselves. A detailed examination of the annotation figures is best done directly from the original documents.

The Timeline emphasizes the early development of TIMATION and GPS, and does not adequately represent the continued NRL space clock development program of later years, a topic to be more fully addressed in a forthcoming history by others.

Due to the vast amount of GPS-related material written by others, no attempt was made to prepare a complete or representative bibliography of non-NRL works, even though representing TIMATION work, if written

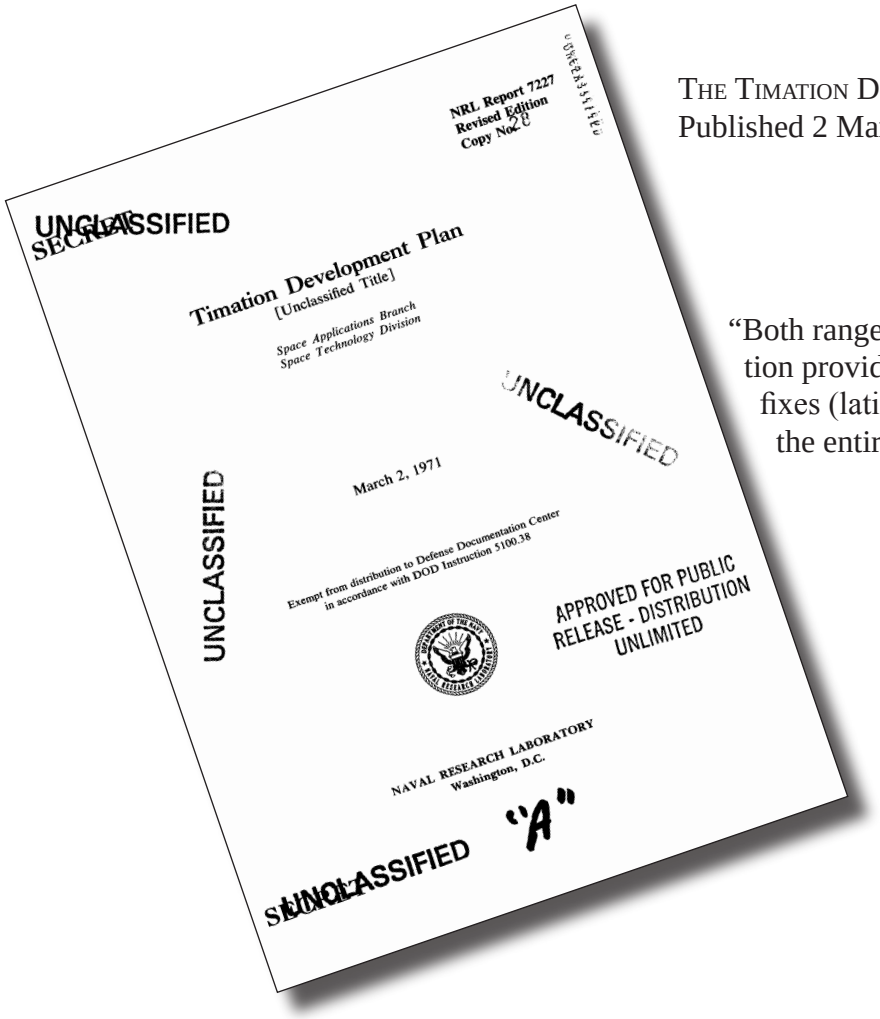
by authors from outside the NRL program, by other Navy offices, or by Department of Defense organizations. However, some non-NRL publications appear as references to entries in the Timeline.

Acknowledgements

This report benefited greatly from the persistent dedication and solid effort of the NRL Ruth H. Hooker Research Library staff, most notably Linda Norton for her extensive help in obtaining documents from other libraries. The assistance of Marybeth Dowdell, the late Mary Templeman, and other library staff, is also gratefully acknowledged. Jim Huizenga of the Navy GPS Library in San Diego, California, provided search results and electronic images. Research at the historic library of the U.S. Naval Observatory was both fruitful and pleasant, and the staff helpful. Linda Greenway supplied high quality photographs from the NRL photo archive, some of them professionally scanned by Mike Savell and Gayle Fullerton. Ron Beard offered images from the extensive files which his NRL Space Applications Branch holds on TIMATION, GPS, and space clocks. The Space Applications Branch contributed substantive entries to the Timeline, and provided documentary support for entries supplied by Jack Brown. Linda Sandy, Surface Chemistry Branch secretary, and her assistants Thaddina Wiley and Erin Wolfe, typed a portion of the abstracts. Nicholas A. Earle scanned the initial core set of papers and entered their bibliographic information into a database during his Science and Engineering Apprenticeship in the summer of 2002.

The authors greatly appreciate the contributions of Donna Gloystein, Jonna Atkinson, and Kathleen Parrish, all from NRL's Technical Information Services Branch, who invested significant effort in improving the quality of the graphics and cover, to the degree attainable with the surviving records that could be located.

These acknowledgements would not be complete without expressing to our wives and families an appreciation for their encouragement, patience, and, as the authoring project lingered on from year to year, forbearance for our investment of personal effort and time devoted to assembling and preparing this bibliography.


NRL Report 7227
Revised Edition
Copy No. 20

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Timation Development Plan
[Unclassified Title]

Space Applications Branch
Space Technology Division

UNCLASSIFIED

March 2, 1971

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Washington, D.C.

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"A"

THE TIMATION DEVELOPMENT PLAN
Published 2 March 1971

"Both range only and range-difference navigation provides continuous three-dimensional fixes (latitude, longitude, and altitude) over the entire globe..." -- p. 11.

NRL NAVIGATION SATELLITES

NAME	TIMATION I	TIMATION II	NTS-1/ TIMATION III	NTS-2
LAUNCH DATE	31 May 1967	30 Sept 1969	14 July 1974	23 June 1977
ALTITUDE	500 n	500 n	7,500 n	10,898 n miles
INCLINATION	70°	70°	125°	63°
WEIGHT	85 lb	125 lb	640 lb	950
FREQUENCIES	400 MHz	150 & 400 MHz	335 & 1580 MHz	335 & 1580 & 1228 MHz
OSC. STAB.	$3pp10^{11}$	$1pp10^{11}$	$5\text{-}1\text{-}.5pp10^{12}$	$2pp10^{13}$
D.C. POWER	6W	18W	100W	400W
BATTERIES	NiCad	NiCad	NiCad	NiCad & NiH

The Naval Research Laboratory's TIMATION Development Plan, published 2 March 1971, proposed a continuation of a series of experimental developmental TIMATION navigation satellites of increasing complexity and capability, and formed a basis on which the subsequently established Department of Defense program could build. Under the Joint Program Office, the TIMATION III satellite was renamed Navigation Technology Satellite 1 (NTS-1) by Deputy Secretary of Defense. NTS-2 was the first satellite of the NAVSTAR GPS Phase I demonstration constellation. (Bartholomew-1978 extends chart to NTS-3, on which construction was begun, but which was later terminated.)

TIMELINE

2 July	1923	Naval Research Laboratory (NRL) is commissioned.
	1942	Joint Chiefs of Staff establish a Radio Propagation Laboratory at National Bureau of Standards (NBS, now the National Institute of Standards and Technology, NIST). {NRC[2] p. 7-8}
	1946	NRL begins space experiments with V2 rockets. {Amato[1] p. 171, 175}
	1946	Office of Naval Research (ONR) is established.
	1946	Emmet and Easton publish report on a proposed air navigation system. {NRL2857[3]}
	1948	World's first atomic (ammonia absorption) clock is built at Radio Propagation Laboratory at the National Bureau of Standards. {NRC[2] p. 8}
	1951	Cesium atomic beam device is completed at NBS, using microwave cavity design of Norman Ramsey of Harvard University, with ONR funding. {NRC[2] p. 8}
Summer/fall	1954	Resolutions are adopted by three international scientific bodies as to the desirability of earth-circling research satellites for the International Geophysical Year. {Odishaw[4] p. 281}, {Kaplan[5] p. 1003}, {Amato[1] p. 188}
24 November	1954	A study of the utility of scientific satellites is proposed to National Science Foundation; Milton Rosen of NRL and Andrew G. Haley of the American Rocket Society are co-proposers. {Haley[6] p. 71}
January	1955	Office of Naval Research lets a contract to the National Company, Malden, Massachusetts, to produce a military atomic clock based on that of Jerrold R. Zacharias of MIT, with engineering characteristics set forward by the Navy Bureaus of Ships and Aeronautics and the Naval Research Laboratory. {NRC[2] p. 8}, {Shostak[7] p. 19-20}
13 April	1955	NRL proposes a Scientific Satellite Program. {NRLmr466[8]}
6 May	1955	National Science Foundation proposes a scientific satellite to U.S. Government. {Odishaw[4] p. 281}, {Kaplan[9] p. 743}
29 July	1955	President Eisenhower's press secretary announces the U.S. satellite program for International Geophysical Year. {Hagen[10] p. 437}, {Odishaw[4] p. 282}, {Kaplan[5], p. 1003}, {Amato[1] p. 188}
4 August	1955	DOD recommends the NRL satellite proposal, which became Project Vanguard at NRL, with objectives to develop and procure a satellite-launching vehicle, to place at least one satellite into orbit during the IGY, to accomplish one scientific experiment, to track its flight and demonstrate that the satellite had actually attained orbit, and to not interfere with the ongoing military missile programs. {Hagen[10] p. 438-9}, {Amato[1] p. 189}
9 September	1955	Project Vanguard begins at NRL, by direction of the Secretary of Defense to the Secretary of the Navy.[10] John P. Hagen becomes project director. {Odishaw[4] p. 282}, {Kaplan[5] p. 1005}, {Amato[1] p. 190}, {Hagen[10] p. 439}
early	1956	The National Company produces Atomichron, the first commercial cesium atomic beam clock. NRL takes delivery {NRC[2] p. 8} of the first unit produced. {Shostak[7] p. 20}
1 July	1957	International Geophysical Year (IGY) begins. {Odishaw[4] p. 282}, {Easton[11] p. 70}

4 October	1957	Soviet Union launches Sputnik I satellite.
3 November	1957	Soviet Union launches Sputnik II satellite. {NASA[12]}
6 December	1957	Attempt to launch NRL's Vanguard satellite is unsuccessful. {Hagen[10] p. 448}, {Amato[1] p. 194}, {NASA[12]}
31 January	1958	First U.S. satellite Explorer I is launched, with vehicle by U.S. Army and satellite by Jet Propulsion Laboratory {NASA[12]} with Van Allen radiation experiment on board. Telemetry transmitter for Van Allen experiment was provided by Martin Votaw of the Vanguard Program. {Wilhelm[13]}
21 February	1958	Space Surveillance system is proposed to the Advanced Research Projects Agency (ARPA) by NRL. {NRL[14]}
17 March	1958	NRL Vanguard I is launched, with vehicle, satellite, launch, and tracking station by NRL. (Launch occurred two years, six months, and eight days after Project Vanguard began.) {Hagen[10] p. 438-9}, {Easton[11] p. 70}
17 March	1958	Frank McClure of Johns Hopkins Applied Physics Laboratory suggests passive Doppler measurements of satellite radio emissions for navigation {Lawrence[15] p. 49, 52} by submarines, which was to become the basis of the TRANSIT navigation system. {Guier [16] p. 16}, {Pisacane[17] p. 7}
20 June	1958	Space Surveillance project is authorized by ARPA. {NRL[14]}
7 August	1958	First observation of a non-radiating satellite is made by NRL's Space Surveillance project. {NRL[14]}
1 October	1958	NASA begins operations. {NASA[18]} Much of Vanguard Team transfers from NRL to NASA to form the core of the Goddard Space Flight Center, Greenbelt, Maryland. {Hagen[10] p. 435}, {Amato[1] p. 197-8} Martin Votaw, Ed Dix and others present a request (later granted) to return to NRL to rebuild a satellite capability at NRL. {Wilhelm[13]}
31 December	1958	International Geophysical Year ends. {Odishaw[4] p. 282}, {Hagen[10] p. 437}, {Easton[11] p. 70}
17 February	1959	Vanguard II is launched by NASA, the first satellite designed to photograph cloud cover of the earth, and forerunner of weather satellites. {Hagen[10] p. 449}
18 September	1959	Vanguard III is launched by NASA and performs additional measurements of the earth's outer magnetic fields and micrometeorite impacts. {Hagen[10] p. 449-50}
	1960	Ramsey develops the hydrogen maser, with ONR funding. {NRC[2] p. 8}
early	1960s	Experimental augmentation of Space Surveillance project is begun in Raymondville, South Texas to demonstrate rapid orbit determination. {Easton[19] p. 10}, {Parkinson[20] p. 120-1}, {Easton[72] p. 2-6}
22 June	1960	NRL's Satellite Techniques Branch launches its first satellites, Solrad I and the classified Galactic RAdiation and Background (GRAB) satellite. (The existence of GRAB, the first reconnaissance satellite launched by the United States, was declassified by the National Reconnaissance Office for announcement during NRL's 75th Anniversary in 1998.) {Wilhelm[13]}
25 June	1960	Aerospace Corporation is established. {Aerospace[21]}
13 April	1960	First developmental TRANSIT satellite to achieve orbit is launched, and operates for 89 days. {Danchik[22] p. 19}
	1961	Naval Space Surveillance System (NAVSPASUR) is commissioned as an operational command {Parkinson[20] p. 120}, with thin fan radar beams and interferometric receivers.
30 March	1961	Patent is filed for "Device for Detecting Objects in Space" (the basis for the Naval Space Surveillance System), inventor Roger Easton (U.S. Patent 3,122,741, issued 25 February 1964).
2 June	1961	Kickapoo Transmitter of Space Surveillance System is operational. {NRL[14]}

December	1961	Pre-selectors are added to NavSpaSur receivers. {NRL[14]}
24 January	1962	First of a series of satellites for calibrating NavSpaSur is launched. {Amato[1] p. 202}
October	1962	5600-foot Alert Antenna is installed at Ft. Steward NavSpaSur station. {NRL[14]}
28 February	1963	Patent is filed for active ranging, inventor Roger Easton (U.S. Patent 3,504,367, issued 31 March 1970).
5 December	1963	First operational navigation Transit satellite is orbited. {Danchik[22] p. 21}
	1964	Roger Easton of the Naval Research Laboratory puts forward a concept, later used by GPS, for a passive ranging satellite system that would orbit precision clocks. {Easton[23] p. 8}, {Space Applications Branch Memorandum 1[24]}, {NRC[2] p. 8}, {NRL6781[25] p. 1}
April	1964	Side tone ranging (STR) (multiple carriers) technique is formulated by Roger Easton, and subsequently demonstrated at the NavSpaSur South Texas experimental complex. {Parkinson[20] p. 121}
September	1964	NRL Timation project begins with a task from the Bureau of Naval Weapons. {Easton[27] p. 107}
16 October	1964	Easton's passive ranging concept is demonstrated using a side-tone ranging receiver, modified from the South Texas experiment and placed at NRL, and a transmitter in Matt Maloof's convertible as he drives it down the I-295 interstate. The road is finished but not yet opened to the public. Two Bureau of Naval Weapons representatives, John Yob and Chester Kleczek, observe the experiment. {R.L. Easton, personal communication[26]}
January	1965	Navy Navigation Satellite System (NNSS, Transit) is operational. {Kennedy[28] p. 34}
March	1965	Timation technique of passive ranging is demonstrated with a fixed transmitter located at NRL for transmitting ranging signals, and an experimental receiver mounted in a moving truck. {Parkinson[20] p. 122, *Labstracts*[29]}
Summer	1965	Bomac Laboratories, Beverly, Massachusetts, delivers two hydrogen masers to NRL. {Shostak[7] p. 23}
October	1965	Timation I satellite fabrication begins, with design based on recent experiments. {Easton[24] p. 1}
November	1965	Timation passive ranging experiments are performed with an airborne transmitter to simulate a satellite transmitter. {Parkinson[20] p. 122}
December	1965	Time/range information derived from stable clocks is combined with celestial navigation by Roger L. Easton, to demonstrate simple and accurate navigation and time determination. {Easton[30] p. 70}
	1966	Timation I satellite is built at NRL Techniques Branch under Dix and Wilhelm. {*Labstracts*[29]}
February	1967	Timation Master Control Station is established at NRL. {Buisson[31]}
31 May	1967	NRL Timation I experimental satellite is launched into 500 mile polar orbit, with a precision quartz oscillator on board. Power and on-time are limited. Timation I provided the first demonstration of navigation based on range measurements from a time synchronized satellite. {NRL6781[25] Abstract, p. 1}, {NRL8360[32] p. 1}, {Bartholomew[33] p. 114}
June	1967	Initial satellite synchronization is performed, with first fixed-point navigation tests. {Parkinson[20] p. 122}, {NRL6781[25] Abstract}
25 October	1967	Use of the Timation I satellite for time navigation and passive ranging are demonstrated by NRL to DoD and Navy representatives at the John Ericsson statue near the Lincoln Memorial in Washington, D.C. {NRL[34]}
27 November	1967	Aviation Week & Space Technology reports successful Navy Timation I tests of "a new navigation satellite technique which could provide continuous position-fixing information for aircraft and other vehicles." {Klass[35] p. 63}

January-May	1968	TIMATION I navigation experiments are performed with small boats, aircraft, and trucks by passive ranging to the satellite. {Easton[30] p. 560}, {Parkinson[20] p. 122}
	1968	Experiments to exploit time transfer using TIMATION I are begun by NRL. {Easton[30] p. 560-1}
15 May	1968	Ship navigation performed using TIMATION I. {Easton[27] p. 109}
22 May	1968	Aircraft position fix taken using TIMATION I. {Easton[27] p. 109}
August	1968	TIMATION I experiments confirm the advantages of combining time navigation with Doppler measurements to provide near-instantaneous positioning with a single satellite. {Easton[23] p. 11}, {Parkinson[20] p. 125}
March	1969	NRL TIMATION II Tracking Station Network is deployed, with stations in Maryland, Florida, Colorado, and Alaska. {Buisson[31]}
30 September	1969	NRL TIMATION II is launched into 500 nm orbit with improved {Bartholomew[33] p. 115} quartz clock on board. {NRL7252[36] p. 1-2} Continuous operation {Buisson[37] p. 277} at 18 watts average power, and range measurement to 33 meters are achieved. {NRL7511[38] Abstract and p.1} Dual frequency (150 and 400 MHz) operation enables correction for ionospheric refraction. {Bartholomew[33] p. 115}
19 October	1969	At Electronic and Aerospace Convention EASCON'69, papers are presented on three approaches {Easton[39]} to navigation satellites (by altitude) by Easton (NRL, mid-altitude) {Easton[40]} by Woodford, et al. (Aerospace, high altitude 24-hr synchronous) {Woodford[41]} by Kershner (JHU/APL, low altitude) {Kershner[42]}
	1970	TIMATION program transitions to the advanced development funding category. Navy formally issues Advanced Development Objective 34-11X, "Defense Navigation Satellite Techniques." {Parkinson[20] p. 126}
8 October	1970	Fundamental GPS patent is filed for "Navigation System Using Satellites and Passive Ranging Techniques," inventor Roger Easton. System includes navigation satellites with extremely precise oscillators, and passive navigation user receivers, all of which produce multifrequency signals. Phase comparisons between satellite signals and local signals indicate range to the satellite and the navigator's location. (U.S. Patent 3,789,409, issued 29 January 1974)
8 October	1970	Patent is filed for "Apparatus And Method For Improving Sensitivity of Navigation System Using Earth Satellites," inventor Roger Easton. (U.S. Patent 3,763,492, issued 2 October 1973)
November/ December	1970	Time transfer experiments are successfully conducted between NRL and widely spaced sites in North America using the TIMATION II satellite. {NRL7559[73]}
	1971	Navy Space Project Office (PM-16) established. {Parkinson[20] p. 126}.
2 March	1971	TIMATION Development Plan is published "… to describe … a satellite position fixing and navigation system that meets the requirements promulgated by the Joint Chiefs of Staff (JCS) Navigation Study Panel in 1968. This navigation system provides continuous all weather instantaneous readout to an unlimited number and variety of users on a worldwide basis." {NRL7227[43] Abstract}
April	1971	TIMATION III design and fabrication begins to address DoD requirements with an experimental satellite demonstration. Ranging frequencies at 335 and 1580 MHz, with range tones to 6.4 MHz, give measurement precision of 1.5 meters. {Parkinson[20] p. 126-7}
8 May	1972	Aviation Week & Space Technology reports on Air Force proposal to "use four repeater satellites to demonstrate feasibility of projected world-wide satellite system" with satellites in synchronous and elliptical orbits. {Miller[44] p. 50, 51}
27 June	1972	NRL satellite system constellation study is published. Satellites are in circular orbits. {NRL7389[45]}

July	1972	First international time transfer between Royal Greenwich Observatory (RGO), England, and DoD Master Clock at United States Naval Observatory (USNO) is performed using the TIMATION II satellite. {Buisson[37] p. 277}
November	1972	Col. Parkinson is transferred to position of program manager at the Space and Missile Systems Organization (SAMSO) for USAF satellite navigation project 621B. {Parkinson[46] p. 2-3 of 17}
December	1972	Rubidium Frequency Standard prototype for TIMATION III satellite is received at NRL from Efratom Elektronik, Munich, Germany. {NRL7904[47], p. 1, 8, 9}
17 April	1973	Deputy Secretary of Defense renames the TIMATION III satellite to Navigation Technology Satellite I (NTS-1). {Klass[48]}
August	1973	Defense System Acquisition and Review Council (DSARC) declines navigation satellite proposal by individual service, and encourages multi-service approach. {Parkinson[20] p. 137}
September	1973	"Labor Day" weekend meeting is held to negotiate the makeup of a multi-service proposal for navigational satellites. {Parkinson[20] p. 137}
26 November	1973	Aviation Week & Space Technology reports that "adopting basically the Navy-proposed constellation arrangement has eliminated one of the major obstacles to Pentagon approval for the (NAVSTAR) program. This in turn has permitted a reduction of the estimated cost of deploying a limited, prototype system…" {Klass[48] p. 46}
17 December	1973	GPS-NAVSTAR Joint Program Office (JPO) is established; DSARC approves NAVSTAR Global Positioning System joint program, with elements of USAF 621B, Navy TRANSIT, and NRL TIMATION. {Parkinson[46, 20]}
22 December	1973	Deputy Secretary of Defense issues Memorandum approving Phase I development of GPS, with emphasis on Navy clock developments necessary for the program. {Clements[49]}
	1973	"NAVSTAR GPS Development Concept Paper No. 133, approved in 1973, called for NRL to continue the technology efforts begun in the TIMATION project. The (NAVSTAR GPS) system concept uses the same basic technique as the TIMATION system concept of passive ranging using precision clocks and a constellation of multiple satellites in circular orbits for worldwide coverage." {Parkinson[20] p. 129}
	1973	TIMATION III is renamed TIMATION IIIa to reflect a redesign to replace body-mounted solar panels with larger paddle style solar panes producing additional power for payload. {Parkinson[20] p. 126}
29 January	1974	Patent is issued for "Navigation System Using Satellites and Passive Ranging Techniques" (the basis of GPS navigation) invented by Roger Easton of NRL. (U.S. Patent 3,789,409, filed 8 October 1970)
April	1974	NRL worldwide TIMATION III Tracking Station Network is deployed, with stations in Maryland, Florida, Guam, Samoa and Seychelles Island. {Buisson[31]}
June	1974	Contractors are selected for the Phase I GPS program: Rockwell International for satellites, Magnavox and Hazeltine for user equipment under subcontract to General Dynamics who also were to develop the satellite control segment and ground-based pseudosatellites. {Parkinson[20] p. 137, see Table 5 p. 155}
14 July	1974	NRL TIMATION IIIa satellite is launched from Vandenberg Air Force Base {NRL7904 [47] p. 1} carrying the first orbital atomic clocks, which were space-qualified by NRL. The satellite's redesignation {DepSecDef memorandum[50]} as Navigation Technology Satellite I (NTS-1) is put into effect. {Amato[1] p. 211}, {Parkinson[20] p. 130}, {NRL7932[51] p. 1}
4 August	1974	An orbital atomic clock is activated for the first time, a rubidium atomic standard on board NTS-1. {NRL7932[51] p. 9-11}
19 November	1974	Director, Defense Research & Engineering, directs NRL to expand cesium clock development for use on subsequent satellites, and to develop hydrogen masers for ground use and for use in NTS-3 and subsequent satellites. {Currie[52]}

12 December	1975	Frequency stability results are published for on-orbit quartz and rubidium atomic oscillators. {NRL7932[51]}
December	1976	NRL worldwide NTS-2 Tracking Station Network is deployed, with stations in Maryland, Panama, Australia, England, and Seychelles Island. {Buisson[31]}
23 June	1977	NTS-2, designed and built by NRL, is launched carrying the first cesium atomic clocks. NTS-2 timing data are continuously transmitted by a side-tone ranging system and by a Pseudo Random Noise Subsystem Assembly (PRNSA). NTS-2 is the first Phase I demonstration for NAVSTAR GPS. NAVSTAR satellites 1 through 6 will complete the demonstration constellation. {NRL8360[32] p. 2, 5, 7}, {Buisson[53] p. 177}, {NRL8375[54] p. 1}
10 July	1977	The first cesium atomic standard to be used in space is successfully locked up on the first attempt on board NTS-2 at 1418 UTC. {NRL8232[55] p. 10, Figs. 7, 14}, {Buisson[53] p. 180}, {NRL8375[54] p. 2}
20 July	1977	The NTS-2 Pseudo Random Noise Subsystem Assembly (PRNSA) is activated. {NRL8232[55] p. 10}
4 August	1977	NRL verifies relativistic clock correction in space for GPS, using the NTS-2 cesium frequency standard. {NRL8232[55] p. 10-11, Figs. 16, 20}, {NRL8375[54] p. 3}, {NRL8419[56] p. 4-5}
October	1977	NTS-3 spacecraft is under development at NRL, and is scheduled to carry the first orbiting hydrogen maser frequency standard. {NRL8232[55] p. 1} The primary data type for all of the NRL technology satellites has been precise time difference measurements, which have been used for time transfer, navigation, and orbit determination. {Buisson[53] p. 177}
March	1978	NRL Tracking Station Network is discontinued. {Buisson[31]}
	1978	Colonel Thomas L. Thurlow Award for 1978 is presented to Roger L. Easton by the Institute of Navigation "For the Outstanding Contribution to the Science of Navigation in the Year 1978." {ION[57]}
17 July	1979	NTS-3 construction is terminated; NRL program is redirected to focus on space clock development for GPS. {NAVELEX Memorandum[58]}
	1991	Operation Desert Storm utilizes GPS under combat conditions, with 16 GPS satellites. {NRL[29] p. 1}
10 February	1993	National Aeronautic Association announces {NRL[59] p. 1} its award of the 1992 Robert J. Collier Trophy {NAA[60]} to GPS Team: • The United States Air Force • The United States Naval Research Laboratory • The Aerospace Corporation • Rockwell International Corporation and • IBM Federal Systems Company
December	1993	Initial Operational Capability of the GPS is declared. {McLaughlin[61] p. 25}
7 June	1995	Patent is filed, inventors C. E. Cohen, B. W. Parkinson, J. D. Powell, D. G. Lawrence, B. S. Pervan and H. S. Cobb, "System and method for generating precise position determinations." (Issued 5 November 1996, United States of America Patent 5,572,218.)
17 July	1995	Full Operational Capability of the GPS is declared by the U.S. Air Force Space Command. {McLaughlin[61] p. 43}
2 August	1996	Roger L. Easton is inducted into the GPS Hall of Fame. {Col. Clay[62]}
	1996	Naval Space Surveillance Center, Dahlgren, Virginia, establishes the Roger Easton Science and Engineering Award. {NRL[63]}
31 December	1996	TRANSIT system is decommissioned, to become the Navy Ionospheric Monitoring System (NIMS) the following day. {Kennedy[28] p. 28}, {Tucker[64] p. 66}

March	1996	Naval Research Laboratory establishes the annual Roger Easton Engineering Excellence Award. {Beard[65]}, {Coffey[66] p. 7}, {McKinney[67] p. 3}
14 November	1997	The Magellanic Premium Award of the American Philosophical Society, the oldest medal for scientific achievement awarded by a North American institution, is awarded for "Global Positioning System (GPS)" to Roger L. Easton and Bradford W. Parkinson. {APS[68]}
	1998	Space Technology Hall of Fame honors the Global Positioning System (GPS) by inducting Roger Easton, Bradford Parkinson, and other participants. {SpaceTechHallofFame.org[69]}
28 November	2000	PTTI Distinguished Service Award 2000 is presented to Roger L. Easton at the 32nd Annual Precise Time and Time Interval (PTTI) Meeting. {PTTI[70]}
13 February	2006	National Medal of Technology is conferred upon Roger L. Easton by President George W. Bush, "For his extensive pioneering achievements in spacecraft tracking, navigation, and timing technology that led to the development of the NAVSTAR-Global Positioning System." {NTM[71]}

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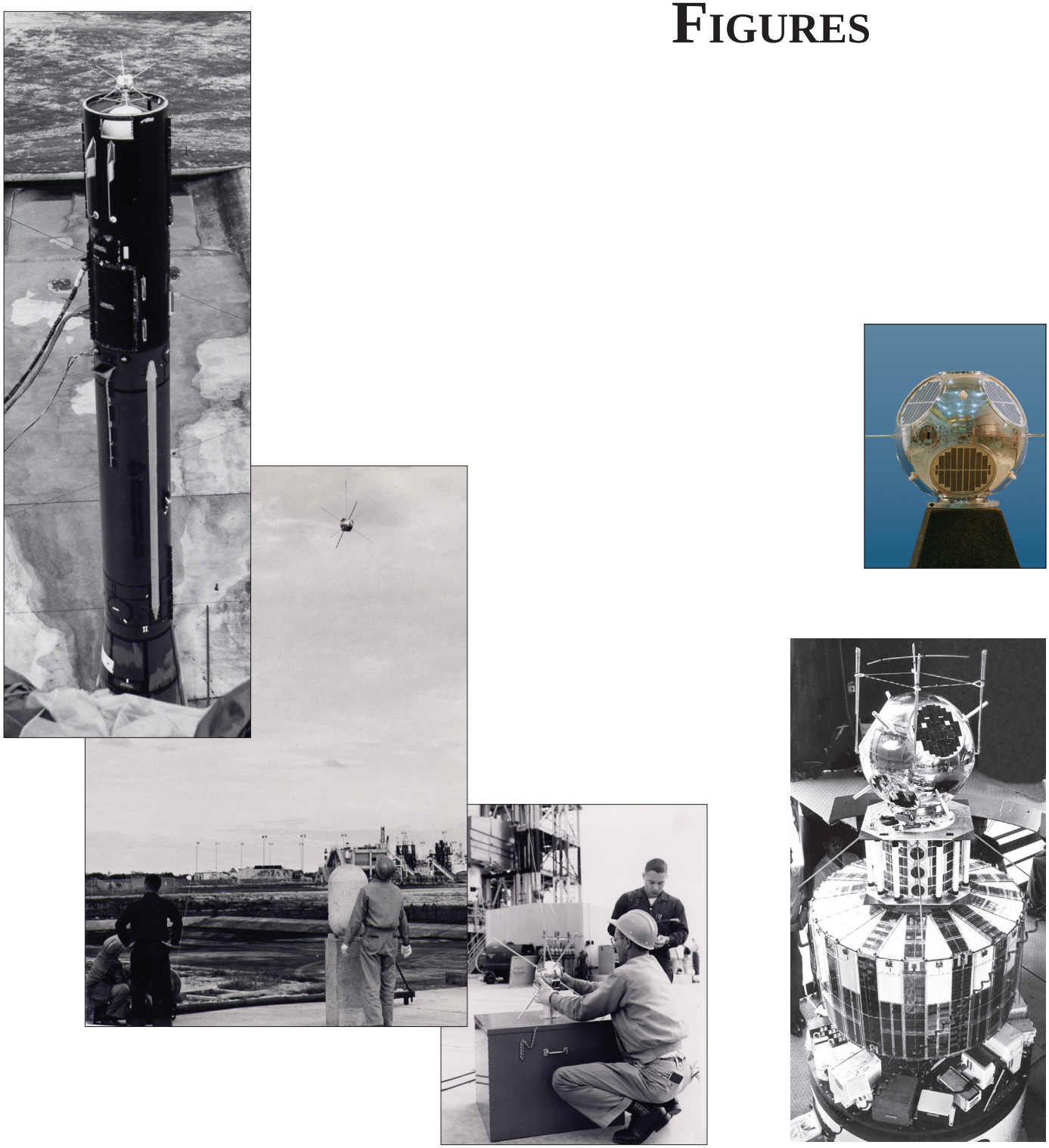
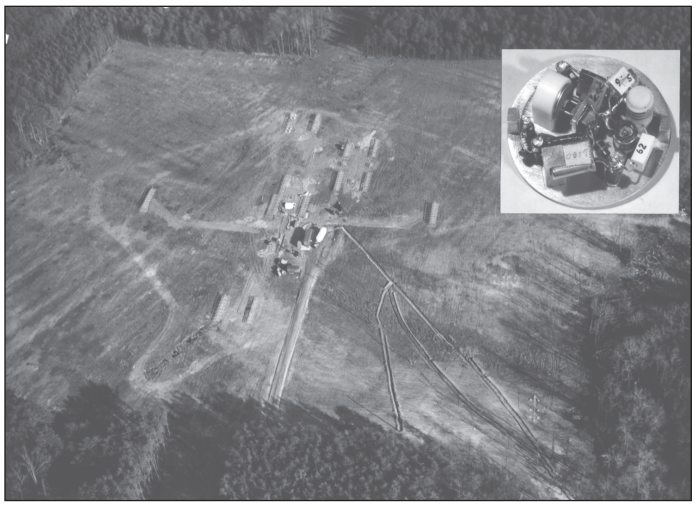
Topical Photographs and Figures



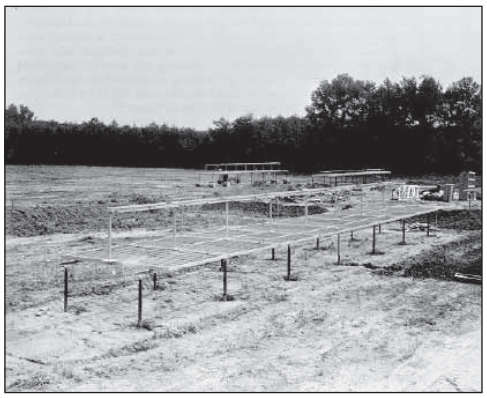
Early NRL Satellites. The NRL Vanguard Satellite (center) is raised into the air (left of center) for pre-launch testing under near free-space conditions. Upper left, the Vanguard Satellite, mounted on the launch vehicle. (NRL Photos) Upper right, the NRL GRAB/Solrad I satellite, the first NRL satellite after Vanguard, was orbited from the same booster as Transit IIA (satellite by Applied Physics Laboratory, not shown) on 22 June 1960 to accomplish the first multiple satellite launch. Lower right, GRAB2/ SolRad3 (top) mated with Injun (middle, by University of Iowa) and Transit 4A (bottom, by APL) atop Able Star #008. (GRAB Brochure[1])

MINITRACK

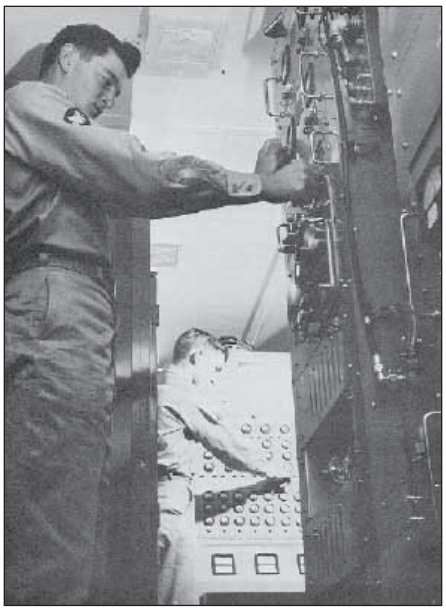
MINITRACK, an outgrowth of NRL experimental rocket programs, was a novel tracking system that did not require optical contact. The all-electronic system used ground receiver stations to determine the location of the flight vehicle carrying an onboard transmitter. MINITRACK was an important component of Vanguard.



MINITRACK, the tracking system for the Vanguard Satellite, was conceived and produced at NRL in 1956. Station at Blossom Point, Maryland, 1958. The crossed North-South and East-West tracking antennas can be seen. Inset shows Vanguard satellite continuous-wave transmitter and telemetry payload. (NRL Photo)



MINITRACK antenna arrays. (NASA SP-4202[2])



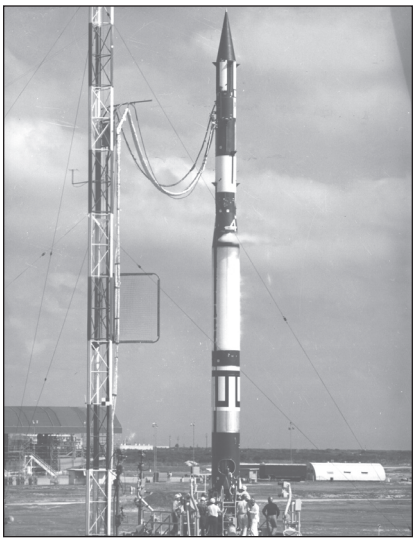
Interior of MINITRACK tracking van. (C. M. Green and M. Lomask, Vanguard: A History, NASA SP-4202,[2] NASA History Office, 1970)

MINITRACK operators. (NRL Photo)

Roger Easton taking MINITRACK data. (NRL Photo)

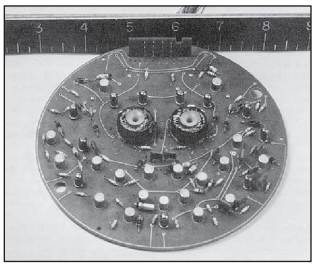
Vanguard

NRL's Vanguard Program was America's first program with a goal to launch an artificial satellite. The program schedule was announced in advance to coordinate with the International Geophysical Year. The Vanguard satellite, though not the first satellite to be launched, is the oldest man-made object remaining in orbit, and is expected to remain aloft for two millennia.

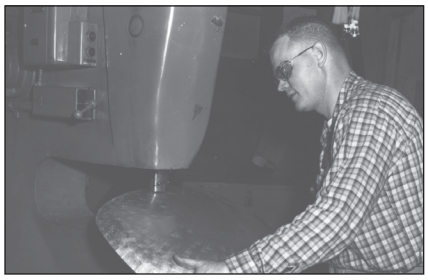


Crews ready Vanguard rocket for launch. (NRL Photo)

Blockhouse for Vanguard at Cape Canaveral. (NASA SP-4202[2])



Breadboard display of miniaturized components for Vanguard. (NASA SP-4202[2])



Metal worker prepares parts for Vanguard. (NRL Photo)

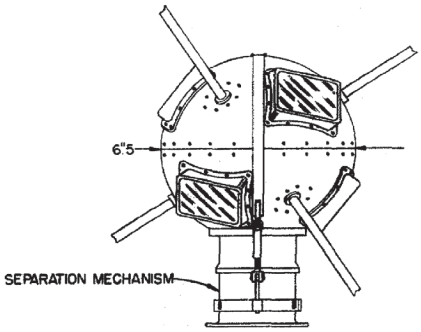
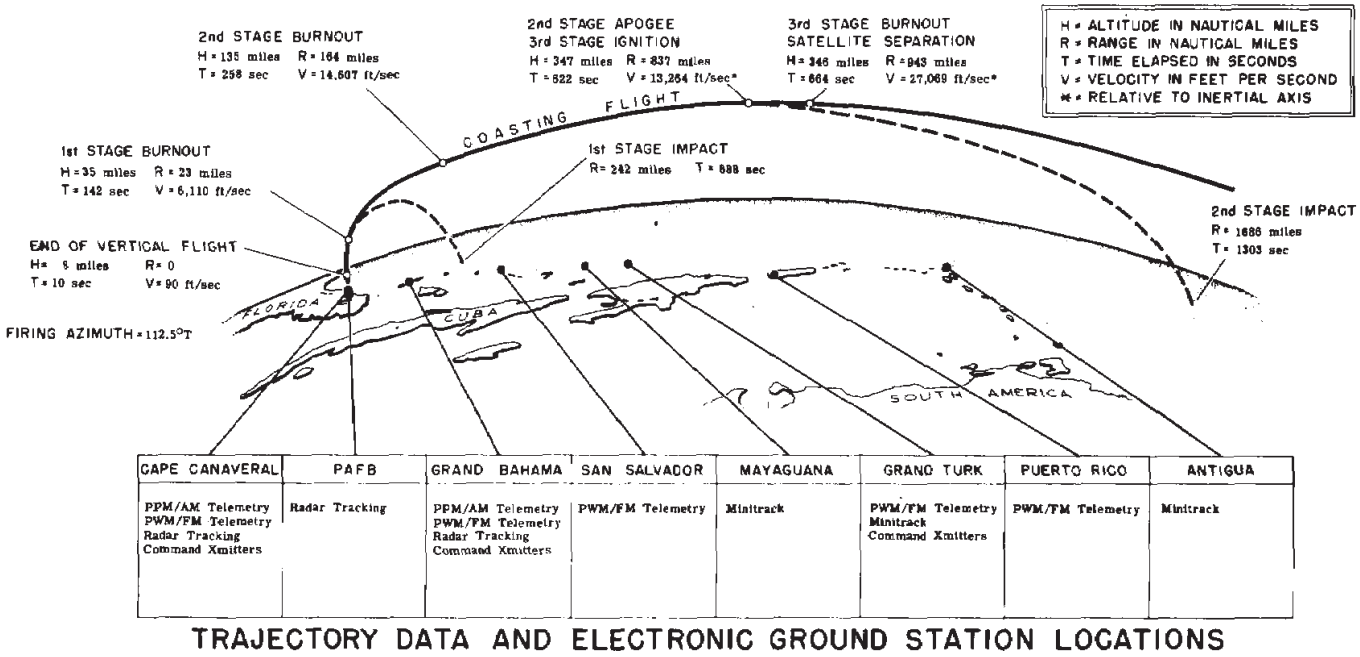


Diagram of the Vanguard I satellite. (NRL Figure[3])

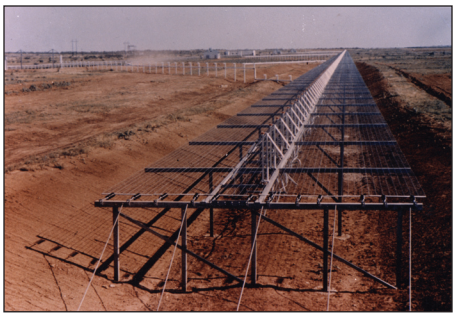
Vanguard nosecone being fitted into position prior to launch. (NASA SP-4202[2])



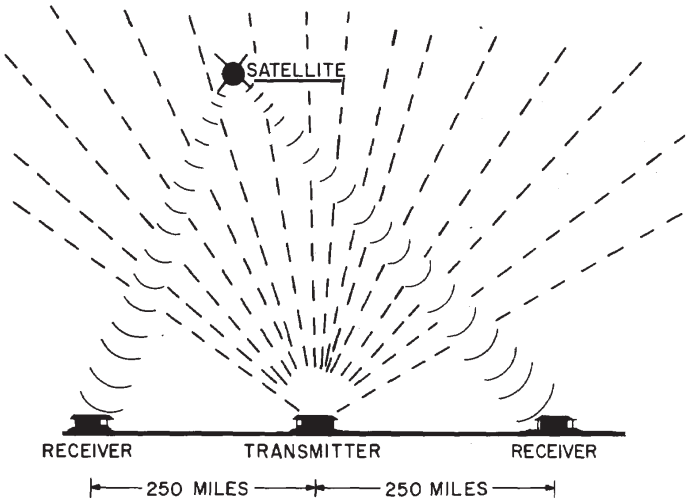
TRAJECTORY DATA AND ELECTRONIC GROUND STATION LOCATIONS

Naval Space Surveillance System

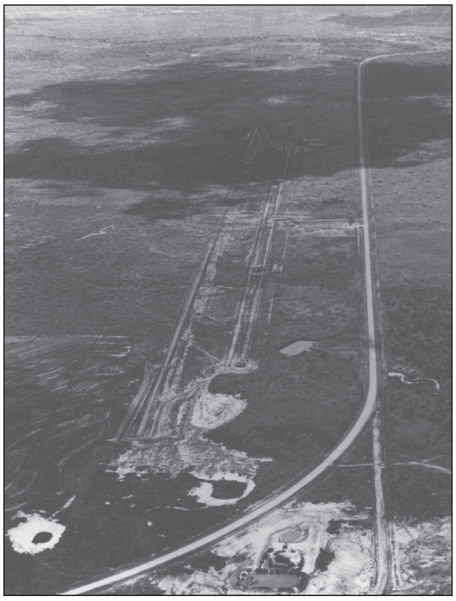
The Naval Space Surveillance System was conceived by Roger Easton to address the problem of determining the orbits of non-radiating satellites overflying the United States. The System remains operational today.



The largest transmitter in the system is located at Kickapoo Lake, Texas. (NRL Photo)



The Naval Space Surveillance System (NAVSPASUR) is a "bi-static" radar. The transmitters illuminate the target and the signals are reflected back to separately located receivers. Observations from two or more receivers are combined to calculate the position of the target. (NRL Figure)



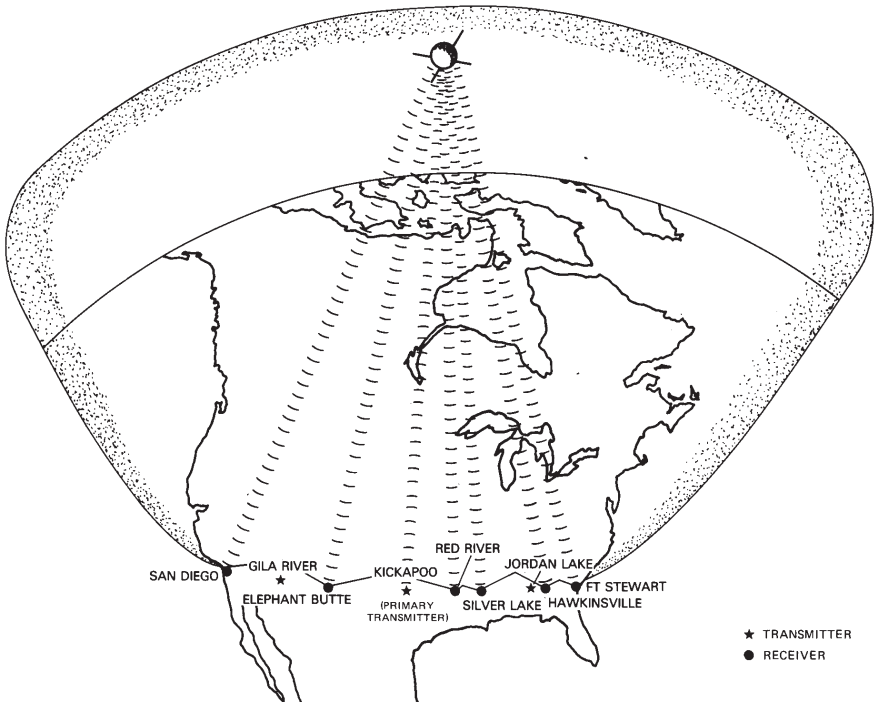
Aerial view of the newly built, 560,000 watt, satellite tracking transmitter with mile-long antenna at Kickapoo Lake. (NRL Photo)

Fifty kilowatt transmitter site at Jordan Lake, Alabama. (NRL Photo)

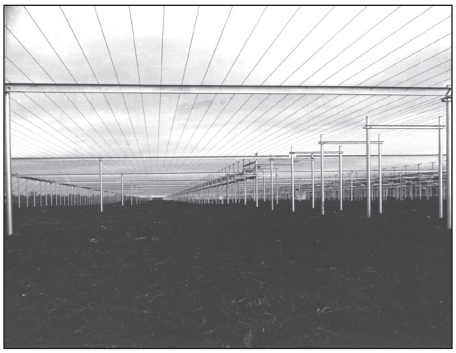
Antenna field at a Space Surveillance site. (NRL Photo)

Antenna array at a NAVSPASUR station. (NRL Photo)

Naval Space Surveillance System (continued)

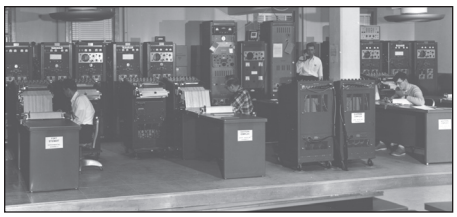


Map of the Space Surveillance System sites, and diagram of fan beam extending up into space. (NRL Figure)



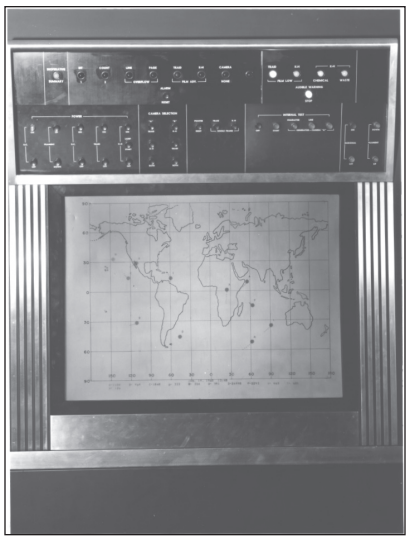
Silver Lake Space Surveillance receiver site. (NRL Photo)

Receiver site at Brown Field, Chula Vista, California. (NRL Photo)

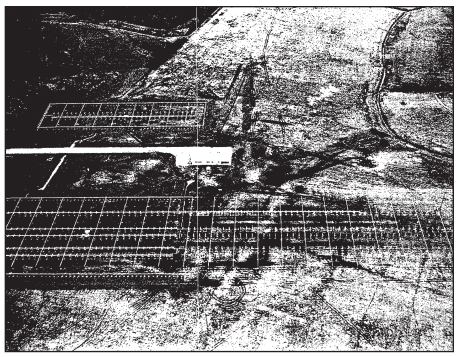


Space Surveillance System Operations Center, Dahlgren, Virginia. (NRL Photo)

NAVSPASUR communications center. (NRL Photo)



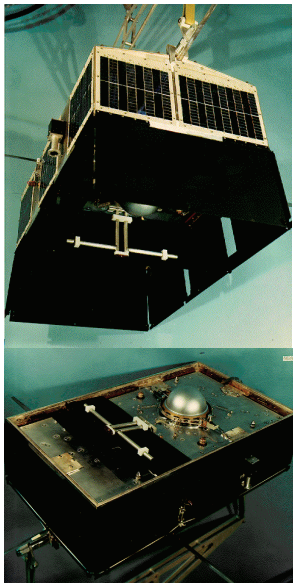
SPACECORE satellite map display for Space Surveillance System. Past, present, or future position of all known and selected satellites is updated by the minute. (NRL Photo)



Aerial view of a portion of the Silver Lake, Mississippi, receiver site. (NRL Photo)

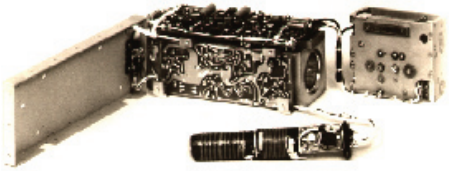
TIMATION I

Roger Easton of NRL conceived of a time-based passive navigation satellite system in 1964. He demonstrated his concept with the TIMATION I satellite, and pursued further development through a progression of navigation satellites.

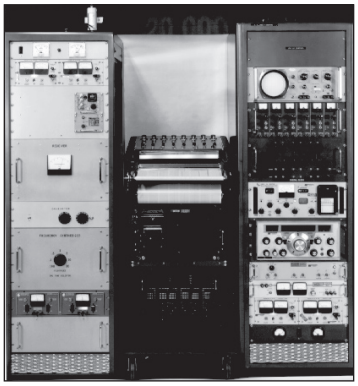


TIMATION I, bottom views. (NRL Photos)

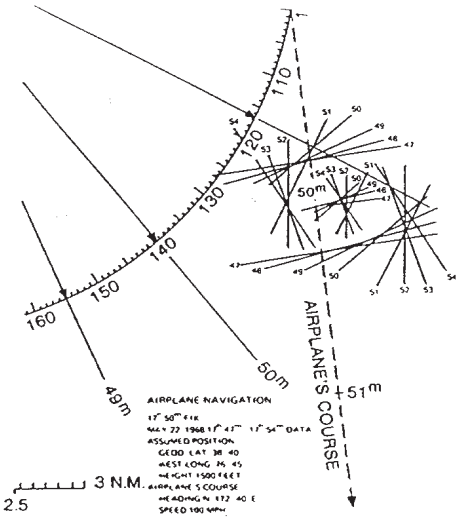
The quartz crystal. (NRL Photo)



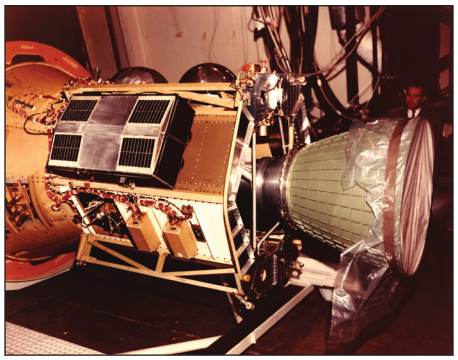
TIMATION I quartz crystal oscillator. The item at right is "Roger's Screwdriver," a rotary actuator for adjusting crystal frequency in space upon command from ground control. (NRL Photo)



Equipment racks for TIMATION I satellite operations. (NRL Photo)

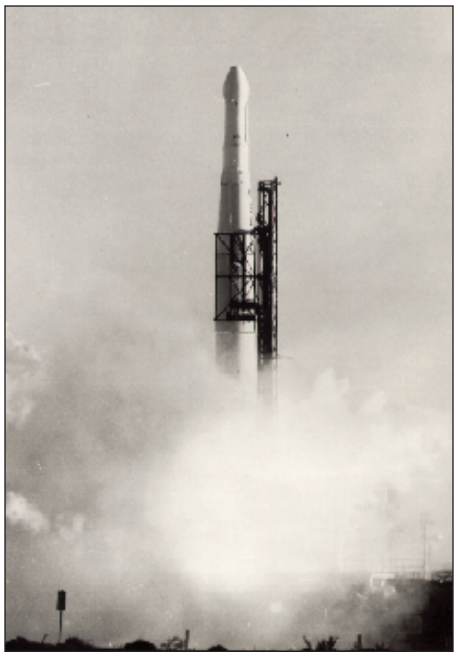


Graphical solution for aircraft position, using TIMATION I data. (Easton-1978[4])



TIMATION I on launch vehicle. (NRL photo) Launched: 31 May 1967. Operated: 2 years.

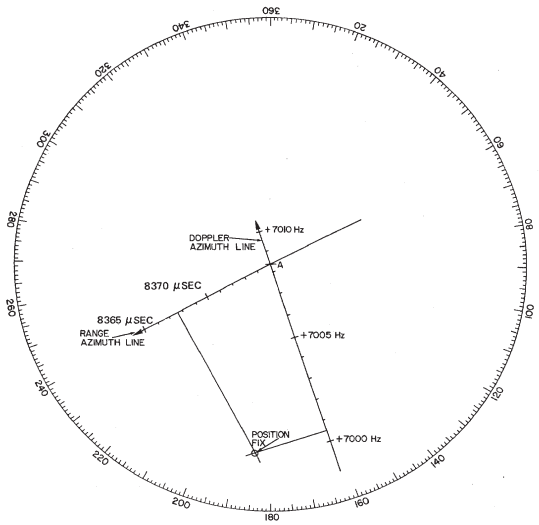
Erecting the TIMATION I launch vehicle. (NRL Photo)



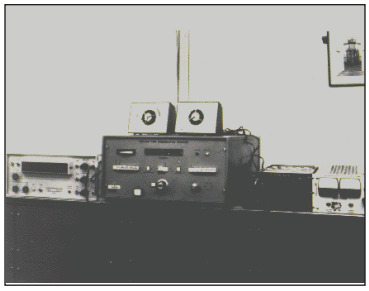
TIMATION I launch. (NRL Photo)

TIMATION II

The TIMATION II satellite carried an improved quartz clock with which effects of radiation in space could be observed. Sufficient power was available to sustain continuous operation. Dual frequency (150 and 400 MHz) operation enabled correction for ionospheric refraction.

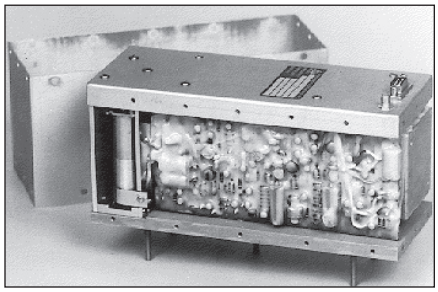


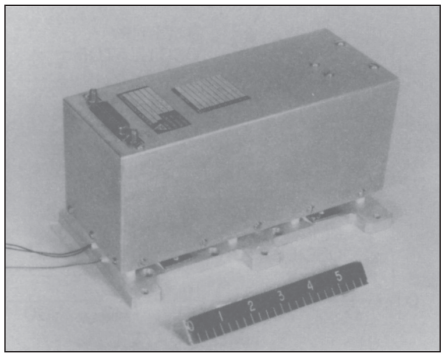
Graphical solution providing an instantaneous fix using range and Doppler measurements from TIMATION II. (NRL7252,[5] NRL7580[6])



TIMATION II receiver. (NRL Photo)

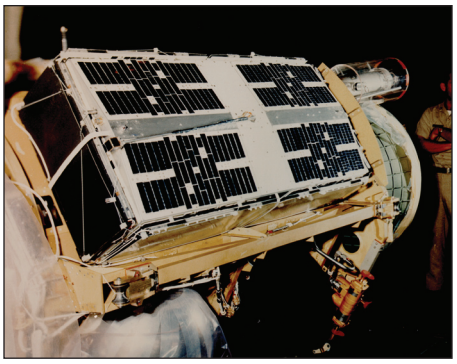
TIMATION II Tracking Sites:
- NRL-DC
- Maryland
- Florida
- Alaska
- Colorado





TIMATION II quartz crystal oscillators. (NRL Photos)

TIMATION II in the lab, with solar panels extended. (NRL Photo)

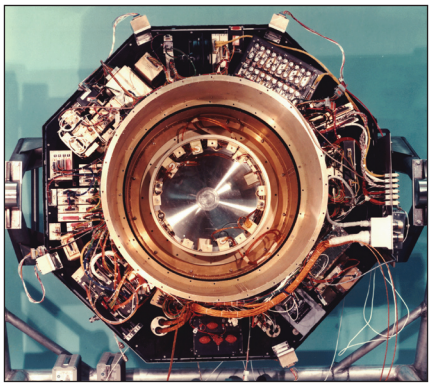


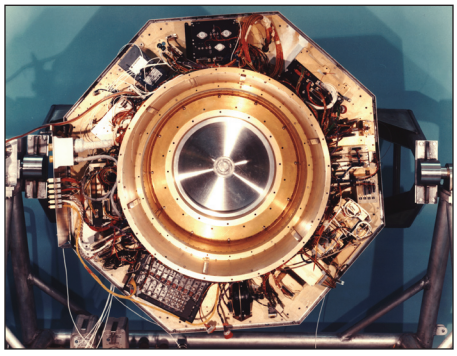
TIMATION II on launch vehicle. (NRL Photo) Launched: 30 September 1969. Operated: 6 years.

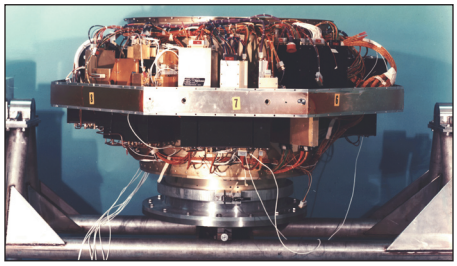
TIMATION II awaiting launch. (NRL Photo)

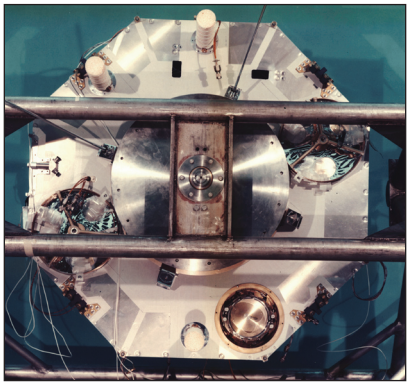
TIMATION III / NTS-1

The successes of the NRL TIMATION satellites provided a basis for a larger effort and a constellation of satellites. To secure broader support, a Joint Program Office was formed, the name NAVSTAR Global Positioning System was coined, and the forthcoming NRL satellite Timation III was renamed to Navigation Technology Satellite 1.

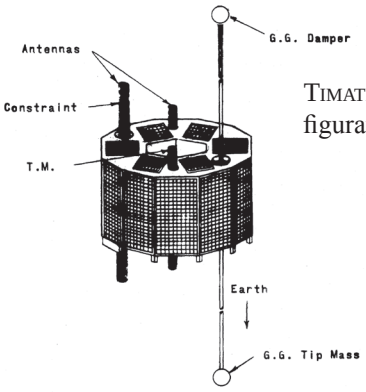






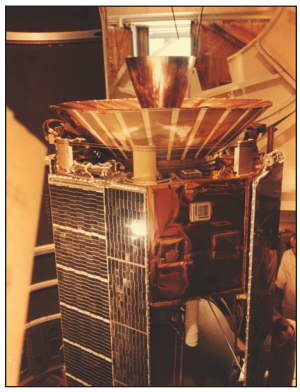


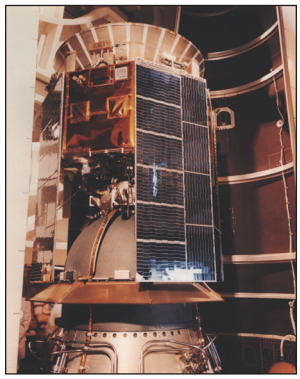
Various cutaway views of the TIMATION-III satellite. For a view of the top layer with solar cells, see page 139. (NRL Photos)



TIMATION III initially proposed orbit configuration. (Easton-1971[7])

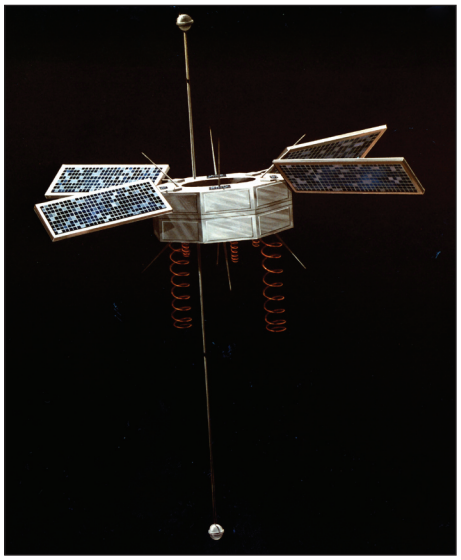
NTS-1 Tracking Sites:
- NRL-DC
- Maryland
- Florida
- Guam
- Samoa
- Seychelles Island





NTS-1 on launch vehicle. (NRL photo) Launched: 14 July 1974. Operated: 5 years, 3 months.

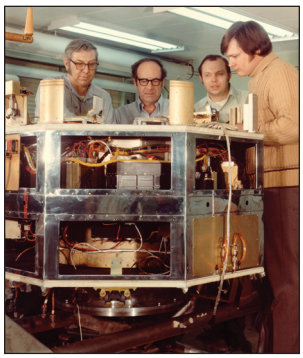
Atlas launch, similar to the launch of NTS-1, which launched through fog and could not be photographed. (USAF Photo)



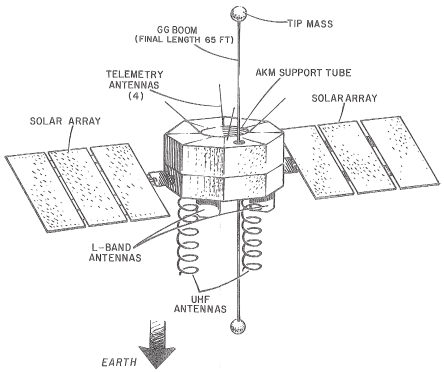
Artist's conception of TIMATION III in orbit. (NRL Photo)

NTS-2

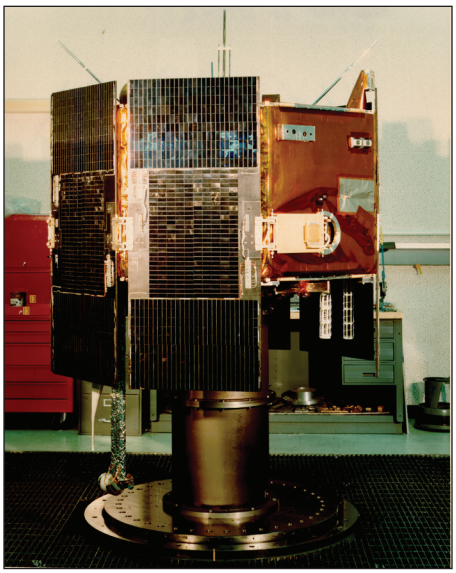
Navigation Technology Satellite 2 was NRL's final navigation satellite. The name TIMATION IV appears on some of the early NRL plans and reports, but was not officially applied to this satellite under the Joint Program. The NRL navigation satellites had successfully prepared the way for the GPS constellation to form. In fact, NRL's NTS-2 was the first satellite of the initial demonstration constellation of GPS satellites.



NTS-2 satellite on test stand at NRL. (NRL Photo)



NTS-2 satellite (*NTS-2* brochure[8]).

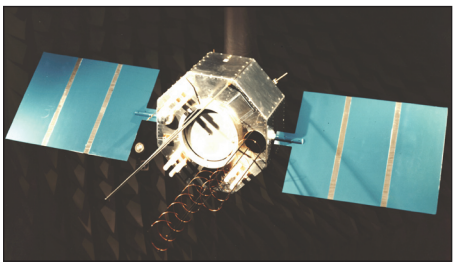


NTS-2 satellite on test stand. (NRL Photo)

Setting the satellite in NRL's large temperature-vacuum test chamber. (NRL Photo)

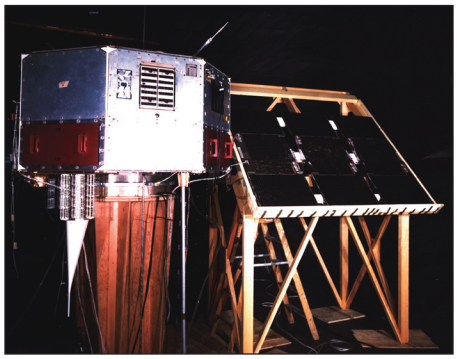
NTS-2 Initial Tracking Sites:
- Maryland
- Panama
- England
- Seychelles Island

NRL Tracking Sites were transitioned to GPS Monitor Sites.

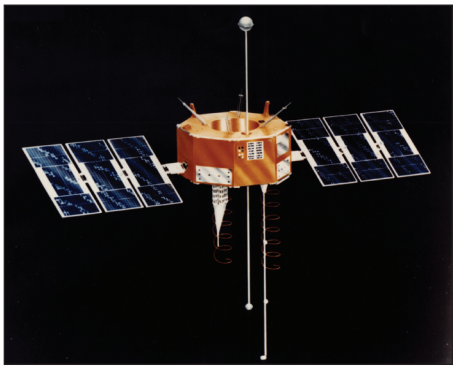


Satellite testing in NRL's anechoic chamber. (NRL Photo)

NTS-2 awaiting launch. (NRL Photo) Launched: 23 June 1977. Operated: 7 years.



Satellite test, with solar panels supported by fixture. (NRL Photo)

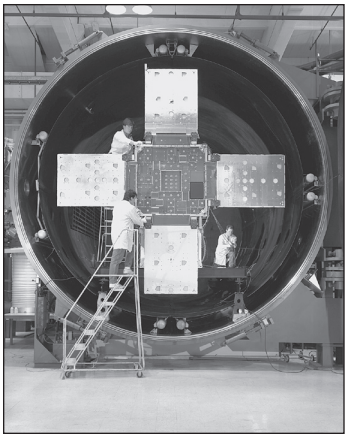


NTS-2, artist's conception. (NRL Photo)

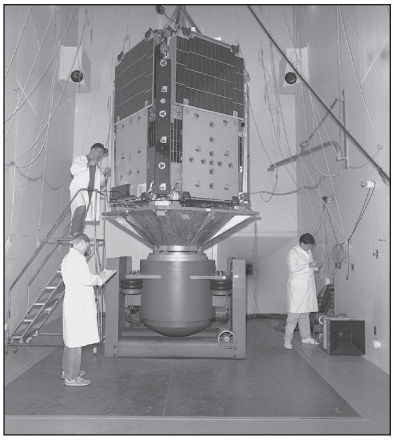
Test Facilities

NRL established and maintained an extensive Satellite Test Facility. Also of importance to TIMATION/GPS is the NRL Precise Clock Evaluation Facility. NRL's facilities are featured in the *NRL Major Facilities* publication.[9]

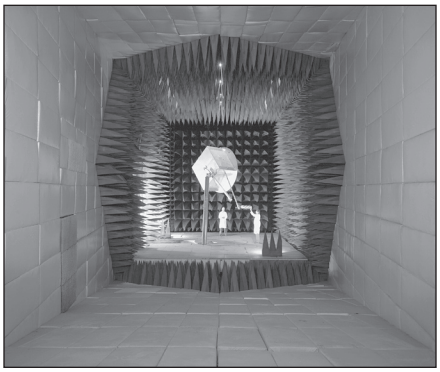
Satellite Test Facility



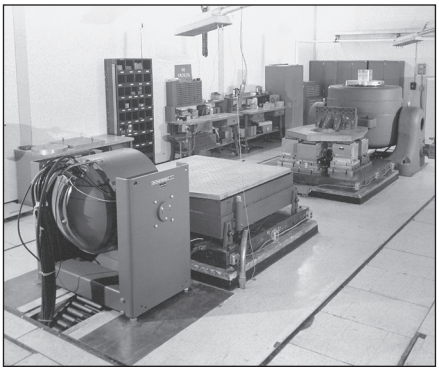
Large thermal-vacuum chamber, purchased prior to the development of the Navigation Technology Satellites. (NRL Photo)



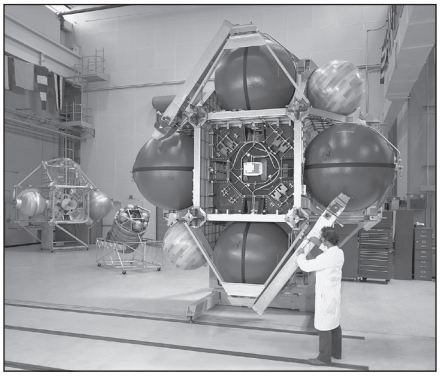
Acoustic test facility. (NRL Photo)



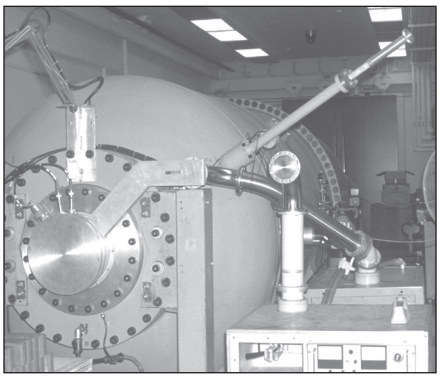
Anechoic chamber, in which NTS-2 was tested. (NRL Photo)



Vibration test facility. (NRL Photo)

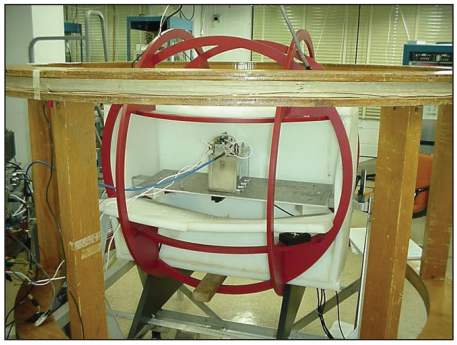


Space vehicle assembly area. (NRL Photo)



Environmental test chamber. (NRL Photo)

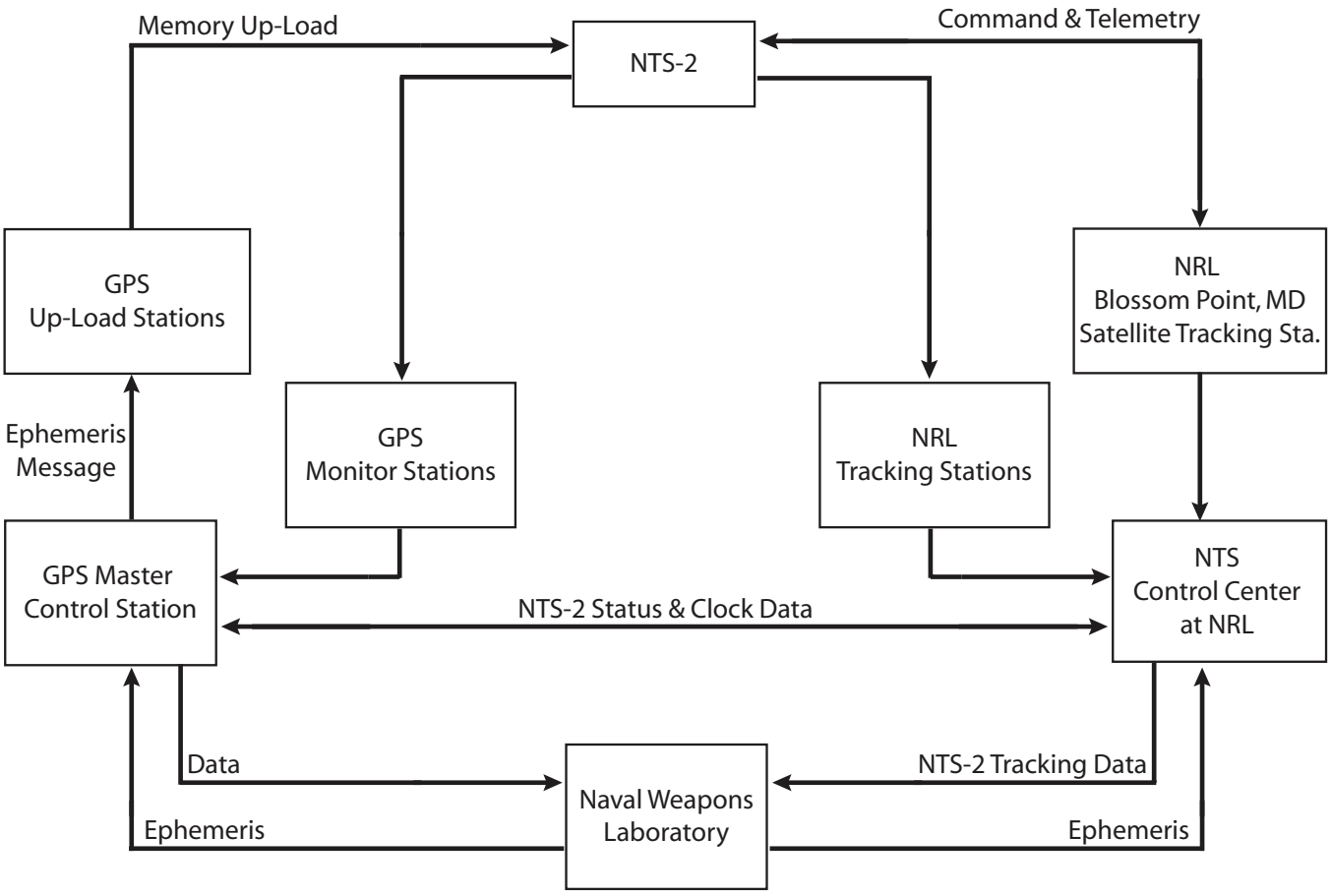
Precise Clock Evaluation Facility



A selection of PCEF equipment, from top: Reference Environmental Chamber, Large Thermal Vacuum Chamber, Three Axis Helmholz Coil, and Life Test. (NRL Photos)

Satellite Command and Tracking

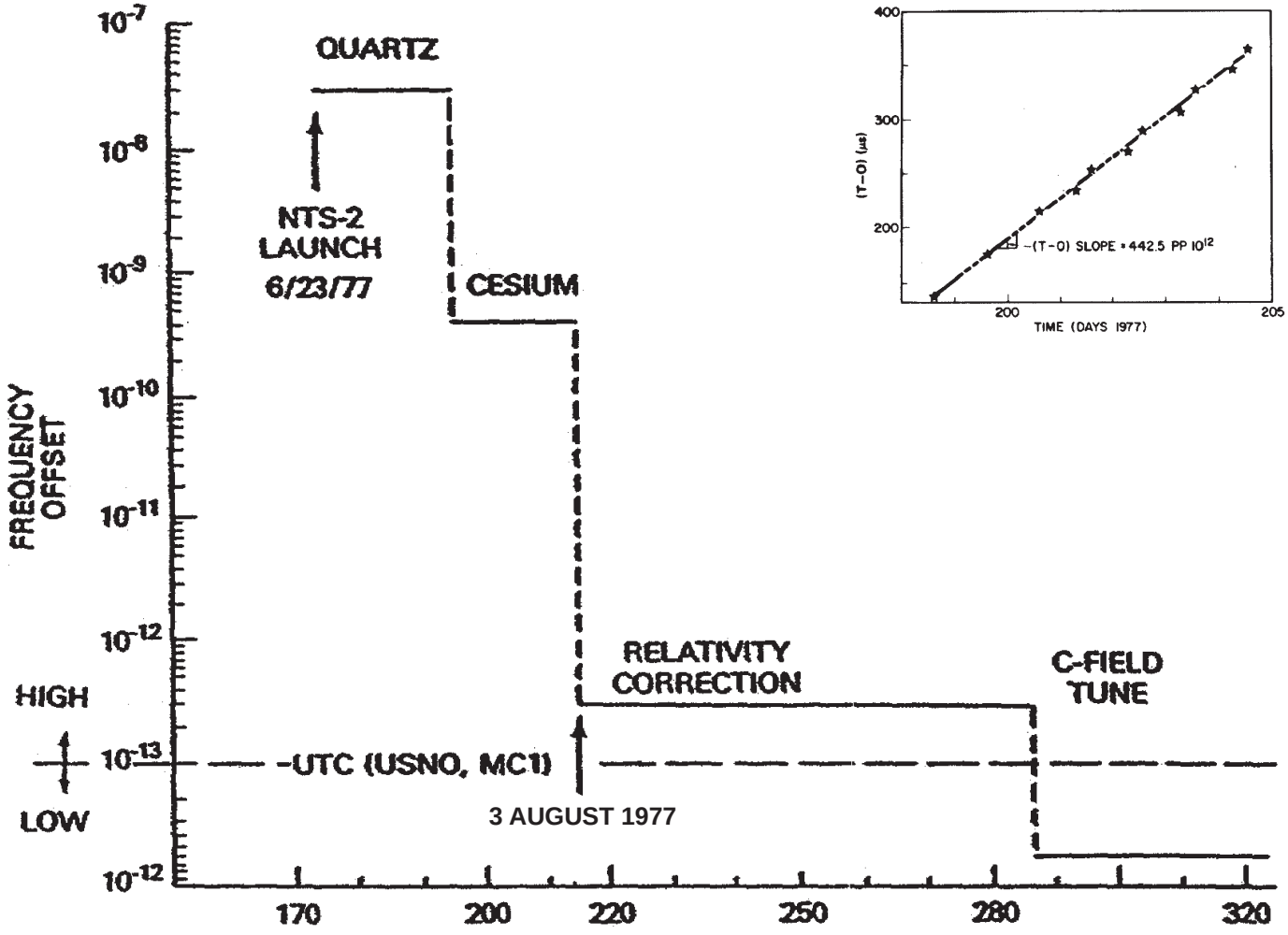
Components of the NRL satellite command, telemetry and tracking network were used for the TIMATION navigation satellites. The NRL role in satellite command, telemetry and tracking continued through the operation of NTS-2.



The tracking and telemetry for NTS-2 was performed by stations operated by NRL and located at Chesapeake Bay, Maryland, in the Panama Canal Zone, at the Royal Greenwich Observatory in England, and on Seychelles Island. Command messages were uplinked at the NRL Blossom Point site. Tracking information was fed into the NTS Control Center located at Naval Research Laboratory, where it was processed and sent out to the Naval Weapons Laboratory in Dahlgren, Virginia, where the satellite orbit and ephemeris were calculated. NWL sent these results back to the NTS CC, and to the GPS Master Control Station in Vandenberg, California. GPS ephemeris information was uploaded to the satellite through GPS Upload Stations. GPS Monitor Stations performed tracking functions in preparation for their becoming the operational tracking network when the NTS tracking network was phased out. (NRL8360, Figure 4[10])

Relativity and Space Clocks

According to the Theory of Relativity, the measured frequency of a clock, as measured on earth, will depend on whether the clock is at rest on earth, or traveling in space. The cesium frequency standards on board the NTS-2 satellite enabled the quantitative verification of this prediction for the first time.



The quartz-oscillator subsystem of one of the two cesium frequency standards on board the NTS-2 satellite was used during launch and orbit insertion. Before lockup by cesium standard 2, the quartz frequency was tuned to a value near the cesium resonance frequency. Cesium standard 2 locked up on the first attempt. The apparent clock rate was then measured by the NTS network to determine the relativistic clock offset. Inset presents the clock rate as measured from the NTS Panama station. After applying the correction for the Panama cesium clock on 7 August 1977, a difference of -1.9×10^{-12} was measured between the theoretical relativistic offset (445.0×10^{-12}) and the NTS-2 cesium frequency standard. These measurements verify the predicted relativistic clock effect to within 1/2 percent. (NRL8375[11] and NRL8419[12])

Instantaneous Navigation Mathematics

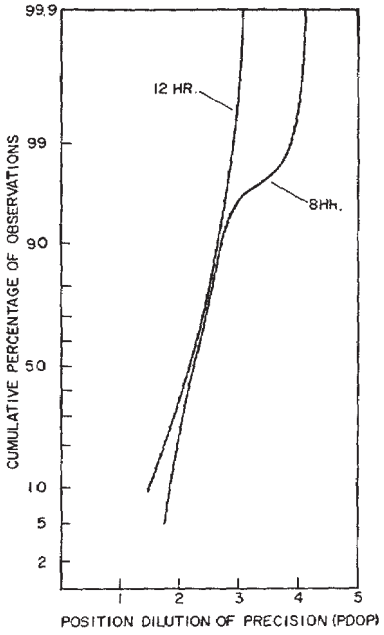
NRL formulated and implemented a solution to the problem of instantaneous navigation using artificial satellites by passive ranging.

$$\begin{bmatrix} N & \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial x_s} & \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial y_s} & \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial z_s} & 0 \\ \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial x_s} & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)^2 & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)\left(\frac{\partial (R_c)_i}{\partial y_s}\right) & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)\left(\frac{\partial (R_c)_i}{\partial z_s}\right) & 2x_s \\ \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial y_s} & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)\left(\frac{\partial (R_c)_i}{\partial y_s}\right) & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial y_s}\right)^2 & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial y_s}\right)\left(\frac{\partial (R_c)_i}{\partial z_s}\right) & 2y_s \\ \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial z_s} & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial x_s}\right)\left(\frac{\partial (R_c)_i}{\partial z_s}\right) & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial y_s}\right)\left(\frac{\partial (R_c)_i}{\partial z_s}\right) & \sum_{i=1}^{N} \left(\frac{\partial (R_c)_i}{\partial z_s}\right)^2 & 2z_s \\ 0 & 2x_s & 2y_s & 2z_s & 0 \end{bmatrix} \begin{bmatrix} \Delta K \\ \Delta x_s \\ \Delta y_s \\ \Delta z_s \\ \Delta g \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} (1)(O-C)_i \\ \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial x_s} (O-C)_i \\ \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial y_s} (O-C)_i \\ \sum_{i=1}^{N} \frac{\partial (R_c)_i}{\partial z_s} (O-C)_i \\ 0 \end{bmatrix}$$

Matrix formulation

Used for

four-dimensional instantaneous solution (x, y, z, t),
three-dimensional instantaneous solution with a good clock (x, y, z), and
two-dimensional instantaneous solution (x, y, t), with altitude constrained.
(NRL7252[5])



Evaluation of PDOP, showing clear advantage of 12-hour orbits for realizing the advantages of atomic clocks. (NRL7227[13])

Formulation of Dilution of Precision (DOP) measures

The fundamental equation for DOP studies at NRL was defined by Equation 50, NRL7252,[5] published in June, 1971. Different formulations of DOP were used, depending on the solutions of interest: 4D instantaneous, 3D instantaneous with good clock, or 2D with altitude constraint.

DOP results for the navigation satellite constellation study were presented in June, 1972, (NRL7389[14]) for the solutions listed above.

The Geometric Dilution of Precision (GDOP) represents the overall solution of uncertainty per unit of observation noise (McCaskill-1976, p. 170[15])

Additional DOP formulations were defined and used to measure particular uncertainties, for example, PDOP (position), VDOP (vertical, altitude, or Z-component), HDOP (horizontal), and TDOP (time).

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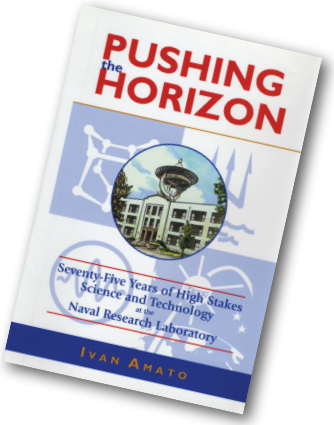

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The Magellanic Premium is "In recognition of essential contributions to creating the global positioning system, thereby making the tools for precision navigation available to everyone."

Presented to Roger L. Easton and Bradford W. Parkinson.

Presented the fourteenth day of November 1997 by The American Philosophical Society at Philadelphia for promoting useful knowledge. The Magellanic Premium was established in 1786 by John Hyacinth Magellan's gift. It is the oldest medal for scientific achievement awarded by a North American institution.

Magellanic Premium medallion of the American Philosophical Society, awarded to Roger L. Easton and Bradford W. Parkinson.

Applications Research Division, *Space Surveillance System - Technical Summary Report No. 1*, NRL Memorandum Report 896, Naval Research Laboratory, Washington, D.C., 31 December 1958.

A program to develop and install a system to detect and track non-radiating satellites was assigned to the Naval Research Laboratory in June 1958 by ARPA. Initially the program involved a feasibility experiment using a 50-kw continuous-wave transmitter and a Minitrack receiving system about 250 miles away. Both transmitting and receiving antennas were 400 feet long. The transmitter illuminates objects in space, and reflections to the receivers permit direction of arrival to be determined by an interferometer method. This system first gave a well-established reflection on 1958 Delta 2 on August 7, 1958.

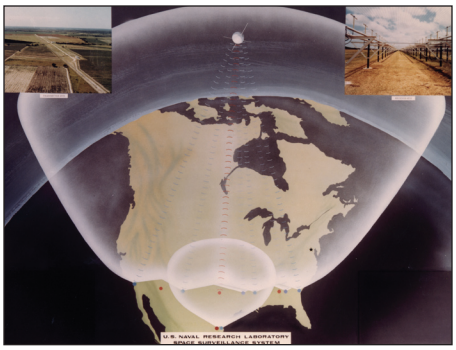
Steps taken to provide an operational capability include (1) adding a second receiver station to form a 3-station complex in the eastern part of the southern U.S. with the transmitter in the center, and (2) reproducing the complex in the western part of the U.S., with all six stations on a great circle. The full Eastern Complex has been operating since November 30, 1958. The Western Complex should be operating in January 1959.

Early results indicated the desirability for larger antennas to extend the system range. The western transmitter will use a 1600-foot antenna and one is programmed for the eastern transmitter in early February 1959. Site acquisition and planning at all stations have been based on a future need for larger antennas. The Fort Stewart receiving site, in the Eastern Complex, will receive a 1600-foot detection system in the next few months. It will also be provided with 400-foot sections whose polarization

Satellite tracking transmitter of the Naval Space Surveillance System, developed by the Naval Research Laboratory. (NRL Photo)

is at right angles to the main beam in order to evaluate the loss of signals resulting from polarization rotation in passing through the ionosphere.

The receiving stations record signals continuously. This information is analyzed to evaluate the system by correlating signals with known satellite data. Correlations have been based upon time-and-look-angle correspondence with predicted passes. Only recently has the system performance been established to the point where precise analysis can be applied. The full operation of the Eastern Complex now permits height determination by triangulation, indicating excellent results in the case of the 1958 Zeta data analyzed to date.



Naval Space Surveillance System. (NRL graphic)

Applications Research Division, *Space Surveillance System - Technical Summary Report No. 2*, NRL Memorandum Report 954, Naval Research Laboratory, Washington, D.C., 30 June 1959.

All six stations of the U.S. Navy Space Surveillance System have been on a 24-hour-per-day operation since February 17, 1959. All known satellites have been observed including the third-stage rockets of the two Vanguards. A total of 407 satellite passes have been recorded, of which 14 were observed simultaneously at the two receiver stations of a Complex. Since June 1, 1959, an Operations Center at the Naval Proving Ground has been in full-time operation receiving four channels of analog data from each receiving station. The NORC computer at NPG has provided line crossing predictions since March 26, 1959.

Both transmitters are operating with 1600-foot antennas and all receivers with the planned 400-foot antennas, except for Fort Stewart where 1600-foot receiving antennas have been installed with larger baselines and more complete dual polarizations. This antenna installation will be evaluated for improvements resulting from its features.

Applications Research Division, *Space Surveillance System*, NRL Report 5419, Naval Research Laboratory, Washington, D.C., October 1959.
NRL5419 LIMITED DISTRIBUTION

Applications Research Division, *Space Surveillance System - Technical Summary Report No. 3*, NRL Memorandum Report 1025, Naval Research Laboratory, Washington, D.C., 31 December 1959.

The U.S. Navy Space Surveillance System consisting of two transmitting and four receiving stations and the Operations Center at Dahlgren, Virginia, continued 24-hour-per-day operation throughout the reporting period. Of a total of 1280 satellite passes recorded by the system, 421 were simultaneously observed by 2 receiving stations, and 3 were observed simultaneously by three stations.

Tatnall NAVSPASUR station. (Photo by Chester J. Kleczek. Used by permission)

In view of the potential threat of Soviet reconnaissance satellites to compromise the security of fleet operations, the Chief of Naval Operations has directed the Naval Research Laboratory to provide the operating fleets with instructions and ephemeris data for Soviet satellites based on Space Surveillance System observation. The NORC computer programs have demonstrated their capability of producing weekly ephemeredes based solely on such observations. By the end of a week, prediction errors for the current Soviet satellite 1958 Delta 2 have not exceeded 20 to 35 seconds of time at the surveillance line. Although analytical methods have been used to make beam-crossing predictions for this satellite with errors less than 5 seconds of time for two weeks in the future, the NORC performance is considered acceptable since this satellite orbit is rapidly degenerating due to atmospheric drag. The fleet uses 1958 Delta 2 as a training vehicle for developing fleet countermeasures and evasive tactics.

Both transmitters continued to operate at 50kw with 1600-foot antennas. All receiving stations were operated with 400-foot antennas during this reporting period. The 1600-foot receiving antennas at Fort Stewart are expected to be put into service in January 1960.

A preliminary survey for installation of a central transmitter at Lake Kickapoo near Wichita Falls, Texas, was completed but further efforts to fill the gap in the center of the present single detection line had to be suspended pending ARPA funding.

Applications Research Division, *Space Surveillance System - Technical Summary Report No. 4*, NRL Memorandum Report 1078, Naval Research Laboratory, Washington, D.C., 30 June 1960.

The U.S. Navy Space Surveillance System consisting of two sensor complexes, one in the eastern portion and one in the western portion of the United States, and the Operations Center at Dahlgren, Virginia, continued 24-hour-per-day operation throughout the reporting period. The increase in number of satellites in orbit has produced a corresponding increase in number of observations. A total of 2080 passes on 24 different satellites were recorded during the past six months.

Funds have been supplied to complete the automatic digital data processing, installation of an alert system at all receiving stations, and installation of 1 500-kw transmitter in the center of the line.

The 1600-foot receiving antennas at Fort Stewart have been evaluated and put into operation. Also, at Fort Stewart, the loss of passes as a result of using a single linear polarization has been evaluated. Indications are that of the total passes received on two orthogonal polarizations, 25 percent are missed on either of the single linear polarized systems.

Comparison of signals received by reflection from meteor trails at frequencies of 432 and 108 Mc indicates very few reflections at the higher frequency compared to those at 108 Mc.

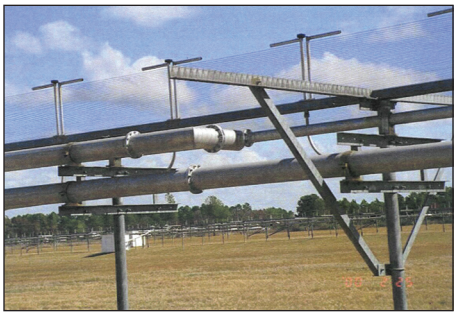
Tatnall NAVSPASUR station. (Photo by Chester J. Kleczek. Used by permission)

Applications Research Division, *Space Surveillance System - Technical Summary Report No. 5*, NRL Report 5756, Naval Research Laboratory, Washington, D.C., 1 March 1962.

The U.S. Navy Space Surveillance System now comprises seven stations on a great circle path across the Southern United States. Activation of the central 560-kw transmitter in June 1961 and narrowband receiving equipment at all four receiver sites has greatly increased the system capability. Currently, the system makes about 700 observations per day and produces orbital elements on over 100 different orbiting objects.

Initial orbital elements obtained from the first satellite pass through the system are based on position, determined by triangulation from two or more receiver stations, and velocity derived by measuring rate of change of phase between the two antennas of a long-baseline interferometer. These data are expected to determine the period to within 5 percent and inclination to 0.5 degree when baselines of one-mile length are completed. The elements are refined in three further steps: two successive passes, passes from the two sides of the orbit, and finally by a differential correction computer program using several days of observations. This final refinement produces the system output in terms of orbital elements usable for any location around the world. They are routinely used to predict future passes of known satellites through the line. Their accuracy is such that currently the passage of stable satellites can be predicted to within one second in time for a week in advance.

Development of automatic data processing using digital techniques is progressing satisfactorily. This system is expected to be operating in the summer of 1962. It will use an IBM 7090 computer on line to produce orbital elements within seconds of the satellite pass through the system. The system capacity will be limited only by computing time and is initially being programmed for a population of about 1500 satellites. Planned extensions and refinements permit handling up to 10,000 satellites before requiring a new higher speed computer.



Tatnall NAVSPASUR station. (Photo by Chester J. Kleczek. Used by permission)

G. W. Arnold, Jr., "Defects in Quartz Crystals," in *10th Annual Frequency Control Symposium*, held at Fort Monmouth, NJ, 15-17 May 1956, 60-74.

Roger Easton (left) and his deputy Al Bartholomew. (NRL Photo)

Optical absorption data are presented on the effects of various impurities when incorporated in the synthetic quartz lattice. These impurities include aluminum, germanium, boron, titanium, chromium, tin and lead. Specifically, the absorption maxima induced by ionizing radiations have been studied as a means of formulating ideas as to the nature of the defects in quartz. Certain of these maxima are found to be regularly present in all of the samples studied, while others appear to be related to specific impurities.

Some observations on easily observable growth features in Y-bar quartz are given.

G. W. Arnold, Jr., "Defects in Quartz Crystals," in *Eleventh Annual Symposium on Frequency Control*, held at Asbury Park, New Jersey, 7-9 May 1957, US Army Signal Engineering Laboratories, Fort Monmouth, NJ, 112-29.

While making routine investigations of polished quartz surfaces, it was observed that rather striking growth features could be seen when such surfaces were viewed by transmitted light and under low magnification.

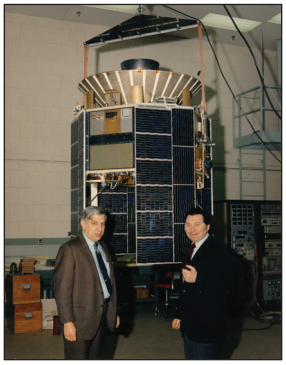
A. W. Baldwin and C. Carson, *The Design of an Inexpensive Multi-Channel Programmed Recorder*, NRL Memorandum Report 2021, Naval Research Laboratory, Washington, D.C., July 1969, 12 pp.

A requirement for a low-cost two channel recorder (under $500.00) has been met in the design of a Polaroid-camera-oscilloscope combination programmed for a six-second record shot. The particular signals recorded are five channels of analog (voltage levels) information which has been sequence commutated prior to recording. The above signals had been previously recorded using a two-channel pen recorder and associated event markers.

C. A. Bartholomew, *Quartz Crystal Oscillator Development for Timation*, NRL Report 7478, Naval Research Laboratory, Washington, D.C., 25 October 1972. NRL7478 LIMITED DISTRIBUTION

C. A. Bartholomew, "Timation III Satellite," in *Proceedings of the Fourth Annual Precise Time and Time Interval (PTTI) Planning Conference*, held at Goddard Space Flight Center, 14-16 November 1972, NASA Report X-814-73-72, 7-13.

This satellite is the third in a series of experimental satellites designed to investigate and demonstrate the techniques of a satellite navigation system. Timation III is designed to measure the error budget for a proposed system and provide one element of a navigation demonstration experiment. Table I lists the principal characteristics of the three satellites and shows the progressive development of the program.



Roger Easton (left) with Timation III / NTS-1 satellite.

C. A. Bartholomew, "Atomic Oscillators for Space Systems," in *Electronics and Aerospace Convention EASCON 74 Record*, held at Washington, D.C., 7-9 October 1974, 403, 403A-403C.

Contemporary space systems demand improved stability in frequency standards. The status of currently available atomic clock oscillators for space is discussed along with trade-offs on performance and cost. Some of the developments in progress as well as those planned for the future are also covered.

Timation is a program conceived at NRL in 1964 to prove that a passive ranging technique combined with accurate clocks could provide the basis for a satellite navigation system with worldwide three dimensional coverage. In 1973 this effort was merged with a DOD, Air Force managed program called the NAVSTAR Global Positioning System (GPS). To date three satellites have been flown in this program: Timation I in 1967, Timation II in 1969 and Timation III (now designated Navigation Technology Satellite One, NTS-1 under GPS) on July 14, 1974. Figure 1 is a comparison of the characteristics of the three satellites along with those projected for NTS-2, the next satellite in this program. This figure shows progressive improvement in oscillator stability with succeeding satellite

as the program has progressed. The early satellites used the quartz crystal oscillator as the frequency standard principally because of size and weight limitation and its high reliability.

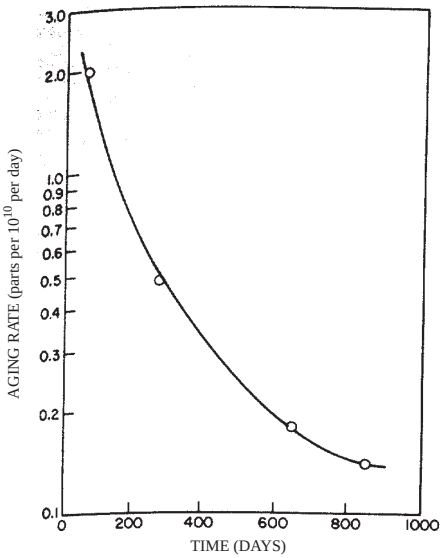
C. A. Bartholomew, "Navigation Technology Satellite I," in *Proceedings of the Sixth Precise Time and Time Interval (PTTI) Planning Meeting*, held at U.S. Naval Research Laboratory, 3-5 December 1974, NASA Report X-814-75-117, 499-501.
The NTS-1 satellite was launched on July 14, 1974. This spacecraft is one of a series of technology satellites to be launched in support of the NAVSTAR GPS Program. NTS-1 was designed to verify the error budget and measure related performance factors including a commercial rubidium vapor frequency standard modified for space conditions. A description of this spacecraft and preliminary performance data will be discussed. (Talk was delivered, evidently by Captain Holmes, who afterward fielded questions. Paper not received for publication.)

C. Bartholomew, "Navigation Technology Satellite Two," NRL Research & Development Highlights **3** (4), 1-2 (1976).
LIMITED DISTRIBUTION: FOUO

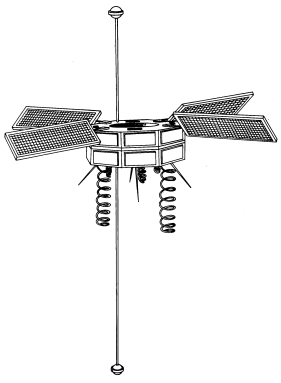
C. A. Bartholomew, "Satellite Frequency Standards," Navigation: Journal of The Institute of Navigation **25** (2), 113-20 (1978).
Satellite Frequency standards have progressed from quartz oscillators used in Navy Navigation Satellite System (NNSS) satellites and early TIMATION launches to rubidium units used in the NTS-1 of NAVSTAR GPS, cesium units in NTS-2, and hydrogen maser units projected for NTS-3.
The reasons that a large NRL effort has been made is that the character of satellite navigation systems has changed.
The NNSS operates on a navigation technique suitable for objects having well known velocities. The parameter used is frequency; the satellites operate at low altitudes so the passes last only for 15 minutes or so. The frequency stability of the satellite clock must be such that the change in frequency does not introduce appreciable error in position fix.
The NAVSTAR GPS is designed to give positions continuously in three dimensions. To do so it uses satellites in much higher altitudes than NNSS. At these altitudes continuous fixes by means of frequency measurement is impractical so ranging is used instead. Since a further requirement is that the user be passive the ranging measurement is obtained by having all satellites have clocks that are synchronized so the user can make measurements on enough satellites that he can determine the clock synchronization parameters. The problem of clock synchronization without near continuous updating of the satellite clocks has determined the search for better satellite clocks, programming through quartz, rubidium, cesium, and now hydrogen maser standards.

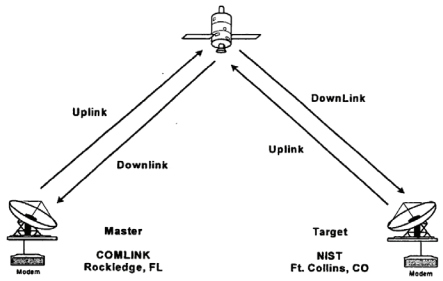
C. A. Bartholomew, "Clocks: Evolution of Frequency Standards," *NATO AGARDOGRAPH, Principles and Operational Aspects of Precision Time Determination Systems*, C. T. Leondes, ed. (Neuilly-sur-Seine, France, July, 1979).
The clocks currently in use in NAVSTAR GPS Technology Satellites and those planned for future phases of the program are the result of a continuing evolution in clock technology. This evolution is a result of the desire to improve clocks in general and more specifically by the change in character of satellite navigation systems and the need for improvement in clock technology to meet the requirements of such systems. This paper describes the evolution as seen from one program.

C. A. Bartholomew, "Satellite Frequency Standards," *Global Positioning System: Papers Published in Navigation*, (Institute of Navigation, 1980).
Reprint. For abstract, see the original journal article (C. A. Bartholomew, "Satellite Frequency Standards," Navigation: Journal of The Institute of Navigation, 1978, 25/2, 113-20).

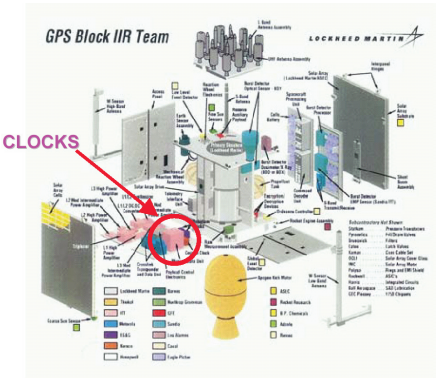


Aging rate of an oscillator of TIMATION I class. (Bartholomew-1978 p.115)


TIMATION III satellite. (Bartholomew-1972, p.9)



Basic two-way time transfer link. (Beard-1997, p.258)



GPS Block IIR satellite layout, with clock location indicated. (Beard-2002, p. 1 of 6)

R. L. Beard, J. Murray and J. D. White, "GPS Clock Technology and Navy PTTI Programs at the U.S. Naval Research Laboratory," in *18th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, 2 December 1986, 37-53.

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.

R. L. Beard, F. Danzy, E. Powers and J. D. White, "Test and Evaluation Methods at the NRL Clock Test Facility," in *43rd Annual Symposium on Frequency Control*, 31 May - 2 June 1989, IEEE, 275 -288.

The Space Applications Branch of the Naval Research Laboratory has developed a special Clock Test Facility to evaluate atomic clocks developed for space and ground application. The facility itself will be described and the methodologies involved in long-term performance testing, initial qualification testing of spacecraft clocks and post-acceptance testing of candidate spaceflight clocks to be evaluated in orbit. The objective of long-term testing is to build a performance and reliability database on newly developed clocks to support eventual operational system acceptance. Initial qualification testing for developing clocks is used to guide development under contract and to support in-house design of components, subsystems and experimental atomic clocks. Typical testing procedures and methodologies will be discussed. The purpose of testing spaceflight clocks is to perform ground testing beyond current acceptance tests of flight candidate cesium beam frequency standards. The additional data will provide a better understood clock for GPS applications by extending the available baseline data, and could result in pre-flight detection of latent defects. Latent defects as used here, represent weaknesses which could result in a much higher piece part failure rate than that indicated by predictive analysis. The procedures of the post-acceptance testing are designed to maximize the amount of available data on a clock while limiting the total amount of usable life consumed in testing. A special experiment, known as the Benign Environment experiment, will be described. This experiment will be designed to quantify the environmental effects on atomic clocks in space. A question has been raised in the evaluation of atomic clocks in the GPS satellites, in that they appear to be performing better in orbit than they did in ground testing. An approach to answering this question will be described along with the means of parameterizing even small effects ordinarily ignored in ground testing.

R. L. Beard, "The Role of Precision Clocks in Satellite Navigation (Abstract only)," presented at the NAV 89 Satellite Navigation, the 1989 International Conference of the Royal Institute of Navigation, London, 17-19 October 1989.

(ABSTRACT ONLY) The advances in satellite navigation capabilities can be traced to the development of highly stable, precision clocks for satellites. The new NAVSTAR Global Positioning Systems (GPS), which is in the operational deployment phase, is dependent upon small, highly stable atomic clocks for successful operation. The U.S. Naval Research Laboratory had played a key role in the development of these clocks and

their relationship to the systems concept will be the subject of this paper.

Early work in the Transit and Timation satellite navigation projects will be covered to show the evolution of satellite clocks from quartz units to the variety of atomic standards now possible. The relationship of the type of standard to the basic principles of system operation will be discussed. The means of maintaining this relationship in system operation is an important aspect in establishing the system concept.

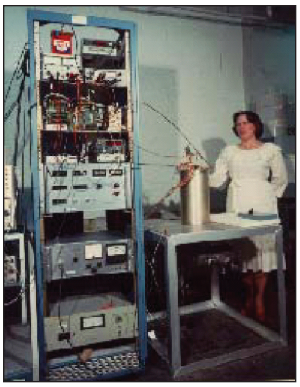
The different types of atomic clocks and the developmental problems encountered will be discussed. The discussion will range from the basic principle of operation through the factors considered in space flight qualification and system application. Examples in the development for GPS will be provided to give an understanding of the issues involved. Advanced types of clocks for GPS and possible application to other systems will be described. The relationship of GPS to the applications of timing and time dissemination in general will be discussed. The time synchronization capability offered by GPS will revolutionize precise timing and its application to other navigation, communication and geodetic systems. Possibilities for future applications and developments will also be summarized.

Maser built by Hughes Research Laboratory for the NRL in the late 1970s. (Beard-2002, p. 3 of 6)

R. Beard, A. Gifford, S. Stebbins, S. Rasmussen and T. Bartholomew, "Interim Report on the Geographic Dependency and Latitude Effects Study (GPS system)," in *45th Annual Symposium on Frequency Control*, 29-31 May 1991, 608-625.

The Geographic Dependency and Latitude Effects Study is an effort underway at NRL to investigate the capability of the Global Positioning System (GPS) to disseminate Universal Coordinated Time as maintained by the U.S. Naval Observatory, UTC(USNO). It is assumed that the users will have access to the GPS Precise Positioning Service (PPS) and will use GPS in the passive mode. That is, they will not exchange data with another location to transfer time by the common view method, but rather will obtain UTC(USNO) via the GPS broadcast message. The study addresses the performance expected from this type of user on a global basis. USNO has demonstrated, through operation at their facility as a user, that the system elements can provide time to less than 25 ns. This seems to indicate that the final link with the user is the source of additional errors limiting performance. The other GPS system elements and the worldwide nature of operation for time dissemination has not been well studied and should no be overlooked. Since USNO, the GPS Master Control Station, and the primary GPS test range at Yuma are covisible, the southern pacific area was chosen as the area of special interest to this study, being the more difficult for operational coverage.

In this study, the effects of the various GPS system error sources are being investigated for their influence on time dissemination. Data is being gathered from a variety of tracking and timing centers to attempt to identify and quantify the errors and their sources. The known influences of GPS satellite position error; propagation effects and the ability to maintain time at remote sites are being investigated. Trends in the error propagation of these different effects will be determined and limits imposed on capability and possible geographic dependency identified. Interim results and tentative conclusions will be presented on these efforts.



NRL Passive Space Advanced Development Model maser. (Beard-2002, p. 4. See also Beard-1986, p. 52)

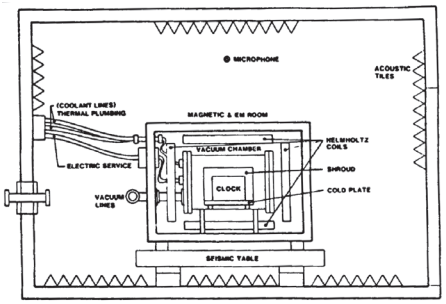
R. L. Beard, "Military time/frequency use of Navstar GPS," in *IEE Colloquium on Precise Time and Frequency - the Beat of a Single Drum*, 11 November 1992, 5/1 -5/4.

The introduction of the NAVSTAR Global Positioning System (GPS) to the military community is having a lesser known, but significant, impact on these systems, dissemination of precise time and frequency. Precise time/frequency and their uses could have a wider ranging influence on military electronic systems than the positioning/navigation aspects. The implications are not as well known or recognized. This paper will briefly

summarize the area of precise time and frequency uses in military systems as a prelude to describing the relationship of GPS in this area. GPS operations and possible applications will also be described.

R. Beard, "Reports on Other Conferences: Institute of Navigation," in *25th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Marina Del Rey, California, 29 November - 2 December 1993, NASA Conference Publication 3267, 519.

Ron Beard, Naval Research Laboratory: I would like to give a brief report on the Institute of Navigation's - actually the Satellite Division's meeting - on the Global Positioning System, which was held in Salt Lake City on the 21st through the 23rd of September of this year. This was the sixth international technical meeting of the Satellite Division, so it was a relatively young meeting. However, it is a very fast-growing meeting. At the first meeting, I think the attendance was on the order of this meeting, or perhaps a little less (at the first meeting); the sixth meeting, this last September, I think the attendance was around 1300 people. It has grown enormously…



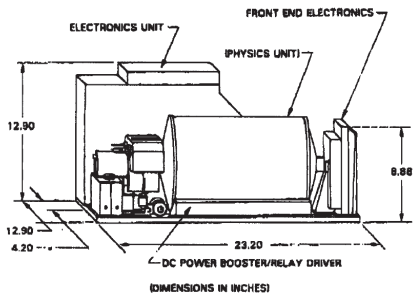
Clock test chamber with benign environment. (Beard-1989, p. 286)

R. L. Beard, J. D. White and J. A. Murray, "Military Applications of Time and Frequency," in *28th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, L. A. Breakiron, ed. held at Reston, Virginia, 3-5 December 1996, 125-139.

The introduction of the NAVSTAR Global Positioning System (GPS) to the military community is having a lesser known, but highly significant, impact on those systems requiring dissemination of precise time and frequency. Precise time/frequency and their uses could have a wider ranging influence on military electronic systems than the positioning/navigation aspects. The implications are not as well known or recognized. Time and Frequency (T/F) are a fundamental function needed by all military electronic equipment. From generation of frequencies for communications to remote sensing of geophysical quantities with time-tagged data requires oscillators, T/F standards, and/or clocks. The application and requirements for these standards and their maintenance of them onto a common timescale is a specialist's area often overlooked in the development and deployment of these systems, only to be addressed later as a operational problem area. The wide spectrum of applications and uses for timing devices within military systems can be categorized into different system types: (1) navigation, (2) communications, (3) identification, (4) remote sensing, (5) intelligence, and (6) weapons.

In addition to using T/F devices and technology, military electronic systems are on diverse platforms, which operate most effectively in a highly coordinated, interactive environment. This requires all units and elements of the operating forces to be referenced to the same time. U.S. military systems are required to be referenced to Universal Coordinated Time (UTC) maintained by the U.S. Naval Observatory (USNO), designated UTC (USNO). From this central reference, time is disseminated through various existing military and scientific systems. Navigation systems are the most immediate and well-known users of T/F, and from this fact are the primary systems used for T/F dissemination. Heretofore, a single system has not had the capability of widely disseminating precise time; consequently, many different systems with different capabilities have been used. Today the NAVSTAR GPS provides a general purpose, highly precise means of disseminating time and has been used operationally since the first technology satellites of the system were launched.

This paper summarizes the areas and application of precise time and frequency uses in military systems with specific examples.



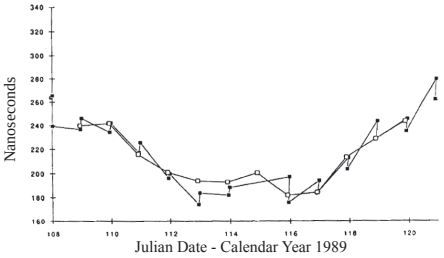
Spaceborne hydrogen maser design. (Beard-1986, p. 52)

R. Beard, I. Galysh, J. Oaks, M. Largay, P. Landis, W. Reid, M. Ehnert, R. Eisenhauer, W. Hanson, L. Nelson, A. Clements, J. Durden, L. Brownhill, J.

Wright, C. Duffy, J. Kasik and J. Buisson, "C- and Ku-Band Two-Way Satellite Time Transfer Comparison Experiment," in *29th Annual Precise Time and Time Transfer Interval (PTTI) Meeting*, held at Long Beach, California, 2-4 December 1997, 253-264.

In the development of a new time dissemination capability for the US Air Force Eastern Missile Test Range, the satcom channels to be used became an issue in terms of performance over different links and available coverage. A primary advantage of C band is that satellite coverage is more widely available in remote areas where Ku coverage is limited or not available at all. To investigate the performance issue, a Two-Way Satellite Time Transfer (TWSTT) experiment was performed to obtain comparative data over both C and Ku band. Time transfers between two sites using atomic frequency standard clocks were performed over both links to compare results in a controlled experiment. The objective of the experiment was to determine the relative precision of TWSTT over the frequency bands.

Time transfers were performed between a station located at Rockledge, Florida and the NIST facility at Ft Collins, Colorado for a period of approximately ten days. GPS receivers were used in common-view mode referenced to the same clocks as an independent comparative measure. Tests were conducted over a wide range of temperature variations and weather conditions. Observations were obtained during snow, heavy rain and sun with temperatures from 8 to 90 degrees Fahrenheit at the two stations. Analysis of the resultant data shows that time transfer over the two links performed equally, with residual RMS results of approximately 5 nanoseconds.



Observations of SV09 at two sites in the Southern Pacific. (Beard-1991, p. 618)

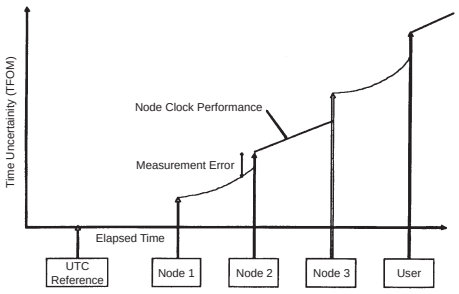
R. Beard, J. White, Moderator, J. Bleich, E. Butterline and M. Cimafonte, "Timing Systems Panel Discussion," in *29th Annual Precise Time and Time Interval (PTTI) Meeting*, 2-4 December 1997, 27-8.

The purpose of this panel was to discuss practical issues of designing, building, operating and maintaining remote precise timing systems.

R. Beard, J. Brad, J. White, O. J. Oaks and G. P. Landis, "Calibration Considerations for the IGS/BIPM Pilot Time Transfer Project Using Carrier Phase," in *30th Annual Precise Time and Time Transfer Interval (PTTI) Meeting*, L. A. Breakiron, ed. 1-3 December 1998, 235-245.

During the spring of 1998 a pilot project was begun between the Bureau International des Poids at Mesures (BIPM) and the International GPS Service (IGS) to investigate the accuracy of time and frequency comparisons using GPS phase and code measurements. The IGS has established a cooperative network of stations around the world, which gather GPS data, analysis centers that provide analysis products from these GPS data and other contributed data. The precision of the data and products has made major contributions to geodynamics and earth sciences and presents the possibility of highly precise time and frequency comparisons.

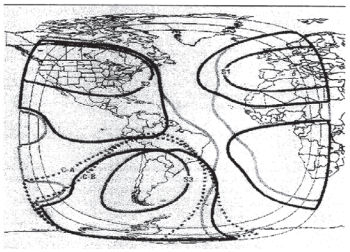
To compare time information between two sites by whatever means requires the time of propagation of the signal through the equipment, cables, and space to be precisely and accurately known. IGS differential measurements with GPS carrier phase data are highly precise and must be accurately calibrated in order to provide time comparisons. This paper will address the problems and possible techniques for calibration for time comparison. Specialized equipment and GPS system simulators will be described that calibrate from signal reception in the antenna through receiver output.



Time figure of merit (TFOM). (Beard-1996, p. 134)

R. Beard, J. White, J. Brad, S. Stebbins, J. Smathers, T. Myers, F. Danzy, A. Frank, W. Reid and J. Buisson, "GPS Block IIR Rubidium Atomic Frequency Standard Life Test," in *30th Annual Precise Time and Time Interval (PTTI) Meeting*, L. A. Breakiron, ed. held at Reston Virginia, 1-3 December 1998, USNO, 145-159.

The Rubidium clocks in the GPS Block IIR spacecraft have little previous flight



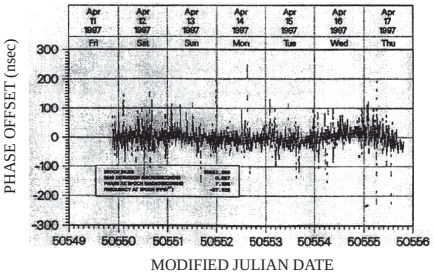
Satellite footprint. (Beard-1997, p. 258)

experience, and they will be the only atomic clocks used on the Block IIR satellites. The U.S. Naval Research Laboratory (NRL) in cooperation with the GPS Joint Program Office (JPO), the GPS Control Segment, Lockheed Martin, ITT and EG&G is conducting a three year life test of two flight qualified EG&G Rubidium Atomic Frequency Standards (RAFS) selected from the operational spacecraft inventory. The two RAFS, serial numbers 28 and 30, were selected as representative of the flight configuration build for Block IIR by ITT and provided by the JPO to NRL for this test. The test is intended to build confidence in these units as operational spacecraft clocks and establish a database of fundamental performance characteristics. The two units are being operated in independent thermal vacuum chambers with high resolution monitoring of the clock's frequency compared to the NRL Hydrogen Maser references. The units' internal monitors that would normally be sent as telemetry and environmental test conditions are monitored and recorded with high resolution.

Output from one of the two units has been used as input to the NRL Time Keeping System Simulator (TKSS). The TKSS was originally built to evaluate the implementation and algorithms used in the Block IIR on-board Time Keeping System (TKS) which determines the satellite's clock signal to the transmitter. Data from the TKSS have been used to evaluate TKS on-orbit performance and serve as an analysis reference. RAFS data from the beginning of the test on 31 March 1997 to the current date and representative TKSS data will be presented. Frequency stability results of the RAFS have routinely shown Allan deviation performance in parts in 10^14 at one day, much better than initially expected. In addition to the data from the two test units, on-orbit data from the Block IIR clocks are being added to the database for life data analysis as satellites are put into service.

R. Beard, J. White, J. Brad, T. Myers, W. Reid, F. Danzy and J. Buisson, "Long Term Ground Test Results for Two GPS Block IIR Rubidium Clocks," presented at the Institute of Navigation National Technical Meeting, Anaheim, California, 26-28 January 2000, 381-87.

The rubidium clock used in the GPS Block IIR space vehicles is a design that had not flown previously in space. A long-term life test of two of these clocks is being conducted in the Clock Test Facility of the Naval Research Laboratory (NRL) to gain information on their reliability and operating characteristics. Data is presented showing the design of the test, the clock performance, and typical behavior of several of the clock telemetry parameters. The performance of the clocks under test is compared with the on-orbit performance of the rubidium clock on Navstar 43—the first operational Block IIR space vehicle.

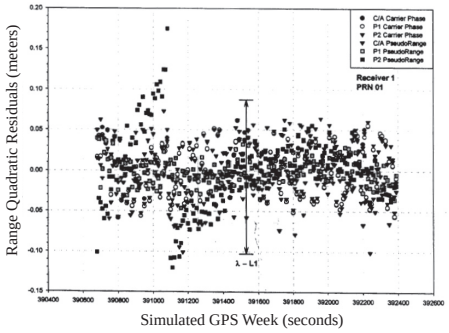


Common View Time Transfer residuals from comparison of Rockledge, Florida, versus Fort Collins, Colorado. Ordinate is phase offset (nanoseconds), abscissa is modified Julian date. (Beard-1997, p. 261)

R. Beard and J. White, "GPS Common Time Reference Architecture," presented at the ION GPS 2000, 13th International Technical Meeting of the Satellite Division of the Institute of Navigation, Salt Lake City, Utah, 19-22 September 2000, 895-904.

The use of the Global Positioning System as the primary and most accurate means of disseminating time and frequency information has created an inherent vulnerability within military systems not directly related to positioning systems. A growing and diverse mix of military positioning, communications, sensors and data processing systems are using precise time and frequency from GPS. The precise accuracies required for their interoperability are likewise becoming more stringent. Consequently, a new system architecture for providing a Common Time Reference to the operating forces and their related subsystems is being developed. This architecture will provide a robust alternative to the former implementations of GPS as a time and frequency subsystem and mitigate the vulnerabilities of those systems to possible GPS countermeasures.

The Common Time Reference approach and its relationship to present GPS time and frequency usage will be described to show the fundamental differences and strengths of the new architecture. A robust architecture comprising distributed time standards and precise time and frequency standards which reduces the sensitivities to GPS anomalies and lack of continuous contact is a primary objective of this approach. Utilization of existing resources and interconnection of these interoperable systems at the fundamental level of time and frequency generation will provide a more inherent capability of these systems to function together. The resultant implementation of this architecture with generic systems will be discussed. Finally, technical directions for development and impact on interoperability will be discussed.

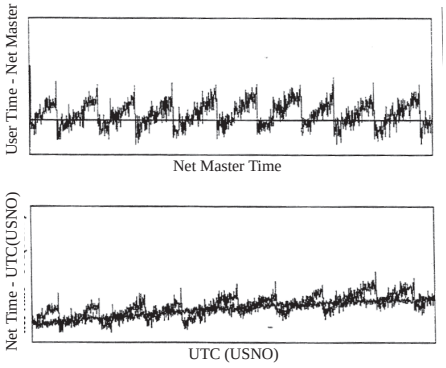


Results from GPS system simulator. (Beard-1998, p. 241)

R. L. Beard and J. D. White, "Common Time Reference Technology for Systems Inter-operability," in *32nd Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, Virginia, 28-30 November 2000, 367-87.

The Global Positioning System (GPS) has become the primary and most accurate means of disseminating time and frequency information. A growing and diverse mix of military positioning, communications, sensor, and data processing systems are using precise time and frequency from GPS. The precise accuracies required for their operation is also becoming more stringent. A new system architecture for providing a Common Time Reference to the operating forces and their related subsystems is being developed. This architecture is to provide a robust enhancement to implementations of GPS time and frequency subsystems. Through its implementation, interoperability between systems are to be enabled by providing a Common Time Reference and the means for systems to operate synchronously as a foundation for common interfaces and data exchange.

The Common Time Reference approach and its relationship to present GPS time and frequency usage will be described to show the concept and approach of this architecture. A robust architecture utilizing distributed time standards and existing standards within individual systems is to provide new capabilities for existing fielded systems without the impact of requiring a major retrofit. This combination of enabling existing and new resources to be used in a common reference will reduce the sensitivity to GPS anomalies and lack of continuous contact for precise updating. These systems would then be interconnected at the fundamental level of internal time and frequency generation, which would provide an inherent basis for functional interoperability. The elements necessary for implementation of this architecture with generic systems will be discussed. Technical developments necessary for implementation of the concept and the impact on interoperability will be discussed.



Network User Time Updates to Net Master. (Beard-2000, p. 372)

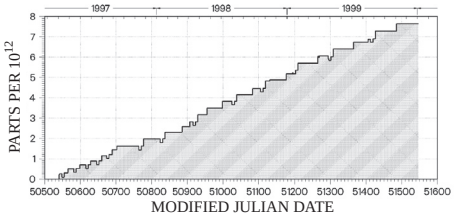
R. Beard, W. Golding and J. White, "Design Factors for Atomic Clocks in Space," in *2002 IEEE International Frequency Control Symposium and PDA Exhibition*, held at New Orleans, LA, 28-30 June 2002, 493-8.

There are very strong differences between the designs of clocks used in space and those used on earth. This paper discusses the impact of mechanical, thermal, radiation hardness, and control requirements on clock performance. The requirements to survive launch and operate in space produce design challenges that go beyond simply increased mechanical strength and remote controllability. There are a number of design issues that can affect clock performance if not handled correctly. For example, the addition of structural members to secure a maser cavity against launch vibration may result in poor cavity frequency control due to the inadvertent modification of thermal paths and cavity stresses. The reliability and radiation hardening requirements drive performance less directly by limiting the designer's choice of critical electronic components to those that can be space qualified. The differences between

clocks intended for short term space experiments and those destined for production space vehicles will be examined.

P. L. Bender, E. C. Beaty and A. R. Chi, "Optical Detection of the Cesium Hyperfine Transition," in *Twelfth Annual Symposium on Frequency Control*, held at Asbury Park New Jersey, 6-8 May 1958, US Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, 593-605.

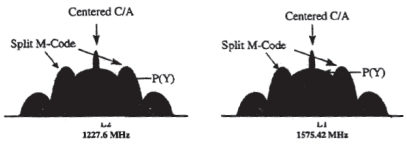
The argon spectral line at 8521.4A has been used in the detection of the cesium hyperfine transition at 9192.63 mc. The argon line was Zeeman split to overlap one hyperfine component of the cesium resonance line at 8521A. A glass bulb containing cesium vapor diffusing in a buffer gas was illuminated by the argon light source and the scattered light was observed. Transitions from the upper ground state hyperfine sublevel to the excited state were produced, and the atoms then returned by spontaneous emission to both ground state sublevels. There was thus a pumping of atoms out of the upper hyperfine level and into the lower one. This depletion of the population of the upper level caused a decrease in the amount of scattered light. Microwaves were then applied to the bulb by a horn antenna. At resonance the difference in population of the hyperfine levels was reduced and an increase in the scattered light was seen. Shifts in the resonance frequency of the (4,0) ==> (3,0) line with buffer gas pressure were observed for He, N2, Ne, Ar and Kr, the smallest being -200 cycles/mm for argon and +580 cycles/mm for Ne1. An upper limit of 10 cycles/cm of argon was found for the expected pressure-dependent line breadth caused by cesium-argon collisions. The microwave frequencies were obtained from an Atomichron by feeding in an accurately known variable frequency at the 6.315920 mc stage in the synthesizer. The basic 5-mc frequency for the multiplication chain was supplied by the 5-mc output from another Atomichron, which was operating normally.



Cumulative frequency corrections.
(Beard-2000, p. 382)

N. D. Bhaskar, J. White, L. A. Mallette, T. A. McClelland and J. Hardy, "A historical review of atomic frequency standards used in space systems," in *Proceedings of the 1996 IEEE International Frequency Control Symposium (50th Anniversary)*, held at Honolulu, Hawaii, 5-7 June 1996, IEEE, New York NY, 24-32.

The remarkable navigational accuracy currently enjoyed by the users of satellite navigation systems is in major part due to the excellent performance of the onboard atomic frequency standards (AFSs). Since the laboratory demonstration of a Cesium AFS in the 50's the performance and reliability of AFSs have significantly improved. Currently Cesium (Cs) and Rubidium (Rb) AFSs are on-board many satellite systems-Navigational Satellites GPS (Global Positioning System-USA) and GLONASS (Global Navigation Satellite System-Russia) and the Communication Satellite MILSTAR (Military Strategic and Tactical Relay-USA). To test the predictions of General Theory of Relativity a hydrogen maser clock was flown in space. In all, we estimate that the total number of space-borne AFSs is no more than several hundred-by all accounts a relatively small sample size for any accurate reliability studies. The manufacturing technology of space qualified AFSs has vastly improved in the last three decades and the significant improvement in performance is primarily due to the maturity of the electronics industry. In this paper we present a historical review of the AFSs used in space systems. We will briefly review the unique requirements for space qualification for frequency standards and outline the performance characteristics of different AFSs which are presently onboard various satellite systems. We also present a brief discussion of the advanced AFSs for potential future space applications.



M-Code, a “Split Spectrum” signal.
(Brad-1999, p. 367)

P. W. Binning and I. Galysh, "Satellite to Satellite Relative Navigation Using GPS Pseudoranges," presented at the National Technical Meeting - Navigation and

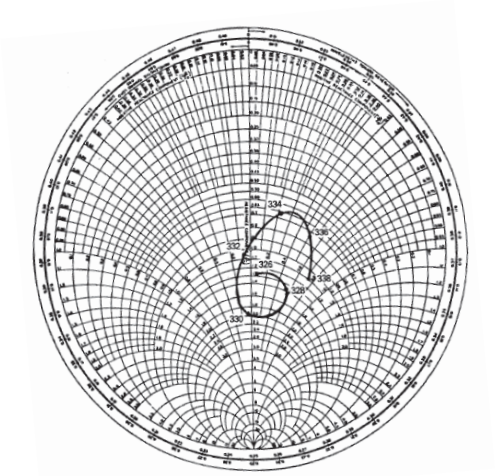
Positioning in the Information Age, 14-16 January 1997, Institute of Navigation, 407-15.

Researchers at NRL have written an orbit determination package which is able to process GPS measurements in an effort to estimate an absolute and a relative spacecraft state. This paper will focus solely on the relative navigation algorithms and the simulated attainable accuracies through the use of GPS simulation hardware. There will be three differential algorithms presented which represent possible methods for determining the relative state between two spacecraft. Two different separation distances will be presented.

P. W. Binning, "A Widelane Integer Resolution Technique for Relative Navigation Between Spacecraft," in *ION GPS-98, the 11th International Technical Meeting of The Satellite Division of The Institute of Navigation*, held at Nashville, Tennessee, 15-18 September 1998, 1577-86.

It is desired to precisely locate two satellites with respect to each other using the Global Positioning System. This is simulated using a Northern Telecom STR2760 GPS signal simulator and an Allen Osborne TurboRogue receiver. The observations are retrieved form the TurboRogue while the truth model is taken from the Nortel. The observations are then processed through the Naval Research Laboratory's orbit determination program OCEAN (Soyka et al., 1997, 1998)

The relative states are estimated using an extended Kalman Filter. The observation update employs the single difference widelane combination of the dual frequency carrier. Inherent in this observation are unknown integers which are determined using a combination of techniques common to terrestrial locating. The results are 1 σ, 3-d, relative position errors on the order of 1 to 3 cm.



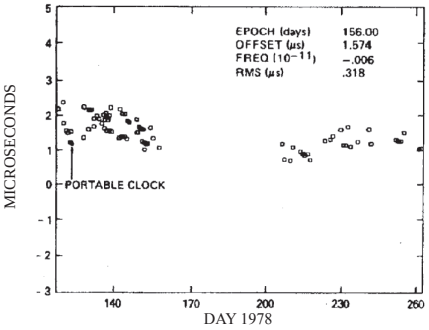
Measured impedance for crossed Yagi system. (Breetz-1976 NRL MR 3330)

P. W. Binning, A. S. Hope and M. T. Soyka, "Orbit determination and prediction concept for NEMO, the Naval EarthMap Observer Program," presented at the ION GPS-99, The 12th International Technical Meeting of the Satellite Division of the Institute of Navigation, Nashville, Tennessee, 14-17 September 1999, 837-47.

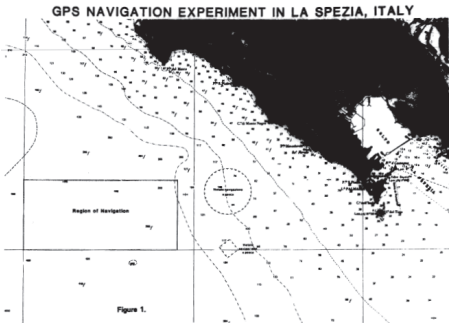
The Naval EarthMap Observer Program (NEMO) is a joint development effort between the Navy and private industry. The primary payload for NEMO is a hyperspectral imaging camera which is to map various regions of the world. A Tensor GPS receiver will be used to aid in determining accurate position knowledge, which is required for image geolocation and onboard autonomous image planning and execution. The following sections will focus on the operations concept for the orbit determination measurement collection, the processing of the GPS measurements on the ground for the precision orbit required for geolocation and the use of this precise ephemeris to predict the onboard position through the use of an onboard propagator.

Demonstration of the algorithm concept will be shown using data from the ORFEUS-SPAS Shuttle Free Flyer. The Tensor GPS receiver which NEMO will be flying is very similar to that which was flown on ORFEUS SPAS. A C/A-code phase ambiguity algorithm will be shown. The OCEAN Filter/Smoother results will be presented. The data will be corrected for the gross time tag errors and the OCEAN preprocessor will combine the ORFEUS SPAS data with data from 27 GPS ground stations to form the Space to Ground Differential observation. This will then be processed in the OCEAN WLS-OD and expected to accuracies will be shown.

The final section will conclude with a wrap-up discussion of the expected NEMO performance based on OCEAN runs with data from TOPEX/Poseidon. Results will also be shown comparing the predicted ephemeris against the estimated ephemeris.



Time transfer results from Paris (USNO Master Clock 1) - (Paris Observatory). (Buisson-1980 NRL Report 8395)



Advanced navigation algorithms for NRL-developed GPS Time Transfer receivers were tested aboard the Italian Naval hydrographic vessel “Magnaghi” during October 1983. (Buisson-1983, p. 217)

J. A. Bowman, "Short and Long Term Stability Measurements Using Automatic Data Recording System," in *27th Annual Frequency Control Symposium*, held at Cherry Hill, NJ, 12-14 June 1973, 440-5.

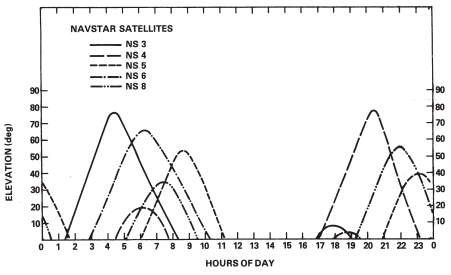
Manual methods of obtaining data for short and long term stability measurements in the time domain of precision frequency and time standards and transfer systems have been replaced with an automatic paper tape data recording system. Existing equipment and systems are used. Interface problems are solved by building interconnecting circuits using integrated (IC) transistor-transistor logic (TTL): a binary code converter, a sequential logic controller, and a serial-to-parallel code converter/buffer. Time-shared computer systems are used instead of a dedicated computer; System design objectives of minimum investment in equipment and maximum flexibility are met.

J. Brad, I. Galysh, D. Koch, J. White and G. Landis, "Testing the Effects on M-code on GPS Timing Receivers," in *31st Annual Precise Time and Time Interval (PTTI) Meeting*, 7-9 December 1999, NASA Conference Technical Publication, 365-71.

The Naval Research Laboratory has measured the effects of several modulation schemes proposed for use as the new Global Positioning System (GPS) M-Code on the operation of existing GPS timing receivers. Three candidate codes were tested at varying power levels to quantify the effects of the new signal added to a traditional GPS signal generated by a 10 channel GPS signal simulator. The M-Codes were generated in hardware to make representative Binary Offset Carrier and Manchester waveforms. Because the new codes may be run at considerably higher power levels than the current C/A and Y code signals, the M-Code signals were added in at power levels up to 40 dB over the existing signals. The test results show that the presence of M-Code signals is detectable. The effects on noise in the pseudorange and timing outputs are small.

J. Brad, O. J. Oaks and E. Powers, "Precision Calibration and Long Term Stability of GPS Timing Receivers," presented at the Institute of Navigation National Technical Meeting, Anaheim, California, 26-28 January 2000, 371-4.

The purpose of this test program was to evaluate the long-term stability of certain GPS timing receivers and to develop accurate methods of laboratory calibration without the use of manufacturer's special test equipment. The testing process began in August of 1999 and continues. It is expected be completed in the fall of 2000.



Visibility of NAVSTAR GPS satellites during the Mediterranean Time Transfer testing on 5 October 1983.Vertical axis is elevation in degrees. (Buisson-1983, p. 219)

L. D. Breetz, "World's Most Powerful VHF Transmitting Station," in *EASCON '68 Record: Electronics and Aerospace Systems Convention*, held at Washington, D.C., 9-11 September 1968, IEEE, 247-51.

This station is centrally located among other transmitting and receiving stations lying on a great circle between Savannah, Georgia and San Diego, California. Through fan-shaped antenna beam-patterns, the planes of which are in register, energy is projected upward illuminating objects passing through. The reflected energy is detected and processed at the receiving stations.

Problems in transmitting a million watts of RF energy in the CW mode through an antenna two miles long to produce an effective radiated power of 13.6 billion watts required many peculiar solutions. The demand for continuous operation dictated a design based on dependability of equipment, protection of equipment and personnel, and ease of operation, maintenance and repair.

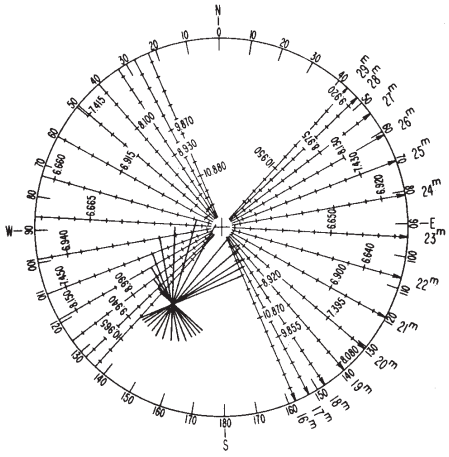
These requirements were satisfied through combinations of circuitry and sectionalized design permitting functional independence, thus nearly eliminating total station failure. This type of design and wide geographical expanse of equipment created a delicate problem of monitoring and control to make the station sections function as one to obtain the desired antenna beam pattern.

L. D. Breetz, *Refractivity Measurements Related to a Minimum Tropospheric Range Error*, NRL Memorandum Report 2294, Naval Research Laboratory, Washington, D.C., July 1971.
NRLmr2294 LIMITED DISTRIBUTION

L. D. Breetz, *A Circularly Polarized Yagi Antenna System for NTS-1 and NTS-2 Ground Stations*, NRL Memorandum Report 3330, Naval Research Laboratory, September 1976.

A circularly polarized yagi antenna system for use with GPS Navigational Technology Satellites (NTS-1 and NTS-2) ground station was designed and a model built and tested. The report describes the design philosophy and techniques used, actual constructional dimensions for the model, and calculated and measured performance characteristics.

R. E. Brescia, R. L. Easton, R. R. Zirm, R. S. Rovinsky and J. H. Fournier, *Tempsat II*, NRL Report 7238, Naval Research Laboratory, 26 February 1971.
NRL7238 LIMITED DISTRIBUTION

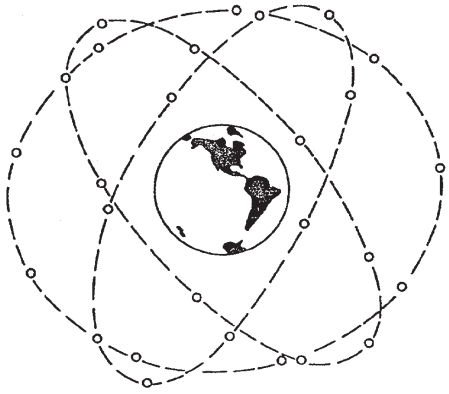


Intercept chart with clock synchronization. (Buisson-1973, p. 282)

J. A. Buisson and H. G. DeVezin, Jr., *Look-Angle-Prediction Technique for Artificial Earth Satellites*, NRL Report 6351, Naval Research Laboratory, Washington, D.C., 30 December 1965.

This report is concerned with the investigation of a method for obtaining look-angle predictions for artificial earth satellites relative to a given point on the earth. The input to the problem consists of the most-recently-determined elliptical orbital elements of the satellite, the spherical coordinates of a station on the earth, and a desired time of search. The results to be obtained for the satellite trajectory are azimuth, elevation, range, range rate (i.e., velocity), and the Doppler frequency shift as a function of time.

The problem has been programmed for use on digital electronic computers in both NELIAC and FORTRAN compiler languages and is available for use at both NRL and the David Taylor Model Basin in the Washington, D.C. area. As part of the checking out procedure, a comparison of the results was made with data obtained at the Radio Research Establishment (RRE) in Malvern, England. It was concluded that the major portion of those discrepancies that exist between the NRL and the RRE data is due to differences in the models used. Examples of both NELIAC and FORTRAN input, an example of the FORTRAN output, and the FORTRAN source program for this problem are included in the appendices.

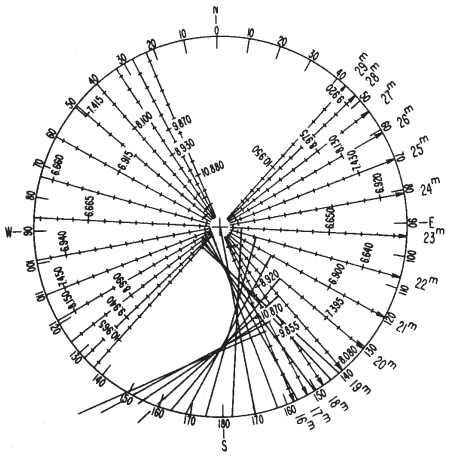


Proposed Timation navigation constellation of 27 satellites in 3 planes of 9 satellites each, inclined at 53° to the equator with a plane-to-plane spacing of 120°. (NRL Report 7389, June 1972)

J. A. Buisson and T. B. McCaskill, *TIMATION Navigation Satellite System Constellation Study*, NRL Report 7389, Naval Research Laboratory, Washington, D.C., 27 June 1972.

The Timation (Time Navigation) technique of passive ranging is a concept that could be expanded to provide a worldwide navigation service. Passive ranging is accomplished by measuring the time difference between electronic clocks located within the satellite and in the navigator's receiver. The Timation technique uses a highly stable, synchronized clock in the satellite; however, the navigator's clock stability may vary considerably, depending on the navigator's equipment and vehicle dynamics.

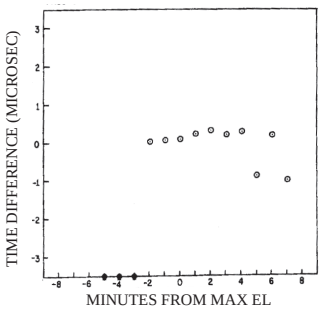
One-hundred and seven satellite constellations are discussed in terms of their influence on earth coverage and navigation fix accuracy. The recommended configuration derived is comprised of three planes with nine satellites (3 X 9) each in 8-hour circular orbits at a 53 degree inclination.



Intercept chart with time synchronization error. (Buisson-1973, p. 282)

J. A. Buisson, "International Time Transfer Using the Timation II Satellite," in *27th Annual Frequency Control Symposium*, held at Cherry Hill, NJ, 12-14 June 1973, 277-85.

During the month of July 1972, a Naval Research Laboratory (NRL) satellite was used in a time transfer experiment between the U.S. Naval Observatory and the Greenwich Observatory in Herstmonceux, England. The satellite



Time comparison between TIMATION II satellite and Royal Greenwich Observatory, England, July 1972. (Buisson-1973, p. 284)

used is called Timation II, a U.S. navigation and time transfer satellite launched by NRL 30 September 1969.

The satellite orbits at an altitude of 500 nautical miles with an inclination of 70 degrees. A passive ranging technique was employed to make measurements at a frequency near 400 MHz. These signals were received first by the station at the Naval Research Laboratory in Washington and about 15 minutes later at the Royal Greenwich Observatory station.

With the location of the satellite and the ground station as known parameters, the time difference between the clock in satellite and the clock at each station was computed when the satellite was above the horizon of the ground station. The time standards at the two sites were then compared. Each site has cesium beam atomic clocks as time standards and had been compared by portable clocks carried in aircraft as well as the Loran C navigation system operated by the U.S. Coast Guard.

The results of this experiment agreed within 1.5 microseconds with the Loran C measurements made at RGO. A traveling clock closure made before the experiment showed a discrepancy of approximately 1.5 microseconds when RGO was compared to Loran C.

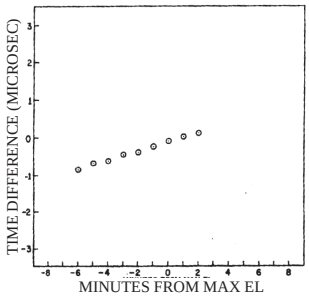
J. A. Buisson, T. B. McCaskill and J. E. Thompson, *Range Navigation Using the TIMATION II Satellite*, NRL Report 7511, Naval Research Laboratory, Washington, D.C., 12 February 1973.

The TIMATION (Time Navigation) technique of passive ranging can be employed to provide a worldwide navigation and time-transfer service. Passive ranging is accomplished by measuring the time difference between electronic clocks located within the satellite and the navigator's receiver. Navigation results were obtained with a prototype system consisting of the TlMATlON lI satellite and four ground stations. The results indicate a CEP position-fixing capability of 33 meters (100 feet) using dual-frequency range measurements. The analysis of the data includes ionospheric refraction, instrumentation error, and the effect of satellite trajectory position error in both the observed and predicted regions.

J. A. Buisson, D. W. Lynch and T. B. McCaskill, *Time Transfer Using the TIMATION II Satellite*, NRL Report 7559, Naval Research Laboratory, Washington, D.C., 3 May 1973.

The TIMATION principles, although originally proposed as a method of navigation, can be used to transfer time between any number of sites. Time-transfer experiments were performed between NRL and several other ground stations using passive ranging techniques and the TIMATION II satellite. The results indicate this method is capable of transferring time to an accuracy of approximately one tenth of a microsecond.

J. A. Buisson, *Geometric Considerations of 3-Plane, 125 deg.-Inclination, 8- and 12-hr Circular Satellite Orbits*, NRL Report 7581, Naval Research Laboratory, Washington, D.C., 7 August 1973.
NRL7581 LIMITED DISTRIBUTION

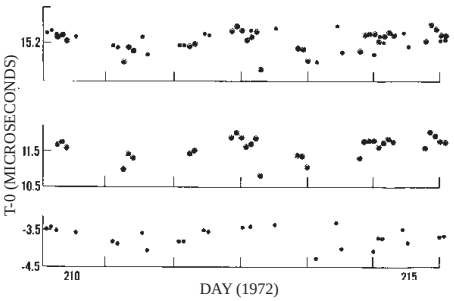


Time comparison between TIMATION II satellite and Naval Research Laboratory, Washington, DC, July 1972. (Buisson-1973, p. 284)

J. A. Buisson, T. B. McCaskill, H. M. Smith, P. Morgan and J. Woodger, "Precise Worldwide Station Synchronization via the NAVSTAR GPS, Navigation Technology Satellite (NTS-1)," in *8th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, Vol. X-814-77-149, held at Naval Research Laboratory, Washington, D.C., 30 November - 2 December 1976, Goddard Space Flight Center, 55-84.

The NTS-l satellite is currently being employed as a precursor to the phase I concept validation program of NAVSTAR GPS. The assigned tasks include measurement of components of the GPS error budget related to the performance of precise satellite clocks and orbital accuracy obtainable in an eight hour orbit.

Station Synchronization results are presented using stations located in the United States, England and Australia. Results show a time difference noise level of 3 ns. These single frequency measurements, collected over the past year, have been processed to produce station synchronization values between cesium clocks located at each station. A one month data span, using a zero satellite clock update time, produced a noise level of 43 ns, with a systematic bias of 9 ns. The synchronization noise level gradually increased as the satellite clock update time increased. The largest value measured is on the order of 250-500 ns, when comparing clocks located at the Australia station with clocks located at the central U.S.A. station. The method employed in precise station synchronization is sensitive to two components of satellite position error. The results show that long term predictions, on the order of 2-3 months, are possible with only a small increase in station synchronization error.



Time transfer via TIMATION II satellite between NRL (USA) and RGO (United Kingdom). (Buisson-1973, p. 285)

J. A. Buisson, R. L. Easton and T. B. McCaskill, "Initial Results of the NAVSTAR GPS NTS-2 Satellite," in *Ninth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held at Washington, D.C., 29 November - 1 December 1977, NASA Technical Memorandum 78104, 177-199.

Navigation Technology Satellite 2 (NTS-2) was successfully launched on June 28, 1977, into a near-12-hour circular orbit. Precise frequency and timing signals are derived from the two cesium frequency standards. This paper discusses the launch and preliminary results which include verification of the relativistic clock effect.

The successful launch of the Navigation Technology Satellite No. 2 (NTS-2) marks the beginning of a new era in navigation and time-keeping history. NTS-2 is the first NAVSTAR GPS Phase I Satellite, which will provide near-instantaneous navigation and time-synchronization service on a worldwide, continuous basis to the DOD community and a wide variety of commercial users. NTS-2 technological features encompass the world's first orbiting cesium frequency standards, built by Frequency and Time Systems (FTS); nickel-hydrogen batteries (developed by COMSAT); three axis gravity gradient stabilization with momentum wheel unloading; control of the spacecraft orbit; verification of Einstein's relativistic clock shift; time interval measurement precision of 3 nanoseconds; and a worldwide network (GE International Time Sharing) for data acquisition.

NTS-2 is also the fourth in a series of NRL technology satellites which have carried quartz, rubidium and cesium oscillators into orbit. The NTS-3 spacecraft, now under development at NRL, is scheduled to carry the first orbiting hydrogen maser frequency standard. The primary data type for all of the technology satellites has been precise time difference measurements, which have been used for time transfer, navigation and orbit determination.

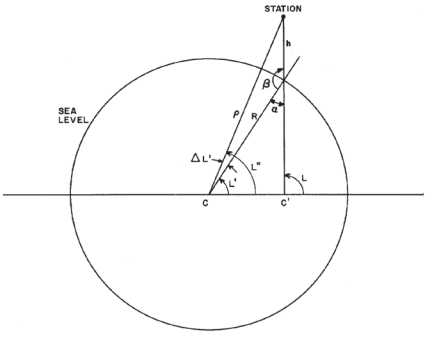


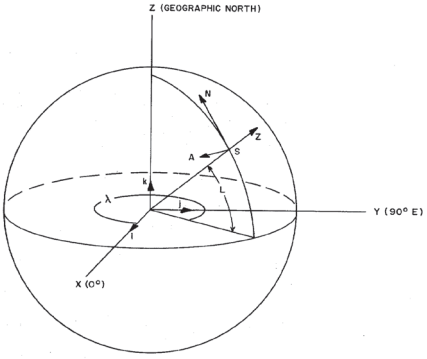
Diagram depicting conversion of geodetic lattitude to geocentric lattitude. (Buisson-1965 NRL Report 6351, p. 39)

J. A. Buisson, T. B. McCaskill, J. Oaks, D. Lynch, C. Wardrip and G. Whitworth, "Submicrosecond Comparisons of Time Standards via the Navigation Technology Satellites," in *Tenth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held at Washington, D.C., 28-30 November 1978, NASA Technical Report 80250, 601-627.

During May through September 1978 a six nation cooperative experiment was performed to intercompare time standards of major laboratories at the submicrosecond level using NTS satellites.

NTS time transfer receivers, which were developed for use with the NTS series of satellites were installed at the Division of National Mapping (DNM), Australia; National Research Council (NRC), Canada; Royal Greenwich Observatory (RGO), England; Bureau International de l'Heure, France (BIH); Institute for Applied Geodesy (IFAG), West Germany; and in the U.S. at the Goddard Space Flight Center (GSFC), National Bureau of Standards (NBS), Naval Research Laboratory (NRL) and the Naval Observatory (USNO).

The results of the clock intercomparisons will be presented.



Relationship of unit vectors located at station S to unit vectors located at the center of the earth. (NRL6351, p. 5)

J. A. Buisson, T. B. McCaskill, O. J. Oaks, M. M. Jeffries and S. B. Stebbins, "Precise Time and Time Interval (PTTI) Measurements from the Navigation Technology Satellites and the GPS NAVSTAR-4 Satellite," in *Proceedings of the Eleventh Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, NASA Conference Proceedings 2129, held at Goddard Space Flight Center, Greenbelt MD, 27-29 November 1979, NASA, 255-281.

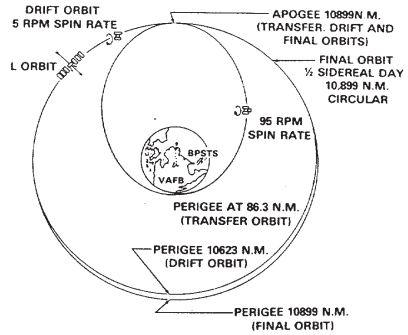
Since the launch of the first NTS spacecraft in 1974, international time transfer experiments have been performed as part of the concept validation phase of the Global Positioning System (GPS). Time Transfer results from both NTS-l and NTS-2 will be presented, including recent measurements from receivers located in South America, Germany, Japan and the United States. A time link to the DOD Master clock allows submicrosecond intercomparison of UTC(USNO,MC1) with clocks in the respective countries via the NTS link. Work is progressing toward a retrofit conversion of existing NTS receivers (located at NASA and foreign observatories) into GPS time transfer receivers.

Initial results will be presented on the long term rubidium frequency stability as measured from the GPS NAVSTAR-4 space vehicle (SV). Analysis has been performed for sample times varying from one to ten days. Using a 154 day data span starting on day 36, 1979, data was collected from the four GPS Monitor Stations (MS) located at Vandenberg, Guam, Alaska, and Hawaii.

A time domain estimate for the NAVSTAR-4 SV clock offset is obtained for each SV pass over the GPS monitor sites, using a smoothed reference ephemeris, with corrections for ionospheric delay, tropospheric delay, earth rotation and relativistic effects. Conversion from the time domain to the frequency domain is made using the two-sample Allan Variance; sigma-tau plots are used to identify the noise processes. Estimates of flicker and white frequency noise for the NAVSTAR-4 rubidium frequency standard are obtained. The contribution of the reference ground clocks and other error sources to the frequency stability estimates are discussed.

J. A. Buisson, O. J. Oaks, T. B. McCaskill, W. J. Hurd, S. C. Wardrip, H. E. Warren and G. G. Whitworth, *A Comparison of Intercontinental Clock Synchronization by VLBI and the NTS Satellite*, NRL Report 8366, Naval Research Laboratory, Washington, D.C., 4 January 1980.

The intercontinental clock synchronization capabilities of Very Long Baseline Interferometry (VLBI) and the Navigation Technology Satellite (NTS) have been compared at the NASA Deep Space Net complexes at Madrid, Spain and Goldstone, California. The VLBI experiments used the Wideband VLBI Data Acquisition System developed at the NASA Jet Propulsion Laboratory. The Naval Research Laboratory NTS Satellites were used with NTS Time Transfer Receivers developed by the Goddard Space Flight Center. The two methods agreed to within about 0.5 microseconds.



Mission sequence of NTS-2 events. (Buisson-1977, p. 186)

J. Buisson, T. McCaskill, J. Oaks, D. Lynch, C. Wardrip and G. Whitworth, *Submicrosecond Comparisons of Time Standards via the Navigation Technology Satellites (NTS)*, NRL Report 8395, Naval Research Laboratory, Washington, D.C., 30 April 1980.

During May through September 1978 a six nation cooperative experiment was performed to intercompare time standards of major laboratories at the submicrosecond level using NTS satellites.

NTS time transfer receivers, which were developed for use with the NTS series of satellites, were installed at the Division of National Mapping (DNM), Australia; in Japan at the Radio Research Laboratories (RRL) and the National Research Laboratory of Metrology (NRLM); National Research Council (NRC), Canada; Royal Greenwich Observatory (RGO), England; Bureau International de l'Heure, France (BIH); Institute for Applied Geodesy (IFAG), West Germany; and in the U.S. at the Goddard Space

Flight Center (GSFC), National Bureau of Standards (NBS), Naval Research Laboratory (NRL), and the Naval Observatory (USNO).

The results obtained by satellite were compared to those obtained by portable clocks. At all stations the differences were less than 0.75 us. The RMS of the data from nine stations is less than 0.4 us.

J. A. Buisson, T. B. McCaskill, O. J. Oaks, M. M. Largay and S. B. Stebbins, *GPS NAVSTAR-4 and NTS-2 Long Term Frequency Stability and Time Transfer Analysis*, NRL Report 8419, Naval Research Laboratory, Washington, D.C., 30 June 1980.

Since the launch of the first NTS spacecraft in 1974, international time-transfer experiments have been performed as part of the concept validation phase of the Global Positioning System (GPS). Time-transfer results from both NTS-l and NTS-2 will be presented, including recent measurements from receivers located in South America, Germany, Japan, and the United States. A time link to the DOD Master clock allows submicrosecond intercomparison of UTC(USNO,MC1) with clocks in the respective countries via the NTS link. Work is progressing toward a retrofit conversion of existing NTS receivers (located at NASA and foreign observatories) into GPS time-transfer receivers.

Initial results will be presented on the long-term rubidium frequency stability as measured from the GPS NAVSTAR-4 space vehicle (SV). Analysis has been performed for sample times varying from 1 to 10 days. Using a 154-day data span starting on day 36, 1979, data was collected from the four GPS Monitor Stations (MS) located at Vandenberg, Guam, Alaska, and Hawaii.

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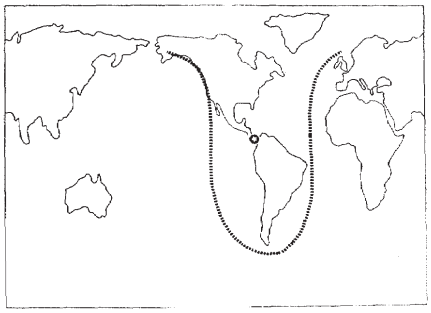


Panama NTS-2 coverage. (Buisson-1977, p. 188)

J. Buisson, O. J. Oaks, M. Lister, S. C. Wardrip, S. Leschiutta, P. G. Galliano, F. Cordara, V. Pettiti, E. Detoma, P. Dachel, H. Warren, T. Stalder, F. Fedele and R. Azzarone, "GPS Navigation Experiment Using High Precision GPS Timing Receivers," in *15th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Naval Research Laboratory, Washington, D.C., 6-8 December 1983, 211-35.

Global Positioning System (GPS) Time Transfer receivers were developed by the Naval Research Laboratory (NRL) to provide synchronization for the NASA Global Laser Tracking Network (GLTN).

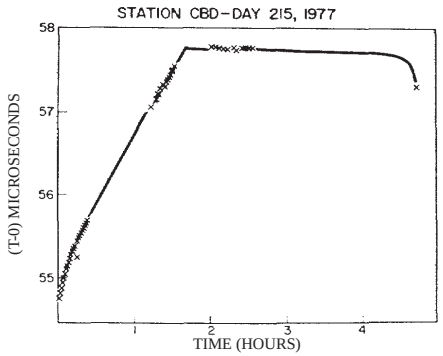
The capabilities of the receiver are being expanded mainly through software modification to:

Demonstrate the position location capabilities of a single channel receiver using the GPS C/A code.

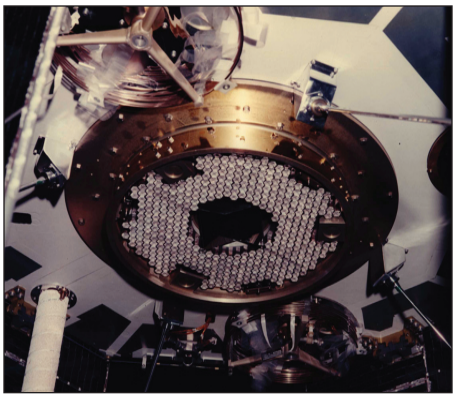
Demonstrate the time/navigation capability of the receiver onboard a moving platform, by sequential tracking of GPS satellites.

Several advanced navigation algorithms were tested, tracking either a full or reduced constellation of the current Phase I GPS satellites.

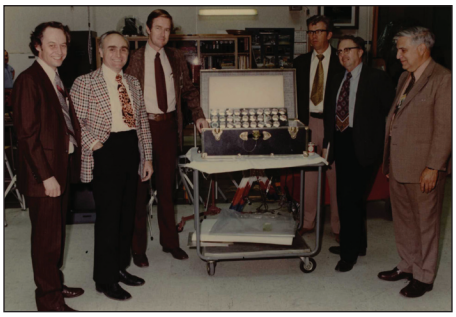
The experiment was conducted during October 1983 onboard the Italian Navy hydrographic ship "MAGNAGHI". The ship provided a stable platform, able to move with constant speed, while keeping track of its own position with high accuracy. The ship was equipped with a wide range of radio navigation equipment, including Raydist, Motorola Mini-Ranger, Toran, Loran-C, Omega and Transit receivers. There were also onboard atomic clocks with submicrosecond accuracy. To keep an accurate track of the ship's position at sea during the experiment, the Mini-Ranger system was



Effect of relativity correction for NTS-2. (Buisson-1977, p. 190)



NTS-1 laser reflector. (Buisson-1977, p. 194)



NTS-2 laser reflector with NRL staff, including (from left) Pete Wilhelm and Herb Rabin, and to the right of the reflector Charles Bartholomew, and Roger Easton at far right. (NRL Photo)

NTS-2 laser reflector. (Buisson-1977, p. 194)

used with transponders located on the seashore. The Mini-Ranger system provided position to an accuracy of 5 to 10 meters.

This experiment was a joint effort between the following US and Italian agencies and organizations: The US Naval Research Laboratory, the NASA/ Goddard Space Flight Center, with the support of the Bendix Field Engineering Corporation, The Italian Navy, the Istituto Elettrotecnico "G. Ferraris" and the Politecnic of Torino (Italy).

J. A. Buisson, O. J. Oaks and H. Warren, "Absolute Calibration and Precise Positioning between Major European Time Observatories and the U.S. Naval Observatory using GPS," in *Positioning With GPS-1985, First International Symposium on Precise Positioning with the Global Positioning System*, held at Rockville, Maryland, 15-19 April 1985, 433-445.

Historically precise time has been transferred from one site to a remote site by means of a method using portable clocks. The method entails the carrying of an active frequency standard and its associated clock from site A to site B. Personnel from the United Sates Naval Observatory (USNO), Bendix Field Engineering Corporation (BFEC), and Naval Research Laboratory (NRL), and others have made portable clock trips by airplane and surface vehicles for the past 15 years. Accuracy of the transfer of time ranges from a few nanoseconds (on a short surface trip) to hundreds of nanoseconds (on an extended overseas trip). Typically the origin of the portable clock trip is a major time keeping observatory, such as USNO, where the portable clock is initially synchronized as close as possible to the master clock (MC) time at that observatory. Upon return to the originating observatory, closure is again made with the master clock and a rate of the portable clock against the master clock is measured. Prior to departure a stationary rate is determined between the two clocks and these two rates (before and after) are compared. Assuming no major difference occurs, the time accumulation between the two clocks is estimated and linearly applied to results obtained from each location on the trip. The import thing to note in such a method is that the portable clock must be kept running during the entire trip; that is, transported "hot". Many logistics problems and additional costs result from this necessity.

A new method called Remote Calibration and Time Synchronization (R-CATS), allows a Global Positioning System (GPS) single frequency clear acquisition (C/A) code time transfer receiver (TTR) to be used instead of the portable clock. The portable TTR can be shipped or carried as luggage with no continuous power requirements. The procedure is similar to the portable clock method. R-CATS performs three major technical functions, calibration of existing GPS TTR, time transfer, and navigation. The TTR is first calibrated against the originating observatory master clock by making observations at the originating observatory with the antenna of the transportable TTR located near the antenna of the GPS receiver currently in use at that observatory. The portable TTR to be used in the R-CATS method is driven by the same clock that is used by the permanent TTR. In the event that a site does not have a GPS TTR the R-CATS method will be used to perform time transfer and coordinate positioning.

J. A. Buisson, O. J. Oaks and M. J. Lister, "R-CATS -- A New Method for Calibrating Global Positioning System (GPS) Remote Sites," in *Seventeenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Washington, D.C., 3-5 December 1985, 201-222.

Historically, precise time has been transferred between two sites by means of a method using portable atomic clocks. The method entails the carrying of an active frequency standard and its associated clock from site A to site B. Personnel from the United States Naval Observatory (USNO), Bendix Field Engineering Corporation (BFEC), Naval Research Laboratory (NRL), and others have made portable clock trips by airplane and surface vehicles for the past 15 years. The accuracy obtained using this method

for the transfer of time ranges from a few nanoseconds (on a short surface trip). Typically the origin of the portable clock trip is a major time keeping observatory, such as USNO, where the portable clock is initially synchronized as close as possible to the master clock (MC) time at that observatory. Prior to departure a stationary rate is determined between the two clocks. Upon return to the originating observatory, closure is again made with the master clock and a rate of the portable clock against the master clock is measured. These two rates (before and after) are then compared. Assuming no major difference occurs, the time accumulation between the two clocks is estimated and linearly applied to results obtained from each location on the trip. The important thing to note in such a method is that the portable clock must be kept running during the entire trip; that is, transported "hot". Many logistics problems and additional costs result from this necessity.

D. Bundy, "Time, navigation and global positioning: NRL's research aids Desert Storm Operations," Labstracts, 23 September 1991, 1, 4, 5.

In the dead of the night, somewhere in Saudi Arabia near the Kuwaiti border, gunners from the 11th Marine Regiment unlimber their self-propelled 155 millimeter guns. Range, elevation, and azimuth coordinates are quickly calculated, and the guns thunder almost in unison, their shells streaking towards an Iraqi artillery battery ten miles away. Before the Iraqis can range on their position and fire back, the Marines are already roaring across the desert to a new position a half mile away where they will unlimber their pieces and fire again.

Success in this nocturnal game of "shoot and scoot," as the Marines called it, depended on precise knowledge of their location at any moment, and on their ability to navigate unerringly across an empty, featureless desert.

Accurate positional information at any time, in any kind of weather, was critically important to all the services in the Persian Gulf War. Because of the NAVSTAR Global Positioning System (GPS) such information was available within a matter of seconds, whenever it was needed.

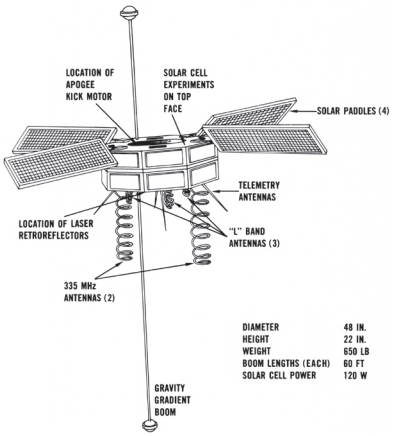
The NAVSTAR GPS is a satellite navigation system, which at present consists of 16 satellites (by 1993, the number of satellites will reach 24) equipped with atomic frequency standards, commonly referred to as atomic clocks...

D. Bundy, "Part II: NRL's space technology aids in Desert Storm Operations," *Labstracts*, 7 October 1991, 4, 5.

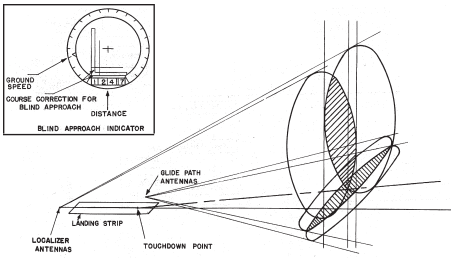
Roger Easton and his colleagues at NRL continued their efforts to produce atomic timekeeping devices that were reliable and sturdy, generated a strong, clear signal, and were small and light enough to fly in space. It was recognized early on that cesium beam standards similar to the ones used in south Texas in the early 1960s possessed the required characteristics, but in the early years of the TIMATION program, they were too large and heavy for space. While the effort to design cesium standards that were small and light enough continued, two rubidium standards were fitted on board the TIMATION III satellite, scheduled for launch in the spring of 1974.

By the time NRL's TIMATION III blasted off, it had been renamed Navigation Technology Satellite I (NTS-l). In 1973, the Defense Department merged NRL's TIMATION program and the Air Force's 621B Project, calling the new program, now under Air Force management, the NAVSTAR GPS Project.

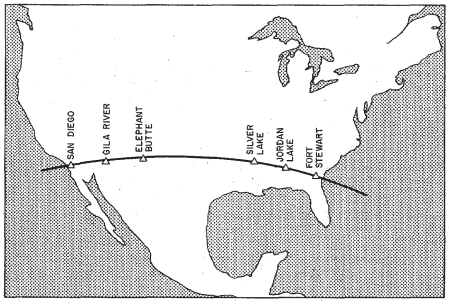
The Air Force's 621B plan called for a dozen satellites in eccentric geosynchronous orbits 22,000 nautical miles high. As an alternative, Roger Easton proposed a constellation requiring more satellites-but orbiting at a much lower altitude. Easton argued that with a constellation of on the order of two dozen satellites in circular orbits approximately 11,000 nautical miles high, it would be possible to have at least four in reach of any ground receiver at all times. A precise three-dimensional positional fix could then be obtained.



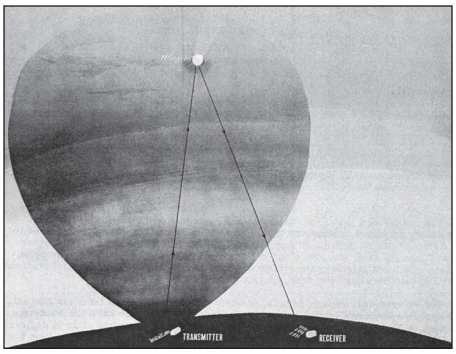
The NRL TIMATION III satellite, redesignated GPS Navigation Technology Satellite I (NTS-I), was successfully placed into a medium altitude orbit, 7,300 nautical miles, on July 14, 1974. The major experiments on TIMATION III were directed toward testing the ability of various satellite components to function in the space environment while providing the accuracy required for precise worldwide navigation. (Bundy-1991, 7 October, p. 5)



Localizer and glide path antenna patterns for a short range air navigation system by Emmet and Easton. Inset: cockpit blind approach indicator. (Emmet-1946 NRL Report 2857, plates 6 and 11)



Space Surveillance System stations. (Chrisman-1959 NRL Report 5366, p. 2)



Components of the Space Surveillance System for detecting “dark” (non-radiating) satellites. (NRL5575-1960, p. 2)

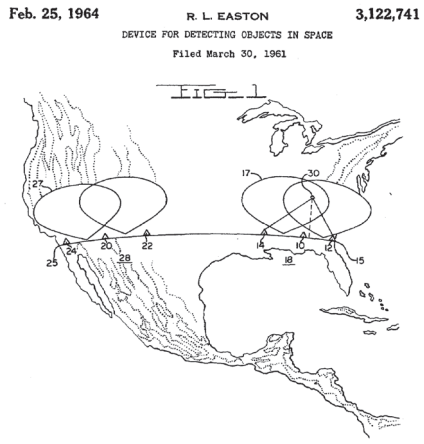
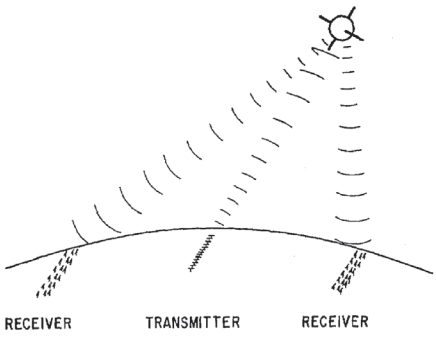


Figure from Roger Easton’s patent for “Device for Detecting Objects in Space.” This invention was realized in the Naval Space Surveillance System. (Easton-1964, Figure 1)



A three-station Space Surveillance complex in which a central transmitter illuminates satellites which reflect radio energy to receivers about 280 miles from the transmitter. (NRL5575-1960, p. 2)

The relative merits of the Air Force's 621B plan and NRL's concept as outlined by Easton were discussed for some time in the Pentagon. When the air cleared, however, Ron Beard (now the branch head in Easton's old branch, the Space Applications Branch, Code 8320) notes that it was Easton's scheme that formed the basis for the NAVSTAR satellite constellation…

D. Bundy, "Time, Navigation, and Global Positioning: Early Navy research paves way for success in Operation Desert Storm," Space Tracks Bulletin (November-December), 8-10 (1991).

Accurate positional information at any time, in any kind of weather, was critically important to all the services in the Persian Gulf War. Because of the NAVSTAR Global Positioning System (GPS) such information was available in a matter of seconds, whenever it was needed.

A. Buonaguro, T. B. McCaskill and J. A. Buisson, *Sequential Range Navigation for the NAVSTAR Global Positioning System*, NRL Report 7880, Naval Research Laboratory, Washington, D.C., 11 July 1975.
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C. H. Chrisman, Jr., J. F. Dowd and M. P. Anderson, *Space Surveillance System - Observations of the Satellite 1958 Zeta*, NRL Report 5366, Naval Research Laboratory, Washington, D.C., 29 June 1959.

All observations made by the Space Surveillance System on the satellite 1958 Zeta (Atlas) during its lifetime (December 18, 1958 to January 21, 1959) are presented. Only the Eastern Complex consisting of the Jordan Lake (Alabama) transmitting station and the Fort Stewart (Georgia) and Silver Lake (Mississippi) receiving stations were in operation at this time. About 70 feet long and 10 feet in diameter, this satellite was large enough to give good reflected signals and afforded the first opportunity for the Space Surveillance System to achieve a triangulation height measurement of a satellite. Between December 19 and January 19, reflected signal observations were made on 37 satellite passes including 18 coincident observations with complete information for height triangulation. These observations were obtained with the use of lower transmitter power and smaller antennas than now employed and in spite of considerable downtime resulting from construction work then in progress.

S. R. Chubb, "Location-corrector for removing sun-induced effects in the global positioning system," 17 December 1996, United States of America Patent 5,585,800.

The system for location-correction for removing the sun-induced effects in the global positioning system (GPS) caused by the problem of transforming the frequency of coherent radio signals to the geocentric inertial coordinate frame involves an implicit, dependence on earth-sun-clock orientation. This is accomplished by determining the systematic errors associated with sun-induced effects that alter the frequency of the transmission of every satellite within the GPS because of the GPS satellites orbit around both the sun and the earth and applying a correction factor to the initially determined position to obtain the true position within 10 cm to one meter.

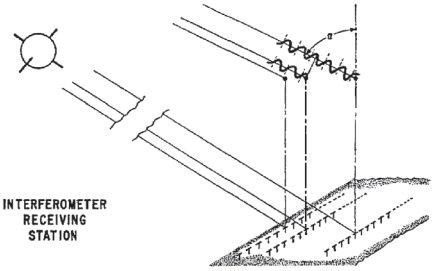
J. L. Clay, Col., USAF, 28 June 1996, USAF letter.

I am pleased to inform you that we have chosen you to become the next member of the NAVSTAR Global Positioning System Hall of Fame. Should you accept, you will be honored as a distinguished contributor to the GPS Program during our annual GPS Dining Out Hall of Fame Induction Ceremony on 2 August 1996.

C. E. Cleeton, *The Space Surveillance System: A Summary Report*, NRL Report 5575, Naval Research Laboratory, Washington, D.C., 31 October 1960.

The Naval Research Laboratory proposed the Space Surveillance System for detecting, tracking, and orbit predicting of nonradiating satellites. The Advanced Research Projects Agency has supported a feasibility experiment as Phase I, which has been completed. Further research and development in the area covered by this System are proceeding. Currently this System provides the only operation capability the Country has to detect noncooperating unannounced satellites.

The performance of the experimental system on typical satellites is illustrated. Coverage extends to about 450 statute miles in height on one-square-meter targets over limited sections of an east-west line. The second phase of the program, now in the development stage, will provide coverage to a height of about 2500 miles with a probability of detection of 95 percent over the extent of the entire line from the east to the west coast. Also automatic processing of the data is to be incorporated to provide a system suitable for operational use. A fully operational system requires a second line to enable precise orbit determination in a single pass. A recommended location is on a line extending in a northwest-southeast direction across the United States. The flexibility of the system design permits extensions and additions of equipment and facilities to meet increased operational requirements.



The interferometer principle for precise measurement of angle of arrival of signals from a satellite, used in the Space Surveillance System. (Cleeton-1960 NRL5575, p. 3)

T. Coffey, "Dr. Coffey honors Roger Easton in ARPAD Speech," *Labstracts*, 6-7, 25 March 1996.

The story begins in 1943 when someone at NRL had the wisdom and ability to hire a young engineer named Roger Easton… While many people deserve credit for what is now GPS, Easton's patent is the enabling patent.

.....To our patrons, I would put this forward as an illustration of why the Navy has a place like NRL. To the young scientists and engineers in the audience, I would urge you to approach things in the spirit of Roger Easton, coupling your own insights and your experience base with those of others to produce great achievements. In spite of what you may hear, there do remain great things to be done. To Roger Easton, we can only extend our thanks for your great contributions to the Navy and the Nation and for gracing us with your presence this evening. In recognition of your great achievements, I am pleased to announce the establishment of a major new NRL award for excellence in engineering achievement to be called the Roger Easton Award. This award will be treated as the engineering equivalent of the E.O. Hulbert Award for Scientific Achievement. It is our great hope, Roger, that you will be able to join us in the not too distant future when we make the first presentation of the Easton Award to an NRL employee…

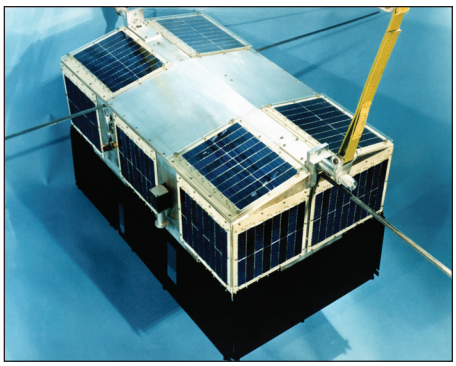
Roger Easton discusses the Vanguard Satellite with his daughter. (NRL Photo)

R. B. Cooley and R. L. Easton, *Inclination Perturbations of Polar-Orbit Satellites*, NRL Report 6928, Naval Research Laboratory, 11 September 1969.

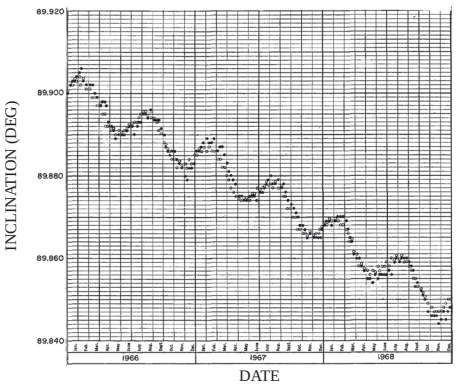
This report describes an investigation of the ability to predict long-term orbital elements for medium-height (satellite orbiting the earth at altitudes above the regions of appreciable drag), earth-orbiting satellites. The particular types of satellites studied are those having nearly circular, polar orbits. The primary element of interest is orbital inclination.

A theoretical equation for predicting the change in inclination caused by the gravitational attraction of the sun and moon is given. Expressions for the orbital elements of the sun and moon required in this inclination-predicting equation are developed. A FORTRAN program listing and computation procedure for determining the inclination of a satellite at any time after a chosen epoch is in the appendix.

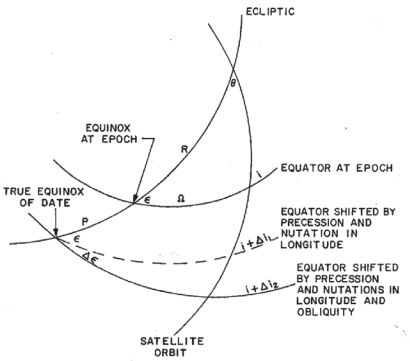
Nine satellites were selected for study. For these satellites, comparison plots of observed and predicted inclinations over a 3-year time interval are shown. The agreement between predicted and observed inclinations is very good for most of the satellites. Theoretical plots of the inclination of Satellite 902 over time intervals of up to 300 years are included.



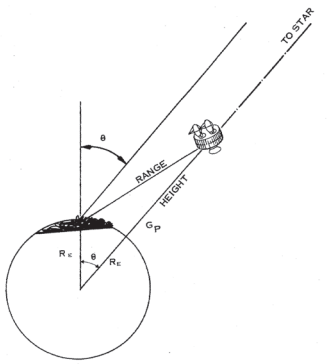
TIMATION I satellite. (NRL Photo)



Theoretical and observed inclination for a polar orbiting satellite after correction for precession and nutation. (NRL6928-1969, p. 10)



The orbital elements of the moon. (NRL6928-1969, p. 5)



Transform to celestial navigation. (Easton-1971, p. 47)

F. Danzy and W. Riley, "Stability Test Results for GPS Rubidium Clocks (Errata published 10 June 1988)," in *Proceedings of the Nineteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Redondo Beach, CA, 1-3 December 1987, 267-8.

This paper presents the results of further long-term stability tests on two prototype GPS rubidium frequency standards. These tests, currently underway at the U.S. Naval Research Laboratory, have resulted in the highest stabilities yet reported for such devices. Both units have smooth, highly modelable drift under 2x10^-14/day and a stability of about 1x10^-14 at 10^5 to 10^6 seconds.

H. G. deVezin, Jr., "The Computation of Optimum Orbital Elements Derived from a Single Coincident Observation of the Naval Space Surveillance System," Thesis for Master of Science, Department of Mathematics, University of Maryland, College Park, MD, 1964.

This thesis is concerned with an investigation into a method of determining the orbital elements of a passive artificial earth satellite using information obtained from a single coincident satellite observation of short time duration. This information is obtained from two receiving stations of the U.S. Naval Space Surveillance System, a CW radar network of three transmitting stations and four receiving stations which sets up an electronic "fence" stretching across the southern United States.

A list of the information given by two receiving stations is as follows: two east-west angles (angles measured in the plane of the detection "fence"), two north-south angles (angles measured normal -to the plane of the detection "fence"), rate of change of east-west direction cosine measured by both stations, and rate of change of north-south direction cosine measured by both stations. In addition the system can be adapted to measure the doppler frequency shift from one of the three transmitters to the receiver station and the distance from one of the three transmitters to the satellite to the receiver station (bi-static range).

All of this information results in redundant data (i.e. more data than are needed to determine the orbit of the satellite). In addition, owing to inaccuracies of the system and owing to noise, different groupings of the information will produce different values of orbital parameters, hence in general the information is inconsistent.

The purpose of this thesis is to arrive at a method of computing orbital elements using all of the information that the system does measure or can be adapted to measure. This method would introduce weighting factors determined, for example, by the accuracy with which the system can measure the parameter in question. This method is then used to study the effect that the addition of doppler shift and bistatic range measurements have on the accuracy of the resulting orbital elements.

R. L. Easton, *Harmonic Power Generation Using Unbaised Ideal Linear Rectifiers*, NRL Report 3581, Naval Research Laboratory, Washington, D.C., 13 December 1949.

Analyses have been made of three half-wave and three full-wave circuits employing unbiased linear rectifiers as harmonic power generators. These three circuits utilize (1) a resistive generator and a resistive load, (2) a resistive generator and a tuned load, and (3) a tuned generator and a tuned load.

The maximum harmonic gain, defined as the ratio of the available harmonic power to the maximum available fundamental power, has been found for each circuit. In all cases the gain decreases as the fourth power of the harmonic. Odd harmonics above the first are not present.

R. L. Easton, *Interim Report on Mass Level Sensor*, NRL Memorandum Report 225, Naval Research Laboratory, Washington, D.C., 23 September 1953.

To measure the propellant outage of the Viking rocket a mass level sensor is being designed and built by Naval Research Laboratory personnel at the White Sands Proving Grounds. As a result of supporting work being done at this Laboratory, a sensor having some advantages over the one currently in use at White Sands has been designed.

R. L. Easton, *Project Vanguard Report No. 21: Minitrack Report No. 2: The Mark II Minitrack System*, NRL Report 5035, Naval Research Laboratory, Washington, D.C., 12 September 1957.
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R. L. Easton, "The Mark II Minitrack System," Journal of the British Interplanetary Society **16**, 390-419 (1958).

During the International Geophysical Year an artificial Earth satellite containing a 108-Mc. transmitter is to be launched and placed in an orbit around the Earth. Although the Department of Defense is building and installing a number of Prime Minitrack stations -- installations to detect and plot the course of the satellite and to record various types of scientific data -- a Mark II Minitrack system, based on the interferometer principle in like manner to the primary system, has been developed, and this will permit amateur volunteer groups to spot and measure the track of the in-flight satellite. This latter system, which may be built and installed by amateur groups at nominal cost, consists in its simplest form of two Yagi antennas in a single baseline from 20 to 500 ft. long, a tee junction at the midpoint, a converter to shift the 108-Mc. satellite frequency to one that could be amplified by a standard communications receiver, and an "S" meter to be used as an indicator of satellite transit. In this simple version the system will indicate passage of the satellite but would provide no lasting or accurate record of scientific value.

By adding improvements in the system, a highly precise installation can be built that will yield data of interest to Project Vanguard personnel at the Naval Research Laboratory where orbit computation of the satellite is to be conducted. Some of these improvements consist of a hybrid junction rather than a tee junction in the transmission line, a graphical or magnetic tape recording in place of the "S" meter, a precise time signal fed to the record, a baseline of 1,000 ft. between antennas, high quality-transmission lines and amplified equipment, antenna systems installed with high precision, and multiple antenna-baseline-systems to provide an increased quantity of geodetic information.

Data read and recorded by the precision Mark II systems may be transmitted to the Vanguard Computing Center in Washington, D.C., where it can serve as an important computational material to study the flight and characteristics of the satellite and can also add to the store of scientific knowledge desired for the IGY objectives.

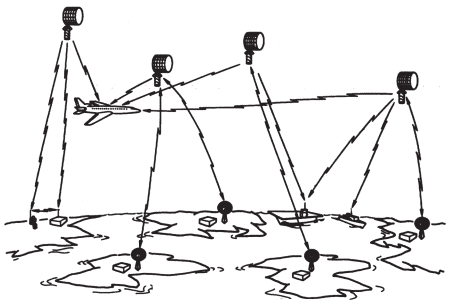
This document presents all the aspects of the design, construction, and calibration of the Mark II system for the serious-minded amateur desiring to carry out radio observations of the satellite.

R. L. Easton and M. J. Votaw, "Vanguard I IGY Satellite (1958 Beta)," Review of Scientific Instruments **30** (2), 70-5 (1959).

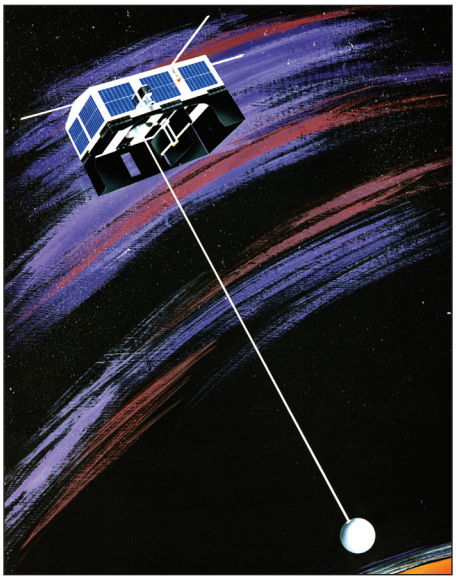
The instrumentation used, the measurements obtained, and the uses of the Vanguard I satellite are described. This satellite contains two transmitters, one powered by batteries for about three weeks and one powered by solar cells (still operating). From the transmitted frequencies temperature information and rotation rates are obtained. The transmitted signals are also used to determine the satellite orbit. An approximate free orbital lifetime of 200 years is predicted.

R. L. Easton and J. J. Fleming, "The Navy Space Surveillance System," Proceedings of the IRE **48** (4), 663-669 (1960).

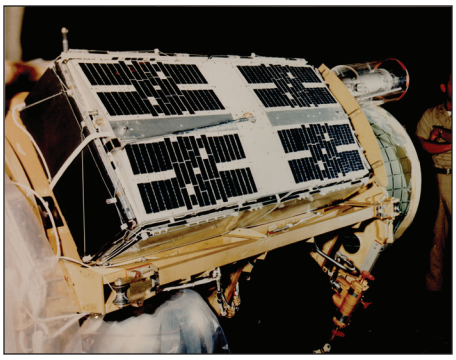
Ericsson statue, near the Lincoln Memorial in Washington, D.C. TIMATION I time navigation and passive ranging were demonstrated by NRL to DoD and Navy representatives at this location on 25 October 1967. John Ericsson was an inventor and marine engineer. (*Labstracts* 15 October 2007)



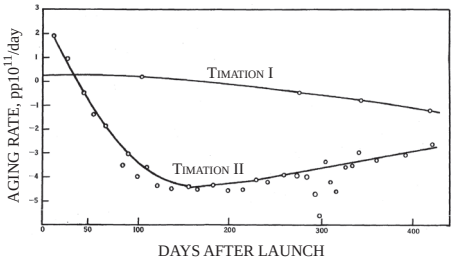
TIMATION navigation system setup. Uplinks transmit commands and ephemeris data. Downlinks transmit ranging, satellite position, tracking and telemetry data. (NRL Report 7227, 1971, p. 10)



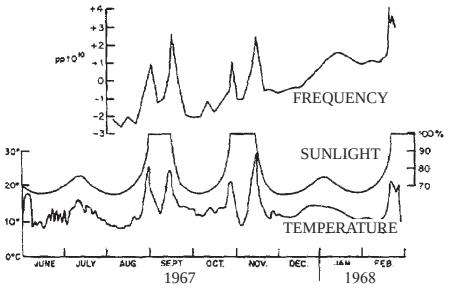
Artist rendition of TIMATION I/II satellite in orbit. (NRL drawing)



TIMATION II satellite. (Easton-1970, p. 13, Easton-1971, p. 55)



Aging rates of crystal oscillators on TIMATION I and TIMATION II satellites. (Easton-1971, p. 55)



Influence of sunlight on temperature and frequency. (Easton-1969, p. 183)

400 Megahertz time dissemination receiver. (Easton-1971, p. 59)

A complete system for satellite detection and tracking and for computations of satellite orbits has been built by the Navy under ARPA sponsorship. This detection system uses a CW transmitter separated from two receiving sites, all having fan-type co-planar antenna beams. The angle of arrival of the reflected signals is measured at each station by the use of an interferometer. The position of the reflecting object is inferred by the point in the fan antenna beam defined by the intersection of the arrival angles at the two receiving stations.

Two ARPA-sponsored Space Surveillance radal (radio detection and location) devices of the type described have been installed in the southern U. S. In addition to the detecting and tracking installation the system includes data transmission lines, a data reduction center, a very high speed computer for orbit determination and predictions, and display devices.

R. L. Easton, "Device For Detecting Objects in Space," 25 February 1964, United States of America Patent 3,122,741.

The present invention relates to an artificial earth satellite observation system and more particularly to a surveillance system capable of detecting and locating non-radiating objects in space.

R. L. Easton, "An Exploratory Development Program in Passive Satellite Navigation," 8 May 1967, Space Applications Branch Technical Memorandum No. 1, 23 pp.

Memorandum reviews the original 1964 conception by Easton of passive ranging to operate with the excellent time keeping ability of the hydrogen maser, the initial Navy contacts made to obtain funding, and the initial 1965 funding arising from the interest of the Astronautics Officer at the Navy Bureau of Weapons. Also in 1965, a test was run with an oscillator in an automobile. A later test used an aircraft as though it were the satellite.

DDR&E stipulated that the satellite be small and of low power, which determined that a quartz oscillator be flown. To avoid interference with tactical communications, a different modulation scheme will be required on subsequent satellites. For compatibility, the satellite provides the doppler signal needed by the NNSS. The satellite, on which work began in late 1965, is ready for launch as of the date of the memorandum.

A general purpose navigation system is envisioned, useable by submarines, ground troops, ships, helicopters, blimps, aircraft and satellites. The heart of the technique is the stable oscillator.

When advanced development funds were denied for fiscal year 1968, the project was stretched out, and much of the work on constellations was decreased.

The stability, reliability and power requirements of various frequency standards are compared, including quartz, rubidium, cesium beam, and hydrogen maser.

With two satellites it will be possible to obtain instantaneous position information when both are visible. With a third satellite visible, it will be possible to obtain position and altitude simultaneously.

User equipment and cockpit displays are discussed.

R. L. Easton, C. A. Bartholomew, D. H. Phillips and M. B. Bloch, "Crystal Oscillator Satellite Experiment," in *22nd Annual Symposium on Frequency Control*, held at Atlantic City, New Jersey, 22-24 April 1968, 342-53.

The purpose of this experiment was to determine the suitability of a crystal oscillator as a satellite frequency standard.

Due to weight and power limitations no possibility existed for using an atomic standard for this task, so the entire emphasis was placed on providing the best crystal oscillator possible.

The results of the experiment are that the oscillator has shown a long-term drift of approximately 3pp 10^12/day, a very acceptable value. The oscillator has also shown a temperature coefficient of approximately 2pp 10^11 per degree C. This coefficient can be reduced for future satellites of this type.

R. L. Easton and T. B. McCaskill, "Satellite Angle and Altitude Measuring System," 15 October 1968, United States of America Patent 3,406,397.

A radio interferometer system for determining from a single receiver site the angle and latitude of a satellite. A transmitted fan-shape beam forms a fence through which the satellite passes and echo signals are detected by pairs of receivers. The phase difference between the signals received at a receiver pair is directly related to the angle of arrival of the signals while the difference between the phase differences obtained from two pairs of receivers is related to both arrival angle and satellite altitude. Additional pairs of receivers are used to eliminate measurement ambiguities.

R. L. Easton, C. A. Bartholomew and R. S. Rovinski, *The Thermal Design of the Timation I Satellite*, NRL Report 6782, Naval Research Laboratory, Washington, D.C., 16 January 1969.

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R. L. Easton and R. Brescia, *Continuously Visible Satellite Constellations*, NRL Report 6896, Naval Research Laboratory, Washington, D.C., 30 April 1969.

The results of this study show that a minimum of six satellites is required in a controlled-orbit constellation to have at least one satellite continuously visible from all points on the earth's surface. The study also examined the number of required satellites for different heights and various minimum elevation angles.

To have two satellites visible at all times it is sufficient to double the number required for a single-satellite condition: to have three satellites simultaneously visible it is sufficient to triple the number required for a single-satellite condition.

A constellation that is to have at least one visible satellite every place on the earth results in approximately twice the coverage of the earth's surface, but to date no easy method has been found for assuming that this duplication can be used to reduce the number required for having two, or three, mutually visible satellites at one time.

R. L. Easton and R. Brescia, "Continuously Visible Satellite Constellations," Report of NRL Progress, 1-5, July 1969.

The results of this study show that a minimum of six satellites is required in a controlled-orbit constellation to have at least one satellite continuously visible from all points on the earth's surface. The study also examined the number of required satellites for different heights and various minimum elevation angles.

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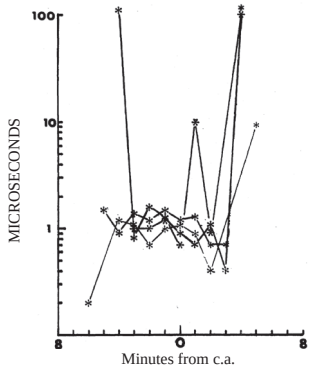
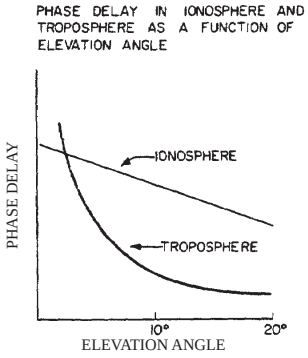
R. L. Easton, "Mid-Altitude Navigation Satellites," in *Electronic and Aerospace Convention EASCON '69 Record*, held at Washington D.C., 27-29 October 1969, IEEE, 180-183.

After considering both lower and higher altitudes the mid-altitude (approximately 1 earth's diameter) polar circular satellite constellation has been selected as a prime possibility for an accurate, all weather, always available, three dimension, U.S. based navigation system. The system designed is based upon using the well-known low altitude satellite techniques to extrapolate this knowledge to higher altitudes.

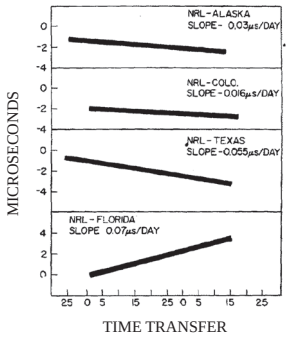
At the higher altitudes the drag and gravitational anomalies decrease rapidly but the knowledge of satellite position has a minimum, at about one earth radius.



Time measurement errors made by NRL-RCA receivers. (Easton-1971, p. 62)

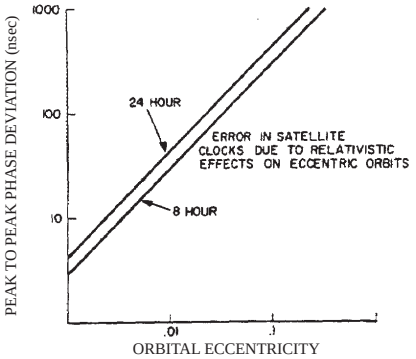


Phase delay in ionosphere and troposphere as a function of elevation angle. (Easton-1969, p. 182)

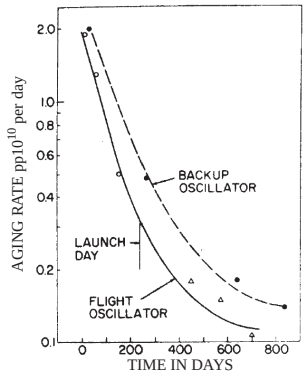


Results using the satellite as a time transfer device between an oscillator at NRL and cesium beam resonators at the four stations shown. (Easton-1969, p. 183)

TIMATION II satellite ground track for 16 November 1971 pass. (Easton-1971, p. 65)



Clock frequency changes due to relativistic effects associated with a varying gravitational field, versus orbit eccentricity. Easton recommended circular orbits on this basis. (Easton-1969, p. 183)



Aging rate of TIMATION I quartz crystal oscillators versus time. (Easton-1970, p. 342)

The combination of gravitational anomalies and knowledge of satellite position shows a rather broad minimum for satellites having periods between 8 and 24 hours.

At present the principal parameter which favors a lower period is the satellite clock, the principal factor favoring higher altitudes is coverage.

The number of satellites visible to an observer at the equator for three planes of 8 satellites per plane is shown for a portion of one day and the background information found from a low altitude satellite is shown and discussed.

R. L. Easton, "Communications System," 13 January 1970, United States of America Patent 3,490,044.

Communication system requiring a very narrow bandwidth for transmission of an input signal (such as from voice or music). Amplitude and frequency modulations of input signal are transmitted as phase modulations of two different frequency signals. After transmission, these phase modulated signals are used to reproduce the input signal.

R. L. Easton, "Method Of Ranging Compatible With Space Surveillance System," 31 March 1970, United States of America Patent 3,504,367.

This invention relates to object detection systems in general and in particular to systems for detecting objects in orbit around the earth in which range information is obtained with only two apparatus locations rather than the three apparatus locations required by the prior art.

R. L. Easton, C. A. Bartholomew, J. A. Bowman and M. Bloch, "A Second Satellite Oscillator Experiment," in *Proceedings of the 24th Annual Symposium on Frequency Control*, 27 April 1970, 339-44.

The performance of a quartz crystal oscillator in the Timation I satellite has been reported in a previous symposium on frequency control and will be reviewed briefly as a basis for comparison. The principal problem with the oscillator in this first satellite was temperature coefficient. The effect of radiation on this oscillator has been deduced from subsequent data and will be presented.

A second experimental navigation satellite was launched in September 1969 in which an improved quartz crystal oscillator was included. Pre and post flight performance of this oscillator will be compared with the earlier unit.

R. L. Easton, "Optimum Altitudes for Passive Ranging Satellite Navigation Systems," Naval Research Reviews **23** (7), 8-17 (1970).

This paper discusses a method for determining optimum altitudes for navigation satellites having different types of transmission (e.g., CW) than the present units.

R. L. Easton, "TIMATION Navigation Satellite (Abstract)," in *Proceedings from (the Second) Precise Time and Time Interval (PTTI) Strategic Planning Meeting*, Vol. 1, held at Naval Research Laboratory, Washington, D.C., 10-11 December 1970, 108.

Timation is a program in technology leading to a navigation system. The Naval Research Laboratory (NRL) performs theoretical analysis, develops critical components, and performs measurements on satellites as required to define a navigation system to meet classified requirements of the Joint Chiefs of Staff. The critical item in a satellite navigation system is the ground station location, which determines the satellite constellation. At present, navigation fixes, instantaneous fixes, and running fixes have been demonstrated and ionospheric refraction measurements have been made. NRL is presently in the process of using experimental satellites for time synchronization.

This abstract is unclassified, but the report is classified confidential, and is in Volume II of the conference proceedings. It can be obtained only by written request to the U.S. Naval Observatory, Technical Officer, Washington, D.C. 20390.

R. L. Easton, "TIMATION Navigation Satellite," in *Proceedings from (the Second) Precise Time and Time Interval (PTTI) Strategic Planning Meeting*, Vol. 2, held at Naval Research Laboratory, Washington, D.C., 10-11 December 1970, 15-55.
LIMITED DISTRIBUTION

R. L. Easton and C. A. Bartholomew, "Crystal Oscillator With Automatic Compensation For Frequency Drift Due To Aging," 2 February 1971, United States of America Patent 3,560,880.
A highly stable crystal oscillator for keeping time precisely wherein the frequency drift due to aging of a quartz crystal is compensated by a programmed electro-mechanical tuning device.

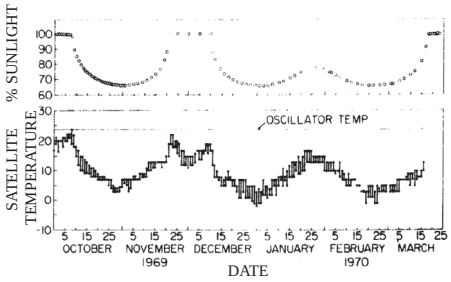
R. L. Easton, "Arrangement to Measure And Compensate For Crystal Orientation Change," 24 August 1971, United States of America Patent 3,600,951.
Method and apparatus for symmetrically arranging two or more crystals so that changes of orientation can be measured but will not disturb the frequency of an ultrastable crystal oscillator.

R. L. Easton, C. A. Bartholomew and R. S. Rovinski, "Passive Temperature Control For Satellite," 7 September 1971, United States of America Patent 3,603,530.
An earth-facing satellite having an inner compartment which contains electronic equipment and an outer housing which is heat isolated from and surrounds the inner compartment except on the bottom side of the satellite. Passive control of the ambient temperature of the inner compartment is obtained by heat exchange between the earth and the bottom side of the satellite and by thermal shields which protect the bottom surface from direct solar radiation.

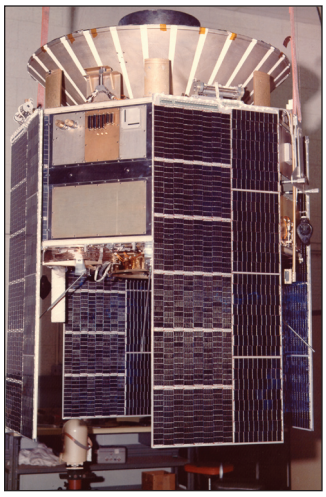
R. Easton, "Timing Receiver for TIMATION Satellite," in *Proceedings of The Third Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Washington, D.C., 16-18 November 1971, 45-68.
This paper presents a brief review of the various methods of time dissemination and a discussion of the timing receiver developed for use with the Timation satellites.
Four time transfer possibilities are listed in Figure 1. LORAN, OMEGA, and TV are suited for a fixed master-fixed user situation (possibility 1 in the figure); user navigation is required for the fixed master-moving user (possibility 2 in the figure, user navigation). This report is concerned with items 3 (moving master-fixed user, master navigation) and 4 (moving master-moving user, navigate both master and user): when the master and/or the user are moving, precise knowledge of their locations is necessary.
There are two very closely related ways of time dissemination today: radio and navigation. Historically, the moons of Jupiter were used to obtain the first measurements of longitude. Later, the moon was used in a navigation system in which time could be determined to about 30 miles (a little over a minute) . Time dissemination today uses the hyperbolic stations, LORAN and OMEGA, and satellites, which make possible the two-way ranging and passive ranging systems.
The satellite has four advantages: (1) well-known position; (2) line-of-sight signal, which allows the use of UHF; (3) worldwide coverage; and (4) a celestial navigation solution identical to the one used in celestial navigation for 200 years (see Figure 2)…

R. L. Easton, C. A. Bartholomew, R. F. Wenzel and R. Carson, *Radiation Effects on Satellite Crystal Oscillators*, NRL Report 7368, Naval Research Laboratory, Washington, D.C., 15 February 1972.
NRL7368 LIMITED DISTRIBUTION

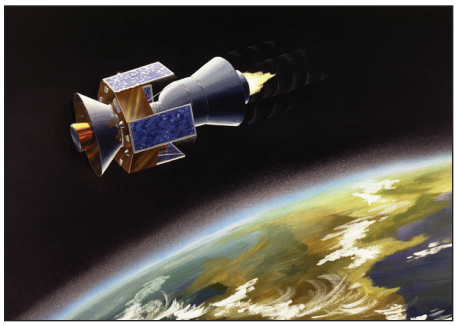
R. L. Easton, "The Role of Time/Frequency in Navy Navigation Satellites," Proceedings of the IEEE **60** (5), 557-563 (1972).



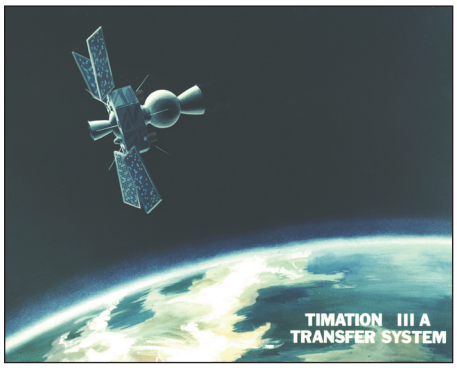
TIMATION II satellite and oscillator temerature, and percent sunlight, versus time. (Easton-1970, p. 342)



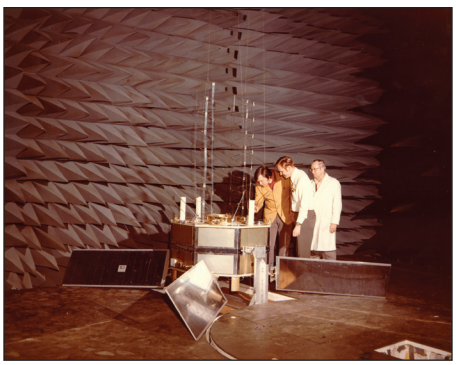
TIMATION III (NTS-1) satellite. (NRL Photo)



NTS-1 in transfer orbit. (McCaskill-1975, p. 428)



TIMATION-III/NTS-1 transfer orbit. (NRL illustration)



NTS-1 satellite in NRL anechoic chamber. (NRL Photo)

This paper discusses the role of time and frequency in three areas:
1) the operational Navy Navigation Satellite System, NNSS;
2) an experimental, low-altitude navigation concept termed TIMATION;
3) proposals for advanced navigation satellites.
These operating, experimental, and proposed systems all use concepts which allow the user to remain passive.
The operational NNSS system uses the Doppler technique to establish user positions to 100 m. In this concept, the frequencies received from the satellite are compared to the frequencies generated in the user equipment. One can also compare the time a signal arrives from a satellite clock to a time generated in the user equipment clock for passive ranging. The paper shows that this passive ranging problem is easily transformed to the celestial navigation problem. Extension of these techniques allows one to use satellites as clock transporters and hence to compare clocks located throughout the globe to 0.5 us. Experimental results are shown. It has been possible to determine the effects of radiation on quartz crystals and to determine that this effect is due principally to protons. System concepts are described which show this clock/time technique can determine user position, velocity, and time continuously, accurately, and globally.

R. L. Easton, "Crystal Oscillator for Satellite," 6 June 1972, United States of America Patent 3,668,527.
Structure and apparatus located on a satellite which control the environment of a crystal oscillator for the purpose of attaining extreme frequency stability and reducing the problems of pre-flight testing and adjusting. The oscillator is located in an evacuated chamber together with heat shields and ovens.

R. Easton, "British American Satellite Time Transfer Experiment," in *Proceedings of the Fourth Annual Precise Time and Time Interval (PTTI) Planning Conference*, X-814-73-72, held at Goddard Space Flight Center, 14-16 November 1972, NASA, 14-28.
At last year's PTTI we ran an actual time transfer between two buildings approximately 300 feet apart. We did this by means of a satellite approximately 500 miles away. Figure 1 shows the results obtained.
This year the Naval Observatory asked that we perform a similar experiment with the Royal Greenwich Observatory (RGO). The Royal Greenwich Observatory, with headquarters in a fifteenth century castle, is at the site shown on the map (Figure 2).
The final data, which we will describe more fully, is shown in Figure 3. The two sets of data are displaced 15.2 microseconds. This displacement represents the difference between the Naval Observatory and RGO clocks as measured in this experiment.
Last year we showed a bit about the theory of time transfer. However, since there is always someone in the audience who is new and did not get the word, I will repeat myself briefly.

R. L. Easton, "Intermittent CW System for Satellite Surveillance," 3 April 1973, United States of America Patent 3,725,924.
An electronic satellite surveillance system wherein transmitters and receivers are located at the same sites and wherein the transmitted signals consist of multifrequency, intermittent, CW electromagnetic energy which is radiated in narrow fan patterns and wherein the receivers include means which allow unambiguous angle and range determination.

R. L. Easton, J. A. Buisson and T. B. McCaskill, *Instantaneous Position Fixing from Measurement of Satellite Range and Doppler*, NRL Report 7580, Naval Research Laboratory, Washington, D.C., 13 August 1973.
A worldwide satellite navigation system (TIMATION) has been proposed that will yield instantaneous and continuous position fixes by suitable satellite

configurations and navigator equipment. The TIMATION project is conducted by NRL under the sponsorship of the Navy Space Project Office (PM-16) and the Naval Air Systems Command. This report addresses the instantaneous position-fixing results obtained by using range and doppler measurements obtained with the TIMATION II satellite and a navigation receiver employing a relatively precise frequency standard. The results are corrected for first-order ionospheric refraction and indicate a two-dimensional position-fixing capability of 105 m RMS (60 m CEP).

BACKGROUND

A significant advantage of satellites as sources of navigation fixes is that it is possible to determine a two-dimensional position fix from a single satellite almost instantaneously (1). Both the range and the Doppler shift are measured simultaneously. This report presents the results of a large number of navigation fixes using the TIMATION II satellite.

The technique, which provides the navigation an instantaneous position with measurements from a single satellite, assumes that the passive user has four known parameters: (a) navigator's velocity, (b) time difference between satellite and user clocks, (c) frequency difference between satellite and ground frequency standards, and (d) navigator's height above the geoid. If these parameters are not known, the navigator can make additional measurements to determine the unknowns.

R. L. Easton, "Apparatus And Method For Improving Sensitivity of Navigation System Using Earth Satellites," 2 October 1973, United States of America Patent 3,763,492.

An improvement to a navigation system which includes earth satellites that carry stable oscillators which are synchronized with a stable oscillator at the navigator's station; the improvement consisting of means that improve system, sensitivity and reduce the effectiveness of jamming by including in the receiver at the navigator's station a tracking oscillator which is locked onto the carrier frequency received from the satellite. The tracking oscillator output is frequency divided down and phase locked with the multifrequency tone signals that are also received from the satellite and then phase compared with similar multifrequency signals which are derived from the stable oscillator at the navigator's station.

Discussing future of NTS-2 are Roger L. Easton (center), NRL NAVSTAR GPS program manager, his satellite builder, Pete Wilhelm (right), and Navy CDR Bill Huston (standing), Navy Deputy Program Manager of the NAVSTAR System. (NRL Photo)

R. L. Easton, H. M. Smith and P. Morgan, "Submicrosecond Time Transfer Between the United States, United Kingdom, and Australia via Satellite," in *Proceedings of the Fifth Precise Time and Time Interval (PTTI) Planning Meeting*, held at Goddard Space Flight Center, 4-6 December 1973, NASA, 163-83.

During 1972 time transfer experiments were run between the U.S. Naval Observatory and the Royal Greenwich Observatory and, in 1973, between the U.S. Naval Observatory and the Division of National Mapping in Canberra, Australia.

In both cases the time transfer agent was the TIMATION II satellite, 1969-82B. The satellite ephemerides were computed by the Naval Weapons Laboratory from data provided by the Defense Mapping Agency TRANET. This net tracked the satellite's doppler transmissions.

The phase of the satellite clock was determined from knowledge of the position of the satellite and of the observer and the computed distance between the two. By monitoring the clock on successive passes the rate of the satellite clock was determined at Washington. By again monitoring the satellite clock at the distant station the satellite clock could be compared to the local clock and this local clock compared to the U.S. Naval Observatory clocks.

In 1972 the RMS of observations at Greenwich deviated by approximately 1/4 microsecond from a straight line when compared to the Naval Observatory. In 1973 the observation errors at Canberra were approximately half as great.

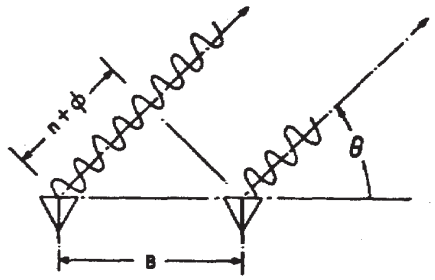
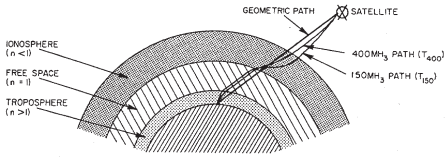


Illustration that the phase of a signal received at one antenna differs from the phase of that signal received at another antenna separated from it by a distance B. (Easton-1968, U.S. Patent Figure 4).



Typical ray path trajectory. The quantities T_{150} and T_{400} give the actual transmission times for the 150- and 400- MHz ranging signals, respectively. (McCaskill-1971 NRL7252, p. 19)

R. L. Easton, "Navigation System Using Satellites And Passive Ranging Techniques," 29 January 1974, United States of America Patent 3,789,409.

A navigation system wherein the navigator's location is obtained by determining the navigator's distance (or range) from one or more satellites of known location. Each satellite transmits multifrequency signals that are derived from a stable oscillator which is phase synchronized with the navigator's equipment that produces similar multifrequency signals. Phase comparison between the signals received from the satellites and the locally produced signals indicates both the distance between the navigator and the satellites and the navigator's location. In determining his location, the presence of the navigator is not revealed since no interrogatory transmission by him is required.

R. L. Easton, D. W. Lynch, J. A. Buisson and T. B. McCaskill, *International Time Transfer Between the U.S. Naval Observatory and the Royal Greenwich Observatory via the TIMATION II Satellite*, NRL Report 7703, Naval Research Laboratory, Washington, D.C., 18 April 1974.
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R. L. Easton, P. Morgan and H. M. Smith, "Satellite time transfer from the U.S. Naval Observatory to the Royal Greenwich Observatory and to Australia," presented at the CPEM 74: Conference on Precision Electromagnetic Measurements, London, 1-5 July 1974, IEE, 281-3.

This paper describes the TIMATION II satellite time transfer experiments between the U.S. Naval Observatory and the Royal Greenwich Observatory in 1972 and the U.S. and Australia in 1973.

The error in the experiment conducted between the RGO and USNO agreed internally and with the external calibrations to within about 1/3 microsecond. The experiment between the U.S. and Australia agreed internally and externally to approximately 0.1 microsecond.

R. L. Easton, P. Morgan and H. M. Smith, "A Summary of Recent Satellite Time Transfers from the U.S. Naval Observatory to the Royal Greenwich Observatory and to Australia," IEEE Transactions on Instrumentation and Measurement **23** (4), 525-6 (1974).

This paper describes the TIMATION II satellite time transfer experiments between the U.S. Naval Observatory (USNO) and the Royal Greenwich Observatory (RGO) in 1972, and between the U.S. and Australia, in 1973. The error in the experiment conducted between the RGO and USNO agreed internally and with external calibrations to within 0.33 us. The experiment between the U.S. and Australia agreed internally and externally to approximately 0.1 us.

R. L. Easton, L. C. Fisher, D. W. Hanson, H. W. Hellwig and L. J. Rueger, "Dissemination of Time and Frequency by Satellite," Proceedings of the IEEE **64** (10), 1482-1493 (1976).

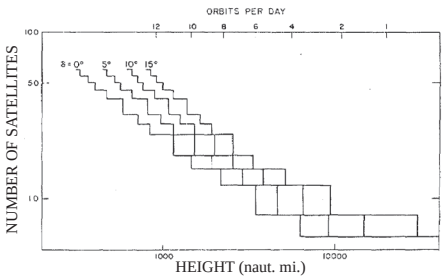
A survey is given of the field of satellite time dissemination covering past experience, present activities, and future planned services with their respective precisions and accuracies. Transponder satellites, clock-carrying satellites, satellite systems, and two-way satellite links are discussed.

R. L. Easton, "The Hydrogen MASER Program for NAVSTAR GPS," in *Eighth Annual Precise Time and Time Interval (PTTI) Meeting*, held at US Naval Research Laboratory, Washington, D.C., 30 November - 2 December 1976, 3-12.

The Department of Defense has assigned to the Navy the task of providing both ground and space maser for NAVSTAR GPS. Two ground masers are being built by the Smithsonian Astrophysical Observatory (SAO) and two contractors, RCA and Hughes, are building preliminary space models. SAO has also succeeded in having a TE 111 cavity maser. The National Bureau of Standards (NBS) in Boulder is building a passive maser. Supplementary research for this program is being conducted at NRL.

R. L. Easton, J. A. Buisson and T. B. McCaskill, *Initial Results of the NAVSTAR GPS NTS-2 Satellite*, NRL Report 8232, Naval Research Laboratory, Washington, D.C., 25 May 1978.

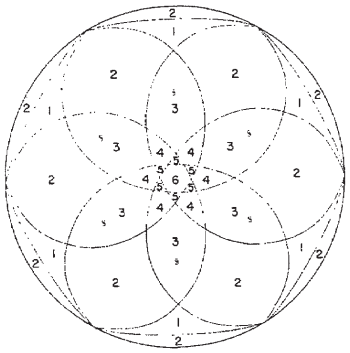
Navigation Technology Satellite 2 (NTS-2) was successfully launched on June 28, 1977, into a near-12-hour circular orbit. Precise frequency and timing signals are derived from the two cesium frequency standards. This report discusses the launch and preliminary results, which include verification of the relativistic clock effect. An International time-transfer experiment is planned, and a worldwide synchronization accuracy of less than 100 nanoseconds is anticipated, based on preliminary time-transfer results between Cape Kennedy and the U.S. Naval Observatory. A proposed NASA laser-tracking network will be used to verify the accuracy of the Global Positioning System (GPS) orbits.



Number and height of polar circular satellites needed to insure at least one having an elevation angle greater than 8 degrees. (Easton, NRL Report 6896, 1969, p. 2)

R. L. Easton, "The Navigation Technology Program," Navigation: Journal of The Institute of Navigation **25** (2), 107-112 (1978).

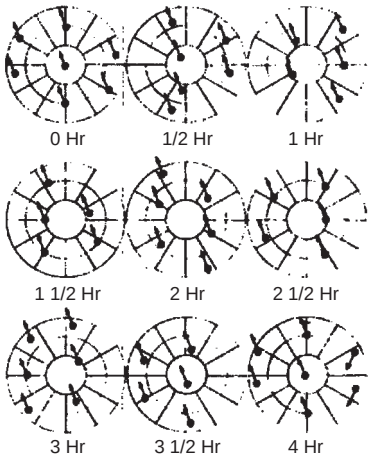
The Navigation Technology Program at the Naval Research Laboratory formally came into being with the merger, directed by the Secretary of Defense in 1973, of the Navy's TIMATION program and the Air Force 621B Project. Both these programs had been established in the mid-1960s to investigate the possibility of developing a satellite passive ranging system to test contemporary military navigation requirements. The Air Force program used an ingenious "inverted range" whereby satellite-type signals were generated by ground stations to provide ranging signals for aircraft positioning, while the Navy actually launched satellites. Both projects made major contributions which were later used in the NAVSTAR Global Positioning System joint program that grew out of the merger.



Constellation coverage with twelve satellites in three planes, for delta (i.e., the required minimum elevation angle for observation) equal to 15 degrees. (Easton, NRL Report 6896, 1969, p. 7)

R. L. Easton and J. A. Buisson, "The Contribution of Navigation Technology Satellites to the Global Positioning System," in *2nd International Geodetic Symposium on Satellite Doppler Positioning*, Volume 2, held at University of Texas, Austin, Texas, 22-26 January 1979, 1111-1152.

The Navigation Technology Satellites, developed by the US Naval Research Laboratory, have been provided as a vehicle for the design and test of basic satellite navigation technology currently in the use in the NAVSTAR Global Positioning System (GPS). Two satellites, TIMATIONS I and II, were flown in 1967 and 1969 to demonstrate the concept of using synchronized clocks to provide time ranging for navigational purposes. Navigation Technology Satellite One (NTS-1), flown in 1974, introduced a rubidium atomic clock and NTS-2, 1977, a cesium clock; both provided increasingly superior navigation accuracy. NTS-3, scheduled for flight in 1981, will utilize a hydrogen maser clock for even better performance and reduced dependency on ground updating. In addition to the clock development, the technology satellites have tested the effect of the radiation environment, the use of retroreflectors for laser tracking, and improved solar cells and batteries. As a result of NTS-2 tests, the SAMSO program office stated that the NAVSTAR GSP* concept had been successfully validated.



Constellation selected by Easton in 1969 includes 3 planes of satellites in 12-hr, polar circular orbits, with 8 satellites per plane, “as a prime possibility for an accurate, all weather, always available, three dimension, U.S. based navigation system.” (Easton-1969, p. 180-3)

R. L. Easton, "The TIMATION Navigation Satellites," *NATO AGARDOGRAPH, Principles and Operational Aspects of Precision Time Determination Systems*, C. T. Leondes, ed. (Neuilly-sur-Seine, France, July, 1979).

The development of stable RF oscillators in the two post World War II decades was essential to the design of passive ranging navigation systems. Early involvement of the U.S. Naval Research Laboratory in this method of time synchronized navigation is outlined. The first NRL satellite used to validate the concept was launched in 1967. Both it and the second satellite used quartz crystal oscillators. The two following satellites use rubidium and cesium standards respectively.

*As printed in original publication.

The Vanguard Satellite atop the Viking launch vehicle. Roger Easton is to the left of the satellite. (NRL Photo)

The lessons learned from the early satellites are summarized, and the merger of TIMATION into the NAVSTAR Global Positioning system Program is described. Selected experimental results from NTS-1 and 2 are analyzed and the plans for NTS-3 are outlined.

R. L. Easton, J. A. Buisson, T. B. McCaskill, O. J. Oaks, S. Stebbins and M. Jeffries, *The Contribution of Navigation Technology Satellites to the Global Positioning System*, NRL Report 8360, Naval Research Laboratory, Washington, D.C., 28 December 1979.

The Navigation Technology Satellites, developed by the Naval Research Laboratory, have been provided as a vehicle for the design and test of basic satellite navigation technology currently in use in the NAVSTAR Global Positioning System (GPS). Two satellites, TIMATION I and II, were flown in 1967 and 1969 to demonstrate the concept of using synchronized clocks to provide time ranging for navigational purposes. Navigation Technology Satellite 1 (NTS-1), flown in 1974, introduced a rubidium atomic clock, and NTS-2, flown in 1977, introduced a cesium clock. Both clocks provided increasingly superior navigation accuracy. A hydrogen maser clock for even better performance and reduced dependency on ground updating is being developed. In addition to the clock development the technology satellites have tested the effect of the radiation environment, the use of retroreflectors for laser tracking, and improved solar cells and batteries. As a result of NTS-2 tests the Air Forces's Space and Missile Systems Organization (SAMSO) program office stated that the NAVSTAR GPS concept had been successfully validated.

R. L. Easton, B. W. Parkinson and S. W. Gilbert, "Comments, with reply, on "NAVSTAR: global positioning system - ten years later" by B. W. Parkinson and S. W. Gilbert," Proceedings of the IEEE **73** (1), 168 (1985).

COMMENTS by Roger L. Easton:

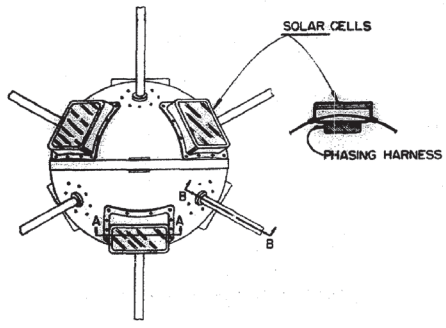
The paper "NAVSTAR: Global Positioning System-Ten Years Later" in the October 1983 issue of the Proceedings was read with great interest by this reader who participated in many of the planning sessions during the formative months of this program. Messrs Parkinson and Gilbert were our team leaders and always performed most capably in the difficult, and often unrewarding task of setting up and managing the fledging project.

However, if as Lord Macaulay said, "History is the myth that historians agree upon," they will get little agreement from this quarter regarding some of their reminiscences. I was surprised to find that "The TIMATION concept was essentially a two dimensional system." Indeed, TIMATION constellations providing two, three, and even four (time update) dimensions were presented the GPS Program Office early on, depending on the number of TIMATION satellites the U.S. could afford to place in orbit.

The remainder of this sentence states, "TIMATION… lacked the ability to provide continuous position updates in a high-dynamic aircraft environment." Also a shocker. This observer failed to discern then and cannot find now any significant difference in the dynamic response capability of the two systems.

In a following paragraph Parkinson and Gilbert state: "The remarkable result is that now; ten years later the basic system design is virtually unchanged." True. Even more true if the sentence had been completed by adding "from the original TIMATION concept."

A more accurate history revisited might have summarized the concept selection by stating: "The 621B concept of clustered satellites at synchronous altitude was rejected because system implementation and maintenance costs were too high, and there was doubt that such constellations could be maintained in stable orbits. The TIMATION concept was selected because it was cheaper and it worked."



Vanguard I Satellite line drawing, showing solar cells and antennas. (Easton-1959, p. 74)

REPLY by B.W. Parkinson and S.W. Gilbert:

As W. MacNeile Dixon once observed, "It is not the lofty sails but the unseen wind that moves the ship." It was not our intention to minimize not detract from the significant contributions made by people like Roger Easton toward the realization of NAVSTAR system. As Roger has noted, the TIMATION orbital configuration was, in fact, the basis for the NAVSTAR system design. At the time however, TIMATION was, indeed, advocated as a two-dimensional system and the need for the third dimension was being seriously questioned by the TIMATION advocates.

The other major legacy of the Navy's TIMATION program, and in particular of Roger Easton and his team at the Naval Research Laboratory, was the development of spaceborne atomic clocks. As we pointed our in our paper; this was the pacing development for the entire NAVSTAR concept.

Likewise, the principal legacy of the Air Force 621B Program was the signal structure and the secure, jam-resistant signal that derived therefrom. The use of the pseudo-random noise ranging codes, as demonstrated during 621B Program testing and more recently during NAVSTAR system testing has proven to be one of the most effective means of achieving the high jam resistance required in todays environment. We are certain that Roger Easton would agree that this factor alone has been essential to continued support and approval of the NAVSTAR system.

In summary, a total system concept is more than the sum of its parts. A great debt is due all those "unseen winds" who, like Roger Easton, offered up the parts and to those who assembled those parts into a "full blown" system.

CLOSURE by Roger L. Easton:

It was a pleasure to read the letter from Messrs. Parkinson and Gilbert in reply to my letter referring to their excellent article "NAVSTAR: Global Positioning System - Ten Years Later." The pleasure comes from seeing how the authors are softening their stand on their description that "The TIMATION concept was essentially a two-dimensional system." They now say "… TIMATION was indeed, advocated as a two-dimensional system and the need for the third dimension was being seriously questioned by the TIMATION advocates."

It is always dangerous to describe someone else's system and it is especially dangerous to point out the system limitations. When TIMATION was proposed, the Navy already had an accurate two-dimensional ship navigation system, called TRANSIT, in operation. TIMATION was designed for aircraft navigation. It was designed to provide three dimensions and three velocities continuously and worldwide.

I know not of the "advocates" who spoke otherwise.

R. Easton, "GPS: time and change," IEEE Spectrum, 4 (letter to the editor in response to I. Getting, IEEE Spectrum Dec. 1993, pp. 36-8, 43-7) (1994).

From my perspective, Ivan Getting ["The Global Positioning System, "December 1993, pp.26-28, 73-47] overstates the role of the Aerospace Corp. and ignores the fundamental contributions of the Naval Research Laboratory (NRL) to the development of the GPS. The GPS uses passive ranging, 12 hour circular orbits, and space born atomic clocks that were originally implemented by NRL in the Timation navigation satellite system. In turn, the ancestry of Timation can be traced to Project Vanguard and the Navy Space Surveillance System, for which NRL also had primary responsibility.

The simple fundamental concept of GPS is the ability to measure range to a transmitter passively if the user and transmitter have synchronized clocks. If the user passively measures the range to four (or more) transmitters that carry synchronized clocks and are at known positions, the user can determine clock time and position in three dimensions.

This concept first was demonstrated to Chester Kleczek and Jon Yob of the Naval Air Systems Command in 1964. They understood that the concept could be used to improve aircraft navigation, and so they promptly funded

Vanguard launch, 17 March 1958. The third stage of the rocket used solid propellant to thrust the second American satellite into orbit. (NRL photo)

Vanguard control room at NRL-DC showing the teleprinters for receiving data from the MINITRACK stations. (NRL photo)

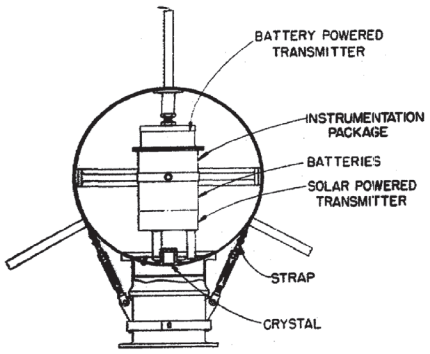


Diagram of internal components of Vanguard I Satellite, including solar-powered transmitter, battery-powered transmitter, and oscillator crystal. (Easton-1959, p. 74)

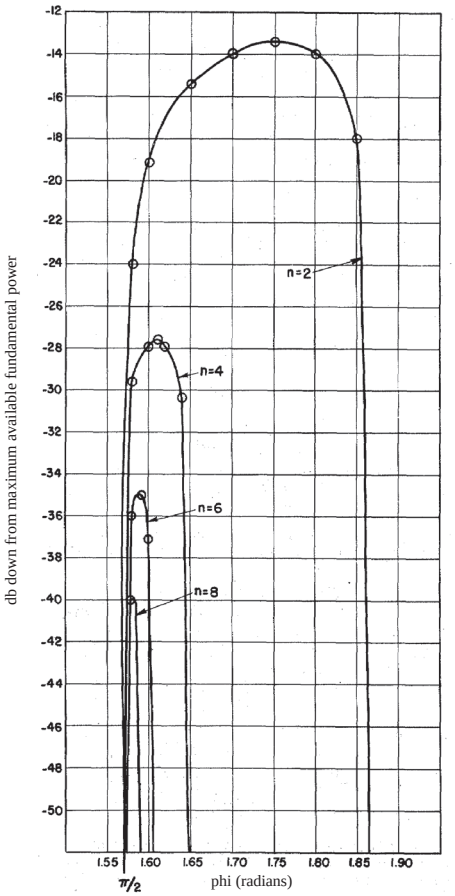
development of a system which was later named "Timation" for TIMe navigATION.

The first Timation satellite was launched on May 31, 1967, and demonstrated the feasibility of the passive-ranging concept. After initial tests and calibration at the naval laboratory, the technique was demonstrated to personnel of the Department of Defense and the Department of the Navy at the John Ericsson statue in Washington, D.C., near the Lincoln Memorial.

The Timation II satellite was launch on August 20, 1969. Timation III, renamed NTS 1 (Navigation Technology Satellite), was launched on June 14, 1974,* and carried quartz and rubidium time standards. NTS-2 was launched on June 23, 1974,* as the first of the GPS Phase-I Satellites. It carried cesium-beam standards and transmitted signals for both Timation and Navstar GPS receivers. The first studies of satellite constellations were made by NRL (Report 7389--"TIMATION Navigation Satellite System Constellation Study").

$$G_n^{\max r1} = \frac{F_{1n}\frac{\cos n\phi}{\cos\phi} - F_{nn}}{\frac{\cos n\phi}{\cos\phi}\left[F_{11}\frac{\cos n\phi}{\cos\phi} - F_{1n}\right]}. \qquad (48)$$

Equation 48 is the exact equation for harmonic gain, maximized with respect to the generator impedance. The maximum G_n as a function of phi has been computed numerically for n = 2, 4, 6, and 8; results are shown in the figure below. (Easton, NRL3581-1949, p. 7)



G_n as a function of phi for Equation 48, above. (Easton, NRL3581-1949, p. 8)

R. Easton, "Letter to the Editor, Getting a Fix on Origins of GPS," Physics Today **48** (12), 91 (1995).

See also:

Original column by Daniel Kleppner, Physics Today, Jan. 1994, p. 9,11.

Getting comment, Physics Today, Oct. 1994, p. 13,15.

Easton comment, Physics Today, Dec. 1995, p. 91;

Getting reply, Physics Today, Dec., 1995, p. 91-2.

Easton comment, Dec. 1995:

The letter on the history of the Global Positioning System by former Aerospace Corp president Ivan A. Getting (October 1994, page 13) could have corrected some very minor mistakes in Daniel Kleppner's "Reference Frame" column, "Where I Stand" (January 1994, page 9). Instead Getting's rewrite of history adds to the propagation of errors on the origins of GPS.

I worked for the Naval Research Laboratory for 37 years before retiring in 1980. The idea of using satellite-carried precise clocks for three-dimensional navigation came to me out of the blue in 1964. Ground tests at NRL were used to demonstrate the principle to Bureau of Naval Weapons personnel later that year. The idea is covered by US patent 3,789,409, entitled "Navigation System using Satellites and Passive Ranging Techniques." I was in charge of the NRL organization that developed satellites for demonstrating the Time Navigation (Timation) concept for the Naval Air Systems Command. Getting introduces an unsubstantiated name change when he writes, "As the decade [of the 1960s] wore on, the Air Force with GPS, the Navy with improved TRANSIT concepts of the Naval Research Laboratory's Timation concepts, and the Army with SECOR competed for the role of the Department of Defense's navigation system."

Actually the only real competition was between the Air Force--Aerospace Corp 621B concept and NRL' s Timation. (The name Navstar GPS came later.)

The 621B concept in its original publication consisted of three or four constellations of 24-hour satellites. Each constellation would have had a single geostationary satellite and either three or four satellites having eccentricities and inclinations such as to trace near-circular ground tracks about the subsatellite point of the stationary unit. According to reference 1, these satellites were to use transponders continually controlled by ground stations.

The Timation concept consisted of an array of satellites carrying high stability free-running clocks updated by ground stations as required. All the satellites are in circular orbits in several planes, all of them with identical high inclinations.

Is the GPS description more like that of 621B or of Timation? You be the judge.

NRL placed four Timation navigation satellites (some of the names were changed later) in orbit. The first two were low-altitude secondary payloads. These units used crystal oscillator clocks. The third unit carried two rubidium

*As printed in original publication.

oscillators obtained from Efratom in Munich through Frequency and Time Systems, a company started by Robert Kern and Arthur McCoubrey. The fourth satellite contained two cesium beam clocks developed for NRL by Kern at FTS. All the results and development plans for Timation were furnished to the Joint Program Office upon its adoption of this concept.

Of the other concepts developed at the time, the one developed for the National Aeronautics and Space administration by Roy Anderson of General Electric was the closest to Timation. Anderson's concept envisaged 24 satellites in four planes of 5600-nautical-mile circular orbits. Anderson's idea, however, used the satellites as transponders rather than clock carriers.

I find Kleppner a bit too prompt with his regrets in his reply to Getting's letter. Also, in writing that "the GPS was initiated by the Navy in the 1970's and taken over by the Air Force in the early 1980's," he should have used "1960s" rather than "1970s," "1970s" rather than "early 1980s" and "the Joint Program Office managed by the Air Force" rather than "the Air Force." Even so, his description was much closer to the facts than were the assertions in Getting's letter.

R. L. Easton, "Improving GPS," presented at the Institute of Navigation Annual Meeting, Cambridge Massachusetts, 19-21 June 1996, 65-70.

The present GPS system can be improved by about a factor of ten by the use of an inverse GPS for correcting satellite positions and time and by the addition of more satellites in equatorial orbits.

R. L. Easton, "GPS Hall of Fame acceptance speech," 2 August 1996.

Acceptance speech upon induction into the GPS Hall of Fame.

R. Easton and R. Anderson, "Past and Future Passive Ranging Navigation," in *ION-GPS-96, Institute of Navigation National Technical Meeting (NTM)*, held at Kansas City, MO, 17-20 September 1996, 689-98.

This paper starts with a description of two navigation concepts that were proposed as general systems. One is the GE proposal to NASA by fellow author Anderson. Its satellite constellation is quite similar to that used by GPS. The second is the 621B proposal by the Air Force-Aerospace team. This concept envisioned four constellations of 24-hour repeating satellites. Each local constellation consisted of one geostationary satellite with three (or more) satellites in inclined, eccentric orbits displaced from the geostationary satellite in such a manner as to have near-circular ground tracks. This type of constellation is very different from those proposed for other navigation systems and from the one in operational use for GPS.

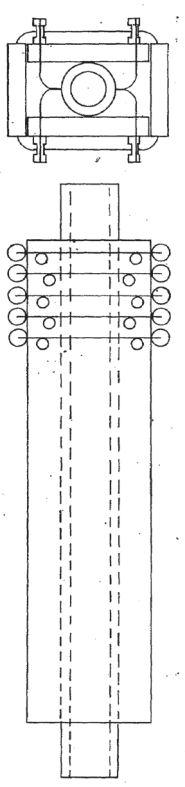
The next subject covered is the TIMATION concept. In it are shown the results obtained from a low altitude satellite and the 3 X 9 8-hr. orbit proposed for the Defense Navigation Satellite system. Both its constellation and satellite clocks are used in GPS.

Azimuth-Elevation plots are shown for the present GPS constellation and possible means of improving the present GPS accuracies are presented.

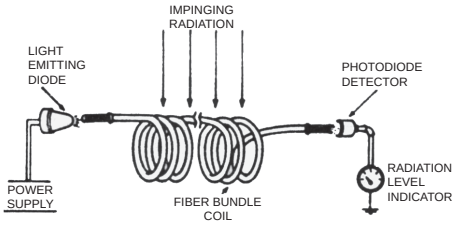
R. L. Easton and T. B. McCaskill, "Defense Navigation Satellite Systems Proposed Prior to GPS," presented at the 55th Annual Meeting of The Institute of Navigation, Cambridge, MA, 28-30 June 1999, 57-61.

Several scenarios describing the start of the Global Positioning System (GPS) have been presented. These stretch all the way from someone dreaming up the system in the dark of night, to its being a derivative of Transit, to "it was developed by the Department of Defense (DoD) primarily for the U.S. military to provide precise estimates of position, velocity, and time". This quoted sentence narrows the size of the source from a few billion people to something close to one million. Wouldn't it be nice to narrow the possibilities to a smaller number?

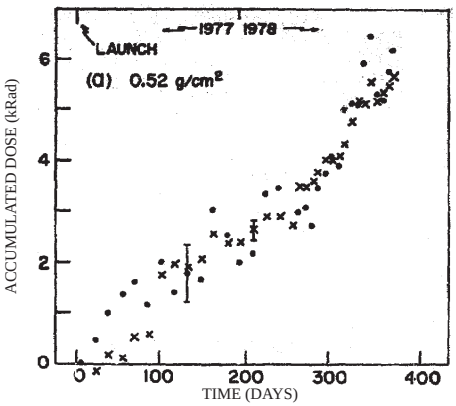
We are often told that the system started in 1973. Some say it was designed on Labor Day weekend of that year. However, were there no concepts existing before this date? Was it designed from scratch on that weekend?



Level sensor for liquid oxygen. (Easton, NRL Report 225, 1953, Fig. 4)



Schematic of NRL fiber-optic dosimeter aboard Navigation Technology Satellite 2. (Evans-1978, p. 1619)



Real time dose accumulated by a fiber optic sensor on board NTS-2, covering the period 23 June 1977 through 6 June 1978. (Evans-1978, p. 1623)

The answer is that the design started long before 1973. Fortunately, we have a snapshot of this development at the EASCON '69 meeting, held October 27-29, 1969 at the Sheraton Park Hotel in Washington, DC. Three articles given at that meeting [1], [21, [3] are of special interest:

"Low-Altitude Navigation Satellite System" by R.B. Kershner of the Johns Hopkins Applied Physics Laboratory (APL),

"Mid-Altitude Navigation Satellites" by R.L. Easton of the U.S. Naval Research Laboratory (NRL), and

"Satellite Systems for Navigation using 24-Hour Orbits" by J.B. Woodward, W.C. Melton & R.L. Dutcher, of the Aerospace Corporation.

We plan to summarize all three papers to give the audience an idea of GPS proposals before GPS existed. We also summarize a prior paper [4] "Study of Satellites for Navigation" by Roy E. Anderson of General Electric (GE) made under contract to the National Aeronautics and Space And Space Administration (NASA).

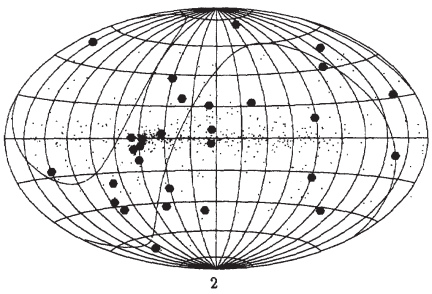
R. L. Easton, "Keynote Address: In The Beginning of GPS," in *32nd Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, Virginia, 28-30 November 2000, 7-16.

Good morning. My talk is on the beginning of GPS. I've given this talk several times. Twice it went quite well. But the last time, it was a dead thud, so I'm warning you. A lot of its acceptance level had to do with the listener's age, because when one talks about 1969 to people who weren't born then, the talk has little current meeting.

GPS is a navigation system consisting of two dozen satellites in circular, inclined orbits. Each satellite contains a number of stable clocks. The satellites transmit clock-based synchronized signals continuously, allowing us to have a system unlimited by the number of participants. Further, in not needing interrogation, the user can observe radio silence. Having all the clocks synchronized is a big thing for GPS. At the time the idea of the satellites carrying the clocks was proposed, all the other proposals used interrogated schemes. Receivers detect signals from several satellites simultaneously (> three for x, y, z, and t). From these observations, position and time are calculated.

Where did GPS start? There have certainly been some wild comments about the beginning: (1) "It was developed by the DoD for the U.S. military," which is true; (2) "GPS can trace its heritage to the Navy's Transit program," which is not true; (3) "It began in 1973," while it actually began in 1964. Comment (1) is not especially helpful and comments (2) and (3) are not supported by the documented evidence. One is reminded of the quotation of Thomas Henry Huxley concerning "the slaying of a beautiful hypothesis by an ugly fact," Everything was going fine with these explanations until a fact came along and destroyed them all.

Let's look at some documented evidence. Early in the proposal stage of advanced navigation systems, in 1969, an EASCON meeting was held in Washington. Three different navigation proposals were discussed. (I've given Dr. White copies of these three proposals in case you would like to read them in full).



A plot in galactic coordinates of the 29 known millisecond pulsars in 1995, proposed as possible frequency references. (Foster-1995, p. 454)

R. L. Easton, "Events in 1964," 22 February 2003, email.

The demonstration was pretty simple. We had receivers for side tone ranging already built for use on the Ranging and Velocity Fence in South Texas. One was modified by Matt Maloof to use only two side tones. A small transmitter was built with the same two side tones. The transmitter was placed in Mr. Maloof's convertible and it was run down Rt. 295. This route was finished but not opened to the public at the time. So the experiment was run in the fall of 1964. Back at the Laboratory we showed how the range between the car and the receiving station varied as the car went down the road.

The two representatives from the Bureau of Naval Weapons, John Yob and Chester

Kleczek, observed the experiment and were suitably impressed and transferred $35,000 seed money to start the project. John Yob has passed on but Mr. Kleczek still lives in Arlington, VA.

R. Easton, "The Guild of Relativity," *Labstracts*, 24 March 2003, 9, reprinted from IEEE Life Members Newsletter.

Editor's note: NRLer John Bowman, of the Information Technology Division, brought a copy of the IEEE Life Members newsletter, for the 3rd & 4th quarters, 2002. On page 4, under the heading of war stories, an article, "The guild of relativity," written by Roger Easton, was published. John Bowman thought fellow NRLers would be interested in this article.

The National Science & Technology Medals Foundation, "National Medal of Technology," http://www.nationalmedals.org, 2006, captured 31 May.

Technology Administration

THE NATIONAL MEDAL OF TECHNOLOGY RECIPIENTS

Roger L. Easton, RoBarCo, Canaan, NH

For his extensive pioneering achievements in spacecraft tracking, navigation, and timing technology that led to the development of the NAVSTAR-Global Positioning System.

J. C. Eidson, M. Fischer and J. White, "IEEE-1588™ Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems," in *34th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, VA, 3-5 December 2002, 243-254.

This paper discusses the major features and design objectives of the IEEE-1588 standard. Recent performance results of prototype implementations of this standard in an Ethernet environment are presented. Potential areas of application of this standard are outlined.

R. A. Emmet, Jr. and R. L. Easton, *An Interim Short Range Air Navigation System*, NRL Report 2857, Naval Research Laboratory, Washington, D.C., 11 June 1946. NRL2857 LIMITED DISTRIBUTION

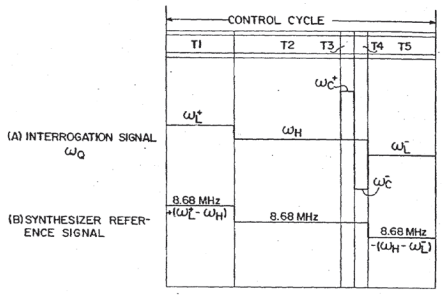
B. D. Evans, G. H. Sigel, Jr., J. B. Langworthy and B. J. Faraday, "The Fiber Optic Dosimeter on the Navigation Technology Satellite 2," IEEE Transactions on Nuclear Science **NS-25** (6), 1619-24 (1978).

A fiber-optic radiation dosimeter has been developed that utilizes the darkening induced in silicate glasses by ionizing radiation. A small, light weight, low-power consuming dosimeter package was deployed on the Navigational Technology Satellite.

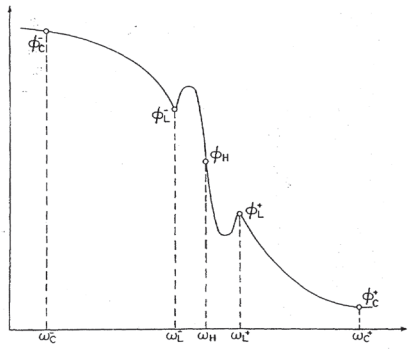
Observed real-time accumulated absorbed dose behind three shield thicknesses for the period July 1977- June 1978 are compared with both the AE4 and the AE17 particle fluence models for outer zone trapped electrons. The observations indicate little shielding improvement above three g/cm2 due to the presence of bremsstrahlung generated within the shielding and give evidence of a harder energy spectrum than predicted by these models. Occasional large dose rate fluctuations may correlate with sunspot activity during late 1977 and early 1978.

R. Evans and J. White, "Time of Day Management for Satellite Communications," in *34th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, VA, 3-5 December 2002, 255-262.

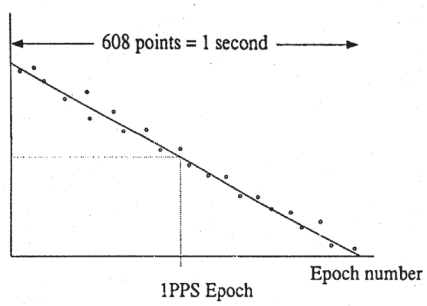
The U.S. Naval Research Laboratory has installed GPS-based timing systems in several DSCS satellite communication facilities to support the Single Channel Transponder program. These systems were originally installed between 1998 and 2000 in 11 sites located around the world. The goals were to manage the satellite crystal oscillators to 25 microseconds and the ground cesium clocks to 5 microseconds. This paper will describe the project's progress, with results showing the time management of the



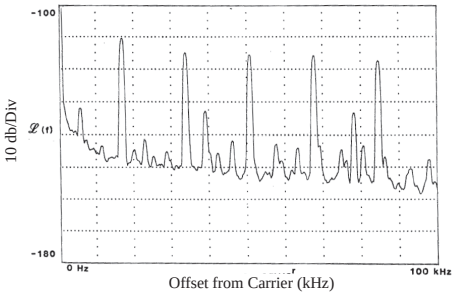
Timing diagrams for a passive maser, from a patent by Frank and White. (Frank-1984, Fig. 3)



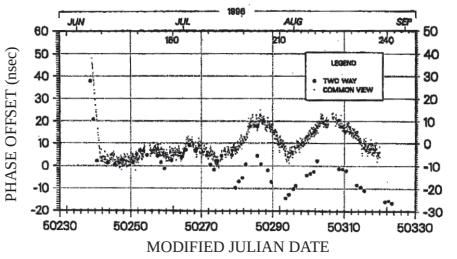
Dispersion curve of the cavity and stimulated emission line for the on-resonance condition in a maser, from a patent by Frank and White. (Frank-1984, Fig. 3)



Curve fit of Time of Arrival measurement, using a two-way time transfer modem with a very small aperture terminal (VSAT). Vertical axis is phase. (Galysh-1990, p. 348)



Phase noise of hydrogen maser. N2 versus P12 phase noise (100 kHz) in decibels, versus offset from carrier. (Gifford-1985, Figure 10)



Results of Timing Subsystem Enhancement to the GPS Monitor Station in Hawaii. Phase offset residuals of disciplined clock from DOD Master Clock using two-way time transfer and linked common-view time transfer. (Galysh-1996, p. 425)

satellite oscillators and the cesium-beam clocks. A Windows-compatible computer program written to facilitate the clock management will also be described.

E. S. Ferre-Pikal, J. R. Vig, J. C. Camparo, L. S. Cutler, L. Maleki, W. J. Riley, S. R. Stein, C. Thomas, F. L. Walls and J. D. White, "Draft revision of IEEE STD 1139-1988 standard definitions of physical quantities for fundamental, frequency and time metrology-random instabilities," in *Proceedings of the 1997 IEEE International Frequency Control Symposium*, held at Orlando FL, 28-30 May 1997, 338 - 357.

This is a draft revision of IEEE Std 1139-1988 Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology. This draft standard covers the fundamental metrology for describing random instabilities of importance to frequency and time metrology. Quantities covered include frequency, amplitude, and phase instabilities; spectral densities of frequency, amplitude, and phase fluctuations; variances of frequency and phase fluctuations; time prediction; and confidence limits when estimating the variance from a finite data set. The standard unit of measure for characterizing phase and frequency instabilities in the frequency domain is L(f), defined as one half of the double-sideband spectral density of phase fluctuations. In the time domain, the standard unit of measure of frequency and phase instabilities is the fully overlapped Allan deviation sigma/sub/y(tau) or the fully overlapped modified Allan deviation Mod sigma/sub/y(tau).

H. F. Fliegel, R. L. Beard, G. P. Landis and S. B. Stebbins, "An Alternative Common View Method For Time Transfer With GPS," presented at the ION GPS-89, The Second International Technical Meeting of the Satellite Division of The Institute of Navigation, Colorado Springs, Colorado, 27-29 September 1989, 37, 463-74.

The standard method of using GPS to compare the time of distant clocks is called the common view technique, by which two or more ground stations simultaneously observe a single GPS satellite, or space vehicle (SV). In the most commonly used form of common view, the positions of the SVs must be known, because the time of arrival of an SV signal must be corrected for the travel time, that is, the range to the various stations, divided by the speed of light. However, common view is one form of multilateration in which M stations on the ground simultaneously range to N points in the sky. In general, solutions can always be obtained for the positions of the M ground points and N skypoints in a coordinate system anchored to any three of them, if M and N are large enough, and if certain singular geometric configurations of the points are avoided.

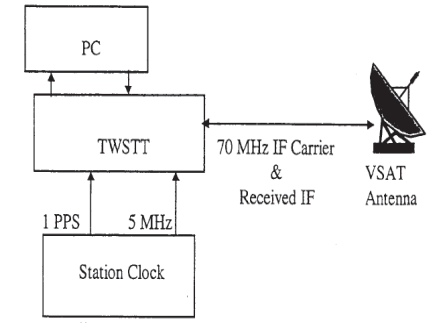
Common view / multilateration can easily be extended to the GPS case, in which pseudoranges take the place of ordinary ranges, and each SV provides four unknowns to be solved for: the three of position, and one of time. If five stations in known locations measure pseudoranges to four SV points, one may solve for four of the station time offsets relative to a reference station, as well as for corrections to the SV broadcast times and positions. If five stations measure pseudoranges to 13 SV points, one may solve for corrections to the station positions, the SV positions, and all the clocks in the system relative to one clock.

We show here how to adapt the principles from the classical geodetic literature on simultaneous ranging to the GPS case, in which clock offsets as well as positions must be estimated. We discuss how to optimize the geographic distribution of common view stations, and the lengths and frequency of times of observation. A proposal for field tests is presented, based on numerical simulations.

H. F. Fliegel, R. L. Beard, G. P. Landis and S. B. Stebbins, "An Alternative Common View Method For Time Transfer With GPS," Navigation: Journal of The

Institute of Navigation **37** (3), 263-72 (1990).

The standard method of using GPS to compare the times of distant clocks is called the common view technique, by which two or more ground stations simultaneously observe a single GPS space vehicle (SV). In the most widely used form of common view, the positions of the SVs must be known because the signal transit times must be calculated. However, common view is one form of mutilateration, by which solutions can be obtained for the positions of both stations and satellites, as well as clock offsets. We show in this paper how to adapt the principles from the classical geodetic literature on multilateration to time transfer. We discuss the need to optimize the geographic distribution of common view stations and the times of observation. A proposal for field tests is also presented, based on numerical simulations.

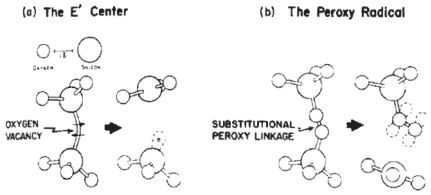


Two-Way Satellite Time Transfer (TWSTT) hardware block diagram. (Galysh-1998, p. 346)

V. J. Folen, W. G. Maisch, J. D. White, C. A. Bartholomew and H. F. Frank, *Hybrid Modes in Anisotropic Dielectrics*, NRL Memorandum Report 4870, Naval Research Laboratory, Washington, D.C., 30 July 1982, 55 pp.
NRLmr4870 LIMITED DISTRIBUTION

R. S. Foster and D. N. Matsakis, "Application of millisecond pulsar timing to the long-term stability of clock ensembles," in *27th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, NASA Conference Publication 3334, held at San Diego CA, 29 November - 1 December 1995, NASA Goddard Space Flight Center, 447-55.

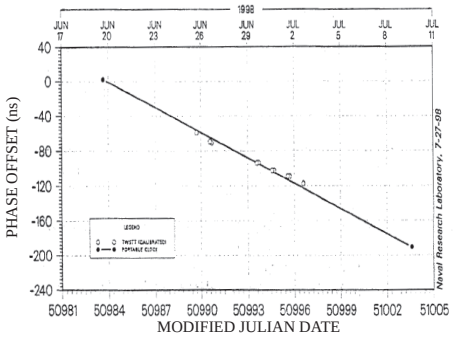
We review the application of millisecond pulsars to define a precise long-term time standard and positional reference system in a nearly inertial reference frame. We quantify the current timing precision of the best millisecond pulsars and define the required precise time and time interval (PTTI) accuracy and stability to enable time transfer via pulsars. Pulsars may prove useful as independent standards to examine decade-long, timing stability and provide an independent natural system within which to calibrate any new, perhaps vastly improved atomic time scale. Since pulsar stability appears to be related to the lifetime of the pulsar, the new millisecond pulsar J1713 +0747 is projected to have a 100-day accuracy equivalent to a single HP5071 cesium standard. Over the last five years, dozens of new millisecond pulsars have been discovered. A few of the new millisecond pulsars may have even better timing properties.



Formation of intrinsic defect centers in alpha-quartz and fused silica by hole trapping at the sites of a neutral Frenkel defect pair. (Griscom-1979, p. 101)

C. Fox, G. A. Gifford, S. R. Stein and T. R. Bartholomew, "GPS Time Determination and Dissemination - A Tutorial," in *Twenty-third Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Pasadena CA, 3-5 December 1991,

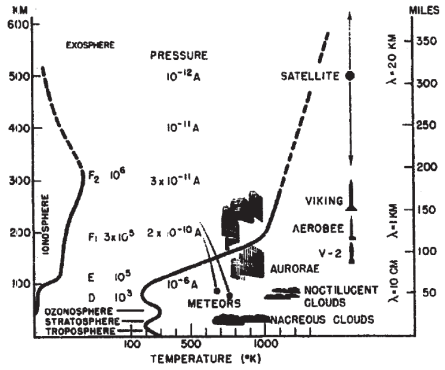
Tutorial includes GPS system concept, performance requirements, configuration (as of 12/91), coarse and precise signal, modulation techniques, operational control segment, master control station, composite clock, monitor stations, Navy clock ensemble, ground antenna, GPS roles of other organizations, method of establishing GPS and SV time, MCS computations, the navigation problem, GPS pseudorange measurement, GPS measurements, GPS navigation message, relativity in GPS, ionospheric and other delays, GPS time transfer modes, GPS-UTC(USNO) synchronization, time transfer error budget, SV 13 clock stability, determining GPS navigation accuracy, navigation performance summary, time transfer performance, GPS time stability, UTC error, denial of full system accuracy, time transfer with and without SA, "bowing" effect, and summary.



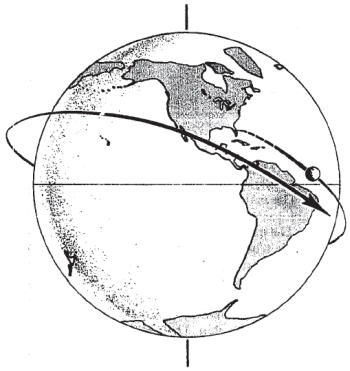
Site Acceptance Test comparison of TWSTT with calibration factor. (Galysh-1998, p. 352)

A. H. Frank and J. D. White, "Passive MASER Using Timesharing for Control of the Cavity and Control of the Oscillator on the Line of Stimulated Emission," 15 May 1984, United States of America Patent 4,449,105.

A passive maser wherein control of the cavity and control of the oscillator on the line of stimulated emission operate in a shared-time mode. A control



Temperature at altitude, showing projected position of the Vanguard Satellite. (Hagen-1956, p. 745)



Planned orbit of the Vanguard Satellite. (Hagen-1956, p. 747)

circuit acts on the injected signal by way of a programmable synthesizer, the injected signal then assuming the successive values omega/sub L//sup +/, omega/sub H/, omega/sub H/ and omega/sub C//sup +/, omega/sub H/ and omega/sub C//sup -/, omega/sub L//sup -/, omega/sub L//sup +/, etc, in stages. omega/sub H/ is centered at the line of stimulated emission omega/sub L//sup +/ and omega/sub L//sup -/, which is symmetrically shifted, interrogate the sides of the emission line; and omega/sub C//sup +/ and omega/sub C//sup -/ which are further symmetrically shifted interrogate the sides of the cavity resonance. The control circuit periodically inhibits the detection action used for controlling the oscillator, and the detection action used for controlling the cavity is carried out only during the inhibition period.

I. J. Galysh and P. Landis, "Two-Way Time Transfer Modem," in *22nd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Vienna, Virginia, 4-6 December 1990, NASA Conference Publication 3116, 345-8.

NRL is developing a two-way time transfer modem that will work with very small aperture terminals (VSAT), commercial satellites, and an atomic clock. The two-way method has been chosen because of its performance and insensitivity to the position of the receivers and satellites. Precision, stability, accuracy, and versatility are the primary design considerations of this modem. The modem is designed to use many off the shelf components.

I. J. Galysh, D. M. Craig, W. G. Reid and J. A. Buisson, "Performance Analysis of the GPS Monitor Station Timing Subsystem Enhancement Program at the Naval Research Laboratory," in *28th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, Virginia, 3-5 December 1996, US Naval Observatory, 417-428.

The U.S. Naval Research Laboratory designed, developed, and installed hardware and software for the GPS Monitor Station Timing Subsystem Enhancement (MSTSE) at the GPS Monitor Station (MS) located at the Kaena Point Satellite Tracking Station, Hawaii. From December 1995 to the present as part of the evaluation of the system, the U.S. Naval Observatory (USNO) has been performing time transfers through the Two Way Satellite Time Transfer portion of the MSTSE. It will be shown that the new cesium-beam frequency standard (CFS) HP5071 has been disciplined to the DoD Master Clock by the MSTSE during this period to within + 3 pp 10^14. The phase measurement subsystem, of the MSTSE has, for the first time, allowed independent measurement of the two operational GPS Monitor Station HP5061 CFSs.

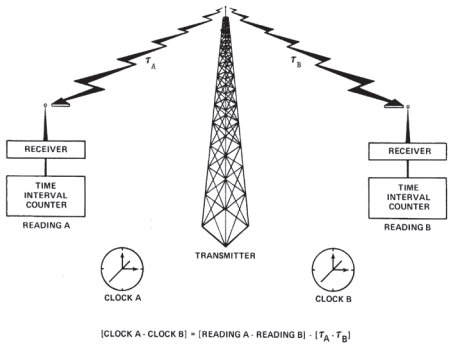
During June 1996 a modification was made to the MSTSE to reflect improvements in the system architecture developed during the initial evaluation period. This modification has increased system performance, improved reliability, and facilitated easy integration with future GPS Monitor Station improvements. This paper describes the equipment configuration and the test data collected after the installation of the MSTSE. Results are presented from data collected from June 1996 through October 1996.

I. Galysh, D. Koch, R. Beard, W. Reid and J. Buisson, "Two-Way Satellite Time Transfer (TWSTT) Applications with the Eastern Range," in *30th Annual Precise Time and Time Interval (PTTI) Meeting*, L. A. Breakiron, ed. held at Reston, Virginia, 1-3 December 1998, USNO, 341-53.

The Eastern Test Range (ETR) at Cape Canaveral, as part of the Range Modernization Program, is incorporating (TWSTT) systems into their tracking network. A detailed study of the mechanization of TWSTT into the ETR systems has been performed. An experiment using different satellite frequencies was completed and was previously reported. A design implementation was also completed and was previously reported. Acceptance testing was successfully performed at the Naval

Research Laboratory (NRL) including over-the-air testing prior to the first installation at the Range Operation Control Center (ROCC), Cape Canaveral. The first phase of ROCC installation was completed in July 1998.

The results of acceptance testing at NRL indicated a sub-nanosecond time transfer capability. Data from those tests will be presented and discussed. Installation test data from the initial phase will be presented. Calibration of these units for absolute time comparison was difficult but will support a nanosecond level capability. The calibration methods and results will be described.



Passive system for differential time transfer. (Hall-1974, p. 36)

H. Gardner, I. Silverman and C. Weaver, *TIMATION I Ground Station*, NRL Report 6876, Naval Research Laboratory, Washington, D.C., 3 April 1969. NRL6876 LIMITED DISTRIBUTION

G. A. Gifford, J. D. White and H. E. Peters, "Hydrogen Maser Research and Development at Sigma Tau Standards and Test of Sigma Tau Masers at the Naval Research Laboratory," in *Seventeenth Annual Precise Time and Time Interval (PTTI) Meeting*, 3-5 December 1985, 105-128.

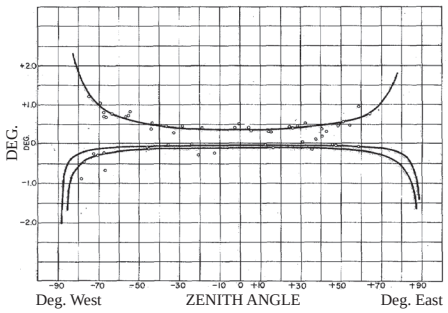
Two hydrogen masers of the active oscillator type using automatic cavity stabilization, but without active feedback gain, were designed, built and tested by Sigma Tau Standards for the Naval Research Laboratory (NRL). The masers were tested at Sigma Tau Standards prior to shipment and again at the NRL for a period of ten weeks following delivery. In addition, Sigma Tau has modified a Small Hydrogen Maser previously built to operate with cavity feedback to become an oscillating maser without feedback.

W. M. Golding, V. J. Folen, A. F. Frank, J. D. White and R. L. Beard, "Reduction of cavity pulling in a passive hydrogen maser," in *Twentieth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Vienna, Virginia, 29 November - 1 December 1988, 123-32.

A new method for detection of the hydrogen resonance in a passive maser has been tested and experimentally verified. This technique, which reduces the effect of cavity pulling on system performance, makes use of several amplitude and phase measurements of the combined transfer function associated with the cavity and hydrogen line. The atomic resonant frequency, determined in this way, has been shown to be essentially free from cavity pulling. For example, we have measured pulling factors 40 times lower than those measured using pure amplitude or phase techniques for the detection of the hydrogen resonance. The smaller cavity pulling factor is important in systems where cavity tuning errors are thought to yield an intrinsic limit on overall clock performance. The technique can be useful as a diagnostic tool, or as the hydrogen resonance detection method in an operational passive maser.

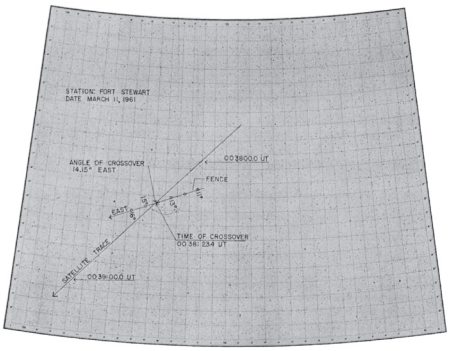
W. M. Golding, A. Frank, R. Beard, J. White, F. Danzy and E. Powers, "The double bulb rubidium maser," in *48th IEEE International Frequency Control Symposium*, 1-3 June 1994, 724 -730.

The proposed design of a new 87Rb maser frequency standard is presented. This device is expected to perform similarly to a hydrogen maser at short and moderate average times. An operating maser of this design would much be more compact than a full size hydrogen maser (the cavity need only be ~6 cm in length and diameter). It should also be much less expensive to build. Optical pumping techniques are used to produce a nearly complete population inversion in an evacuated wall coated cell. The population inversion is produced in a cell separated from the microwave interaction region to eliminate problems with light shifts. Since no buffer gas is used the atoms are free to travel through an exchange tube from the optical pumping region to the maser interaction region where oscillation can

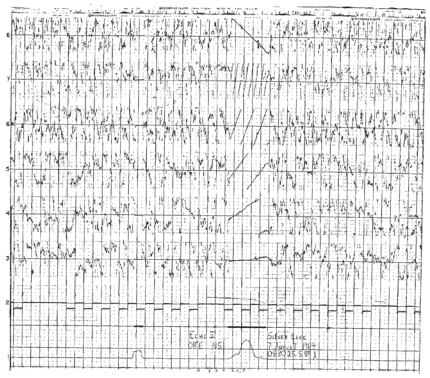


Zenith angle error, Silver Lake, Mississippi. (Hayden, NRL Report 5741, 1962, p. 9)

Sample of the recorded data from which the zenith angle of the satellite is determined. (Hayden, NRL5741-1962, p. 5)



Satellite trail and fence projection superimposed on a star chart. (Hayden, NRL5741-1962, p. 6)



Typical phase output from six antenna-pair systems (channels 3-8) for a satellite passage. Channel 1 shows the AGC voltage and channel 2 displays the shutter voltage of the camera which photographed the satellite trail. These outputs are for passage of the Echo I satellite through the “fence” on August 7, 1964, 083025.5 UT. (Hayden, NRL6385-1966, p. 11)

take place. The system will be completely closed-cycle since atoms will return from the maser region to the optical pumping region where they will be repumped. This eliminates the need for a vacuum system, greatly simplifying operation. The principles of operation and the basis of the stability estimates will be discussed.

D. L. Griscom, "Point Defects and Radiation Damage Processes in alpha-Quartz," in *Proceedings of the Thirty Second Annual Frequency Control Symposium*, held at Atlantic City, New Jersey, 30 May - 1 June 1979, 98-109.

The natures of point defects in alpha-quartz are briefly reviewed, including the results of a number of very recent electron spin resonance (ESR) studies. Some common impurity-related defects are considered, although emphasis is placed upon those defects encountered in electronic-grade and premium-Q quartz crystals. Only in a few cases have known defect centers been positively correlated with specific optical absorption bands. Transient optical absorption and luminescence have been measured in a field-swept synthetic quartz crystal and in several high purity fused silicas following pulsed irradiation by 500 keV electrons. The results are interpreted as indicating the formation of transient E' centers and perhaps transient oxygen vacancies. Various cathodoluminescence, radioluminescence, and photoluminescence spectra of alpha-quartz and fused silica are also reviewed. Results found in the literature, together with the present time-resolved data, strongly indicate that a luminescence spectrum peaking near 4.3 eV is due to the recombination of electrons with holes trapped at the sites of isolated oxygen vacancies. A ubiquitous blue luminescence (~2.8 eV) is possibly associated with the formation of transient oxygen vacancy-peroxy linkage intimate pairs. Other possibilities and data are also discussed.

D. U. Gubser, S. A. Wolf and J. E. Cox, "Shielding of longitudinal magnetic fields with thin, closely spaced, concentric cylinders of high permeability material," Review of Scientific Instruments **50** (6), 751-6 (1979).

Formulae for the longitudinal shielding effectiveness of *N* thin, closely spaced, concentric cylinders of high permeability material have been developed and experimentally tested. For shields which cannot be oriented, or which change their orientation in the ambient field, the shielding effectiveness for longitudinal fields is generally the limiting criterion and no design formulae have previously been published for more than two shields. A simple diagrammatical method of writing the shielding formula is presented. Use of these equations is demonstrated by application to the design of magnetic shields for hydrogen maser atomic clocks. Examples of design tradeoffs such as size, weight, and material thickness are discussed. Experimental data on three sets of shields fabricated by three manufacturers are presented.

D. U. Gubser, S. A. Wolf, A. B. Jacoby and L. D. Jones, "Magnetic Shielding and Vacuum Test for Passive Hydrogen Masers," in *13th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Washington, D.C., 1-3 December 1981, 791-800.

Vibration tests on high permeability magnetic shields used in the SAO-NRL Advanced Development Model (ADM) hydrogen maser have been made. Magnetic shielding factors were measured before and after vibration at the Goddard Space Flight Center, magnetic field facility. Preliminary results indicate considerable (<25%) degradation.

Test results on the NRL designed vacuum pumping station for the ADM hydrogen maser are also discussed. This system employs sintered zirconium carbon getter pumps supplied by SAES Getters, to pump hydrogen plus small ion pumps to pump the inert gases. In situ activation tests and pumping characteristics indicate that the system can meet design specifications.

J. P. Hagen, "The Exploration of Outer Space with an Earth Satellite," *Proceedings of the IRE* (June), 744-7 (1956).

Sometime during the coming geophysical year (July, 1957 to December, 1958) an attempt will be made to launch an artificial satellite in an orbit around the earth. The Office of Naval Research has been assigned the responsibility to perform this task and has established Project VANGUARD in the Naval Research Laboratory to carry it out. The Department of Defense turned to the Navy to manage this triservice project because of its extensive experience in upper-atmosphere research with rockets.

The satellite which Project VANGUARD intends to launch in an orbit is a small one, yet must be a research vehicle. The National Committee for the IGY of the National Academy of Sciences has established a panel which is concerned with the nature of the scientific experiments to be done in the vehicle. Work is in progress not only on the vehicles, but on the experiments to be done in the satellite.

Experiments conducted in an artificial earth satellite circling the earth in the outer tenuous region of our atmosphere can greatly increase our knowledge of the atmosphere-its structure, its constituents, and the powerful radiations both electromagnetic and corpuscular that impinge upon it and help determine its state.

J. P. Hagen, "The Viking and the Vanguard," Technology and Culture **4** (4), 435-51 (1963).

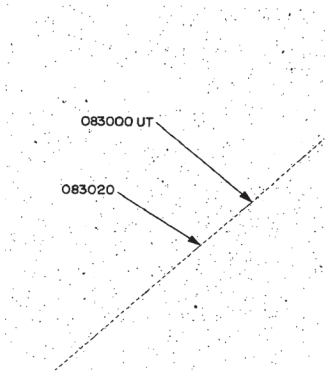
Great confusion still reigns among the general public in regard to Project Vanguard, the first United States earth satellite program created as a contribution to the International Geophysical Year (I. G. Y.). Vanguard was fated to become a so-called "propaganda failure" in what was to unfold in the popular press as a "space race." 1 Vanguard's scientific and technological accomplishments, overshadowed by the psychological impact of the Soviet Sputnik, deserve recognition beyond the space science community; inevitably they will receive full historical analysis. This paper only briefly examines how Project Vanguard came about, its role in the evolution of rocket technology, and the application of missile-derived rocketry to basic scientific purpose.

J. P. Hagen, "Vanguard - The Laboratory Ventures into Space," Report of NRL Progress, 30-32, July 1973.

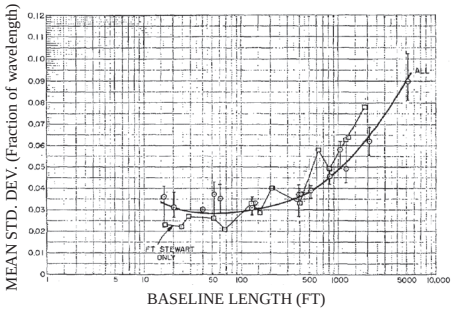
On March 17, 1973, 200 people gathered to celebrate the 15th anniversary of the launching of the first Vanguard satellite. Eighteen years ago, in the fall of 1955, a team of about 150 men and women, coming mainly from within the divisions of the Laboratory, was organized to attempt this country's first venture into space. The group, bound together in stress and adversity and sharing the success which culminated the effort, now periodically assembles to celebrate the anniversary.

Following World War lI the Laboratory emerged from its wartime status with a well-rounded group of capable scientists in most of the scientific disciplines. Among these were people working on such things as upper atmosphere research, rocket development, and radio astronomy. Many of these people were brought together to form the Atmosphere and Astrophysics Division. The Division pursued an active program in probing the earth's atmosphere with scientific rockets and developed new and better rockets for this purpose. This phase of the work is discussed in Milton Rosen's paper in this issue.

Because of the background acquired in the design, construction, and flight of scientific instruments in rockets and in the design and construction of rockets, the Division and the Laboratory were in a strong competitive position in 1955 to offer to take part in the Earth Satellite Project proposed as a part of the U.S. participation in the International Geophysical Year (IGY). Talk of possible earth satellites was not new. Designers at the Laboratory and elsewhere had for some time realized that rocket capabilities had reached the point where serious consideration should be given to undertake the launching of a satellite. All that was lacking was



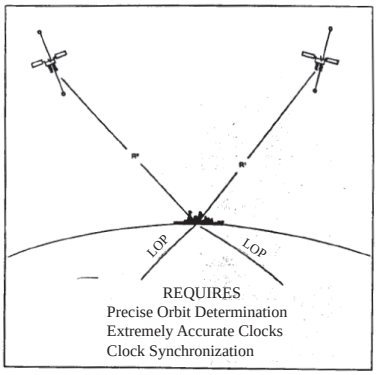
Echo I satellite pass photographed on August 7, 1964. (Hayden, NRL Report 6385, 1966, p. 12)



Weighted mean standard deviation vs baseline length for all Space Surveillance receiving stations. The Ft. Stewart data is also plotted separately. (Hayden, NRL Report 6385, 1966, p. 19)

$$\mathbf{s}_{\Delta v}^{-} = \mathbf{\Phi}\left(t_{\Delta v}, t_k\right)\mathbf{s}_k^{+}$$
$$\mathbf{s}_{\Delta v}^{+} = \mathbf{s}_{\Delta v}^{-} + \left[\mathbf{0}_{3\times 1}^{T}\ \Delta\mathbf{v}^{T}\ \mathbf{0}_{2\times 1}^{T}\right]^{T}$$
$$\mathbf{s}_{k+1}^{-} = \mathbf{\Phi}\left(t_{k+1}, t_{\Delta v}\right)\mathbf{s}_{\Delta v}^{+}$$

Propagation of state from t_k to t_{k+1}, where the - and + indicate state vector values before or after the measurement or a maneuver. (Highsmith-1999, p. 404)



TIMATION concept for ships. (Holmes-1976, p. 30)

approval and money. Those were the days before "big" science, and while several groups were bold enough to plan and propose, none were bold enough to approve and fund.

The coming of the IGY changed all this. The launching of a satellite was proposed in an international forum and was backed by international scientific unions. Under the prodding of the National Academy of Sciences and the newly formed National Science Foundation, the government agreed to include such a program in the IGY and set out immediately to find a group to carry out the project. NRL won out in the competition which took place during the summer of 1955. The Laboratory was notified on September 9, 1955 that it had been chosen and received funds to proceed on October 6, 1955…

A. G. Haley and M. W. Rosen, "On the Utility of an Artificial Unmanned Earth Satellite, A Proposal to the National Science Foundation, Prepared by the ARS Flight Committee, 24 November, 1954," *Jet Propulsion* (February), 71-8 (1955).

This is a proposal to the National Science Foundation that the Foundation sponsor a study of the utility of an unmanned, earth-satellite vehicle. The proposal is made by the American Rocket Society in the normal exercise of its functions. The role of the Society in this manner is made clear by the following policy statement adopted by the Board of Directors: "The American Rocket Society should act as a 'catalyst' and should promote interest and sound public and professional thinking on the subject of space flight. It should not attempt to evaluate the merits of individual proposals or undertake work on the subject of its own accord. It should, however, encourage such activity on the part of other organizations."

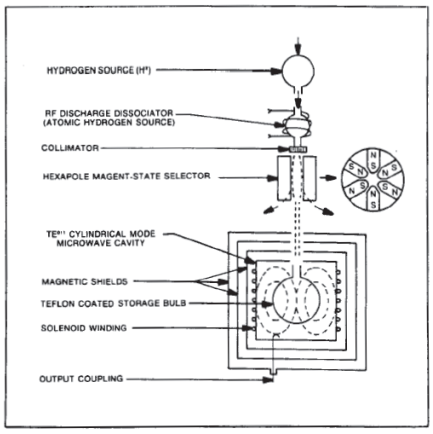
It is apparent, then, that the Society cannot undertake to make the study. It can, however, serve the National Science Foundation in a number of ways, and believes it is doing so in bringing this subject to the Foundation's attention. Should the Foundation elect to sponsor the study the Society could assist by encouraging scientists and engineers both inside and outside the Society to participate. The Society would be willing to perform any other service within its functions and abilities to assist the National Science Foundation in implementing this proposal.

R. G. Hall, T. N. Lieberman and R. R. Stone, "Review of Available Synchronization and Time Distribution Techniques," in *Proceedings of the Sixth Precise Time and Time Interval (PTTI) Planning Meeting*, X-814-75-117, held at U.S. Naval Research Laboratory, 3-5 December 1974, NASA, 29-37.

The methods of synchronizing precision clocks will be reviewed placing particular attention to the simpler techniques, their accuracies, and the approximate cost of equipment. The more exotic methods of synchronization will be discussed in lesser detail.

The synchronization techniques that will be covered will include satellite dissemination, communication and navigation transmissions via VLF, LF, HF, UHF and microwave as well as commercial and armed forces television. Portable clock trips will also be discussed.

Before we discuss methods of synchronization, we briefly review who the users of Precise Time and Time Interval (PTTI) are, and why they need synchronization.

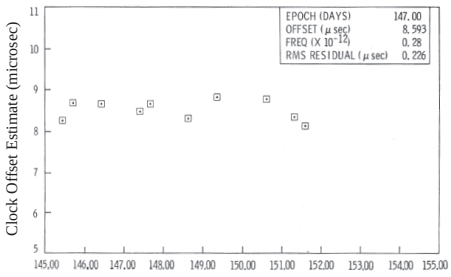


Simplified hydrogen maser, offering potential for improved position precision. (Holmes-1976, p. 54)

C. C. Hayden and S. H. Knowles, "Naval Space Surveillance Center Uses of Time, Frequency and Phase," in *23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Pasadena California, 3-5 December 1991, NASA Conference Publication 3159, 127-32.

The Naval Space Surveillance Center (NAVSPASUR) is an operational naval command that has the mission of determining the location of all manmade objects in space and transmitting information on objects of interest to the fleet. NAVSPASUR operates a 217 MHz radar fence that has 9 transmitting and receiving stations deployed in a line across southern CONUS. This surveillance fence provides unalerted detection of all

satellites overflying CONUS. NAVSPASUR also maintains a space catalog of all orbiting space objects, including payloads, rocket bodies and debris, and distributes information on satellite orbits to the fleet and other users by means of Navy tactical communication circuits and other means. NAVSPASUR plays an important role as operational alternate to the primary national Space Surveillance Center (SSC) and Space Defence Operations Center (SPADOC) located in Colorado Springs, Colorado. In executing these responsibilities, NAVSPASUR has need of precise and/or standardized time and frequency in a number of applications. These include maintenance of the radar fence references to specification, and coordination with other commands and agencies for data receipt and dissemination. Precise time and frequency must be maintained within each site to enable proper operation of the interferometry phasing technique used. Precise time-of-day clocking must exist between sites for proper intersite coordination. After 'time tags' are attached to the data at the receiver sites, proper referencing and standardization are necessary at the Dahlgren, Va. operations center to ensure proper data synchronization and communications with the fleet and other agencies.



NTS-1 time transfer results for Madrid. (Hurd-1978, p. 638)

L. O. Hayden, *Optical Calibration of the U.S. Naval Space Surveillance System*, NRL Report 5741, Naval Research Laboratory, 14 March 1962.

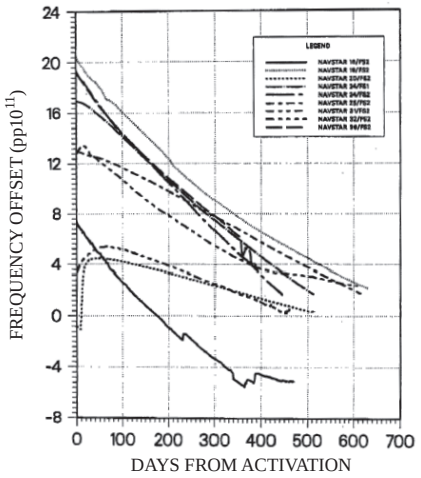
A project was initiated in the Spring of 1960 to calibrate the Space Surveillance System by means of ballistic cameras. The principle behind this calibration is a comparison between the positions of the Echo balloon as determined by radio-frequency reflections of the Space Surveillance System and as determined by photographs against a star background. The preliminary results show that all stations have zero errors of less than 0.1 degree at the zenith. A second error having a standard deviation of about 0.05 degree is due in part to the limited precision of measurement used. The report describes the work done prior to the second phase of calibration, that phase leading to a much higher precision.

L. O. Hayden and T. B. McCaskill, *Optical Calibration Analysis of the U.S. Naval Space Surveillance*, NRL Report 6385, Naval Research Laboratory, Washington, D.C., 25 April 1966.

A preliminary optical calibration of the U.S. Naval Space Surveillance System was made in 1961 using graphical methods. Since then, calibration has been continued using better equipment and data reduction methods to determine more precisely the characteristics of the system. It is shown that the 108-MHz system studied is capable of measuring angles within a standard deviation sigma of 1/2 min of arc at zenith.

Electronic calibration methods used in setting up the 108-MHz system are shown to have a mean accuracy of approximately 3.5 percent of a wavelength for baselines up through 520 ft in length. Bias errors for baselines of 1040 ft and longer are larger than for the shorter base-lines and must be corrected to obtain maximum accuracy from the system.

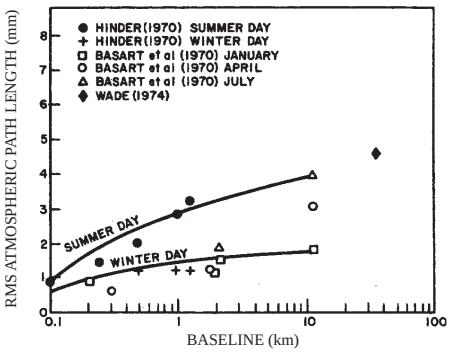
Baselines in the range of 16 to 520 ft have (for Echo passes) a mean standard deviation of ±0.0348 delta, which is independent of baseline length and angle of arrival and is internal to the system. The random error for longer baselines increases until it reaches a mean standard deviation of ±0.098 delta for the 5200-ft baseline.



Rubidium clocks corrected frequency offset from DOD Master Clock. (Hutsell-1996, p. 210)

L. O. Hayden and T. B. McCaskill, "Space Surveillance System," *Report of NRL Progress*, April 1966, 35-6.

A preliminary optical calibration of the Space Surveillance System was made in 1961 using graphical methods. Since then, calibration has been continued using better equipment and data reduction methods to determine more precisely the characteristics of the system. It is shown that the 108-MHz system studied is capable of measuring angles within a standard deviation of 1/2 min of arc at zenith.



Variation of RMS pathlength with baseline. (Johnston-1974, p. 377)

L. O. Hayden, "Space Surveillance System," *Report of NRL Progress*, May 1966, 34.

A transistorized digital clock and coder unit has been developed which is being used as part of the time standard equipment at the U.S. Naval Space Surveillance Stations in Hawkinsville, Georgia, Red River, Arkansas, and Raymondville, Texas, which were instrumented in 1965. This unit is powered by a 24-v battery and is capable of 24 hr of emergency service in case of commercial power failure. It employs two cascaded gates, one switching at 0.1-sec intervals and the other at 1.0-sec intervals. Decimal digits are read out in binary format at a rate of one decimal digit per second. Each group of pulses comprising a decimal digit is clearly separated from the next pulse group. Once the code is learned, it is much easier to recognize than the one formerly used in the Space Surveillance System.

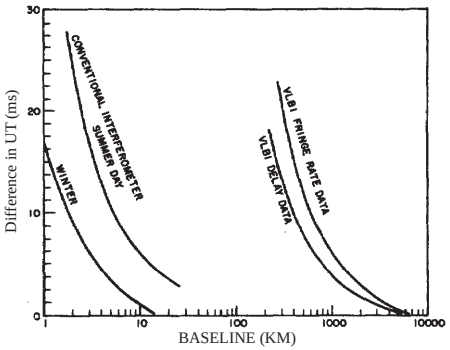
L. O. Hayden, *Transistorized Digital Clock with Serial Binary-Coded Readout*, NRL Report 6389, Naval Research Laboratory, 10 May 1966.

A transistorized digital clock and coder unit has been developed which is being used as part of the time standard equipment at the U.S. Naval Space Surveillance Stations in Hawkinsville, Georgia, Red River, Arkansas, and Raymondville, Texas, which were instrumented in 1965. This unit is powered by a 24-v battery supply and is capable of 24 hours of emergency service in case of commercial power failure. Decimal digits are read out in binary format at a rate of one decimal digit per second. Each group of pulses comprising a decimal digit is clearly separated from the next pulse group. Once the code is learned, it is much easier to recognize than the one formerly used in the Space Surveillance system.

The transistorized circuitry used in this unit has resulted in a considerable reduction in size and power input (12 w) as compared with the vacuum tube unit which has been used for a similar purpose in other Space Surveillance stations. Also, the error in coding due to aging of components has been eliminated since only two levels must be distinguished in the binary logic as compared with the ten voltage levels of the decimal logic in the earlier equipment. The new unit employs two cascaded gates, one switching at 0.1-sec intervals and the other at 1.0-sec intervals.

D. Highsmith and P. Axelrad, "Relative State Estimation Using GPS Flight Data from Co-Orbiting Spacecraft," presented at the ION GPS 1999, 12th International Technical Meeting of the Satellite Division of the Institute of Navigation, Nashville, Tennessee, 14-17 September 1999, Institute of Navigation, 401-409.

The objective of this research is to use flight data to develop and demonstrate the most accurate and robust GPS-based methods for relative navigation for two cooperative co-orbiting vehicles in LEO. A Kalman filter that directly estimates the relative state between two co-orbiting vehicles using single difference pseudorange observations has been developed. This filter is used in conjunction with an existing GPS absolute orbit determination utility, which provides an estimate of the absolute orbit of the passive vehicle to the relative filter. The Clohessy-Wiltshire equations are used for state and error propagation. This filter has been designed using flight data from the STS-80/ORFEUS-SPAS flight experiment performed in December 1996. The root-mean-square (RMS) relative position errors are 6.4m radial, 5.3m in-track, and 1.3m cross-track. The RMS velocity errors are 0.022m/s radial, 0.018 m/s in-track, and 0.013 m/s cross-track. Though the relative positions are no better than NASA/JSC results, this fairly simple filter achieved an overall improvement of more than 70% in relative velocity. This is an excellent beginning upon which to build future adaptations, which may include relative J2, relative drag, and carrier phase processing.



Accuracy in UT1 determination versus equatorial baseline. (Johnston-1974, p. 377)

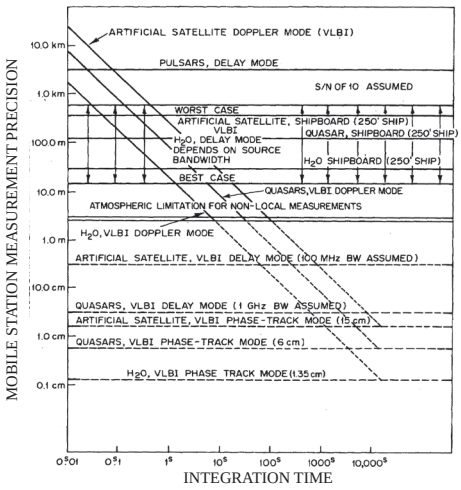
D. E. Highsmith, P. W. Binning and P. Axelrad, "Design and Test of an Algorithm

for Satellite-to-Satellite Time Transfer," presented at the ION GPS 2000, 13th International Technical Meeting of the Satellite Division of the Institute of Navigation, Salt Lake City, Utah, 19-22 September 2000, Institute of Navigation, 1582-94.

An algorithm which solves for accurate relative GPS receiver clock bias and frequently in near real time is presented and tested. Single frequency P-code (P1) double difference observations are used to solve for precise relative position and velocity states. The precise positions are then used as known parameters in a second pass through a three-state clock filter. This filter uses P1 single differences and differences in time of single frequency carrier phase (L1) single differences to solve for relative receiver clock bias, frequency, and frequency drift.

The algorithm is tested using hardware-in-the-loop simulation, with the truth clock biases measured with a universal time interval counter (UTIC). The UTIC measures the difference between the 1 pulse per second output of the receiver and a reference pulse generated at the simulated GPS system time: Simulated GPS signal errors include ionosphere, GPS constellation, and multipath. With an along-track separation of 50km at an altitude of 1300 km, relative position 3-D RSS error is less than 15cm. At 100 km separation, the 3-D RSS error is less than 24 cm. For both 50 and 100 km separations at 10 second measurement update intervals, relative clock bias RMS error is 0.6 ns or less. Relative frequency RMS errors are less than 0.03 ns/s (3 X 10-11) for 10-second averages.

These results represent the estimation accuracy of the relative clock filter, one portion of the time transfer error budget. Actual on-orbit of the time transfer performance would also include effects due to calibration uncertainties, thermal variations, and other environmental disturbances. Under the proper conditions, however, the results indicate that this algorithm can be used by spacecraft in low Earth orbit with separations of up to 100 km to perform nanosecond-level time transfer on orbit in near real time.

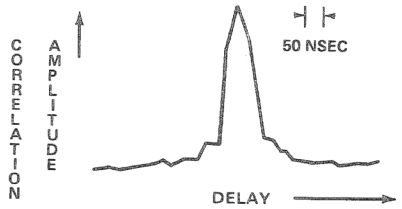


Inherent precision for a signal-to-noise ratio of 10 for various interferometric navigation systems. S-band operation is assumed for artificial satellites, and X-band for the quasar system. (Knowles-1973, p. 56)

D. Holmes, "NAVSTAR Technology," Countermeasures Magazine, 27ff, December 1976.

The Naval Research Laboratory pioneered development of time synchronized navigation satellites within Navy. The first U.S. TIMe navigaATION satellite, TIMATION I, was launched by NRL in 1967 and has been followed by TIMATION II and a Navigation Technology Satellite (NTS-1) sponsored by the joint DoD NAVSTAR Program Office at SAMSO. A second NTS satellite is scheduled for launch from Vandenberg Air Force Base early next year.

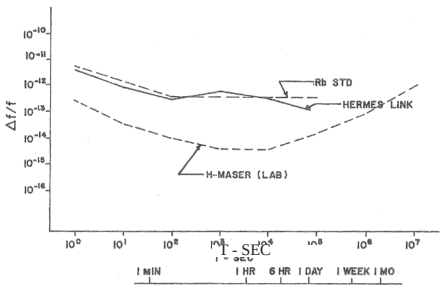
Accurate time synchronization is a major technical requirement for NAVSTAR, and NRL has been given responsibility for the clock development. This new clock technology became possible as a result of discoveries made in atomic physics during the early years of this century. For NTS-1, the Laboratory modified a rubidium atomic standard manufactured by the German firm, EFRATOM, which performed successfully. NRL is presently testing cesium clocks developed by Frequency and Time Systems, Inc., which will be flown on NTS-2 in early 1977. NRL is also sponsoring a hydrogen maser clock program for NAVSTAR at the Smithsonian Astrophysical Observatory and the research labs of Hughes Aircraft and RCA. Potentially, the hydrogen maser offers the best accuracy and long term stability of all the clock developments. A hydrogen maser clock is scheduled to be launched on NTS-3 in 1981.



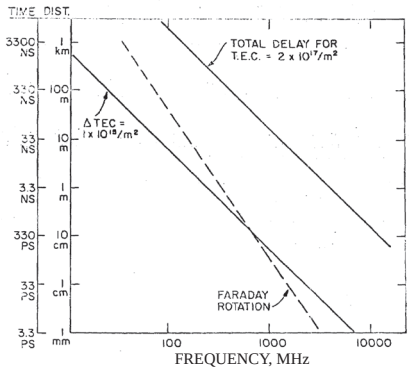
Correlation amplitude versus fringe frequency for rubidium standard and hydrogen maser. (Knowles-1976, p. 533)

D. C. Holmes, "TEMPUS: A Proposal for an International Time Transfer and Precision Tracking Satellite," in *Tenth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held at Washington, D.C., 28-30 November 1978, NASA Technical Report 80250, 693-707.

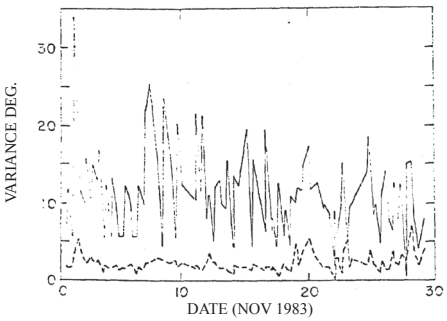
Since W.G. Cady carried his piezo resonator to seven laboratories in England,



Comparison of phase stability for Rubidium standard, HERMES link, and Hydrogen maser (in the lab). (Knowles-1979, p. 479)



Ionospheric effects on group delay. (Knowles-1984, p. 238)



Scatter in ionospheric phase measurements for Green Bank interferometer for the month of November, 1983. Dotted line marks short baseline; solid line marks long baseline. Data, covering the month of November 1983, is grouped into morning twilight, day, evening twilight and night. (Knowles-1984, p. 239)

France, Italy, and the United States in 1923, the primary method of coordinating time between international stations has involved the use of traveling clocks. These were first transported by ship and train, more recently by aircraft. Project TEMPUS also requires traveling clocks but these will revolve thousands of kilometers above the earth in artificial satellites.

D. Howe, R. Beard, C. Greenhall, F. Vernotte and B. Riley, "A Total Estimator of the Hadamard Function Used for GPS Operations," in *32nd Annual Precise Time and Time Interval (PTTI) Meeting*, 29 November 2000, 255-268.

We describe a method based on the Total deviation approach whereby we improve the confidence of the estimation of the Hadamard deviation that is used primarily in GPS operations. The Hadamard-total deviation described in this paper provides a significant improvement in confidence indicated by an increase of 1.3 to 3.4 times the one degree of freedom of the plain Hadamard deviation at the longest averaging time. The new Hadamard-total deviation is slightly negatively biased with respect to the usual Hadamard deviation, and (t) values are restricted to less than or equal to T/3, to be consistent with the usual Hadamard's definition. We give a method of automatically removing bias by a power-law detection scheme. We review the relationship between Kalman filter parameters and the Hadamard and Allan variances, illustrate the operational problems associated with estimating these parameters, and discuss how the Hadamard-total variance can improve management of present and future GPS satellite clocks.

W. J. Hurd, J. Buisson, J. Oaks, T. McCaskill, S. C. Wardrip, H. Warren and G. Whitworth, "Sub-Microsecond Comparison of Intercontinental Clock Synchronization by VLBI and the NTS Satellite," in *Tenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Naval Research Laboratory, Washington, D.C., 28-30 November 1978, NASA TM 80250, Goddard Space Flight Center, 629-642.

The intercontinental clock synchronization capabilities of Very Long Baseline Interferometry (VLBI) and the Navigation Technology Satellite (NTS) were compared in May 1978 by using both methods to synchronize the Cesium clocks at the NASA Deep Space Net complexes at Madrid, Spain and Goldstone, California. The VLBI experiments used the Wideband VLBI Data Acquisition System developed at the NASA Jet Propulsion Laboratory. The NTS Satellites which were designed and built by the Naval Research Laboratory were used with NTS Timing Receivers developed by the Goddard Space Flight Center. The two methods agreed at about the one-half microsecond level. The VLBI system also obtained long term stability information on the HP506lA-004 Cesium standards by measuring delta-T/T over four 3-4 day intervals obtaining stability estimates of (1 + 1) x 10^-13 for the combined timing systems.

S. T. Hutsell, W. G. Reid, L. J. D. Crum, L. H. S. Mobbs and J. A. Buisson, "Operational Use of the Hadamard Variance in GPS," in *28th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, Virginia, 3-5 December 1996, 201-214.

With upcoming GPS Block IIR launches scheduled, rubidium clock estimation will require more attention than ever before during the next decade of GPS operations. GPS Master Control Station (MCS) estimation architecture relies on a three-state polynomial clock model, which does not include a time-variant decay parameter for frequency drift. Since current GPS rubidium frequency standards exhibit significant time-dependent frequency drift changes, the MCS is compelled to make precise utilization of the random run FM process noise parameter, known as q3.

The work of various scientists over the past three decades has shown the Hadamard variance to converge for random run FM. At PTTI '95, the 2d Space

Operations Squadron (2 SOPS) introduced an algorithm that presented a simple, convergent polynomial relationship between the Hadamard variance and the MCS's Kalman filter process noise parameters. Until recently, however, neither the Hadamard variance nor the Hadamard-Q equation had actually been put to use in GPS.

The Naval Research Laboratory (NRL) has now created analysis software designed to employ the Hadamard variance in their clock analyses, to supplement their already existing software, which makes use of the Allan variance. This paper presents results of the NRL analysis using both the Allan and Hadamard variances for several operational GPS rubidium frequency standards, as well as results from the recent operational use of the Hadamard-Q equation, by 2 SOPS personnel, based on the NRL analysis data.

Institute of Navigation, "Colonel Thomas L. Thurlow award for 1978 to R.L. Easton," Navigation: Journal of The Institute of Navigation **26**, 258-9 (1979).

"For the Outstanding Contribution to the Science of Navigation in the Year 1978" Citation:

The Colonel Thomas L. Thurlow Navigation Award for the outstanding contribution to the science of navigation for the year 1978 was presented to Roger L. Easton. The citation reads as follows:

Roger L. Easton has long been recognized as a world authority and pioneer in spacecraft navigation and timing technology. His scientific accomplishments have been directly responsible for extending the state-of-the-art and subsequently making technically feasible such advanced global space systems as the Timation Navigation Satellites, the Navigation Technology Satellites and the NAVSTAR-Global Positioning System. The latter system, to be comprised of twenty-four satellites, has been selected as a primary United States global navigation system of the mid 1980s with a predicted geoposition and altitude accuracy of ten meters. Since passive ranging navigation accuracy is predicated on establishing and maintaining a precise satellite timing standard, Mr. Easton has devoted many years to this particular facet of the navigation problem. He has directed and participated in establishing accuracy limits and extending the technology of time-keeping. He was charged with the responsibility of space qualifying first rubidium and later cesium clocks achieving increasing accuracies of one part in ten to the minus twelve and one part in ten to the minus thirteen, respectively, over a one to ten day interval. More recently, while on location with the National Bureau of Standards in Boulder, Mr. Easton designed, implemented and evaluated a new hydrogen maser cavity approach. This design has achieved an accuracy of one part in ten to the minus fourteen per ten-day interval which is an order of magnitude improvement over the cesium clock.

Institute of Navigation, *Global Positioning System: Papers Published in Navigation* (Institute of Navigation, 1980), GPS Redbooks Vol. 1.

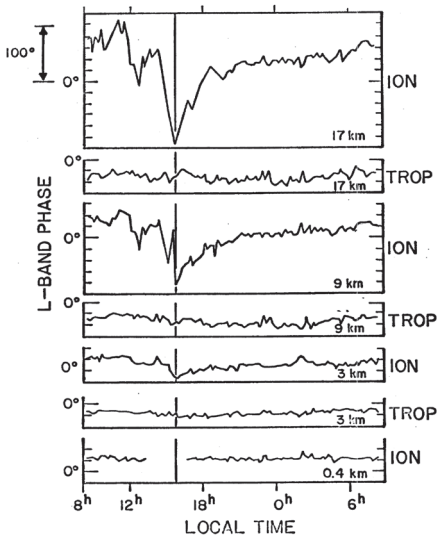
Reprints of papers published in Navigation (Institute of Navigation).

Includes reprint of 1978 article "The Navigation Technology Program" by R.L. Easton, first published in Navigation, Vol. 25 No. 2, 1978, pp. 107-112.

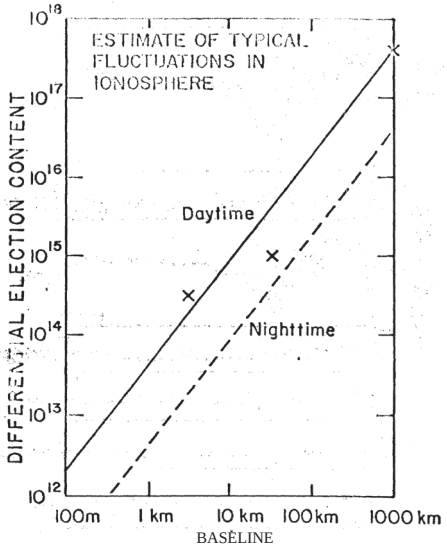
K. J. Johnston, "Radio Astronomy," in *Proceedings of the Sixth Precise Time and Time Interval (PTTI) Planning Meeting*, held at U.S. Naval Research Laboratory, 3-5 December 1974, NASA Report X-814-75-117, 373-9.

Conventional and VLBI interferometer techniques show promise for accurate determination of UTl, polar motion, and radio source position catalogs.

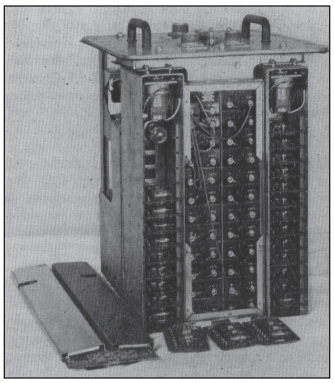
K. J. Johnston, J. A. Buisson, M. J. Lister, O. J. Oaks, J. H. Spencer, W. B. Waltman, G. Elgered, G. Lundqvist, A. E. E. Rogers, T. A. Clark, C. Ma, A. C. Johnson, K. Kingham, W. J. Klepczynski, G. Luther, A. J. Kubic and D. D.



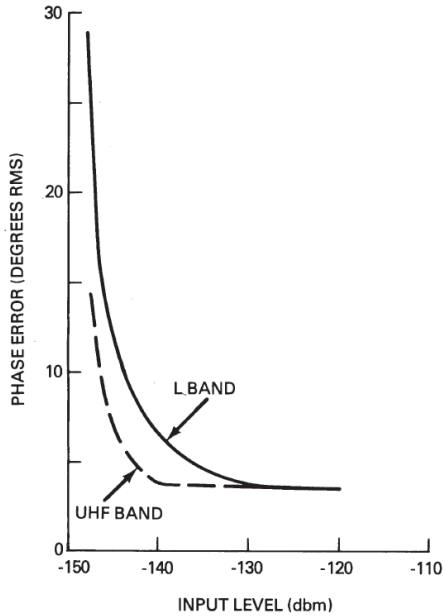
Sample ionospheric measurements made using a series of baselines with the Very Large Array, illustrating the detection of an ionospheric disturbance. The graph shows both non-dispersive, or tropospheric, and dispersive or ionospheric differential phases. Long vertical bars mark source changes. (Knowles-1984, p. 243)



Amplitude versus size parameters of ionospheric irregularities. (Knowles-1984, p. 244)



Telemetering transmitter used for rocket experiments, removed from its pressurized container. The circuitry for each of the 23 channels can be quickly unplugged for servicing. The two motors at the top are used for periodically transmitting calibrating voltages while in flight. Note the almost exclusive use of subminiature tubes. (Krause-1947, p. 432)



Phase error versus input signal level to a TIMATION III receiving system. (Landis-1976 NRLmr3324, p. 23)

McCarthy, "Precise Time Transfer Using MKIII VLBI Technology," in *Fifteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Naval Research Laboratory, Washington, D.C., 6-8 December 1983, 443-55.

It is well known that Very Long Baseline Interferometry (VLBI) is capable of precise time synchronization at subnanosecond levels. This paper deals with a demonstration of clock synchronization using the MKIII VLBI system. The results are compared with clock synchronization by traveling cesium clocks and GFS. The comparison agrees within the errors of the portable clocks (± 5 ns) and GPS (± 30 ns) systems. The MKIII technology appears to be capable of clock synchronization at subnanosecond levels and appears to be a very good benchmark system against which future time synchronization systems can be evaluated.

E. C. Jones, E. D. Powers, A. H. Frank and J. A. Murray, *Static Timing Tests of the R-2332/AR, R2331/URN, MANPACK (RPU-1), and the Texas Instrument MANPACK AN/PSN-9 NAVSTAR Global Positioning Systems User Equipment at the Naval Research Laboratory*, NRL/MR/8150--95-7754, Naval Research Laboratory, Washington, D.C., 10 July 1995.
NRLmr8150 LIMITED DISTRIBUTION

M. S. Kaplan, "Precise Time and Frequency Measurement Requirements for Spaceborne Distributed Aperture Technology," in *Seventeenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Washington, D.C., 3-5 December 1985, 19-21.

This paper describes requirements for precision time, frequency, and position measurement for a new research program at the Naval Research Laboratory under the sponsorship of the Strategic Technology Office of the Defense Advanced Research Projects Agency. The purpose of this effort is to study the potential for spaceborne distributed aperture (SDA) technology to address a variety of military applications. These applications include surveillance, reconnaissance, and electronic warfare. Additionally, this technology could address a number of Strategic Defense Initiative (SDI) concerns, e.g., detecting, identifying, tracking, and performing kill assessment on reentry vehicles. This technology differs from conventional approaches, e.g., a monostatic space-based radar (SBR) for aerial surveillance, in that sensor elements are distributed among many space platforms. This approach offers many potential advantages over conventional techniques. For example, in the aforementioned SBR application, a constellation of distinct transmitting and receiving spacecraft forming what can be called a "multistatic" radar, provides many "look angles" at a target. Additionally, it is possible to coherently combine the inputs from many receiving spacecraft in order to form a very large distributed aperture, thousands of kilometers in size.

M. G. Kaufman and F. X. Downey, *Data Transmission for the NRL Space Surveillance System*, NRL Report 5522, Naval Research Laboratory, Washington, D.C., 19 August 1960.
NRL5522 LIMITED DISTRIBUTION

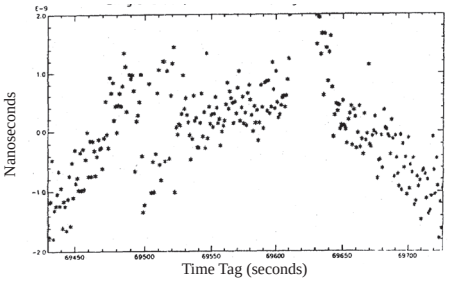
S. H. Knowles, K. J. Johnston and E. O. Hulburt, "Applications of Radio Interferometry to Navigation," in *Proceedings of the Fifth Precise Time and Time Interval (PTTI) Planning Meeting*, held at Goddard Space Flight Center, 4-6 December 1973, NASA, 47-58.

Radio astronomy experiments have demonstrated the feasibility of making precise position measurements using interferometry techniques. The application of this method to navigation and marine geodesy is discussed, and comparisons are made with existing navigation systems. The very long baseline technique, with a master station, can use either an artificial satellite or natural sources as position references; a high-speed data link is required. A completely ship-borne system is shown to be feasible,

at the cost of poorer sensitivity for natural sources. A comparison of doppler, delay and phase-track modes of operating a very long baseline configuration is made, as that between instantaneous measurements and those where a source can be tracked from a horizon to transit. Geometric limitations in latitude and longitude coverage are discussed. The characteristics of natural radio sources, their flux, distribution on the sky, and apparent size are shown to provide a limit on position measurement precision. The atmosphere and frequency standard used both contribute to position measurement uncertainty by affecting interferometric phase.

S. H. Knowles, W. B. Waltman, N. W. Broten, D. H. Fort, K. I. Kellermann, B. Rayhrer, J. L. Yen and G. W. Swenson, "First Results From a Satellite Data Link Radio Interferometer," in *Eighth Annual Precise Time and Time Interval (PTTI) Meeting*, held at US Naval Research Laboratory, Washington, D.C., 30 November - 2 December 1976, 529-33.

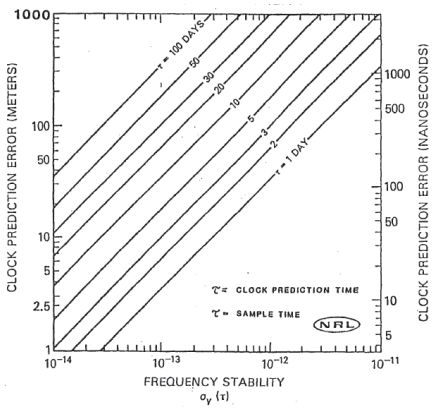
Since 1967 radio astronomers have been using the Very Long Baseline Interferometer (VLBI) technique to link together radio telescopes separated by continental or intercontinental distances, forming a radio telescope with extremely high resolving power. This high resolving power has had important results in radio astronomy, and is of interest for a wide variety of possible applications including highly precise time transfer, earthquake prediction, and station location. Previous experiments have relied on recording the signals from each antenna on television-type video recorders. This technique has several disadvantages. It is limited in bandwidth and thus sensitivity, cannot produce real-time results and is inherently quite unreliable. In November 1976 our group completed the first successful demonstration of an improved method of operating a long baseline radio interferometer, using a geosynchronous satellite as the connecting data link. The experiment was carried out by an international team of Canadian and American scientists. Large radio astronomy antennas in Lake Traverse, Ontario, and Green Bank, West Virginia were connected via satellite link. The satellite used was the Communications Technology Satellite, a joint Canadian-U. S. effort.



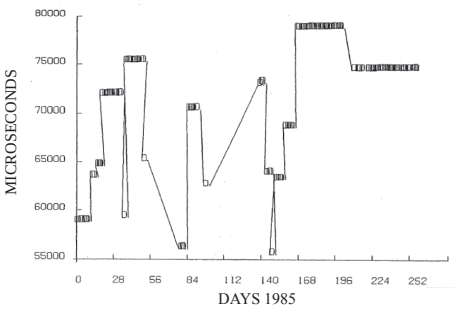
Results from satellite testing of a two-way time transfer modem. (Landis-1991, p. 256)

S. H. Knowles, W. B. Waltman, W. B. Klepczynski, N. W. Broten, D. H. Fort, K. I. Kellermann, B. Rayhrer, G. W. Swenson and J. L. Yen, "Real-Time Accurate Time Transfer and Frequency Standards Evaluation Via Satellite Link Long Baseline Interferometry," in *Ninth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held at Washington, D.C., 29 November - 1 December 1977, NASA Technical Memorandum 78104, 135-8.

Radio interferometry on natural sources, which has been an important radio astronomy technique, requires two connections between the antennas a data link and a local oscillator synchronization link. For baselines of up to a few kilometers, these connections are made by cables, and for up to about 50 kilometers by direct microwave link. Radio interferometry over longer distances has used the "VLBI" technique, which records the two data streams on magnetic tape for later correlation and uses independent atomic frequency standards at each station. An alternative method for long-baseline interferometers is to use an artificial satellite as a real-time link between the two antennas. This method was first successfully demonstrated by our group in November 1976, and reported on at the 8th PTTI Conference. This report records the results of an experiment by our group conducted in February 1977 to demonstrate the feasibility of a real-time accurate time transfer. Observing sites at Green Bank, West Virginia (National Radio Astronomy Observatory) and Lake Traverse, Ontario (Algonquin Radio Observatory) were used for the experiment. A communications satellite known variously as Hermes or CTS-1 was made available courtesy of the Canadian Ministry of Communications. Cesium beam time standards belonging to the US Naval Observatory were transported to each site as an independent check on the accuracy of the



Clock prediction performance versus frequency stability. (Largay-1987, p. 46)



Clock difference between GPS Master Station Guam and NAVSTAR #8 during 1985. (Largay-1987, NRLmr6076, p. 21)

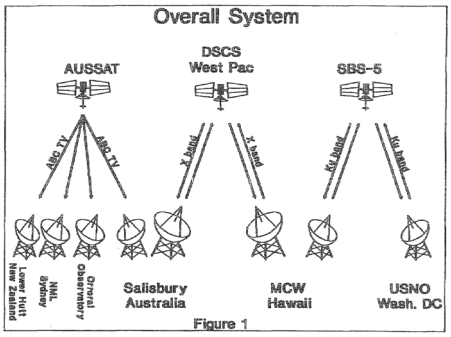
time transfer; they were calibrated at the beginning and end of each trip. The actual experiment was performed on 20 February 1977, at 1955 UT, observing the natural radio source 3C84 at 2.8 cm wavelength.

S. H. Knowles, W. B. Waltman, J. L. Yen, W. H. Cannon, W. Petrachenko, N. W. Broten, C. Costain, D. H. Fort, J. A. Galt, J. A. Popelar and G. W. Swenson, "Time Transfer via Satellite-Link Radio Interferometry," in *Proceedings of the Eleventh Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, NASA Conference Proceedings 2129, held at Goddard Space Flight Center, Greenbelt MD, 27-29 November 1979, NASA, 471-81.

Very long baseline interferometry using natural radio sources has been shown to be an excellent time transfer method. Our group has linked antennas using a synchronous communications satellite instead of the customary independent frequency standards and tape recorders. We have performed a successful preliminary time transfer using a wide-band data link that was accurate at the 100 nanosecond level, and have compared frequency standards to a part in 10^-13 over a 24-hour period using a phase coherent satellite link. The narrow-band phase coherent link method is potentially capable of timing accuracy of 10 picoseconds, and frequency comparison accuracy of 10^-16, and is in addition economical of spectrum usage. We plan to continue development of this latter method using the newly-launched ANIK-B satellite.

S. H. Knowles, "Ionospheric Limitations to Time Transfer by Satellite," in *Proceedings of the Sixteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at NASA Goddard Space Flight Center, 27-29 November 1984, NASA, 229-45.

The ionosphere can contribute appreciable group delay and phase change to radio signals traversing it; this can constitute a fundamental limitation to the accuracy of time and frequency measurements using satellites. Because of the dispersive nature of the ionosphere, the amount of delay is strongly frequency-dependent (1/f^2). At the 1.5 GHz frequency band used in the GPS systems the vertical-incidence ionospheric excess delay is typically 5 nanoseconds during the daytime (based on a total electron content of 10^17/m^2), and 20% of that at night. Even at X-band, the total daytime ionospheric delay of about 1 nanosecond is enough to make compensation necessary for implementation of extremely precise time transfer schemes such as the coherent satellite link proposed by Knowles. Calibration using models is an unreliable procedure because of the variable nature of the ionosphere. It is possible in principle to provide a self-calibration by observing at two frequencies simultaneously. While this technique has on occasion proven successful in reducing ionospheric errors, a fuller understanding of the underlying phenomenon is necessary in order to understand the basic limitations it mandates in time transfer techniques.



Proposed time transfer to the South Pacific. (Luck-1991, p. 358)

E. H. Krause, "High Altitude Research with V-2 Rockets," Proceedings of the American Philosophical Society **91** (5), 430-46 (1947).

The study of the heavens is an ancient science. It began with speculation about the movement and constitution of the sun; it later moved into the greater universe of the stars; and more recently expanded into that small but very interesting region of space represented by the earth's atmosphere. It seems fitting that a review of the more modern aspects of this subject should be made here since Franklin himself, the founder of the American Philosophical Society, made some of his more important contributions to science in this field.

G. P. Landis and L. D. Breetz, *Ionospheric Propagation Delay Measurement Techniques Using Dual Phase Coherent Doppler Frequencies and a Thin Shell Model*, NRL Report 6861, Naval Research Laboratory, Washington, D.C., 8 April 1969.

A theoretical approach was made to developing a technique for approximating the time error of a signal from a satellite caused by free electrons reducing the electromagnetic propagation speed. The development involved the use of the Transit satellites' dual frequency transmissions at 400 and 150 MHz, the AN/SRN-9 receiver, and knowledge of the orbital location of the satellite. The technique gives a reasonable close delay measurement for a given satellite at a given time under a given ionospheric condition.

G. P. Landis, I. Silverman and C. H. Weaver, *A Navigation Technology Satellite Receiver*, NRL Memorandum Report 3324, Naval Research Laboratory, Washington, D.C., July 1976.

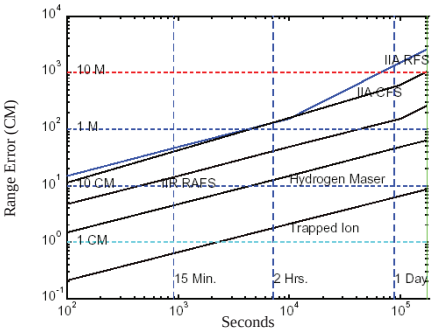
This report is a general functional description of a special purpose receiver for use with the Navigation Technology Spacecraft. The receiver consists of an R.F. front end that was developed by the Magnavox Research Laboratory and a data conversion unit built "in-house" at NRL. The receiver system operates on signals that are transmitted in a sidetone ranging spectrum by the Navigation Technology Satellite. The signals generated by the spacecraft system and received by the receiver system are "synchronized" by time standards located both on the spacecraft and at the receiver station. The time difference between transmission and reception of these signals is used to determine the distance between the spacecraft and the receiving station antennas.

The report describes the implementation of a phase locked loop, sidetone ranging system with a real-time digital correlation technique. The technique involves interfacing an "on-line" data averaging network with a dynamically operated data storage network. The technique provides advantages of minimizing drift errors because of environmental conditions, precision and flexibility in readout capabilities, and maximizing reliability of operation.

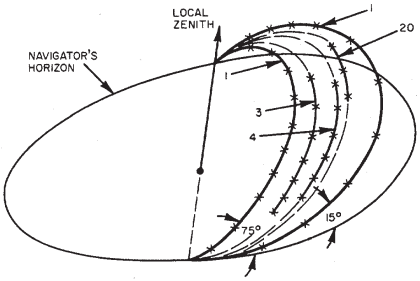
G. P. Landis, S. Stebbins, R. L. Beard and H. F. Fliegel, "Alternative Timing Networks with GPS," in *21st Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Redondo Beach, California, 28-30 November 1989, 205-13.

An approach to determining accurate time from GPS with an independent network of receiving stations has been investigated. The methods of using the Global Positioning System (GPS) for transferring time in previous work has been by the "common view" and "melting pot" methods. Both of these techniques have used simplified single frequency receivers operating on the clear/acquisition (C/A) GPS codes and assumes that the satellite transmissions are quality observables producing "GPS time," accurately traceable to UTC(USNO). In the case of "common view," the position of the satellite is assumed to be accurately known from the satellite transmissions. Then the time delays due to position at the two common view sites may be accurately measured for time comparisons. In the "melting pot" method, an individual site measures "GPS Time" as determined from observing all GPS satellites in view resulting in an accurate over-solution of the GPS system time. The satellite broadcasts then provide the UTC-GPS time correction. The investigation into an independent network was performed on the basis of using the simplified C/A receiving equipment to produce accurate timing information regardless of the GPS broadcast information accuracy. The technique can be used to improve the inherent capabilities of these single frequency receivers or maintain accuracy with degraded GPS signals. The similarities with geodetic positioning using GPS will be described. A proof-of-concept experiment will be discussed and data presented to verify the technique.

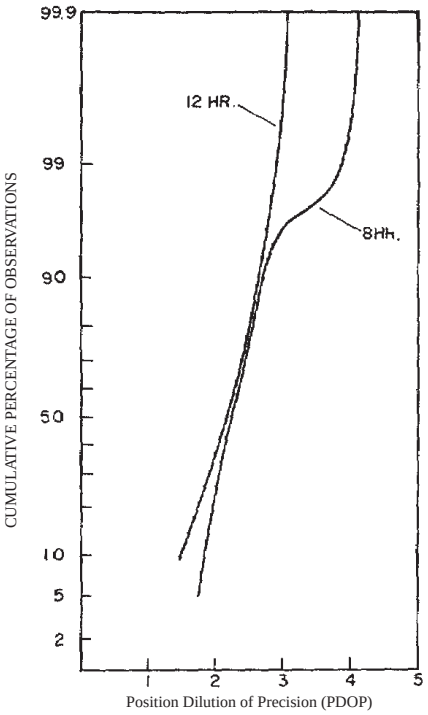
G. P. Landis, J. D. White, A. Gifford, R. L. Beard and J. A. Murray, "A New Two-Way Time Transfer Modem," in *21st Annual Precise Time and Time Interval (PTTI) Meeting*, held at Redondo Beach, CA, 28-30 November 1989, 131-7.



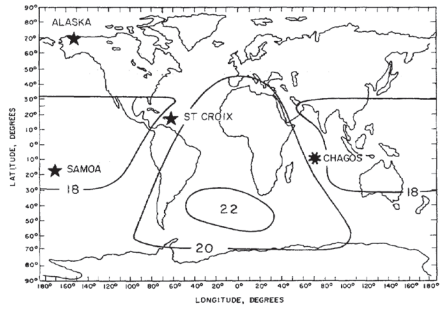
Estimated Atomic Frequency Standard (AFS) range error. RAFS and CAFS are rubidium and cesium frequency standards, respectively. (Martoccia-1997, p. 1080)



Single-pass geometry for range or doppler ranging, associated with a near-circular 500-naut-mi orbit. The x's on each trajectory represent times at which navigational data might be obtained using the satellite. The numbers are relative GDOP (Geometric Dilution of Precision) factors which indicate the effect of partial data collection during a satellite pass. (NRL Report 7252, 1971, p. 22)



Position Dilution of Precision (PDOP) comparisons of 8-hr and 12-hr orbits using 3-by-9 constellations, 10-degree masks, 53-degree inclination for the 12-hr orbit, and 55-degree inclination for the 8-hr orbit. From TIMATION Development Plan (NRL7227-1971, p. 136)



Error contours in feet for 3 (planes) -by- 9 (satellites per plane), 53-degree inclination orbit, 12-hour constellation. The ground stations are shown for good user clock. From TIMATION Development Plan. (NRL7227-1971, p. 137)

The use of commercial communications satellites for precise time transfer has been performed with a variety of techniques for a number of years. Military communications systems can also provide this function in a few deployed systems. This paper will describe a new design of a time transfer modem that can be produced a reasonable cost and enable users to make direct comparisons with the Naval Observatory with nanosecond precision. A flexible, all-digital design is being implemented that will enable a variety of different codes to be employed. Compatibility with existing equipment, such as the HARTL Modem, is a goal of this development. The design and operating modes of this equipment will be described.

G. P. Landis, I. J. Galysh, G. Gifford and A. Osborne, III, "A New Two-Way Time Transfer Modem," in *23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Pasadena, California, 3-5 December 1991, NASA Conference Publication 3159, 247-57.

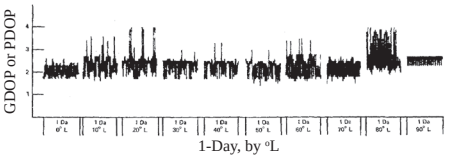
The use of commercial communication satellites for precise time transfer has been performed with a variety of techniques for a number of years. Military communications systems can also provide this function in a few deployed systems. This paper will demonstrate a new design of a time transfer modem that can be produced at a reasonable cost and enable users to make direct comparisons with the Naval Observatory with nanosecond precision. A flexible all-digital design is being implemented that will enable a variety of different codes to be employed. The design and operating modes of this equipment are demonstrated.

G. P. Landis and I. Galysh, "NRL/USNO two way time transfer modem design and test results," in *1992 IEEE Frequency Control Symposium*, 27-9 May 1992, 317-26.

The Naval Research Laboratory (NRL) has developed a two-way time transfer modem for the United States Naval Observatory (USNO). This modem in conjunction with a Very Small Aperture Terminal (VSAT) and a communication satellite can achieve sub nanosecond time transfer performance. The purpose of this paper is to present an overview of the hardware and software design of the digital modem showing its unique features and results of satellite testing. Time transfer performance is achieved in the hardware by a combination of stability, matching and calibration. Hardware stability is achieved by using synchronous digital methods in both the transmitter and receiver sections. Analog components are kept to a minimum and are wide band where possible to promote delay stability. Identical narrow band filters are used in the transmitter and the receiver section to help match temperature dependent delays. Time transfer between sites is a master slave technique, a master site transferring time to a network of slave sites. The master transmits first, specifically addressing a slave site and the slave site responds. This allows the master to operate on a predetermined schedule based on satellite availability, and the target to respond based only on signals it receives. Once communications has been established, data is exchanged in both directions through the satellite, thus eliminating the need for an additional communication path. A personal computer (PC) is used for operator interface, modem control, data collection and processing. With this method, both sites can be automated. Initial tests have been conducted to evaluate and verify modem performance and reduce the effects of other systematic errors. Modem tests at a common location were performed by direct connection and through two VSAT's. Tests used a common oscillator to the two modems to examine optimum comparison conditions. The test results will be presented.

G. P. Landis, I. Galysh and T. Petsopoulos, "A New Digital Phase Measurement System," in *33rd Annual Precise Time and Time Interval (PTTI) Meeting*, L. A. Breakiron, ed. held at Long Beach, California, November 2001, US Naval Observatory, 543-59.

The Naval Research Laboratory (NRL) is developing a digital phase measurement system. The measurement system uses high speed Analog to Digital Converters (ADC) to make tens of millions of measurements per second, Digital Signal Processing (DSP) hardware for intermediate calculations, and a PC for the final phase calculations. Performance of the present configuration is limited by a 12-bit analog-to-digital converter. Averaging times can be as small as 0.0001 seconds. Multiple input frequencies to over 10 MHz can be measured simultaneously. Modular construction will allow for expansion to many channels. Absolute phase measurements are possible. Inputs to channels can be switched between frequencies and then returned to an original frequency without losing phase coherency of the measurements. This system to be used in the laboratory and may be used on the GPS satellites to monitor a hot backup clock. The basic system measures the coefficient of a Discrete Fourier Transform (DFT) at the assumed frequency of the input signal. This paper will describe the special purpose DSP hardware and software used to measure the signal and transform the measurements into conventional clock parameters.



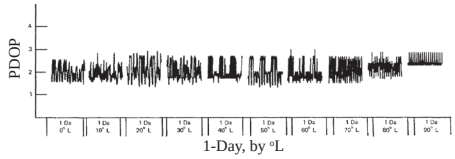
Position geometric dilution of precision (PDOP) for the 3-by-9 constellation using 8-hr periods and circular orbits at a 55-degree inclination. From TIMATION Development Plan (NRL Report 7227, 1971, p. 136)

G. P. Landis and J. White, "Limitation of GPS Receiver Calibrations," in *34th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, VA, 3-5 December 2002, NASA Conference Publication 3159, 325-332.

The Naval Research Laboratory (NRL), as part of the Global Positioning System (GPS) Center of Expertise (COE) test program, performs absolute calibration of GPS receivers for time transfer. NRL did a simulation of this calibration method to verify the procedure. The simulation focused on the effects of filters, external to receiver, on receiver calibration. Two areas were investigated in this simulation. Will changes in the data from two different types of receivers track if the bandwidth of the signal source to both receivers change? If a filter is added between the antenna and a receiver, can this combination be calibrated in parts or must this combination be calibrated together?

M. M. Largay and J. A. Buisson, *On-Orbit Frequency Stability Analysis of the GPS NAVSTAR 8 Rubidium Clock and NAVSTARs 9 and 10 Cesium Clocks*, NRL Memorandum Report 6076, Naval Research Laboratory, Washington, D.C., 17 September 1987.

This report describes the on-orbit frequency stability performance analysis of the Global Positioning System (GPS) NAVSTAR 8 rubidium clock and the NAVSTARs 9 and 10 cesium clocks. Time domain measurements, taken from three GPS monitor sites and from the United States Naval Observatory (USNO), have been analyzed to determine the short and long-term frequency stability performance of the NAVSTAR clocks. The data presented include measurements from 1985.



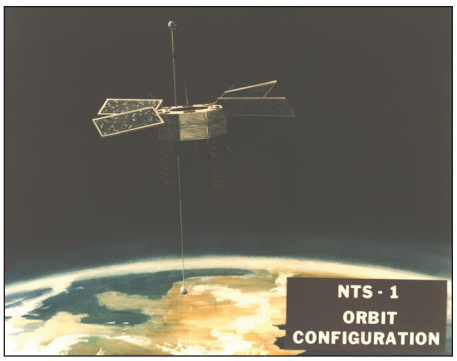
Position geometric dilution of precision (PDOP) for the 3-by-9 constellation using 12-hr periods and circular orbits at at 53-degree inclination. From TIMATION Development Plan (NRL Report 7227, 1971, p. 137)

S. Linsenmeyer, C. Gregerson and R. Beard, "Issues Necessitating a Common Time Reference in the U.S. Navy," http://tycho.usno.navy.mil/ptti/ptti2000/abstracts.html, 2000, captured 30 November.

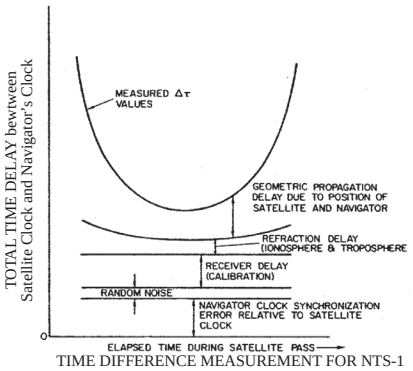
(Presentation abstract only.) This briefing discusses the impact of incorrect implementation of the United States of America Chairman of the Joint Chiefs of Staff timing policy. The brief systematically addresses each policy area and shows the associated level of compliance. Finally, with regard to the United States Navy, calls for the implementation of a common time reference making time a utility on board U.S. Naval vessels.

J. Luck, J. Dunkley, T. Armstrong, A. Gifford, P. Landis, S. Rasmussen, P. Wheeler, T. Bartholomew and S. Stein, "A Proposed Time Transfer Experiment Between the USA and the South Pacific," in *23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Pasadena California, 3-5 December 1991, NASA Conference Publication 3159, 351-63.

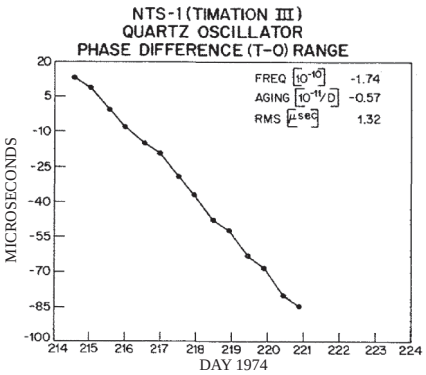
This paper describes the concept, architecture and preliminary details of an



The NTS-1 (TIMATION III) satellite in orbit configuration. (McCaskill-1975, p. 429; McCaskill-1975 NRL7932, p. 2)



NTS-1 (TIMATION III) time difference measurement. (McCaskill-1975, p. 430)



Quartz (T-0) versus time, days 214-221, 1974. (McCaskill-1975, p. 430)

experiment directed towards providing continuous Ultra High Precision (UHP) time transfer between Washington, DC; Salisbury, SA Australia; Orroral Valley, ACT Australia; and Lower Hutt, New Zealand. It further describes a proposed method of distributing UTC(USNO) at a high level of precision to passive users over a broad area of the South Pacific.

D. W. Lynch, *Navy's Space Surveillance System's Two-Point Orbit*, NRL Report 6072, Naval Research Laboratory, Washington, D.C., 13 March 1964. NRL6072 LIMITED DISTRIBUTION

C. D. Martoccia, R. L. Beard and A. Wu, "Atomic Frequency Standards Technology Roadmap for the Future GPS Satellites," in *ION GPS-97, Institute of Navigation Satellite Division, 10th International Technical Meeting*, held at Kansas City; Missouri, September 1997, 1075-84.

Atomic Frequency Standards (AFS) in the GPS satellites are essential in providing GPS users accurate position, velocity and time determinations. Two Rubidium (Rb) AFSs and two Cesium (Cs) AFSs are employed for the current GPS Block II/IIA satellites. Two Rb AFSs and one Cs AFSs are planned for the GPS Block IIR satellites. However, the production of the Cs AFS is experiencing major manufacturing and testing problems, so the configuration of three Rb AFSs has been selected for at least the first ten GPS Block IIR satellites. In the GPS Block IIF program, three Cs AFSs and Rb AFS will be installed.

In the United States, the capabilities of producing space-qualified AFS are presently limited to only three companies (Kernco, Frequency & Time Systems and Frequency Electronics Inc.) for the Cs AFS and one (EG&G) for the Rb AFS. The commercial market for spaceborne AFS does not exist and military usage is limited primarily to GPS. Since the market demand for the future spaceborne AFS for the GPS program will be, on the average, about twelve units per year based on three launches per year and four AFSs per satellite, this type of production rate would not provide the economic justification for the sustainment of the AFS manufactures. Also the commercial applications of the accurate AFS are seriously hampered because the accurate time can easily be obtained from the GPS receivers.

Looking into the requirements for the future GPS, it is necessary to develop a long range plan for the AFS technology roadmap to assure an adequate supply now for continuous GPS sustainment. We not only have to ensure that AFS will be available in the future, we also have to address the continuing demand for the improvement in accuracy and reliability, and ease of operation, diagnostics and production by introducing new AFS technologies.

In this paper we will examine the following topics: (1) Space proven AFS industrial base, (2) Special study for the AFS technology insertion plan, (3) Refinement of the current AFS technologies, (4) Development of the new AFS technologies, and (5) AFS roadmap schedule.

T. B. McCaskill, J. A. Buisson and D. W. Lynch, *Principles and Techniques of Satellite Navigation Using the Timation II Satellite*, NRL Report 7252, Naval Research Laboratory, Washington, D.C., 17 June 1971.

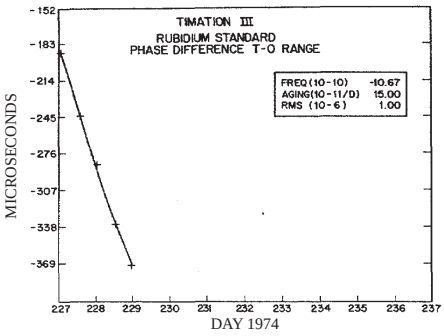
The Timation II satellite is an experimental model of a range and doppler measurement satellite navigation system sponsored by the Naval Air Systems Command. In this report the satellite is described briefly, along with the ranging concept and the range and doppler measuring equipment. The basic navigation equations for range, doppler, and simultaneous range and doppler measurements are developed, along with several alternate techniques depending upon the user equipment. An analytical expression is developed for experimentally determining the range error due to first-order ionospheric refraction. The system biases are identified with clock difference (range bias) and frequency difference (doppler bias). An error

analysis is performed to determine the influence of geometry and system noise upon navigation accuracy.

T. B. McCaskill, C. W. Arvey and H. B. Gardner, *DOPPLER Only Navigation Using the Timation II Satellite*, NRL Report 7657, Naval Research Laboratory, Washington, D.C., 3 December 1973.

The TIMATION II satellite is an experimental model which is part of a range and doppler measurement satellite system proposed by NRL as the Navy's candidate for the Department of Defense Navigation Satellite System (DNSS). The TIMATION project has been conducted at NRL under the sponsorship of the Navy Space Project Office (PME-106) and the Naval Air Systems Command. A doppler mathematical model has been devised which permits ready analysis of the doppler data collected at the CBD field station over a 1-1/2-year time period.

The studies performed have shown that the best navigational accuracies, having an RMS of 53 meters (174 feet), are achieved by using dual-frequency doppler measurements. The 400-MHz single-frequency data give the next best accuracy, with an RMS of 84 meters (276 feet), and are followed by the 150-MHz single-frequency data, which yield an accuracy of 739 meters (2424 feet) RMS. The data collected are three types: 1K, 10K, and 40K doppler count. By varying the count interval, the effect of measurement time on navigational accuracy can be observed.



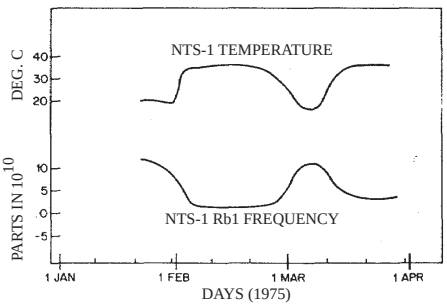
Rb-1 (T-0) versus time before C-Field tune. (McCaskill-1975, p. 432)

T. B. McCaskill and J. A. Buisson, "NTS-1 (TIMATION-III) Quartz and Rubidium Oscillator Frequency Stability Results," in *29th Annual Symposium on Frequency Control*, held at Atlantic City, New Jersey, 28-30 May 1975, Electronic Industries Association, Washington, D.C., 425-435.

This paper describes frequency stability results obtained from the NTS-l satellite. NTS-l has three on-board frequency sources, one quartz oscillator and two rubidium resonators. These are used to derive the precise time and frequency signals radiated by the spacecraft.

The data taken from each of three 2.5 hr. daily passes are time difference or frequency difference. These data are incorporated into a single value for each pass which is subsequently used in the Allan Variance computation.

The results presented here employ single frequency measurements at 335 MHz. Analysis of these results indicate an effect on frequency stability that correlates with the orbit. The results further indicate the rubidium frequency is dependent upon the space-craft temperature, which confirms previous NRL pre-flight analysis.



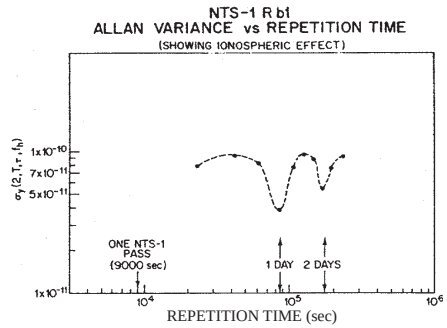
Rb-1 frequency and temperature versus time, all stations. (McCaskill-1975, p. 433)

T. B. McCaskill and J. A. Buisson, *NTS-1 (TIMATION III) Quartz- and Rubidium-Oscillator Frequency-Stability Results*, NRL Report 7932, Naval Research Laboratory, Washington, D.C., 12 December 1975, 24 pp.

This report describes frequency stability results obtained from the NTS-1 satellite. NTS-1 has three on-board frequency sources: one quartz oscillator and two rubidium resonators. These are used to derive the precise time and frequency signals radiated by the spacecraft.

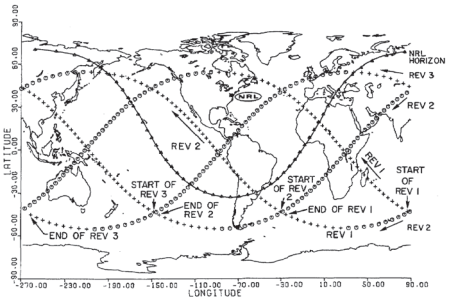
The data taken from each of three 2.5-hr daily passes are time difference (range) or frequency difference (doppler). These data are incorporated into a single value for each pass which is subsequently used in computing long-term Allan-variance results.

The results presented here employ single-frequency measurements at 335 MHz. Analysis of these results indicate an effect on measured frequency stability that correlates with a resonant term in the orbit. The results further indicate the rubidium frequency depends on the space-craft temperature, which confirms previous NRL preflight analysis.



Rb-1 Allan Variance versus repetition time. (McCaskill-1975, p. 434)

T. McCaskill, J. Buisson and A. Buonaguro, "A Sequential Range Navigation Algorithm for a Medium Altitude Navigation Satellite," Navigation: Journal of The Institute of Navigation **23** (2), 164-177 (1976).



NTS-1 ground track for day 262. (McCaskill-1975 NRL7932, p. 3)

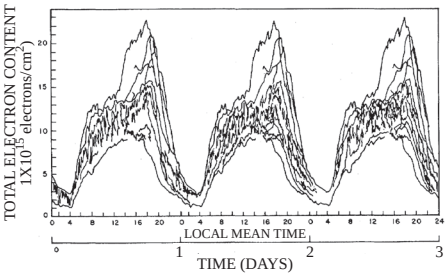
This paper describes a sequential algorithm which employs sequential passive time difference measurements and a-priori estimates of position and bias parameters to determine the navigator's position, clock and frequency bias parameters. A covariance analysis is presented using simulated measurements from the NTS-1 satellite.

T. McCaskill, J. White, S. Stebbins and J. Buisson, "NTS-2 Cesium Frequency Stability Results," in *32nd Annual of Frequency Control Symposium*, held at Atlantic City, NJ, 31 May - 2 June 1978, Electronic Industries Association, 560-566.

NTS-2 was successfully launched on 23 June 1977 and maneuvered into a pre-assigned constellation position as part of the Phase I demonstration for NAVSTAR GPS. NTS-2 carries two cesium frequency standards. Precise timing signals, derived from one of the cesium frequency standards, are continuously transmitted. Time difference measurements are then made by the NTS ground stations.

The NTS-2 time differences are used to fit an orbit to the observations over a (typical) six day span. Clock offsets are then obtained using the reference orbit and other measured parameters; these clock offsets are then used to estimate the cesium frequency stability. The frequency stability is measured through the use of the Allan Variance; the frequency values are calculated using pairs of time difference measurements.

Estimates of frequency stability have been obtained for one of the two cesium frequency standards for sample times from one to nine days. Coefficients for white frequency and flicker frequency noise have been estimated. For sample times of ten days or longer, an upper bound for the cesium aging rate with respect to UTC(USNO, MCl) has been obtained.



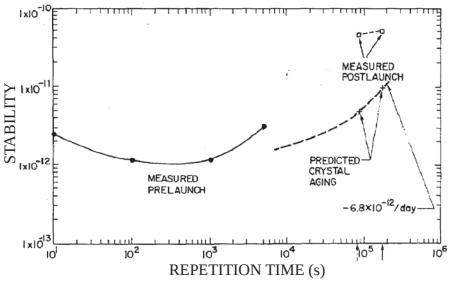
Total electron content in 1-m^2 vertical column. (McCaskill-1975 NRL7932, p. 18)

T. B. McCaskill, J. Buisson, J. White and S. Stebbins, *Stability Analysis of the Cesium Frequency Standard on Board Navigation Technology Satellite 2 (NTS-2)*, NRL Report 8375, Naval Research Laboratory, Washington, D.C., 4 February 1980.

NTS-2 was successfully launched on June 23, 1977, and maneuvered into a pre-assigned constellation position as part of the Phase I demonstration for NAVSTAR GPS. NTS-2 carried two cesium frequency standards. Precise timing signals, derived from one of the cesium frequency standards, were continuously transmitted. Time differences were then measured by the NTS ground stations.

The NTS-2 time differences were used to fit an orbit to the observations over a (typical) 6-day span. Clock offsets were then obtained using the reference orbit and other measured parameters; these clock offsets were then used to estimate the cesium frequency stability.

Estimates of frequency stability have been obtained for one of the two cesium frequency standards for sample times of from 1 to 9 days. Analysis of the results indicates a white frequency noise of 0.00000000011 divided by the square root of the sample time in days for sample times of 1 to 5 days with a flicker floor of 0.00000000000017 for sample times from 5 to 9 days. For sample times of 10 days or longer an attempt was made to check for cesium aging with respect to the Universal Time Coordinated of Master Clock 1 at the United States Naval Observatory. The value for aging was not significantly different from zero; that is, no cesium aging was found.



Quartz oscillator stability measurements. (McCaskill-1975 NRL7932, p. 19)

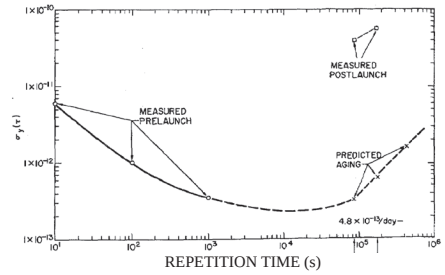
T. B. McCaskill, S. Stebbins, C. Carson and J. Buisson, "Long Term Frequency Stability Analysis of the GPS NAVSTAR 6 Cesium Clock," in *Proceedings of the Thirteenth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, NASA Conference Publication 2220, held at Naval Research Laboratory, Washington, D.C., 1-3 December 1981, 451-468.

Time domain measurements, taken between the NAVSTAR 6 Spacecraft Vehicle (SV) and the Vandenberg GPS Monitor Site (MS), by a pseudo random noise (PRN) receiver, have been collected over an extended period of time and analyzed to estimate the long term frequency stability of the

NAVSTAR 6 onboard frequency standard, referenced to the Vandenberg MS frequency standard.

The technique employed separates the clock offset from the composite signal by first applying corrections for equipment delays, ionospheric delay, tropospheric delay, earth rotation and the relativistic effect. The data are edited and smoothed using the predicted SV ephemeris to calculate the geometric delay. Then all available passes from each of the four GPS monitor stations, are collected at 1-week intervals and used to calculate the NAVSTAR orbital elements. The procedure is then completed by subtracting the corrections and the geometric delay, using the final orbital elements, from the composite signal, thus leaving the clock offset and random error.

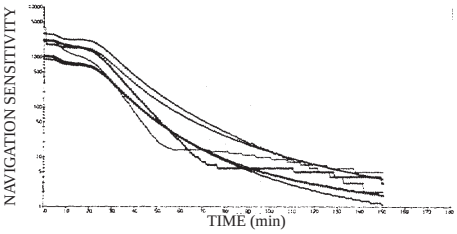
Frequency stability estimates of clock performance are then made using the clock offsets to calculate the Allan Variance, sigma/sub/y(tau), for the spacecraft oscillator, using sample times that vary from 1 to 10 days. The results indicate a combined clock/ephemeris frequency stability of l.3x10^-13 or less, for sample times varying from one day up to ten days. Future work will include analysis of cesium standards on SV 5 and 6 as well as a rubidium standard on SV 5.



Rubidium-1 stability measurements. (McCaskill-1975 NRL Report 7932, p. 19)

T. B. McCaskill, S. B. Stebbins, C. Carson and J. A. Buisson, *Long Term Frequency Stability Analysis of the GPS NAVSTAR 6 Cesium Clock*, NRL Report 8599, Naval Research Laboratory, Washington, D.C., 20 September 1982.

This report describes the on-orbit performance evaluation of the NAVSTAR 6 cesium clock. Time domain measurements, taken between the NAVSTAR 6 spacecraft and the Vandenberg GPS monitor station, by a spread spectrum receiver, have been collected for about 100 days and analyzed to estimate the long term frequency stability of the NAVSTAR 6 cesium clock. The results indicate a combined clock/ephemeris frequency stability of 1.3 x l0^-13, or less, for sample times varying from 1 to 10 days. Future work will include analysis of other orbiting GPS cesium and rubidium clocks.



Covariance analysis plot for day 91, 11^h 30^m. (McCaskill-1976, p. 173)

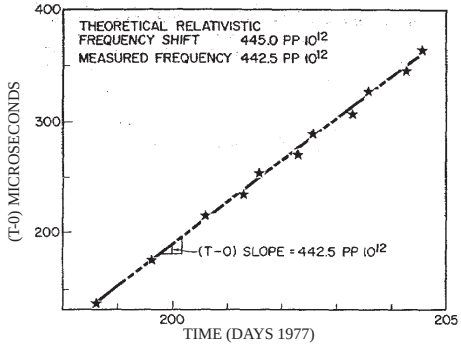
T. B. McCaskill, J. A. Buisson and S. B. Stebbins, "On-Orbit Frequency Stability Analysis of the GPS NAVSTAR's 3 and 4 Rubidium Clocks and NAVSTAR's 5 and 6 Cesium Clocks," in *Fifteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Naval Research Laboratory, Washington, D.C., 6-8 December 1983, 171-209.

This paper describes the on-orbit frequency stability performance analysis of the GPS NAVSTARs 3 and 4 rubidium clocks, and the NAVSTARs 5 and 6 cesium clocks. Time-domain measurements, taken from the four GPS monitor sites, have been analyzed to estimate the short- and long-term frequency stability performance of the NAVSTAR clocks. The data analyzed includes measurements from 1981, 1982, and the first 100 days of 1983. Short- and long-term results are presented for data collected during 1982. The Allan variance was used as the measure of frequency stability performance in the time domain.

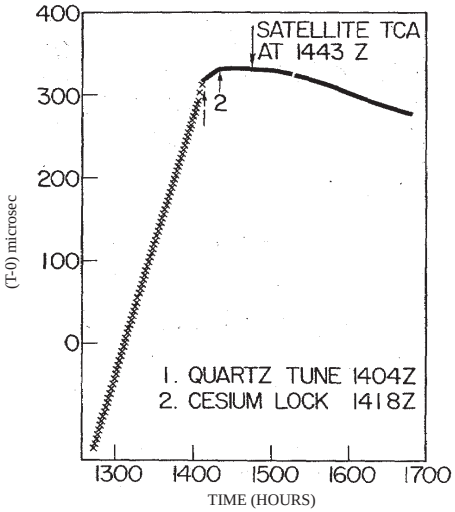
The time-domain noise analysis results indicate a white noise FM process is present, in both rubidium and cesium clocks, for sample times of 900- and 1800-seconds. The projected value of this white noise FM process to a 1-day sample time agrees closely with the 1-day sample time stability results, for both rubidium and cesium clocks, indicating an underlying white noise FM process for sample times ranging from 900 seconds to 1 day.

A random walk FM process was measured for the NAVSTARs 3 and 4 rubidium clocks for sample times of 1 to 10 days. A flicker noise FM process was measured for the NAVSTARs 5 and 6 cesium clocks, for sample times of 1 to 10 days.

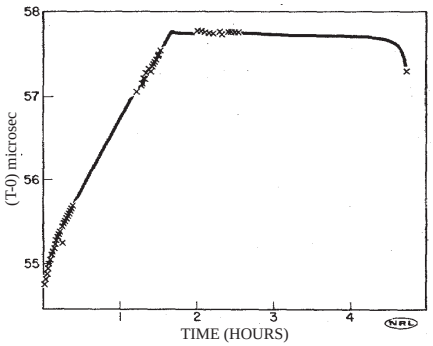
The NAVSTARs 3 and 4 rubidium clock long-term frequency stability values are in good agreement with the expected performance. The NAVSTAR-3



Measured relativistic frequency shift, Station CBD (NRL Chesapeak Bay Detachment), day 215, 1977. (McCaskill-1978, p. 564)



Cesium #2 lock-up, 7/13/1977. Data from NTS-2, Panama Canal Zone. (McCaskill-1978, p. 564)



Measured relativistic frequency correction, NTS station CBD, day 215, 1977. (McCaskill-1978, p. 564)

short-term stability results indicate an anomaly which has peak effect at a 1.25- hour sample time.

T. B. McCaskill, J. A. Buisson and S. B. Stebbins, *Frequency Stability Analysis of GPS NAVSTARs 3 and 4 Rubidium Clocks and the NAVSTARs 5 and 6 Cesium Clocks*, NRL Report 8778, Naval Research Laboratory, Washington, D.C., 20 December 1983.

This report describes the on-orbit frequency stability performance analysis of the Global Positioning System (GPS) NAVSTARS 3 and 4 rubidium clocks and the NAVSTARS 5 and 6 cesium clocks. Time domain measurements, taken from the four GPS monitor sites, have been analyzed to estimate the short- and long-term frequency stability performance of the NAVSTAR clocks. The data presented include measurements from 1981, 1982, and the first 100 days of 1983.

T. B. McCaskill, J. A. Buisson, M. M. Largay and W. G. Reid, "On-Orbit Frequency Stability Analysis of the GPS NAVSTAR-1 Quartz Clock and the NAVSTARS-6 and -8 Rubidium Clocks," in *Proceedings of the Sixteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at NASA Goddard Space Flight Center, 27-29 November 1984, NASA, 103-25.

This paper presents an on-orbit frequency stability performance analysis of the GPS NAVSTAR-1 quartz clock and the NAVSTARs-6 and -8 rubidium clocks. The clock offsets were obtained from measurements taken at the GPS monitor stations, which use high performance cesium standards as a reference.

Clock performance is characterized through the use of the Allan variance, which is evaluated for sample times of 15 minutes to two hours, and from one day to 10 days. The quartz and rubidium clocks' offsets were corrected for aging rate before computing the frequency stability. The effect of small errors in aging rate is presented for the NAVSTAR-8 rubidium clock's stability analysis.

The analysis includes presentation of time and frequency residuals with respect to linear and quadratic models, which aid in obtaining aging rate values and identifying systematic and random effects. The frequency stability values were further processed with a time domain noise process analysis, which is used to classify random noise process and modulation type.

NAVSTAR-1 results indicate good performance for a quartz clock. Comparison of the quartz clock's stability with the best on-orbit cesium clock results indicates that the cesium standard is more stable by at least a factor of two for a 900 second sample, and increases to two orders of magnitude for a one day sample time.

The NAVSTAR-8 rubidium clock differed from the NAVSTAR-6 rubidium clock in its improved thermal environment. This rubidium clock exhibited an effect that lasted for nearly five months. Following this transient, the rubidium clock performed with better-than-expected stability. A final discussion of quartz, rubidium, and cesium on-orbit will be presented.

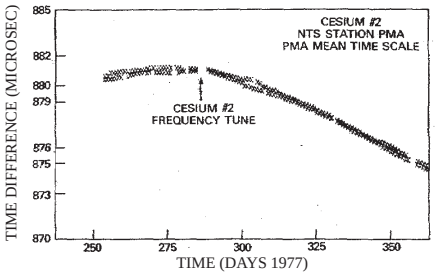
T. B. McCaskill and J. A. Buisson, "On-Orbit Frequency Stability Analysis of NAVSTAR GPS Clocks and the Importance of Frequency Stability to Precise Positioning," in *Proceedings of the First International Symposium on Precise Positioning with the Global Positioning System; Positioning with GPS - 1985*, held at Rockville, MD, 15-19 April 1985, US Department of Commerce, National Ocean and Atmospheric Administration, National Ocean Service, 37-50.

A description of the NAVSTAR Global Positioning System (GPS) and its primary mode of navigation will be presented. This mode of GPS system navigation is then contrasted with that of the Navy Navigation Satellite System (NNSS) single pass mode of navigation, with emphasis on the relative importance of time synchronization and clock stability in the two systems.

An on-orbit frequency stability analysis of NAVSTAR cesium, rubidium, and

quartz clocks will be presented. The clock off-sets were obtained using smoothed pseudorange and integrated pseudorange-rate measurements, taken from the GPS monitor stations (MS). The MSs use high performance cesium clocks to drive their receivers, and to provide a ground-based time and frequency reference for GPS time. A smoothed orbit is used to separate the orbital and clock signals from the pseudorange measurements.

Clock performance is characterized through the use of a time domain - frequency stability profile, which is evaluated for sample times of 15 minutes to two hours, and from one day to 10 days. Aging rate corrections were made for the quartz and rubidium clocks before computing their frequency stability. The sensitivity of frequency stability to small errors in the aging rate is presented for the NAVSTAR-8 rubidium clock. The frequency stability values obtained were processed to classify random noise process and modulation type, which are then compared with a generic frequency stability profile to separate GPS system effects from clock effects. Results of the GPS on-orbit frequency stability analysis are presented for quartz, rubidium, and cesium clocks. These results may then be used to predict GPS navigation performance and the potential for precise positioning.



NAVSTAR GPS NTS-2 results. Time difference UTS (NTS) - UTC (PMA, Mean) in microseconds, versus time in days. (McCaskill-1978, p. 565)

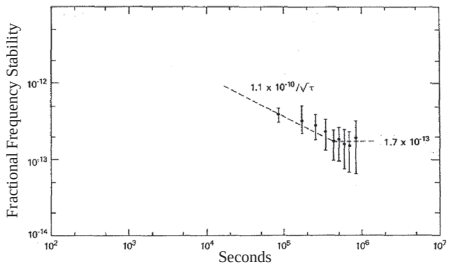
T. B. McCaskill, J. A. Buisson and T. J. Hogan, "On-Orbit Frequency Stability Analysis of GPS NAVSTAR Cesium and Rubidium Clocks," in *21st Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Redondo Beach, California, 28-30 November 1989, 239-258.

Naval Research Laboratory (NRL) on-orbit analysis of GPS NAVSTAR cesium and rubidium clocks has been performed using a three-year database that extended from 1 Jan., 1986 to 31 Dec., 1988. The NAVSTAR clock offset measurements were computed from pseudo-range data observed using a single frequency GPS receiver. Time and frequency inputs were derived from the U.S. Naval Observatory (USNO) time ensemble. Orbital data was obtained from the NAVSTAR broadcast ephemeris.

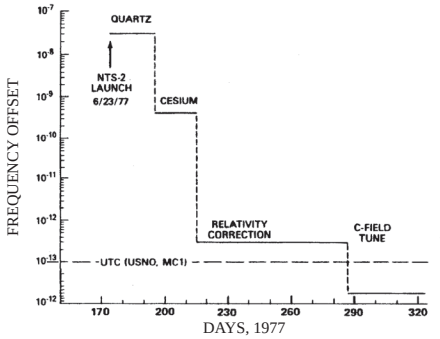
A key feature of the NRL NAVSTAR clock analysis is the capability to analyze phase and frequency discontinuities, solve for the discontinuity, and correct the clock data. This feature was developed primarily as a means to solve and correct for the NAVSTAR time or frequency adjustments that are required to keep NAVSTAR clock time close to GPS time. Discontinuities are analyzed to find both the amount and the probable cause for the break. This feature makes possible the use of sample times of 100-days or more, and the analysis of data to identify and model long term clock, system, and environmental effects.

Results for this NAVSTAR clock analysis will include the presentation of clock off-set, frequency offset, and aging as a function of time. The NAVSTAR eclipse cycles will be superimposed on selected plots to demonstrate temperature sensitivity on several rubidium clocks. Clock performance in the time domain will be characterized using frequency stability profiles with sample times that vary from 1 to 100-days. Included in this analysis is the impact of clock aging on NAVSTAR frequency stability performance. It is demonstrated that uncorrected aging on the order of 1 x 10^-13/day has a measurable effect on NAVSTAR one-day frequency stability. It is further demonstrated that uncorrected aging on the order of 1 x 10^-15/day has negligible impact on one-day frequency stability and only a small effect on 100-day frequency stability.

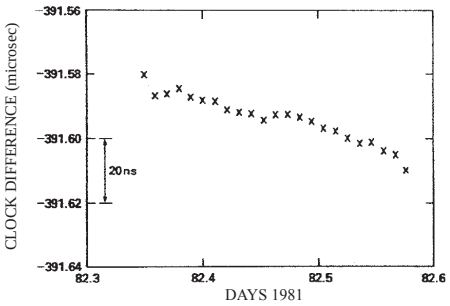
The NAVSTAR rubidium clocks varied considerably in frequency stability results. The earlier NAVSTAR rubidium clocks have significant temperature coefficients. The four NAVSTAR cesium clocks demonstrated excellent and consistent performance for all sample times that were evaluated. Composite NAVSTAR frequency stability and time-prediction uncertainty plots are included that summarize clock analysis results for NAVSTAR clocks using sample times that vary from one-day to 100-days. All of the NAVSTAR clocks analyzed in this report meet the GPS one-day specification for frequency stability performance.



NTS-2 Cesium #2 versus Panama time scale. Cesium fractional frequency versus sampling time (Allan variance procedure). (McCaskill-1978, p. 566)



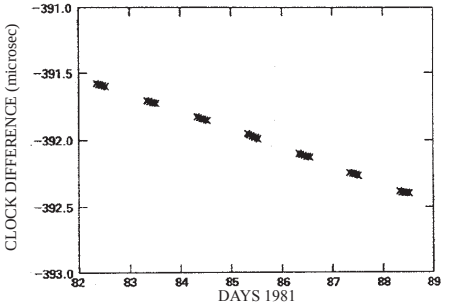
History of the NTS-2 frequency offset, plotted in 1977 with respect to days. (McCaskill-1980 NRL8375, p. 4)



Single pass clock difference NAVSTAR-6 (SV9) and the GPS Vandenburg Monitor Site (VMS). (McCaskill-1981, p. 464)

T. B. McCaskill, W. G. Reid and J. A. Buisson, "Frequency Stability of On-Orbit GPS Block-I and Block-II NAVSTAR Clocks," presented at the Institute of Navigation (ION) GPS-90 Conference, Boulder, Colorado, 19-21 September 1990, 131-137.

On-orbit analysis of the Global Positioning System (GPS) Block-I and Block-II NAVSTAR clocks has been performed by the Naval Re-search Laboratory using a multi-year database. The NAVSTAR clock phase-offset measurements were computed from pseudo-range measurements made by the five GPS monitor sites and from the U.S. Naval Observatory precise-time site using single or dual frequency GPS receivers. Orbital data was obtained from the NAVSTAR broadcast ephemeris and from the best-fit, post-processed orbital ephemerides supplied by the Naval Surface Weapons Center or by the Defense Mapping Agency. Clock performance in the time domain is characterized using frequency-stability profiles with sample times that vary from 1 to 100 days. Composite plots of NAVSTAR frequency stability and time-prediction uncertainty are included as a summary of clock analysis results. The analysis includes plots of the clock phase offset and frequency offset histories with the eclipse seasons superimposed or selected plots to demonstrate the temperature sensitivity of one of the Block-I NAVSTAR rubidium clocks. The potential impact on navigation and on transferring precise time of the degradation in the long-term frequency stability of the rubidium clocks is discussed.



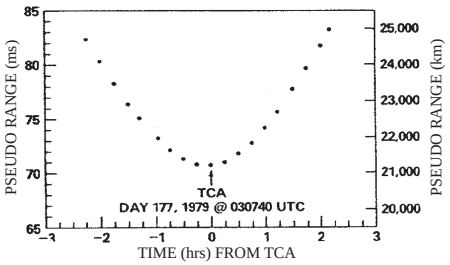
One week of clock differences between NAVSTAR-6 (SV9) and the GPS Vandenburg Monitor Site (VMS). (McCaskill-1981, p. 464)

T. B. McCaskill, W. G. Reid, J. A. Buisson and H. E. Warren, "Frequency stability of GPS NAVSTAR Block I and Block II on-orbit clocks," in *23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Pasadena California, 3-5 December 1991, NASA Conference Publication 3159, 307-319.

Analysis of the frequency stability of on-orbit NAVSTAR clocks is performed by the Naval Research Laboratory. This work was sponsored by the GPS Joint Program Office. The frequency stability is presented for sample times of one day to 30 days. Composite frequency-stability profiles are presented for the Block I and Block II NAVSTAR clocks. Several NAVSTAR cesium clocks show frequency stabilities of a few parts in 10^14 long sample times. Time-domain noise-process analysis shows the dominant noise type to be white frequency noise for sample times of one to ten days. The non-stationary stochastic behavior of one of the cesium clocks, illustrated by its frequency-stability history, shows that the frequency stability is not always time-invariant.

T. B. McCaskill, W. G. Reid, J. A. Buisson and H. E. Warren, "Analysis of the Frequency Stability of On-Orbit GPS Navstar Clocks," in *Proceedings of the 47th IEEE International Frequency Control Symposium*, held at Salt Lake City, Utah, 2-4 June 1993, IEEE, New York, 23-32.

The Naval Research Laboratory analyzes the performance of the on-orbit Navstar clocks for the Global Positioning System (GPS) Joint Program Office and conducts special analyses for the GPS master control station (MCS) whenever a clock exhibits anomalous behavior. This analysis will focus on the long term behavior of the cesium and rubidium clocks using sample times of one-day or more. The analysis includes frequency and aging histories, frequency-stability profiles, time-domain noise process profiles, and anomaly detection. Events that perturb the normal clock behavior are of particular interest. The semiannual eclipse seasons will be superimposed on selected plots to investigate the temperature sensitivity of the clocks. Of particular interest is the nonstationary stochastic behavior of one of the cesium clocks, illustrated by its frequency-stability history, showing that the frequency stability is not always time-invariant. The frequency stability is presented for sample times of one day to 300 days. Time-domain noise-process analysis shows the dominant noise type to be white frequency noise for sample times of one to ten days.

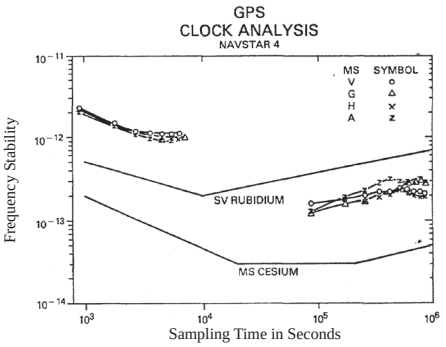


Typical NAVSTAR pseudo-range signature, plotted every 15 minutes. Day 177, 1979, 030740 UTC. (McCaskill-1981, p. 464)

Composite frequency-stability profiles are presented for the Block I and Block II clocks. Several clocks show a frequency stability of a few pp10^14 for long sample times.

T. B. McCaskill, W. G. Reid, J. A. Buisson and H. E. Warren, "Effect of Broadcast and Precise Ephimerides on Estimates of the Frequency Stability of GPS NAVSTAR Clocks," presented at the ION GPS-93, Sixth International Technical Meeting of the Satellite Division of The Institute of Navigation, Salt Lake City, Utah, 22-24 September 1993, 121-8.

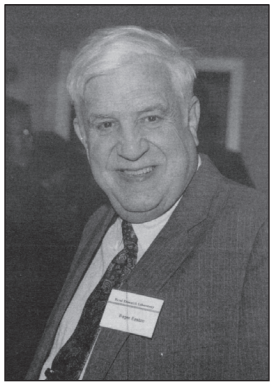
Frequency stability analysis of on-orbit Navstar clocks is performed by the Naval Research Laboratory using both the broadcast and the precise post-processed ephemerides. The phase offset between the Navstar clock and the reference clock is computed from pseudorange measurements obtained by dual-frequency GPS receivers at the five GPS monitor sites and at the U.S. Naval Observatory precise-time site. The broadcast ephemerides are generated at the GPS Master Control Station by a Kalman filter using data collected from the five GPS monitor stations. The precise post-processed ephemerides are generated by the Defense Mapping Agency (DMA) using data collected from the five GPS monitor sites and from five additional DMA monitor sites. In this paper the frequency stability is estimated for two Navstar cesium clocks-a Block I cesium clock (Navstar 9) and a Block II cesium clock (Navstar 23)-using both the broadcast and the precise ephemerides. A significant improvement in the estimate of the frequency stability of the Block II clocks has been achieved using the precise ephemeris.



NAVSTAR-4 clock analysis. Allan deviation using 5-day data sets, 1982. (McCaskill-1983, p. 199)

T. B. McCaskill, W. G. Reid, M. M. Largay, O. J. Oaks, J. A. Buisson and H. E. Warren, "Measurement and Analysis of the Frequency Stability of GPS NAVSTAR Clocks," presented at the Conference on Precision Electromagnetic Measurements CPEM-94, Boulder, Colorado, 27 June - 1 July 1994, IEEE, New York, 1-4.

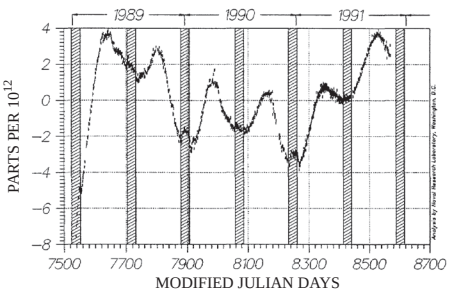
Analysis of the frequency stability of Global Positioning System (GPS) on-orbit Navstar clocks is performed by the Naval Research Laboratory (NRL). Clock offsets for each Navstar clock are derived from smoothed pseudorange measurements collected as the Navstar space vehicle passes over the tracking station. The clock offsets are further smoothed and estimated at the time of closest approach (TCA) of the space vehicle (SV) over the tracking station. Analysis of more than 50 Navstar clocks by NRL shows that the majority of these clocks provides performance that is better than the GPS frequency stability specification. This precision measurement technique is capable of determining one-day frequency stabilities of the Navstar GPS clocks to an accuracy of better than 1 x 10^-13.



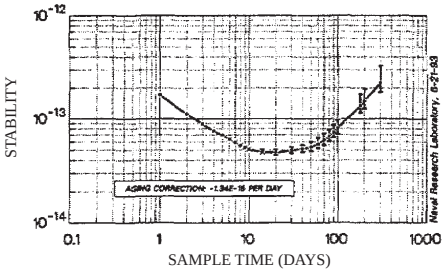
Roger Easton at his induction into the GPS Hall of Fame. (McKinney-1996, p. 1)

T. B. McCaskill, M. M. Largay, O. J. Oaks, W. G. Reid, J. A. Buisson and H. E. Warren, "(Presentation:) Measurement and Analysis of the Frequency Stability of GPS NAVSTAR Clocks," presented at the Conference on Precision Electromagnetic Measurements CPEM-94, Boulder, Colorado, 27 June - 1 July 1994, IEEE, New York.

Analysis of the frequency stability of Global Positioning System (GPS) on-orbit Navstar clocks is performed by the Naval Research Laboratory (NRL). Clock offsets for each Navstar clock are derived from smoothed pseudorange measurements collected as the Navstar space vehicle passes over the tracking station. The clock offsets are further smoothed and estimated at the time of closest approach (TCA) of the space vehicle over the tracking station. Analysis of more than 50 Navstar clocks by NRL shows that the majority of these clocks provide performance that exceeds the GPS frequency stability specification. This precision measurement technique is capable of determining one-day frequency stabilities of the Navstar GPS clocks to an accuracy of better than 1 x 10^-13.



NAVSTAR 11 frequency offset. (McCaskill-1991, p. 315)



Frequency stability profile for the NAVSTAR-9 cesium clock. (McCaskill-1993, p. 27)

T. B. McCaskill, W. G. Reid, J. A. Buisson and H. E. Warren, "Effect of Broadcast and Precise Ephemerides on Estimates of the Frequency Stability of GPS NAVSTAR Clocks," International Journal of Satellite Communications **12** (5), 435-441 (1994).

Frequency stability analysis of on-orbit Navstar clocks is performed by the Naval Research Laboratory using both the broadcast and the precise post-processed ephemerides. The phase offset between the Navstar clock and the reference clock is computed from pseudorange measurements obtained by dual-frequency GPS receivers at the five GPS monitor sites and at the U.S. Naval Observatory precise-time site. The broadcast ephemerides are generated at the GPS master control station by a Kalman filter using data collected from the five GPS monitor stations. The precise post-processed ephemerides are generated by the Defense Mapping Agency (DMA) using data collected from the GPS monitor sites and from five additional DMA monitor sites. In this paper the frequency stability is estimated for two Navstar cesium clocks-a Block I cesium clock (Navstar 9) and a Block II cesium clock (Navstar 23)-using both the broadcast and the precise ephemerides. A significant improvement in the estimate of the frequency stability of the Block II clocks has been achieved using the precise ephemeris.

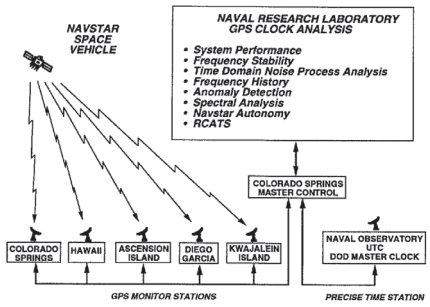


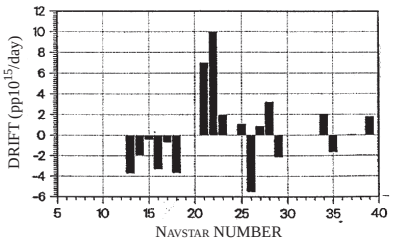
Diagram of the information flow from a single NAVSTAR space vehicle to each of the monitor stations. (McCaskill-1993, p. 122)

T. B. McCaskill, W. G. Reid, O. J. Oaks, R. L. Beard, J. A. Buisson and H. E. Warren, "Performance of Global Positioning System (GPS) On-Orbit NAVSTAR Clocks," in *49th IEEE International Frequency Control Symposium*, held at San Francisco, California, 31 May - 2 June 1995, IEEE, 133-9.

The Naval Research Laboratory (NRL) analyses the performance of the on-orbit Navstar clocks in the Global Positioning System (GPS). This work is sponsored by the GPS Joint Program Office and is done in cooperation with the GPS Master Control Station. NRL has analyzed the performance of more than 50 Navstar atomic clocks with a total lifetime of more than 150 years. The results presented in this paper are a summary of the performance of the 25 Navstar atomic clocks that were operational during 1995.

NRL analysis of on-orbit Navstar clocks is performed using a multi-year database that includes data from initial activation of each clock through the first quarter of 1995. The Navstar pseudorange data was observed using single and dual-frequency GPS Precise Positioning Service (PPS) receivers that correct for the effects of selective availability. Quality of clock operation is calculated using both broadcast and post-processed precise ephemerides.

This presentation includes a description of the Navstar clocks that are currently operating in the GPS constellation. The Navstar clock performance in the time domain is characterized by frequency-stability profiles with sample times that range from 1 to 10-days, or more. The results presented show an improvement in the frequency stability over earlier Block I Navstar clocks with the majority of the currently operating Navstar clocks having a frequency stability for a sample time of one day of 1 pp10^13 or better.



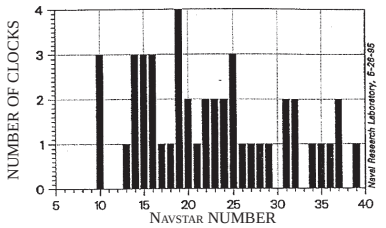
Average linear drift of cesium clocks, 1 December 1994 to 1 April 1995. (McCaskill-1995, p. 137)

T. B. McCaskill, W. G. Reid, O. J. Oaks, R. L. Beard, J. A. Buisson and H. E. Warren, "Performance of GPS Monitor Station Time References and On-Orbit NAVSTAR Clocks," in *Satellite Division of the Institute of Navigation 9th Technical Meeting GPS-96 Conference*, held at Kansas City, Missouri, 17-20 September 1996, 241-9.

Analyses by the U.S. Naval Research Laboratory (NRL) of the performance of clocks in the Global Positioning System (GPS) will be presented. The analyses are performed for all Navstar space vehicle clocks that have been operated on-orbit and for the time reference at each of the monitor stations of the GPS Control Segment. The behavior of the Navstar clocks currently in use will be described. The number, type, and length of operation of the on-orbit clocks will be detailed and their positions in the constellation identified. A significant portion of the analysis will be devoted to the

frequency drift (aging) characteristics of Navstar rubidium clocks because of an expected increase in the use of these clocks in the GPS constellation.

Analysis is performed using a multi-year database which includes pseudorange data collected from the time of initial activation of each clock. The pseudorange data is collected from GPS Control Segment and Defense Mapping Agency (DMA) receivers. These receivers gather the worldwide tracking data necessary for system operation. Consequently, the data is corrected for Selective Availability and Anti-Spoofing. On-orbit clock performance is computed using the post-processed precise ephemerides supplied by DMA and observations collected at the DMA site located at the U.S. Naval Observatory (USNO). All observations are referenced to the DoD Master Clock.



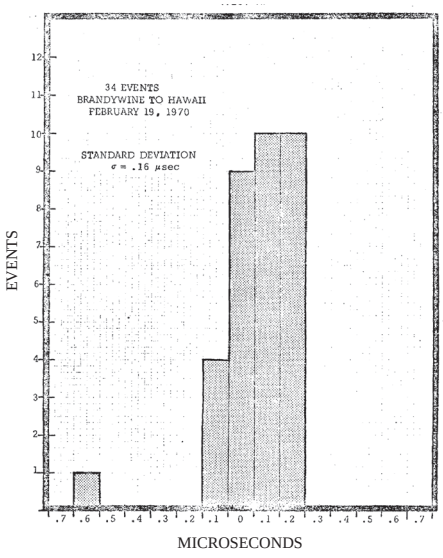
For each of the NAVSTAR space vehicles, the number of clocks that have been placed in operation since the space vehicle was inserted into the constellation. (McCaskill-1995, p. 135)

T. B. McCaskill, "Analysis of the Frequency Stability History of GPS Navstar Clocks," in *Proceedings of the 1997 IEEE International Frequency Control Symposium*, 28-30 May 1997, IEEE, New York, 295-303.

The two-sample Allan variance has been the standard metric for assessing the frequency stability of atomic clocks which may be characterized by nonstationary noise processes. The convergence of the Allan Variance for the noise types typical of atomic clocks might appear to suggest that the variance could be estimated to an arbitrary degree of accuracy by processing more data over longer and longer periods of time, which would lead to progressively smaller confidence intervals. This tacit assumption, however, was called into question because of the behavior of one of the Global Positioning System (GPS) on-orbit Navstar atomic clocks whose frequency stability profile exhibited significant change with the processing of additional data. Because of the peculiar nonstationary behavior of this clock, a model for the frequency stability history was developed and is now incorporated as a routine part of the analysis of Navstar clocks conducted by the Naval Research Laboratory (NRL).

The frequency stability history corresponds to the output of an N-sample moving average filter operating on the sequence of squared first differences of the M-day frequency offset measurements. This procedure assumes that the stochastic process has increments whose second order properties are slowly evolving over time such that, to a reasonable approximation, it has stationary increments over the N sample interval.

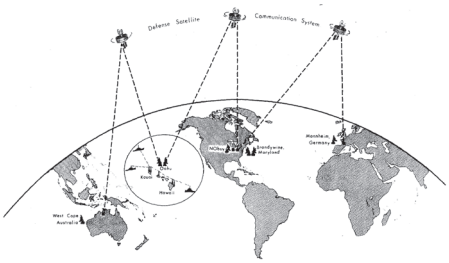
Frequency stability histories are presented using from one to 120-sample averages-the number of samples averaged representing a compromise between the time resolution and the stability of the estimate. Included are frequency stability histories for both cesium and rubidium on-orbit Navstar clocks. The results indicate that the frequency stability of most of the Navstar clocks is invariant over the useful life of the clock, that the frequency stability of still others improves after an initial transient. The frequency stability history is now used to detect and measure degradation in the frequency stability. Significant changes in the frequency stability are reported to the GPS Master Control Station (MCS).



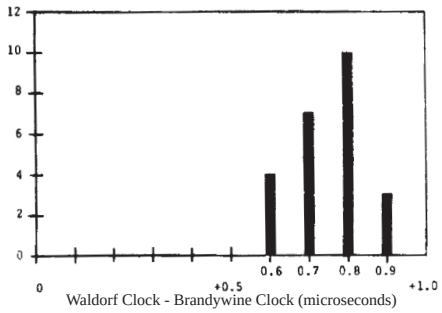
Results of time transfer experiment between Helemano, Hawaii and Brandywine, Maryland, 19 February 1979, using the Defense Satellite Communicaton System. (Murray-1970, p. 66)

T. B. McCaskill, O. J. Oaks, M. M. Largay, W. G. Reid, H. E. Warren and J. A. Buisson, "Performance of Global Positioning System Block II/IIA/IIR On-Orbit NAVSTAR Clocks," in *31st Annual Precise Time and Time Interval (PTTI '99) Systems and Applications Meeting*, held at Dana Point, CA, 7-9 December 1999, 75-90.

Analysis of the performance of all on-orbit Navstar space vehicle clocks and Global Positioning System (GPS) monitor station reference clocks is performed by the Naval Research Laboratory (NRL), in cooperation with the GPS Master Control Station, under the sponsorship of the GPS Joint Program Office. The measurements are collected by multi-channel GPS receivers located at the Air Force and National Imagery and Mapping Agency (NIMA) monitor stations. The offset of each Navstar clock, computed every 15 minutes, is referenced to the Department of Defense Master



Schematic proposing global time transfer with the Defense Satellite Communication System (DSCS). (Murray-1970, p. 78)



Test results of a satellite time transfer modem, 28 October 1970, from Brandywine, Maryland, to Waldorf, Maryland. (Murray-1971, p. 193)

Clock. The resultant Navstar clock offsets are then used to compute frequency offset, drift offset, frequency stability profiles, and frequency stability histories. The beginning-of-life, steady state and end-of-life performance of selected cesium and rubidium atomic clocks is presented. Frequency stability results are presented using sample times that vary from 15 minutes to several days. The stability for sample times of less than one day characterizes the measurement noise, while the stability for sample times in excess of one day characterizes both the periodic effects in the on-orbit data and the long-term performance of the Navstar atomic clocks.

D. McKinney, "NRL retiree Roger Easton named to GPS Hall of Fame," *Labstracts*, 18 November 1996, 1,3.

Mr. Roger Easton, a former NRL employee who retired in 1980, was inducted into the "NAVSTAR GPS Hall of Fame." The Global Positioning System (GPS) Joint Program Office's Hall of Fame program recognizes "unique individuals who have made substantial and exceptionally distinguished contributions to the development and sustainment of the nation's Global Positioning System." Mr. Easton was cited for "his overwhelming contributions to engineering applications in navigation satellite technology, which have made GPS a reality."

J. McNair, "Science and Engineering Award named for former NRL employee," *Labstracts*, 6 May 1991, 1.

An award named in honor of former NRL employee, Roger L. Easton, has been created by the Naval Space Surveillance Center (NAVSPASUR) in Dahlgren, Virginia. According to NAVSPASUR offices, the Roger Easton Science and Engineering Award was established on the 30th anniversary of NAVSPASUR to recognize individuals who have made significant achievements in the fields of science, engineering, or management for the advancement of naval space surveillance.

The award citation notes that Roger L. Easton is the theoretical and practical creator of the technological and managerial base that led to the establishment and deployment of the complete Naval space surveillance radio interferometry system for satellite detection and tracking and for computation of satellite orbits. Mr. Easton developed this system while working at NRL.

Roger Easton, a research physicist who joined NRL in 1943, spearheaded a number of space systems vital to the Navy and the nation. While at NRL, Mr. Easton is credited with designing *Vanguard I*. In addition, Easton is also recognized for conceiving the idea of the time-based navigation satellite system in the early 1960s (TIMATION, for time navigation) sponsored by NAVAIR, which led to the Global Positioning System. Easton retired from NRL as head of the Space Applications Branch in 1980.

J. T. Mengel, N. R. Best and R. L. Easton, *Rocket Research Report XIII - A Single Axis Phase-Comparison Angle-Tracking Unit*, NRL Report 4393, Naval Research Laboratory, Washington, D.C., 2 September 1954.
NRL4393 LIMITED DISTRIBUTION

J. T. Mengel, R. L. Easton and C. A. Schoroeder, *Application of Radio Phase-Comparison Techniques to the Study of Atmospheric and Rocket-Flame Refraction*, NRL Report 4598, Naval Research Laboratory, 7 September 1955.
NRL4598 LIMITED DISTRIBUTION

J. T. Mengel, "Tracking the Earth Satellite, and Data Transmission by Radio," Proceedings of the IRE **44** (6), 755-60 (1956).

The next round of problems created by an earth satellite after it is placed in its orbit are those associated with proving that the satellite is in fact orbiting, and the measurement of its orbit. The magnitude of these problems for optical methods is discussed, and the Minitrack system developed by the

Naval Research Laboratory for acquisition and tracking of the satellite by radio techniques is described. A sub-miniature radio transmitter operating continuously for at least two weeks will be provided within the satellite to illuminate antennas at ground tracking stations. By phase-comparison techniques, these ground stations will measure the angular position of the satellite as it passes through the antenna beam, recording its "signature" automatically without the need for initial tracking information. Analysis of this signature will provide the complete angular history of the satellite passage in the form of direction cosines and time. These data will be transmitted immediately to a central computing facility for the computation and publication of ephemeredes. Specific ephemeredes will be transmitted to each principal optical tracking station to provide acquisition data to them. The probable tracking accuracies and the major problems associated with the Minitrack System are described.

M. Miranian, E. Powers, J. Brad and J. White, "Initial Test Results for a New PPS GPS Timing Receiver," in *31st Annual Precise Time and Time Interval (PTTI) Meeting*, 7-9 December 1999, 357-63.

A new Global Positioning System (GPS) timing receiver has been built for the U.S. Naval Observatory. The new receiver is a 12 channel, Precise Positioning Service (PPS), unit capable of tracking GPS Y-Code signals and internally removing the effects of Selective Availability. It is based on the receiver being used in the GPS Monitor Stations by the GPS Control Segment.

Testing is being done at the Naval Research Laboratory (NRL) using the GPS signal simulator. The NRL simulator is capable of producing 10 simultaneous signals with Selective Availability and Y-Code. Initial test results show that prior problems with timing calibration due to uncertainties in the initial conditions in the receiver have been solved. Ionospheric delay measurements in the receiver have been shown to be stable to less than one nanosecond with a small bias. Additional data will be presented showing the measured effects of temperature on the receiver.

M. Miranian, E. Powers, L. Schmidt, K. Senior, F. Vannicola, J. Brad and J. White, "Evaluation and Preliminary Results of the New USNO PPS Timing Receiver," in *32nd Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, Virginia, 28-30 November 2000, 79-89.

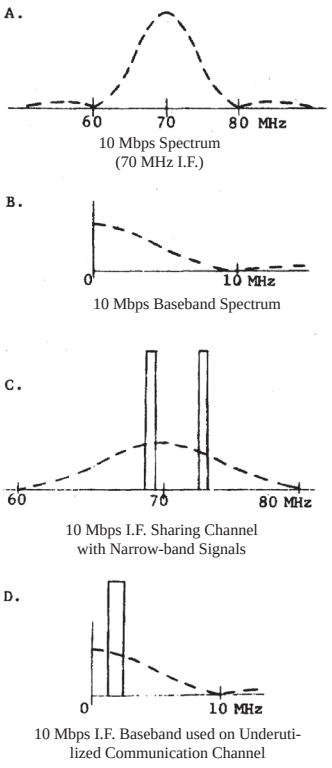
The U.S. Naval Observatory (USNO) is tasked to provide the Global Positioning System (GPS) with a reliable and stable reference to UTC (USNO). This is accomplished using GPS Precise Positioning Service (PPS) timing receivers with a UTC (USNO) reference input. The USNO monitors GPS Time from all available healthy satellites. On a daily basis, the GPS Time correction, based on the entire constellation with respect to UTC (USNO), is determined and provided to the GPS Master Control Station (MCS) 2nd Satellite Operations Squadron (2 SOPS) at Schriever AFB in Colorado.

The USNO's GPS PPS operations have been limited to a single-channel receiver, which only allows tracking of one satellite at a time. Since February 2000, the USNO has been evaluating a 12-channel GPS PPS timing receiver, based on the GPS Monitor Station receiver. The unit is capable of tracking P(Y)-code and removes the effects of Selective Availability (SA). This paper describes the various tests conducted, the receiver's performance, and expected improvements to the USNO GPS PPS operations.

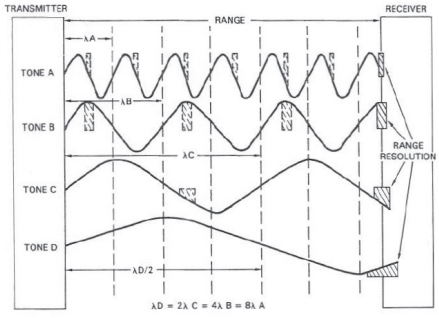
R. B. Moore, *Satellite Celestial Navigation*, NRL Memorandum Report 1750, Naval Research Laboratory, Washington, D.C., 27 February 1967.

Satellite range and location data can be used to determine the location of an observer. This report discusses how the above may be done by using conventional celestial navigation methods.

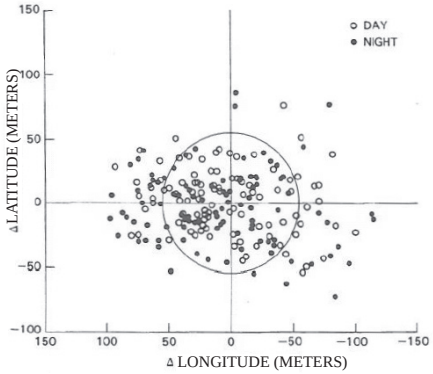
In lieu of sighting with a marine sextant or a bubble octant to obtain an observed altitude (Ho), a receiver and a phase-measuring technique can be used to determine a parametric range distance between the satellite and the



Time transfer modem spectra. (Murray-1971, p. 112)



Resolution of range tone ambiguities. Tone A has good range resolution but is ambiguous. Tones B, C, and D resolve the ambiguity. (Murray-1985, p. 57)



TIMATION II navigation using dual frequencies to resolve diffraction errors. (Murray-1985, p. 59)

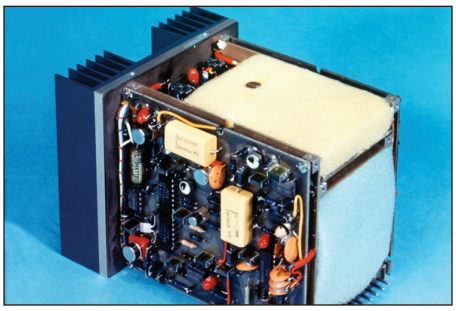
observer. Satellite height and range parameters can be reduced to obtain the value for an observed "virtual altitude" (VHo), which is then used in the same manner as the standard Ho measurement.

J. A. Murray, "Satellite Communications System," in *Proceedings from (the Second) Precise Time and Time Interval (PTTI) Strategic Planning Meeting*, Vol. 1, held at Naval Research Laboratory, Washington, D.C., 10-11 December 1970, 55-78.

The responsibility of the Naval Observatory to maintain precise time coordination on a worldwide basis requires frequent comparisons of distant time standards with the Observatory reference clock. Perhaps the best available means of making these comparisons has been to transport accurately calibrated atomic clocks from the Observatory to the distant locations and to make direct on-site measurements. This method however accurate, is also expensive.

The use of communications satellites to perform the long-distance comparisons (or time transfers) has been investigated and proved feasible. The Defense Satellite Communications System (DSCS) contains the potential for making the accurate Observatory reference economically available to many vital areas of the world.

Under sponsorship of the Naval Electronics Systems Command and with the cooperation of the Observatory and Defense Communications Agency (DCA), the Laboratory has produced techniques for using certain DSCS links in a non-interfering manner, and successful time transfers have been made on an experimental basis. Use of DCA facilities on an operational basis is planned for the near future.



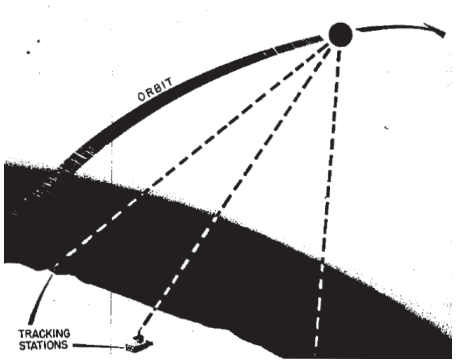
Efratom rubidium frequency standard for TIMATION III, with cover removed. (Nichols-1973, p. 393)

J. A. Murray, D. L. Pritt, L. W. Blocker, W. E. Leavitt, P. M. Hooton and W. D. Goring, "Time Transfer by Defense Communications Satellite," in *Twenty-Fifth Annual Frequency Control Symposium*, held at Atlantic City, New Jersey, 26-8 April 1971, 186-93.

Time pulses are effectively passed from one Defense Communications satellite terminal to the other as specified points on the high-speed pseudo-random codes used by the communications modems at the stations. If the specified points of the codes used in both directions of transmission occur at approximately the same time, propagation time between terminals is effectively cancelled in a relatively simple computation or electronic process to yield the time difference between clocks. Interpolation methods have been developed, however, to permit the time transfer to be made when the specified points are not contemporaneous.

A modem designed specifically for time transfer service at stations not equipped with suitable modems has been developed at NRL. This time transfer modem employs a pseudo-random code, which operates at a 10 MHz bit rate and cycles once each 810 microseconds. Ambiguities are resolved by inverting the phase of the code for one code cycle at prearranged times, such as once per minute. The NRL modem has been used experimentally via satellite between a pair of Maryland stations. Other experimental transfers were made between Maryland and Hawaii using the communications modems of the DCA stations.

The experiments have produced verified accuracies in the order 0.1 microseconds. It is believed that an increase in accuracy will result from a planned increase in resolution of the measuring equipment. Confirmation of this increase, however, will be difficult because alternate precise time transfer methods are not generally available.



Geodetic studies to be furthered by the proposed artificial satellite. Purpose: shape and dimension of earth; precise geographical coordinates; distribution of crustal mass. Method: tracking and triangulation. Practical benefit: better navigation and mapping. (Newell-1955, p. 712)

J. A. Murray, Jr., "Mini Modem for PTTI Dissemination," in *Proceedings of The Third Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Washington, D.C., 16-18 November 1971, 103-116.

Precise comparisons of clocks are now regularly made over several Defense Satellite Communication System (DSCS) trunks employing

communications modems that use high-speed pseudo-random codes. Under the primary sponsorship of the Naval Electronic Systems Command, the Naval Research Laboratory (NRL) is continuing the development program to extend the use of the technique to certain other stations that are not equipped with appropriate modems. The Army has also contributed to the development funding and will be furnished with a time transfer system between two of its satellite terminals.

While the development effort is directed mainly at satellite time transfers, the techniques and equipment may also be used in other communications systems, such as line-of-sight microwave links. The techniques are intended to make use of existing communication facilities in a non-interfering manner wherever possible.

J. A. Murray, "Hawaii PTTI Test Bed," in *Proceedings of the Fourth Annual Precise Time and Time Interval (PTTI) Planning Conference*, held at Goddard Space Flight Center, 14-16 November 1972, NASA Report X-814-73-72, 182-93.

The Navy's Precise Time and Time Interval (PTTI) program concerns many systems having to do with communications, navigation, and other time-coordinated activities. To assess the ability of the current PTTI research and development efforts to serve these systems, a test bed is being established. The Naval Communication Station at Wahiawa, Hawaii, was selected for the site because of its involvement in or proximity to a number of activities that are either dependent upon the Naval Observatory or as a common reference, or could benefit from the presence of accurate time and frequency standards.

A prime goal in the effort is to develop a repertoire of techniques and equipment that will permit communications facilities to be served most effectively by their ties to a common time reference. The test bed will provide guidance for the implementation of precise time and frequency discipline at other facilities.

One product of the test-bed problem will be an assessment of the accuracy of the time-discipline chain from the Observatory to each level of use. While it is possible to estimate potential accuracies from equipment and media characteristics, the practical accuracies attainable in an operational environment must be verified or ascertained.

The Collier Trophy.

J. A. Murray, Jr., "Platform distribution system specifications," in *37th Frequency Control Symposium*, held at Philadelphia, Pennsylvania, 1-3 June 1983, 516-18.

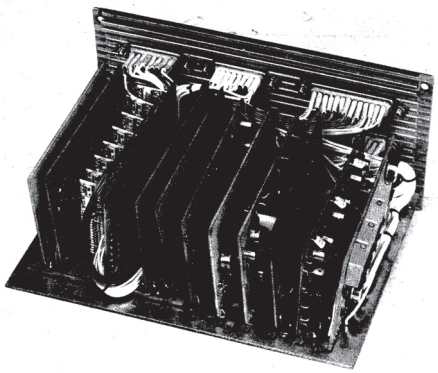
Platform distribution systems form the link between a time dissemination system traceable to the U.S. Naval Observatory master clock system and the local systems that require precise timing. The distribution system serves the functions of establishing and maintaining accurate time and frequency and distributing it to the user systems.

Although the designs of these systems vary widely, there are certain technical factors that are repeatedly encountered. In this paper, these factors and other considerations that are important when designing or specifying platform distribution systems are discussed. Also presented are certain areas in which standardization could benefit not only platform distribution system implementation but the user systems development as well.

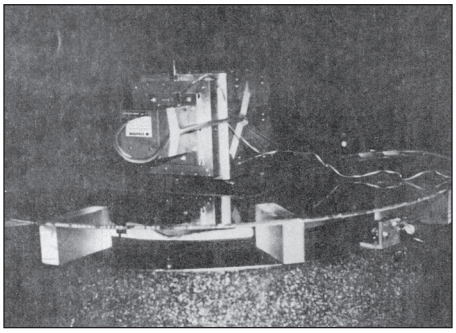
J. A. Murray and R. L. Beard, "Space Navigation and Time," NRL Review, 55-67 (1985).

Warfare is undergoing a basic change. More and more, individual systems are being integrated to maximize their collective power. While the computer has been a major influence on this change, a precise knowledge of position and accurate time are vital to progress. Our developing space capability is heavily involved in this revolution.

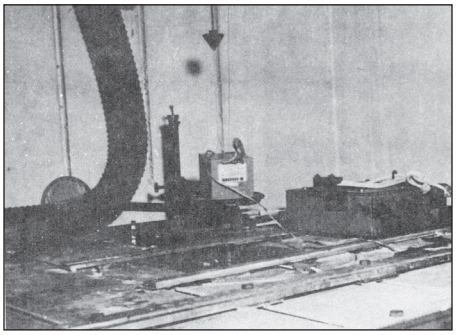
Position determination and time have been linked since the first attempts at dead reckoning where elapsed time and speed were used to estimate distance



TIMATION IIIA logic and tuning control for both the Rubidium Vapor Frequency Standard and the quartz oscillator. (Nichols-1973, p. 133)



Oscillator for TIMATION III mounted for vibration testing. (Nichols-1973, p. 395)



Oscillator for TIMATION III is mounted for irradiation testing. (Nichols-1973, p. 397)

Angle-of-attack indicators are adjusted on the top of the nose cone. The silver Vanguard satellite is seen at left center. (NRL PAO-1963 (est.), Figure 2)

traveled through the water. A significant step forward for navigation was the 18th-century development of a chronometer that would keep accurate time aboard a rolling ship so that the longitude of the vessel could be determined accurately. Now, time and position are used together in integrated systems that provide intelligence, targeting, weapon delivery, and communications. Through the development of space technology and improved clocks, accurate time and position can be provided by the same space navigation system. In modern systems, time is precisely related with the instantaneous positions of electromagnetic waves traveling through space at about 0.3 m/ns. Many systems will require position accuracies of a few tens of meters and, for some purposes, measurements to 30 cm or less are needed. Clock errors of a nanosecond may be significant.

For many years, NRL has been improving the Navy's capability in space systems for navigation and precise timing, many in conjunction with the U.S. Naval Observatory (USNO). We will describe NRL's work from tracking the earliest satellites through our part in developing the Global Positioning System, and how space, navigation, and time have come together in the work. Within NRL, this evolution has involved many diverse scientific and technical areas, from astrophysics and the relativistic effects on clocks in orbit to atomic and molecular beam optics and complete system and satellite design. Few scientific and technical disciplines escape attention in the sophisticated space systems that demand the ultimate in precision.

J. A. Murray and J. D. White, "MIL-STDS and PTTI: What's Available and What Needs to be Done," in *24th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at McLean, Virginia, 1-3 December 1992, NASA Conference Publication 3218, 123-35.

The systems developer who needs PTTI capability has relatively little guidance in the form of military standards, particularly for systems using atomic clocks or other sources of very precise time and frequency. This paper will discuss the existing standards, including MLL-STD-188-115, MIL-F-2991(EC), and DOD-STD-1399. These documents were written several years ago and do not always reflect current practice or take advantage of more recent technology improvements. User needs have also changed over the years and some of those needs such as more detailed time codes are not being met. We will summarize what's available and what's good and bad about it.

The second part of the paper will make suggestions about what should be done in the future to promote and facilitate good PTTI design practice. Topics will include clock performance parameters, environmental considerations, time codes, signal isolation and time dissemination.

National Aeronautic Association, "Robert J. Collier Trophy for The NAVSTAR Global Positioning System (GPS)," 4 May 1992, awards program and trophy inscription.

Award to GPS team including NRL presented by the National Aeronautic Association.

Inscription on the Collier Trophy (displayed in NRL Administration Building, Bldg. 43):

To the Global Positioning System Team,
The United States Air Force,
The United States Naval Research Laboratory,
The Aerospace Corporation,
Rockwell International Corporation and
IBM Federal Systems Company

For the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation 50 years ago.

Collier Award caption, from the display in Bldg. 43, NRL:

The Navstar Global Positioning System (GPS)

In the 1960s, the Naval Research Laboratory (NRL) and the Aerospace Corporation developed the initial concept for a system that could provide precise, all-weather, real-time, 24-hour, worldwide navigation information. The NRL concept was proven in 1967 with the launch of its Timation I Satellite. The Air Force, along with Aerospace, established a GPS program office in 1972 and, in 1974, awarded Rockwell International the contract to build the satellites and user receivers for concept demonstration. IBM was chosen to develop the initial satellite command and control segment.

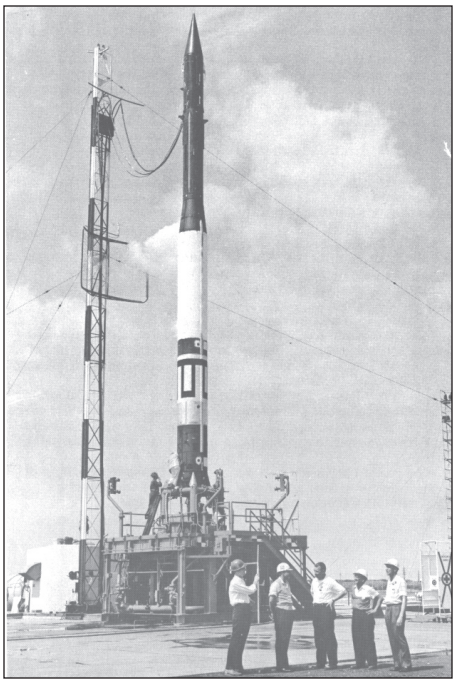
NRL's Navigation Technology Satellite II, launched in 1977, was the first satellite in the Navstar GPS. The GPS is based on NRL's concept of time, range, range-rate navigation, and a 12-hour orbit. The developmental Block I satellites were an unprecedented success. In more than 700 air, land, and sea tests conducted between 1977 and 1979, they exceeded all performance requirements and affirmed the system's extraordinary precision- 20 times more accurate than the world's next-best global navigation system.

Rockwell was awarded the contract to build 28 Block II operational satellites, the first of which was launched in 1989. IBM was selected to develop the ground system, which became operational in 1986. The U.S. Space Command became the system operator.

The Navstar GPS satellites transmit a constant signal generated by on-board atomic clocks originally developed by NRL. These clocks are so precise that they gain or lose only one second every 3 million years. Users equipped with a receiver/processor simply lock onto the signals of four satellites, and their latitude, longitude, altitude, and velocity are automatically computed - within meters - by triangulation.

The remarkable precision proved invaluable during Desert Storm, in targeting pinpoint strikes and positioning troops in featureless terrain. GPS has also been used in Operation Restore Hope to help aircraft land on makeshift Somalian airfields. Apart from its primary military function, the satellite system serves numerous peacetime functions like air traffic control, scientific surveying, harbor navigation, and measurement of ocean waves.

Today, a combination of development and production satellites is orbiting the Earth, transmitting continuous navigation signals to users around the world. The system hoped for 30 years ago has become the DOD standard and, in the process, revolutionized the science of navigation.



NRL scientists hold a conference before the 72-foot-long Vanguard rocket while technicians make final checks of the vehicle. (NRL PAO-1963 (est.), Figure 3)

Naval Center for Space Technology, "NCST webpage," http://ncst-www.nrl.navy.mil, 2005, captured 3 March.

Web pages from the Naval Center for Space Technology (NCST) at the Naval Research Laboratory, http://ncst-www.nrl.navy.mil.

This castle is the headquarters for the Royal Greenwich Observatory. The actual readouts from the TIMATION II satellite were made from a nearby building. (*Labstracts* 4 December 1972, p. 4)

H. E. Newell, Jr., "Appendix C: The Satellite Vehicle and Physics of the Earth's Upper Atmosphere," Jet Propulsion, February issue, 73-5 (1955).

The purpose of the present note is to consider the usefulness of the satellite vehicle for scientific research and to point to a few important experiments which might be done with such a vehicle.

Roger Easton makes an adjustment on the receiving equipment used to record signals from TIMATION II at the Royal Greenwich Observatory. (*Labstracts* 4 December 1972, p. 4)

H. E. Newell, Jr., "The Satellite Project," Scientific American **193** (6), 29-33 (1955).

Some time in the next few years a new object will appear in the heavens. It will be quite inconspicuous: only an observer who knows exactly when and where to look for it will be able to see it at all. But as men lift their heads and, watching, catch a glimpse of this faint body racing across the sky, they will feel the excitement of witnessing a great historic event. For the tiny object circling the heavens will be metal that man has touched, a satellite that man has made and flung from the earth into space. It will be mankind's first feeler on the space frontier.

The man-made satellites that the US is planning to launch for the International Geophysical Year (1957-58) are still, of course, only scribbles and sketches on pieces of paper. The design details have yet to be worked out.

Roger Easton, accompanied by CAPT Paul Gaffney, holds the Collier Trophy. (*Labstracts* 10 May 1993, p. 6)

But there has been enough progress in rocketry in the last few years to make the experts of more than one nation confident that a target date can at last be set for achieving this project - a first step toward mankind's age-old dream of breaking the chains that bind him to the earth.

No specific details of the program for creating the artificial satellite have been announced. This article can, however, outline some of the problems facing the designers, as well as ways in which a satellite may be used to study our planet and outer space. It should be emphasized that the following is not a description of actual plans but simply a review of possibilities.

H. E. Newell, Jr., "Scientific Uses of an Artificial Earth Satellite," *Jet Propulsion* **25** (12), 712-713 (1955).

Since the announcement that the United States plans to launch artificial satellites for physical research during the International Geophysical Year, there has been much speculation about what actually will be done in the satellite. Many of the researches and techniques, which have appeared in print, are beyond the capabilities of the first satellite vehicles as they are now envisioned, and must be considered as future possibilities when larger and heavier satellites are launched. The following listing of things, which can be done in a research satellite attempts to differentiate between those experiments, which can be carried out in the first small "birds," and those experiments which will probably have to await further development of engineering techniques.

S. Nichols, *R. F. Insertion Loss Measurements of Earth Receiving Station Coaxial Network Elements*, NRL Memorandum Report 2390, Naval Research Laboratory, February 1972.

The insertion loss of specially developed 1 5/8 inch rigid coaxial transmission line and several passive components were predicted theoretically and confirmed by measurement, individually and as a completely assembled network for a low noise receiving system. The results show that the components have insertion losses of 0.01 dB to 0.06 dB depending on type, and a total network insertion loss of less than 0.2 dB. Comparison of calculated and measured values show the accuracy to be within three thousandths of a dB.

S. A. Nichols, J. D. White and R. B. Moore, "Evaluation of a Rubidium Standard for Satellite Application," in *27th Annual Frequency Control Symposium*, held at Cherry Hill, NJ, 12-14 June 1973, 390-99.

A new, compact rubidium vapor frequency standard has been introduced which shows considerable promise for use in the Navy TIMATION III navigation satellite.

To qualify the unit for use in this program a series of measurements were made of environmental stability and laboratory performance. It was found that aging was typically better than 2.5 x 10^-12/day and that short-term stability for 1000 second averaging was as low as 4.2 x 10^-13. As delivered by the manufacturer, Efratom, it withstood all environmental conditions satisfactorily except that the vibration tolerance was not as good as the TIMATION III goal. Replacement of selected components with space-qualified items is expected to remedy the problem.

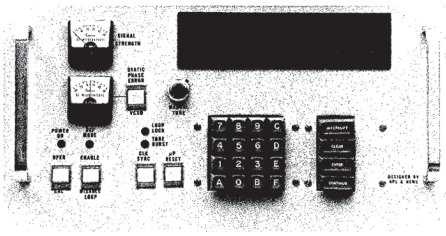
All data available at the present time indicate a high probability that this rubidium standard will be a part of the forthcoming TIMATION III satellite.

First photograph transmitted over a "space" radio circuit. (NRL PAO-1963, p. 1)

S. A. Nichols, "Digital Frequency Control of Satellite Frequency Standards," in *Proceedings of the Fifth Precise Time and Time Interval (PTTI) Planning Meeting*, held at Goddard Space Flight Center, 4-6 December 1973, NASA, 127-45.

In the Frequency and Time Standard Development Program of the TIMATION System, a new miniaturized Rubidium Vapor Frequency Standard has been tested and analyzed for possible use on the TIMATION IIIA launch, scheduled for early 1974, as part of the Defense Navigation

Satellite Development Program. The design and construction of a Digital Frequency Control by NRL, was required to remotely control this Rubidium Vapor Frequency Standard as well as the quartz oscillator in current use. This control must be capable of accepting commands from a satellite telemetry system, verify that the correct commands have been sent and control the frequency to the requirements of the system.

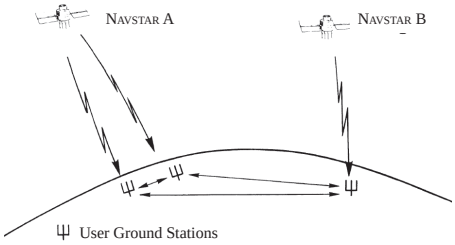


NTS Time Transfer Receiver. (Oaks-1979 NRL8312, p. 11)

S. A. Nichols and J. White, "Satellite Application of a Rubidium Frequency Standard," in *28th Annual Frequency Control Symposium*, held at Fort Monmouth, NJ, 29-31 May 1974, 401-5.

The miniature rubidium frequency standard reported on a last year's Frequency Control Symposium has been incorporated in a Frequency Standard System to be flown on the TIMATION III satellite, also know at NTS-1, a part of the Global Positioning System. Last year's paper presented preliminary test results and since that time, extensive testing and modifications have been made on these units.

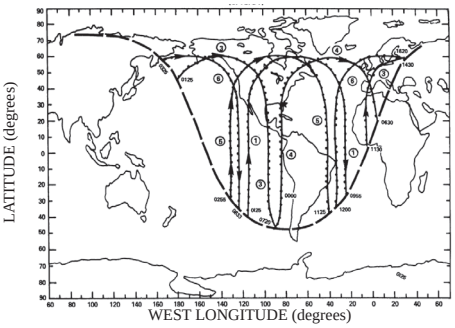
Eleven different units have been analyzed: thermal vacuum testing has been done on six units, four flight-qualified standards have been produced and aging characteristics for periods of over one year are available. These results will be presented.



NAVSTAR GPS synchronization by time transfer. (Oaks-1981, p. 432)

S. A. Nichols, J. D. White and F. Danzy, *Design and Ground Test of the NTS-1 Frequency Standard System*, NRL Report 7904, Naval Research Laboratory, Washington, D.C., 5 September 1975.

The NRL TIMATION III satellite, redesignated as GPS Navigation Technology Satellite I (NTS-1) was successfully placed into a medium altitude orbit, 7,300 mi, on July 14, 1974. One of the major experiments performed with the satellite is the investigation of the space- environment performance of two rubidium controlled frequency standards and a specially developed quartz oscillator. System design, ground testing, and flight qualification modifications were performed at NRL. This included modifying commercial-quality rubidium standards to levels acceptable to the flight environment; the design and construction of power control, RF switching, and remote digital tuning circuits; and ground testing the candidate frequency standards in terms of short-term stability (Allen Variance), aging, warmup, tuning characteristics, DC power consumption and environmental effects due to vacuum, radiation, vibration, and temperature.

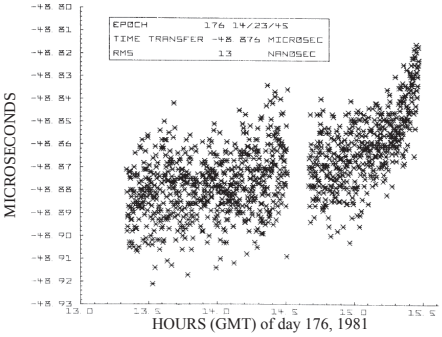


NAVSTAR MILA ground track, 6/15/1981. (Oaks-1981, p. 435)

S. A. Nichols and D. G. Woodring, "Applications of Atomic Frequency Standards to Satcom Spread Spectrum Systems," in *32nd Annual Frequency Control Symposium*, held at Atlantic City, NJ, 31 May - 2 June 1978, 555-9.

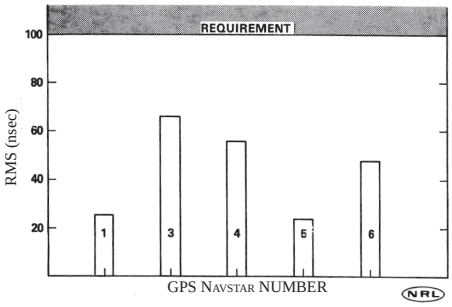
With the advent of spread spectrum systems as a means of secure communications via satellite, the requirements for the system clock must be carefully analyzed. A number of trends in the characteristics of military SATCOM have placed stricter requirements upon the system frequency standard and have militated in favor of atomic standards such as the trend in communication system design toward higher R.F. frequencies, wider spread spectrum bandwidths, and autonomous operation. At the same time the effects of the mobile platform environment and limitations on cost have strongly influenced system design. Most current system designs incorporate modems, which utilize one of two spread spectrum signal techniques, or hybrids of these techniques. Namely, direct sequence pseudo-noise (PN) modulation, or frequency hopping (FH).

This paper will present these parameters and show the relationship between currently available frequency standards and two types of modems under development.

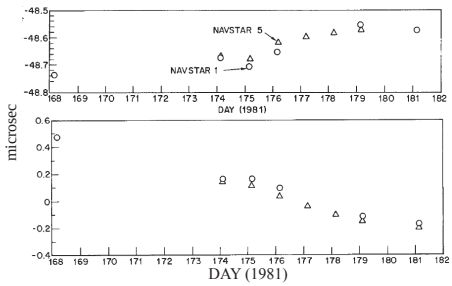


MILA vs GPS via NAVSTAR 6. Abscissa is hours (GMT) of day 176, 1981. Ordinate is milliseconds. (Oaks-1981, p. 442)

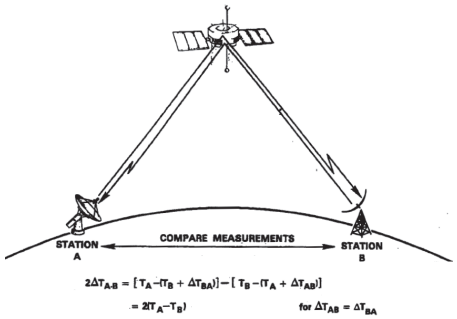
A. W. Niles and R. L. Easton, *Rocket Research Report No. XVII - Propellant Level Sensors for Viking*, NRL Report 4454, Naval Research Laboratory, Washington,



Time transfer of USNO-MILA, showing rms in nanoseconds against NAVSTAR number, in relation to the requirement. Measurements were made at NASA Goddard's MILA facility at the Kennedy Spaceflight Center, Florida. (Oaks-1981, p. 448)



Field-test results from all the NAVSTAR 1 and NAVSTAR 5 passes (1981). Measurements were taken at the Kennedy Spaceflight Center. Upper plot, ground clock minus spacecraft clock (microsec). Lower plot, USNO clock minus ground clock (microsec). (Oaks-1982 NRL8608, p. 12)



Two-way time transfer (Oaks-1985, p. 79)

D.C., 17 December 1954.
NRL4454 LIMITED DISTRIBUTION

NRL Public Affairs Office, "Four Decades at NRL," 1963, brochure.
Pamphlet commemorating the Laboratory's 40th year.

NRL Public Affairs Office, "U.S. Navy Communication by Satellite Relay: The World's First Operational 'Space' Radio Circuit," 1963 (est.), brochure.
Pioneered by the Naval Research Laboratory, the Communication Moon Relay (CMR) system offers reliable long distance communication presently limited only by the availability of the moon, which has to be within sight of the antennas, and by the number of radio terminals, which are too few in number to make CMR a widespread system. These limitations would be overcome by the use of man-made passive satellites in fixed orbits around the earth and by increasing the number of stations.

NRL Public Affairs Office, "The Vanguard I Satellite," 1963 (est.), brochure.
Vanguard I, America's second successful satellite, has traveled over 690 million miles through space since March 17, 1957, when the technical know-how of the U.S. Naval Research Laboratory made the launch a success.
The small satellite has established a record for the longest lifetime for operation of a transmitting satellite in orbit. Its life expectancy, initially estimated at a few weeks, is now conservatively estimated at up to 200 years.

NRL Public Affairs Office, "Four NRL plankowners at the Laboratory's 40th year," 2 July 1963, brochure.
The 40-year history of the U.S. Naval Research Laboratory closely parallels the technological advances of the radio and electronics industry itself. Many of the big steps forward were taken by NRL people.
Four of the original "plank owners" --charter employees of the Laboratory at its dedication July 2, 1923, -- are still employees of NRL. The following vignettes highlight some important moments of the past.
Leo C. Young -- radio detection and ranging
Louis A. Gebhard -- radio and radar, high frequency radio transmission, ionosphere measurement
Raymond B. Owens -- frequency control and radio crystals
Robert J. Colson -- sound transducers

NRL Public Affairs Office, "NRL 'Firsts' during its 40-year history," 2 July 1963, brochure.
The U.S. Naval Research Laboratory has generated a long and impressive list of scientific "firsts" during its 40-year history which is undisputed by the research and development community of the world.
Following is a list of the most outstanding accomplishments of NRL personnel performing over the past four decades. All are fully documented.

NRL Public Affairs Office, "45 Years of Progress," 1968, brochure.
Pamphlet commemorating the Laboratory's 45th year.

NRL Public Affairs Office, "NRL Plays Key Role in Study of Time Variation," *Labstracts*, 4 December 1972, 4.
NRL personnel and research staff members at the Naval Observatory in Washington, D.C. and the Royal Greenwich Observatory in Herstmonceaux, England, have successfully used a crystal oscillator aboard NRL's orbiting TIMATION II satellite to measure minute variations in the time kept by atomic clocks in the two nations. The six-day series of tests achieved accuracies to within one-half of a millionth of a second (1/2 microsecond).
Researchers are vitally concerned with the preciseness of such timekeeping instruments because accurate time measurement is essential to the

operation of both aircraft and ship navigational systems…

NRL Public Affairs Office, "NRL - an Inventor's Dream of Yesterday… Fifty Years of Science for the Navy and the Nation," *Labstracts*, 2 July 1973, 16.
Issue commemorating the Laboratory's 50th year.

NRL Public Affairs Office, *Launch of the NRL TIMATION III Satellite*, Naval Research Laboratory, Spring 1974, 4-fold single sheet brochure.
The NRL TIMATION III spacecraft is the latest in a series of experiments designed to demonstrate the capabilities of satellites in providing extremely accurate world-wide navigational capability for ships, aircraft and ground forces. NRL conceived the program in 1964 and launched TIMATION I in 1967 and TIMATION II in 1969 to prove that a system using a passive ranging technique combined with highly accurate clocks could provide the basis for a new and revolutionary navigation system with three-dimensional coverage throughout the world.

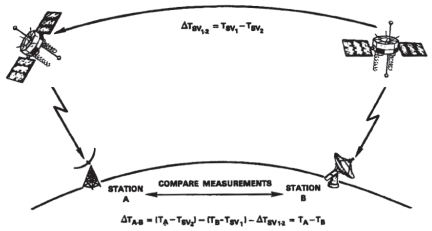
NRL Public Affairs Office, "NRL's TIMATION III: First NAVSTAR Satellite Successfully Launched," NRL Research and Development Highlights, **1**/1 December 1974.
LIMITED DISTRIBUTION

NRL Public Affairs Office, "Navigation Technology Satellite NTS-2, developed by the Naval Research Laboratory," Spring (est.) 1977, brochure.
The NAVSTAR Global Positioning System is based on the Naval Research Laboratory's TIMATION research program and the U.S. Air Force's 621B project, both initiated in the early 1960's… Includes NAVSTAR background, NTS-2 Spacecraft Overview, diagram of the satellite, map of ground stations, launch-orbit profile, GPS system characteristics, and table of NRL navigation satellites.

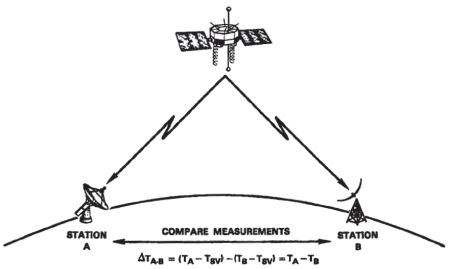
NRL Public Affairs Office, "Capt Noel Notes that PRNSA on NTS-2 Activated; Initial Test Successful," *Labstracts*, 29 July 1977, 1.
The Pseudorandom Noise Signal Assembly (PRNSA) navigational equipment on the Navigation Technology Satellite-2 (NTS-2) has been activated and is performing as planned, said Capt L.M. Noel, NRL Commanding Officer.

NRL Public Affairs Office, "NRL recognized for NAVSTAR Global Positioning System contributions," *Labstracts*, 10 May 1993, 1, 6, 7.
NRL was honored by the National Aeronautic Association (NAA) for significant contributions to the development of the NAVSTAR Global Positioning System (GPS).
In a ceremony hosted by the National Aviation Club on May 4, NAA awarded the association's 1992 Robert J. Collier Trophy jointly to NRL, the U.S. Air Force, the Aerospace Corporation, Rockwell International, and IBM Federal Systems Company. ADM Stanley R. Arthur, Vice Chief of Naval Operations, accepted the trophy for NRL and the Navy.

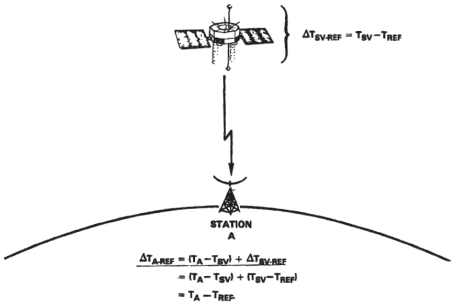
NRL Public Affairs Office, "Awards for Innovation," http://www.nrl.navy.mil/content.php?P=75thANNIVESARYAWARDS, 1998.
Major innovations, with impact and references to primary documents, achieved by the Naval Research Laboratory during the years 1923-1998. Seventy five innovations are covered, including TIMATION and NAVSTAR GPS.
To commemorate the 75th anniversary of the Naval Research Laboratory (NRL), 75 innovations were formally recognized in a ceremony held on June 19, 1998 in Washington, D.C. These innovations were selected to reflect the breadth and the sustained impact of the Laboratory's program. They include some of NRL's most important contributions to science, technology, national security, and society. They are, however, not to be interpreted as the 'Top 75.' While a few are scientific in nature, such



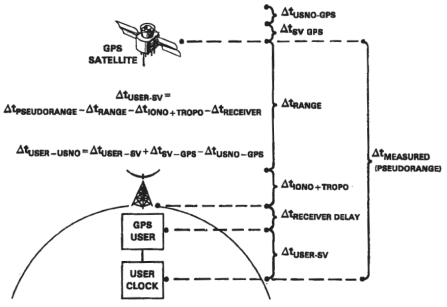
Time transfer by non-simultaneous measurements. (Oaks-1985, p. 80)



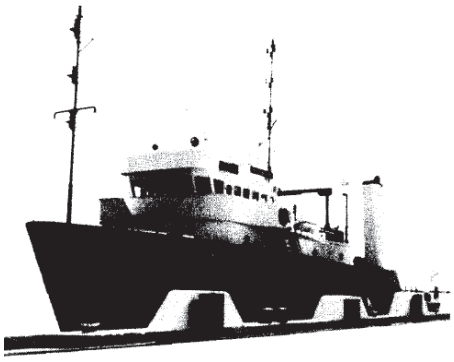
Time transfer by simultaneous measurements. (Oaks-1985, p. 81)



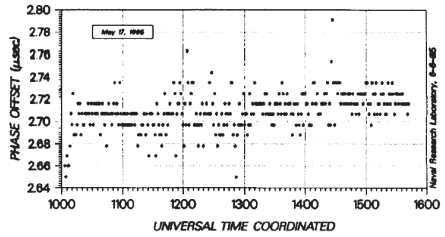
Time transfer by direct measurement. (Oaks-1985, p. 83)



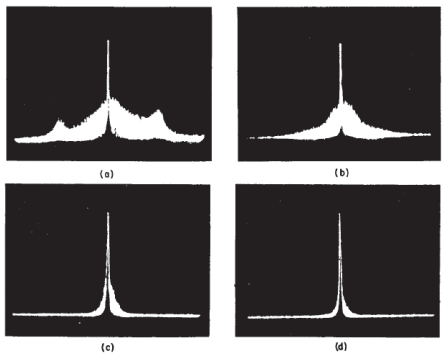
Time transfer via GPS. (Oaks-1985, p. 88)



RV Ranger vehicle used for testing a precise time transfer receiver (TTR) in mobile mode. (Oaks-1995, p. 402)



Sea trial results of testing a precise time transfer receiver. (Oaks-1995, p. 407)



Output spectra of NRL hydrogen maser frequency translator. (O'Neill-1975, p. 3)

as the Nobel Prize-winning work in chemistry, most are technological innovations that have found use in military and/or industrial applications. All are unclassified. Therefore, some major contributions, in areas such as space systems and electronic warfare, could not be publicly recognized.

NRL Public Affairs Office, "Longest Orbiting Satellite Marks 40-Year Anniversary in March," 12 March 1998, Press Release 8-98r.

Vanguard I, the world's longest orbiting man made satellite, built by the Naval Research Laboratory (NRL) and launched at Cape Canaveral, Florida, in 1958, will mark its 40th year in space on March 17. In the years following Vanguard's launch, the small satellite has made more than 158,061 revolutions of the earth and travelled over 4.59 billion nautical miles. The first solar-powered satellite, Vanguard I was the second artificial satellite successfully placed in earth orbit by the United States. (Vanguard predecessors, Sputniks I and II and Explorer I have long since fallen out of orbit.) Just six inches in diameter and weighing just 3 pounds, Vanguard was described by then-Soviet Premier Nikita Khrushchev as "the grapefruit satellite." As part of the scientific program for the International Geophysical Year (1957-58), NRL was officially delegated the responsibility of placing an artificial satellite with a scientific experiment into orbit around the earth. Designated Project Vanguard, the program was placed under Navy management and DoD monitorship. NRL was responsible for developing the launch vehicles; developing and installing the satellite tracking system; and designing, constructing and testing the satellites. The tracking system was called Minitrack. The Minitrack stations, designed, built and initially operated by NRL, were along a North South line running along the east coast of North America and the west coast of South America. Minitrack was the forerunner of another NRL-developed system called NAVSPASUR, which is operational today and a major producer of spacecraft tracking data. In late 1958, responsibility for Project Vanguard was transferred to NASA, forming the nucleus of the Goddard Space Flight Center. After the transfer, NRL rebuilt their spacecraft technology capability and have developed some 87 satellites over the past 40 years for the Navy, DoD and NASA. NRL's relationship with NASA is still very active; for example, NRL is currently developing the Interim Control Module for NASA's International Space Station. Vanguard met 100 percent of its scientific objectives, providing a wealth of information on the size and shape of the earth, air density, temperature ranges and micrometeorite impact. It proved that the earth is pear-shaped, not round; corrected ideas about the atmosphere's density at high altitudes and improved the accuracy of world maps. NRL space scientists say that the Vanguard I program introduced much of the technology that has since been applied in later U.S. satellite programs, from rocket launching to satellite tracking. For example, it proved that solar cells could be used for several years to power radio transmitters. Vanguard's solar cells operated for about seven years, while conventional batteries used to power another onboard transmitter lasted only 20 days. Although Vanguard's solar-powered "voice" became silent in 1964, it continues to serve the scientific community. Ground-based tracking of the satellite provides data concerning the effects of the sun, moon and atmosphere on satellite orbits. Vanguard will be prominently featured at NRL's 75th Anniversary celebration to be held the week of June 17, 1998.

NRL Public Affairs Office, "NRL GPS pioneer Thomas McCaskill to retire after 42 years at NRL," *Labstracts*, 29 July 2002, 5.

Editor's Note: Mr. Thomas B. McCaskill, of the Space Systems Development Department, is retiring after 42 years of service at NRL.

NRL Public Affairs Office, "President announces Roger Easton recipient of National Medal of Technology," *Labstracts*, 28 November 2005, 1,5.

President George W. Bush has announced that Roger L. Easton is the recipient of the National Medal of Technology for his extensive pioneering achievements in spacecraft tracking, navigation and timing technology that led to the development of the NAVSTAR-Global Positioning System (GPS). The White House made the announcement on Monday, November 14. The Nation's highest honor for technology, the National Medal of Technology is awarded to individuals who embody the spirit of American innovation and who have advanced the Nation's global competitiveness.

Easton, the former head of NRL's Space Applications Branch, Space Systems Division, retired from NRL and Federal Service in 1980, and later served as a consultant to NRL to conduct assessment of industry proposals for upgrading the Naval Space Surveillance System and to explore his concept for improving GPS geo-locational accuracy from 1994 to 2000. He began his career at NRL in 1943 as a research physicist, working on radar beacons and blind landing systems in the Radio Division, and served as an active duty Naval officer conducting research aboard the Lab from 1944 to 1945.

He was awarded the National Medal of Technology for "his invention of the Minitrack satellite tracking system used to track Vanguard satellites and determine orbits; his development of the Naval Space Surveillance System still in use today cataloging all known man-made space objects orbiting Earth; his invention of a "Navigation System Using Satellites and Passive Ranging Techniques" and his subsequent development of Time Navigation and Navigation Technology Satellites that formed the technological basis for modern GPS."

(See "Roger Easton recipient of National Medal of Technology," page 5.)

O. J. Oaks, Jr., J. A. Buisson and T. B. McCaskill, *Initial Design for NTS Time Transfer Receiver*, NRL Report 8312, Naval Research Laboratory, Washington, D.C., 16 May 1979.

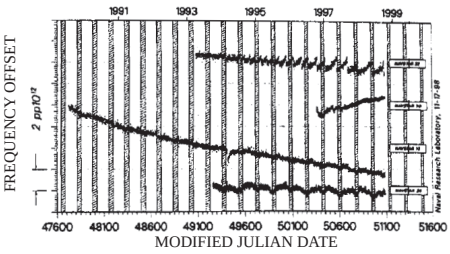
A Time Transfer Receiver (TTR) was designed to utilize the Navigation Technology Satellites (NTS) for making precise time comparisons between a master station and remotely located stations. The receiver processes a 335-MHz sidetone ranging signal from an NTS satellite using a microcomputer-controlled processor. The receiver-processed data are then compared to data obtained at the master station to arrive at a time comparison. The nominal accuracy of the results is approximately 200 ns.

J. Oaks, A. Frank, S. Falvey, M. Lister, J. Buisson, C. Wardrip and H. Warren, "Global Positioning System Time Transfer Receiver (GPS/TTR) Prototype Design and Initial Test Evaluation," in *13th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Washington, D.C., 1-3 December 1981, 419-449.

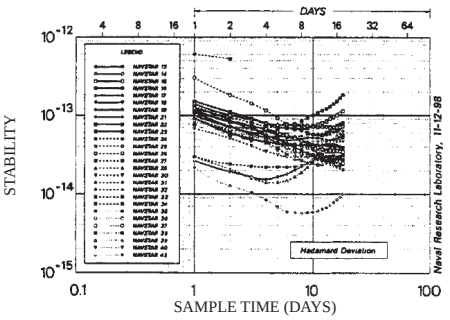
Time transfer equipment and techniques used with the NRL Navigation Technology Satellites have been modified and extended for use with the GPS satellites. A prototype receiver was built and field tested at NASA's Kennedy Spaceflight Center.

The receiver uses the GPS L1 link at 1575 MHz with C/A code only to resolve a measured range to the satellite. A theoretical range is computed from the satellite ephemeris transmitted in the data message and the user's coordinates. Results of user offset from GPS time are obtained by differencing the measured and theoretical ranges and applying calibration corrections. These results may be referenced to Naval Observatory Time through published values of offsets of GPS Time from USNO Master Clock 1.

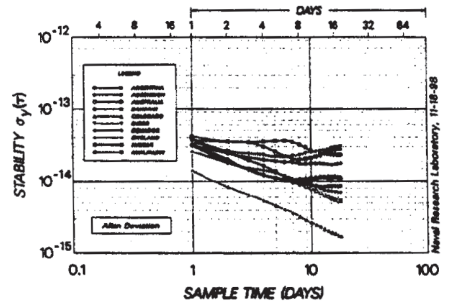
Results of the first field test evaluation of the receiver are presented. Measurements were made at NASA Goddard's MILA facility located in the Kennedy Spaceflight Center, Fla. Portable clock measurements were made for comparison, and all measurements were referenced to the Naval Observatory.



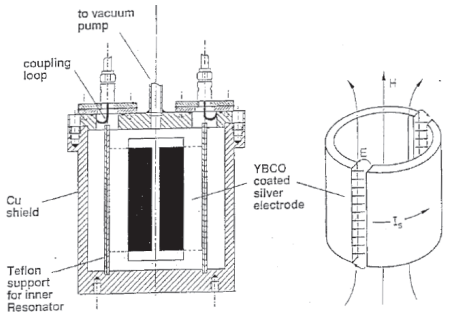
One-day frequency offset history of NAVSTAR clocks (Plane B) from DoD Master Clock. (Oaks-1998, p. 141)



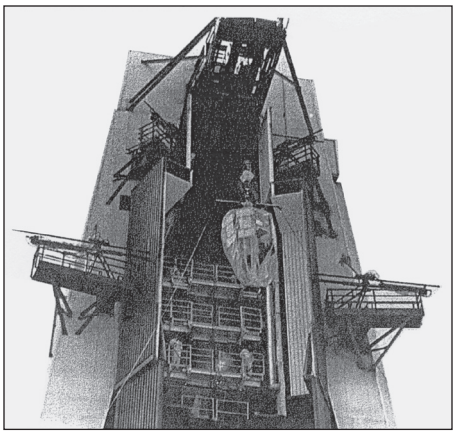
Frequency stability of NAVSTAR clocks, 1 April - 30 September 1998. (Oaks-1998, p. 142)



Frequency stability profile comparison of time references with respect to DoD Master Clock via linked common-view time transfer, 1 April to 1 October 1998. (Oaks-1998, p. 143)



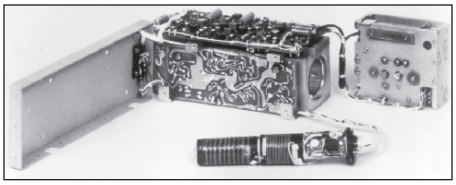
Schematic of compact loop-gap maser resonator with the field configuration at the inner electrodes. (Opie-1991, p. 2945)



NTS-II being placed on the Atlas-F Booster at Vandenberg Air Force Base. (Parkinson-1995, p. 131)

O. J. Oaks, Jr., A. H. Frank, S. R. Falvey, M. J. Lister, J. A. Buisson, S. C. Wardrip and H. F. Warren, *Prototype Design and Initial Test Evaluation of a Global-Positioning-System Time-Transfer Receiver (GPS TTR)*, NRL Report 8608, Naval Research Laboratory, Washington D. C., 27 July 1982.

Time-transfer equipment and techniques used with the NRL Navigation Technology Satellites have been modified and extended for use with the GPS satellites. A prototype receiver was built and field tested at NASA's Kennedy Spaceflight Center. The receiver uses the GPS L-band link at 1575 MHz with only the course-acquisition code to resolve a measured range to the satellite. A theoretical range is computed from the satellite ephemeris transmitted in the data message and the user's coordinates. Results of user offset from GPS time are obtained by differencing the measured and theoretical ranges and applying calibration corrections. These results may be referenced to Naval Observatory (USNO) time through published values of offsets of GPS time from USNO Master Clock 1. In the first field test of the receiver, at the Kennedy Spaceflight Center, portable clock measurements were made for comparison, and all measurements were referenced to USNO. Initial results demonstrate a time-transfer accuracy better than 200 ns. The results have shown possibilities for improvement in receiver performance to obtain time transfers accurate to 50 to 100 ns worldwide. Experiments are planned for late 1982 to demonstrate the improved capability.



TIMATION I quartz oscillator showing oven assembly and remote screwdriver-end mounting gearbox. (Bartholomew-1978, p. 114), (Parkinson-1995, p. 124)

O. J. Oaks, "Time Transfer by Satellite," in *17th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Washington, D.C., 3-5 December 1985, 77-92.

Time transfer by satellite provides a reasonable means of time dissemination and synchronization for any location which can accommodate a satellite receiver. Several satellite systems have been used to perform time transfer, and commercial receivers are available that provide the link between the user and the satellite. Different methods of time transfer by satellite are described and related to commercially available user equipment. Relative cost and accuracy of the methods are compared to time transfer methods using the NAVSTAR Global Positioning System.

O. J. Oaks, W. Reid, J. Wright, C. Duffey, C. Williams, H. Warren, T. Zeh and B. James, "GPS Moving Vehicle Experiment," in *27th Annual Precise Time and Time Interval (PTTI) Meeting*, held at San Diego, California, 29 November - 1 December 1995, Goddard Space Flight Center, NASA Conference Publication 3334, 397-408.

The Naval Research Laboratory (NRL), in the development of timing systems for remote locations, had a technical requirement for a Y code (SA/AS) GPS precise time transfer receiver (TTR) which could be used both in a stationary mode or mobile mode. A contract was awarded to the Stanford Telecommunication Corporation (STEL) to build such a device. The Eastern Range (ER) also had a requirement for such a receiver and entered into the contract with NRL for the procurement of additional receivers. The Moving Vehicle Experiment (MVE) described in this paper is the first in situ test of the STEL Model 5401C Time Transfer System in both stationary and mobile operation.

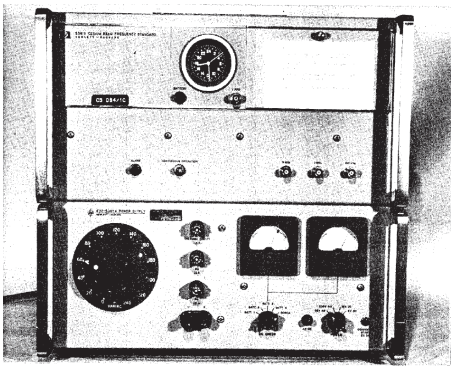
The primary objective of the MVE was to test the timing accuracy of the newly developed GPS TTR aboard a moving vessel. To accomplish this objective, a joint experiment was performed with personnel from NRL and the ER at the Atlantic Undersea Test and Evaluation Center (AUTEC) Test Range at Andros Island. This range is under the direction of the Naval Undersea Warfare Center (NUWC), Newport, Rhode Island. The test was conducted through the West Palm Beach (WPB) Detachment of the NUWC.

Results and discussion of the test are presented in this paper.

Hydrogen masers at the Naval Research Laboratory. Hydrogen Maser I on the right has operated for 6 years as the NRL standard. (Phillips-1970, p. 329)

O. J. Oaks, T. B. McCaskill, M. M. Largay, W. G. Reid and J. A. Buisson, "Performance of GPS On-Orbit NAVSTAR Frequency Standards and Monitor Station Time References," in *30th Annual Precise Time and Time Interval (PTTI) Meeting*, 1-3 December 1998, 135-44.

The U.S. Naval Research Laboratory (NRL) conducts comprehensive analyses of the Global Positioning System (GPS) atomic frequency standards under the sponsorship of the GPS Joint Program Office (JPO) and in cooperation with the 2nd Space Operations Squadron (2SOPS) at the Master Control Station (MCS) in Colorado Springs, Colorado. Included in the analysis are the on-orbit Navstar space vehicle clocks and the ground reference clocks at each of the five Air Force and seven National Imagery and Mapping Agency (NIMA) GPS monitor stations. A presentation will be made of the performance of the Navstar clocks currently operating in the constellation which are characterized through the use of phase, frequency, drift, and stability histories in addition to frequency stability profiles based on the Allan and Hadamard variances. Clock performance is analyzed using a multi-year database comprised of pseudorange measurements collected by each of the 12 GPS monitor stations. Results of these analyses are routinely used by the MCS in optimizing the q's in the Kalman filter. Continuous 15-minute measurements of the phase offset of each monitor station time reference from the DoD Master Clock are obtained from Linked Common-View Time Transfer from the reference clock at the NIMA Washington, DC monitor station. The method is extended to obtain continuous 15-minute measurements of the phase offset of each active Navstar space vehicle clock from the DoD Master Clock. Hence, the performance of all space and control segment clocks is referenced to the DoD master clock. Discontinuities in the phase and frequency of the clocks are removed to yield the unperturbed performance of the clocks. The corrections, together with the probable cause of the discontinuity, are summarized. Examples of the frequency history and the exhaustive calculation, for every multiple of the sample period of 15 minutes from 15 minutes to 12 days, of the frequency stability profile for several Navstar space vehicle clocks and for the time reference at each of the GPS monitor stations will be presented. Analysis of the performance of the first on-orbit Block IIR operational rubidium clock will be presented. A comparison of the performance of this clock will also be made with that of a Block IIR flight candidate rubidium clock currently undergoing life testing in the Clock Test Facility of the Naval Research Laboratory.



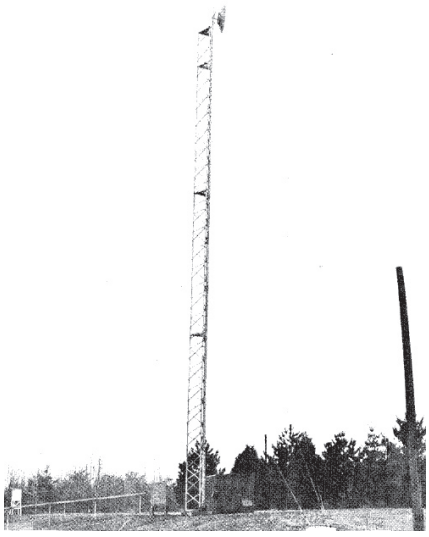
Cesium beam traveling clock, time and frequency standard. (Phillips-1970, p. 329)

Hewlett-Packard 5060A Cesium Beam Frequency Standard. (NRL photo)

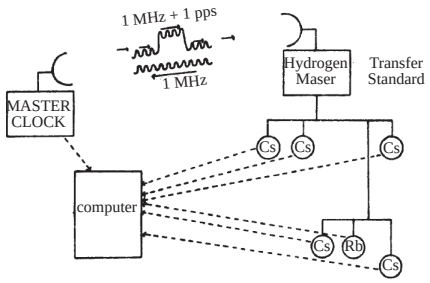
J. Oaks, T. B. McCaskill, M. M. Largay and J. A. Buisson, "Performance of Global Positioning System Block II/IIA/IIR On-Orbit Navstar Clocks," in *33rd Annual Precise Time and Time Interval (PTTI) Meeting*, L. A. Breakiron, ed. held at Long Beach, CA, 27-29 November 2001, 469-480.

Analysis of the performance of all on-orbit NAVSTAR space vehicle clocks and Global Positioning System (GPS) monitor station reference clocks is performed by the Naval Research Laboratory (NRL), in cooperation with the GPS Master Control Station, under the sponsorship of the GPS Joint Program Office (JPO). The measurements used in the analysis are collected by multi-channel GPS receivers located at the Air Force and National Imagery and Mapping Agency (NIMA) monitor stations. The offset of each NAVSTAR clock offsets are then used to compute frequency offset, drift offset, frequency stability profiles, and frequency stability histories.

The performance of selected cesium and rubidium atomic clocks will be presented. Frequency stability results are calculated using sample times that vary from 15 minutes to several days. The operational NAVSTAR timing signals will be ranked (according to frequency stability) for samples times of 6 hours and 1 day. In addition, the Block IIR clocks will be compared to results from an ongoing NRL laboratory life-test on two flight-qualified



Microwave tower and antenna at the Naval Research Laboratory's satellite research communications terminal, Waldorf, Maryland. (Phillips-1970, p. 331)



Local time synchronization for laboratory. (Phillips-1971, p. 214)

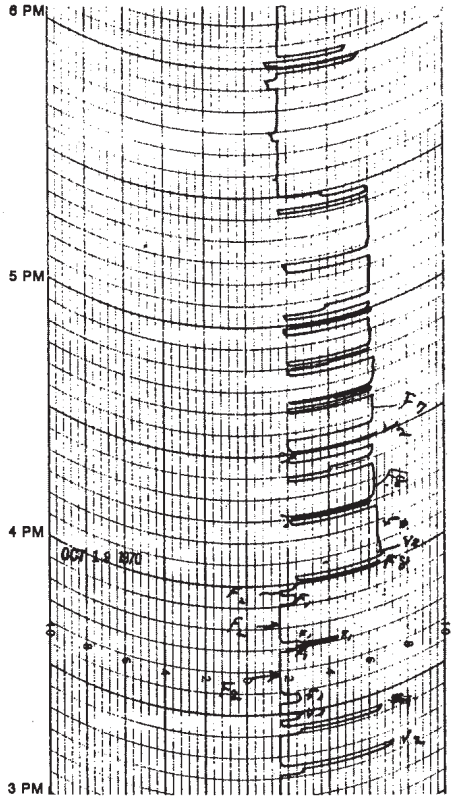
Block IIR rubidium atomic frequency standards. Observed clock behavior and anomalies will be discussed.

J. Oaks, M. M. Largay, W. G. Reid and J. A. Buisson, "Global Positioning System Constellation Clock Performance," in *34th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, VA, 3-5 December 2002, 77-82.

An overview of the Global Positioning System (GPS) constellation with respect to the lifetimes of space vehicles and space vehicle clocks, both active and deactivated, is presented. Analysis of clock performance with respect to frequency stability is reviewed. The operational Navstar timing signals are ranked according to frequency stability for a sample time of 1 day. In addition, the performance of the Block IIR clocks is compared to that of two flight-qualified Block IIR rubidium atomic frequency standards undergoing life tests in the NRL Precision Clock Evaluation Facility. This work was performed under the sponsorship of the GPS Joint Program Office.

J. Oaks and J. A. Buisson, "Satellite Time Transfer Past and Present," in *34th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, VA, 3-5 December 2002, 7-18.

An overview of past accomplishments is presented that shows the development of satellite time transfer techniques and capabilities that are used today. The development is traced from the concepts and early demonstrations using a single satellite to the global coverage now provided by a constellation of satellites. Predictions of future technology are compared with what has been accomplished over the last 25 years. Cooperative experiments performed jointly by colleagues of the PTTI Meetings were key to the development. These experiments demonstrated the potential of time transfer by satellites having global coverage. Some of the results are reviewed and compared to current capabilities.



Television station WTTG color burst frequency versus maser (NRL). Full scale is 279 nanoseconds. (Phillips-1971, p. 215)

J. J. O'Neill, D. H. Phillips and R. R. Stone, "UHF Frequency Translator Based on Regenerative Division," in *27th Annual Frequency Control Symposium*, held at Fort Monmouth, NJ, 12-14 June 1973, 312-6.

A frequency translator operating in the UHF band at a frequency of 1420.40575178 MHz (1) derived from the Naval Research Laboratory's hydrogen maser has been designed, constructed, and operated. Its output is a greatly amplified and highly stable sub-multiple (1/3) version of the original input frequency. The device is configured as a classical regenerative divider with a very weak input signal which requires significant amplification before divider action can take place. This amplified sub-multiple signal, derived solely from the transition of the hydrogen atom, is then available to produce stable standard frequencies in the UHF band or to phase lock a low frequency crystal oscillator to produce maser controlled standard frequencies.

J. J. O'Neill, D. H. Phillips and R. R. Stone, *Hydrogen Maser Frequency Translator*, NRL Report 7858, Naval Research Laboratory, 27 June 1975.

A frequency translator which operates at the atomic hyperfine transition frequency of the hydrogen maser has been designed, constructed, and operated. This device, which operates in the uhf band at a frequency of about 1420 MHz, provides an output signal with a magnitude sufficient to be utilized in synthesizer or phase-locked systems. Lower frequency signals can be produced from these systems whose frequency stability is directly controlled by the hydrogen maser. Significant improvement in spectral purity can be realized through the use of this technique.

D. B. Opie, H. E. Schone, M. Hein, G. Muller, H. Piel, D. Wehler, V. Folen and S. Wolf, "A superconducting hydrogen maser made from electrophoretic YBa2Cu3O7-delta," *IEEE Transactions on Magnetics* **27** (2 Part 4), 2944-7 (1991).

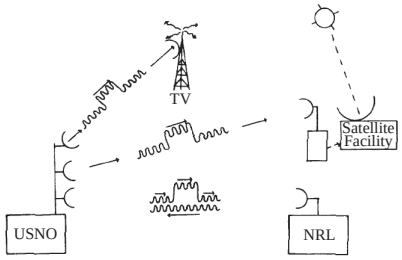
A compact loop-gap hydrogen maser resonator has been constructed by electrophoretic deposition of YBCO onto silver. The resonator is tuned to operate at the hyperfine transition frequency of hydrogen (1.42 GHz). This device is considered to be the first step towards a superconducting cavity for a compact hydrogen maser to be used in the Global Positioning System (GPS). The required miniaturization of the resonator reduces its Q value. This effect can be compensated for by the low surface resistance of YBCO at 77 K. Large and curved polycrystalline YBCO layers can be obtained by the electrophoretic deposition technique. In this contribution we report on the construction and test of three loop-gap resonators which are being prepared for the high-temperature superconductor space experiment (HTSSE) are discussed. The loop-gap electrodes are the lossiest parts of such a resonator. In a first step these electrodes, with a surface of 150 cm2, were covered with YBCO. The Q values of the resonators at 77 K ranged between 2.3×10^4 and 3.1×10^4 and exceed the minimum requirement for a later maser application. They correspond to a surface resistance between 0.7 and 1.4 m/Omega/ which is a factor of three to five below the equivalent value of copper. The cavities can be excited in a higher-order mode (HOM) at 4.3 GHz with a field distribution that is still sensitive to the superconducting electrodes. Thus, the experimental requirements for the HTSSE project can be fulfilled.

D. B. Opie, H. E. Schone, M. Hein, G. Muller, H. Piel, H.-P. Schneider, V. Folen, A. Frank, W. M. Golding and S. Wolf, "A high T/sub c/ superconducting resonator for a compact hydrogen maser," in *45th Annual Symposium on Frequency Control*, 29-31 May 1991, 467 -476.

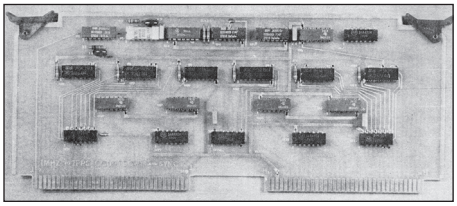
The advent of high Tc superconductors (HTSC) has made feasible the application of superconductivity to practical microwave devices. The measured surface resistance, Rs, of the new HTSC materials is lower than that of copper measured at the same temperature, 77K, and frequency, 1.42 GHz. An interesting application of these new materials is the miniaturization of microwave cavity resonators. In this report we describe the development, testing and evaluation of a superconducting compact hydrogen maser resonator made from electrophoretic Y/sub 1/ Ba/sub 2/ Cu/sub 3/ O/sub 7-delta/ (YBCO). This compact loop-gap resonator, based on a previously suggested maser resonator [1], is made superconducting using an electrophoretic process developed for the deposition of thick film polycrystalline HTSC on large non-planar metallic substrates. At 77K we obtain cavity quality factors comparable to those of standard size, room temperature TE/sub 011/ maser resonators. The fields of the resonator have been studied using numerical techniques to determine the dependence of the filling factor, eta-prime, and the cavity quality factor, Qc, on the geometric parameters. This information is used to optimize the cavity design with respect to the effects of thermal radiation on the maser performance at 77K.

D. B. Opie, C. T. Butler, W. M. Golding, F. Danzy, J. Yates and M. C. Sharp, "Operation of a neural network controlled crystal oscillator," in *48th IEEE International Frequency Control Symposium*, 1-3 June 1994, 600 -603.

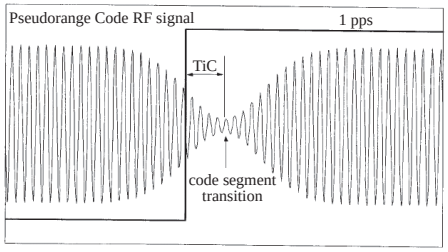
The neural network control at a quartz oscillator has been demonstrated. We have shown that a single neural network can correct an oscillator's output frequency while several environmental sources of frequency shift act on the oscillator. The advantage that a neural network offers over microprocessor controlled oscillators or Kalman filter control techniques is that a neural network does not need an a priori modal of the physical system to arrive at the correct control algorithm. The results of this demonstration indicate that a neural network can have beneficial applications in a variety of frequency standard devices. We believe that the neural network will work best as a control system supervisor, rather than as the main controller of the frequency standard system…



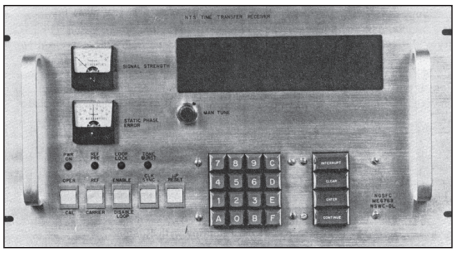
Complementary local time transfer methods. (Phillips-1971, p. 216)



MHz to PPS countdown and sync. (Phillips-1981, p. 335)



Measuring the tick-to-code delay. (Plumb-2001, Figure 2)



Compact, low cost timing receiver for receiving and processing Navigation Technology Satellite ranging sidetones. (Raymond-1976, p. 101)

U.S. Naval Research Laboratory, *75th Anniversary Awards for Innovation*, NRL/PU/1001--98-359, June 1998. This publication summarizes major accomplishments of the first 75 years of the Naval Research Laboratory.

W. H. Ottley, National Aeronautic Association, "Global Positioning System Team wins 1992 Collier Trophy," *Labstracts*, 1 March 1993, 1.

On February 10, the National Aeronautic Association (NAA) selected the Global Positioning System (GPS) Team composed of the U.S. Air Force; Naval Research Laboratory; the Aerospace Corporation of El Segundo, California; Rockwell International Corporation of Seal Beach, California; and IBM Federal Systems Company of Bethesda, Maryland as winners of the 1992 Robert J. Collier Trophy, America's most distinguished aviation award.

A special 35-member committee of national aviation leaders named by NAA President Malvern J. Gross chose the GPS Team from among eight individuals and organizations nominated earlier. The balloting took place in Arlington, Virginia.

The citation accompanying the presentation of the trophy will honor the Global Positioning System Team "for the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation 50 years ago."

B. W. Parkinson, T. Stansell, R. Beard and K. Gromov, "A History of Satellite Navigation," *Navigation: Journal of The Institute of Navigation* **42** (1, Special Issue), 109-164 (1995).

Navigation by use of earth satellites is expanding explosively. Current estimates are that 60,000 civil sets are being produced each month. With increased use in automobiles, ships, and airplanes, this application of satellites is expected soon to rival the communications applications. This paper traces the evolution of satellite navigation from the early stages of the Navy's Transit system through the developmental Navy and Air Force programs known as Timation and 621B. These early efforts contributed strongly to the synthesis of the current satellite navigation system called GPS. GPS has demonstrated a wide range of applications, from precise survey (at the millimeter level) to the landing of airplanes with positioning uncertainties of a few centimeters. The paper describes the operation of all of these systems, as well as the two Russian systems, Cicada and GLONASS. As the applications expand, GPS will touch every citizen of the world in ways that even today are not fully appreciated.

E. C. Pavlis and R. L. Beard, "Laser Retroreflector Experiment on NAVSTAR 35 and 36," in *26th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Reston, Virginia, 6-8 December 1994, NASA Conference Publication 3302, 427-41.

In GPS one of the primary errors contributing to positioning inaccuracy is the performance of the on-board atomic clock. To determine and predict the performance of this atomic clock has been a problem due to the ambiguity of the orbital position error and clock uncertainty in the Radio Frequency (RF) tracking of the navigation signals. The Laser Retroreflector Experiment (LRE) on-board NAVSTAR 35 and 36 provides a means of separating these ambiguous errors by enabling highly precise and accurate satellite positions to be determined independently of the RF signals. The results of examining onboard clock behavior after removing the orbital position signatures will be discussed. GPS RF tracking data from various DoD and other sites are used to reconstruct the onboard clock data and examine the clock behavior. From these data, the effects of clock performance on GPS positioning performance can examined.

D. H. Phillips, R. E. Phillips and J. J. O'Neill, "Time and Frequency Transfer Via Microwave Link," in *Twenty-Fourth Annual Frequency Control Symposium*, held at Atlantic City, New Jersey, 27-9 April 1970, 325-31.

A two-way microwave link between the Naval Research Laboratory and the Naval Observatory has been established to transfer both time and frequency information with high accuracy. Time and frequency information is transmitted simultaneously by algebraically adding together a precision 1 MHz signal and 1 pps, thus providing continuous phase information for frequency comparison and epoch time by the pulse. Phase resolution is better than 10 nanoseconds and determination of epoch time better than 0.1 microseconds. Seven precision standards have been intercompared via the microwave link. Continuous phase recording since September 1969 has shown no diurnal dependence and very little effect due to seasonal and temperature changes.

A second microwave link has been established between the Naval Observatory and the Naval Research Laboratory's satellite research communications terminal in Waldorf, Maryland.

D. H. Phillips, R. E. Phillips and J. J. O'Neill, *Time and Frequency Transfer Via Microwave Link*, NRL Report 7140, Naval Research Laboratory, 26 June 1970, 18 pp.

A two-way microwave link between the Naval Research Laboratory and the Navy Observatory has been established to transfer both time and frequency information with high accuracy. Time and frequency information is transmitted simultaneously by algebraically adding together a precision 1 MHz signal and 1 pps, thus providing continuous phase information for frequency comparison and epoch time by the pulse. Phase resolution is better than 10 nanoseconds and determination of epoch time better than 0.1 microseconds. Seven precision standards have been intercompared via the microwave link. Continuous phase recording since September 1969 has shown no diurnal dependence and very little effect due to seasonal and temperature changes.

A second microwave link has been established between The Naval Observatory and the Naval Research Laboratory's satellite research communications terminal in Waldorf, Maryland.

D. H. Phillips, R. E. Phillips, J. A. Bowman and J. J. O'Neill, "Methods of Local Time and Frequency Transfer," in *Proceedings of the Twenty-Fifth Annual Frequency Control Symposium*, held at Atlantic City, New Jersey, 26-8 April 1971, 209-16.

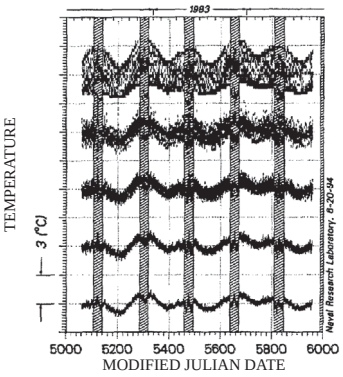
Several methods of local time and frequency transfer have been experimentally utilized by the Naval Research Laboratory during the past year. Results have shown that several of the methods such as the microwave link and T.V. time transfer have great promise. Cable can provide accurate time and frequency transmission for short distances such as the Laboratory. A disciplined time and frequency standard (DTF) with built-in memory logic and a high quality crystal is being developed and could serve as the terminus of a microwave or T.V. link. The hydrogen maser was used as a transfer standard to make crosschecks for various standards and between the various techniques for time transfer. Total evaluation shows the combination of all these techniques yielding a time and frequency distribution net of high accuracy to serve as a base for navigation, timekeeping, and communications.

D. H. Phillips, "Digital Processing Clock," in *13th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Washington, D.C., 1-3 December 1981, 325-346.

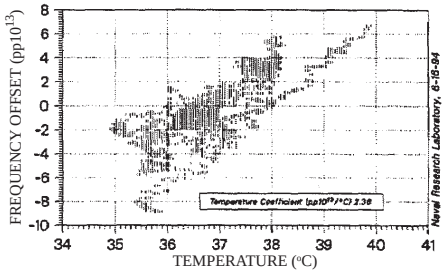
The Digital Processing Clock SG 1157/U has been developed by Naval Research Laboratory and is:

(1) compatible with the PTTI world where it can be driven by an external cesium and built in test equipment shows synchronization with that cesium through the 1 PPS

(2) built to be expandable to accommodate future time keeping needs of the Navy as well as any other time ordered functions.



Effect on the temperature measurements of a moving average filter. (Reid-1994, p. 785)



Scatter plot showing the results of plotting the frequency of the Block II NAVSTAR 16 cesium clock as a function of the temperature. (Reid-1994, p. 789)

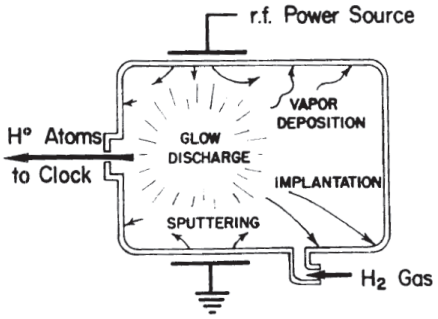
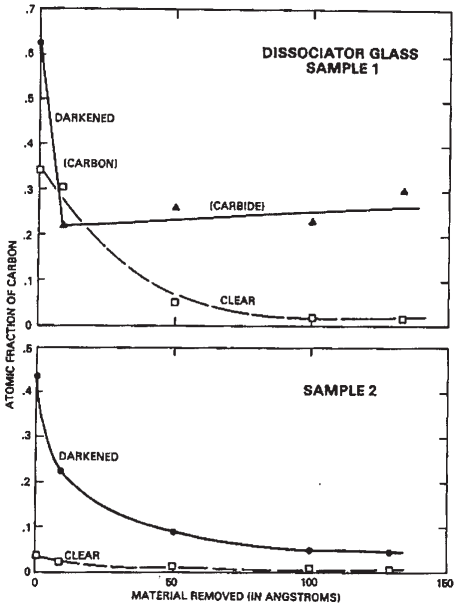


Diagram of hydrogen dissociator used in hydrogen maser. (Ritz-1977, p. 363)



Atomic emission spectroscopy analysis of inner and outer surfaces of the hydrogen dissociator, showing atomic fraction of carbon as a function of Angstroms of material removed. (Ritz-1977, p. 368)

Examples of this expandability are the recent inclusion of an unmodulated XR3 time code and the 2137 modulated time code (XR3 with 1 kHz carrier).

D. H. Phillips, "No Warmup Crystal Oscillator," in *13th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Washington, D.C., 1-3 December 1981, 831-850.

During warmup, crystal oscillators often show a frequency offset as large as 1 part in 10^5. If timing information is transferred to the oscillator and then the oscillator is allowed to warmup, a timing error greater than 1 millisecond will occur. For many applications, it is unsuitable to wait for the oscillator to warmup.

For medium accuracy timing requirements where overall accuracies in the order of 1 millisecond are required, a no warmup crystal concept has been developed. The concept utilizes two crystal oscillators, which are used sequentially to avoid using a crystal oscillator for timing during the trauma of warmup.

One oscillator may be a TCXO which preserves timing information during the warmup of the second crystal oscillaotr, which has a much higher frequency accuracy once warmed up.

This paper will show the accuracy achieved with practical TCXOs at an initial start over a range of temperatures. A second design utilizing two oven controlled oscillators will also be discussed.

R. Phillips, *Method for Calculating a Two-Point Single-Pass Orbit*, NRL Report 6846, Naval Research Laboratory, Washington, D.C., 15 May 1969.
NRL 6846 LIMITED DISTRIBUTION

J. F. Plumb, J. White, E. Powers, K. Larson and R. Beard, "Simultaneous Absolute Calibration of Three Geodetic-Quality Timing Receivers," in *33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held at Long Beach, California, 27-29 November 2001, US Naval Observatory, 349-358.

The simultaneous calibration of three geodetic-quality timing receivers is performed with a Global Positioning System (GPS) signal simulator. Internal delays for each receiver are measured as a function of the phase difference between the one pulse per second and 20 MHz clock inputs. A calibration curve for each receiver is derived and the curves are compared.

J. Plumb, K. Larson, J. White, E. Powers and R. Beard, "Stability and Error Analysis for Absolutely Calibrated Geodetic GPS Receivers," in *34th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, VA, 3-5 December 2002, 309-324.

The absence of absolute calibration data for geodetic-quality Global Positioning System (GPS) receivers and their associated equipment has limited the application of these instruments for time transfer. We have conducted a series of tests in order to calibrate two such geodetic receivers. Receiver calibration is made with respect to a dual-frequency GPS simulator. Inaccuracies due to the simulator itself are minimized by the calibration procedure. The antenna and associated cables are calibrated using a vector network analyzer. Incorporating this information, we are able to provide an error budget for the absolute delay of an entire GPS receiver site. Methods for reducing this error budget are proposed.

The absolute calibration results for one receiver are compared to the results from a similar calibration performed 1 year earlier. Calibration stability is found to be on the order of 1 nanosecond for pseudoranges transmitted on both of the GPS frequencies (1575.42 and 1227.6 MHz). Laboratory calibration values are compared to in situ measurements in two modes: two receivers running off one antenna with a common clock, and two receivers running off two separate antennas with a common clock. Agreement is within the expected uncertainties based on the error budget described above. Using baselines on the order of 1000 km, calibrated GPS Carrier- Phase time

transfer results are then compared to calibrated GPS Common View and Two-Way Satellite Time Transfer results. Agreement is again observed within the expected uncertainties.

Calibration of the carrier-phase technique must also include errors due to modeling of the observations (e.g., satellite orbits, atmospheric propagation) that are beyond the scope of this paper.

E. D. Powers and F. Danzy, "Interim Results from the Characterization Testing of the Engineering Development (EDM) Rubidium Clocks for Satellite Applications," in *22nd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Vienna Virginia, 4-6 December 1990, NASA Conference Publication 3116, 325-330.

This paper presents some interim results from the environmental testing program to evaluate the Engineering Design Model (EDM) of the EG&G Spaceborne Rubidium Clock. This effort is in support of the GPS BLOCK IIR program and is intended to characterize the performance of EG&G design for BLOCK IIR satellite application. Two EG&G EDM units are currently under test at NRL's Clock Test Facility to measure the long-term frequency stability, drift, and frequency versus temperature characteristics.

E. Powers, A. Gifford and P. Wheeler, "Hydrogen Maser Performance at the United States Naval Observatory and the Naval Research Laboratory," in *45th Annual Symposium on Frequency Control*, 29-31 May 1991, 582 -585.

The United States Naval Observatory (USNO) has been using hydrogen masers for over six years as part of the USNO Master Clock. The Naval Research Laboratory (NRL) has also been using masers references as part of the NRL Clock testing facility since September 1985. The masers reported on in this paper will include the Smithsonian Astrophysical Observatory VLG-11, VLG-12 and masers from the Sigma Tau Standards Corporation. This paper will describe the operation of the masers at USNO and NRL including stability, aging rates, and reliability.

F. T. Powles, *Instrumentation for the Classification of Space Signals*, NRL Report 5488, Naval Research Laboratory, Washington, D.C., July 1960.
NRL5488 LIMITED DISTRIBUTION

PTTI Executive Committee, "PTTI Distinguished Service Award 2000 to R.L. Easton," in *32nd Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, Virginia, 28-30 November 2000, 5-6.

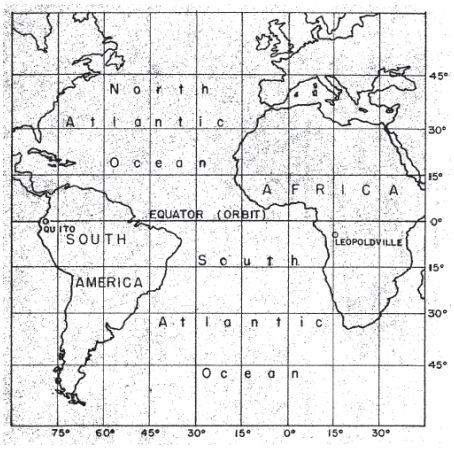
PTTI Distinguished Service Award 2000, presented to Roger L. Easton by Dr. Joseph D. White.

Captain, thank you for the opening remarks. I am the Chairman of the PTTI Executive Committee, and mostly what I get to do in that job is delegate things to others and stand back and watch things happen. But every now and then, I find a good job that I like to keep for myself, and this is one of them.

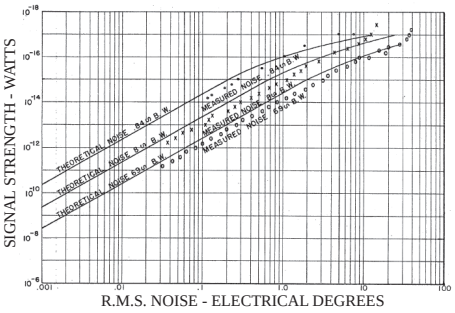
The PTTI has its Distinguished PTTI Service Award. We award this sometimes annually, sometimes less. It kind of depends on how we feel and whether we feel we have good candidates. In this case, this year we have an exceptional person that we're honoring, a man that I've been honored to work for and to know for 20-something years now. Roger Easton will be our award winner this year.

Most of you have known Roger at one time or another during his career, which has been quite long and distinguished. Some of you knew him before I have met him. I worked for him from 1973 to 1980, I guess it was. He's done a number of other things since he retired. And I thought I'd just take a minute to go over briefly some of Roger's accomplishments, and there are a lot; I'm reducing them to just the big ones here today.

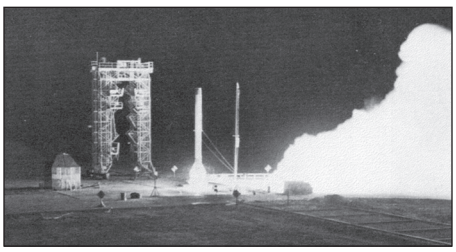
Roger worked for NRL and the Navy continually from World War II up to 1980. Among his accomplishments there were the design and the construction



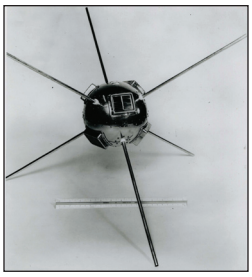
MINITRACK stations proposed by Army Map Service. (Rocket Development Branch-1955 NRLmr466, Figure 2)



Signal strength versus noise for various post-detection band widths. (Predetection band width 3 x 10^4.) (Rocket Development Branch-1955 NRLmr466, Figure 3)

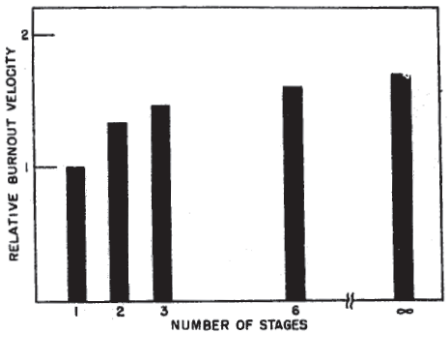


Night firing of a Viking rocket, predecessor to the Vanguard satellite launch vehicle. (Rosen-1955, Chapter 9)

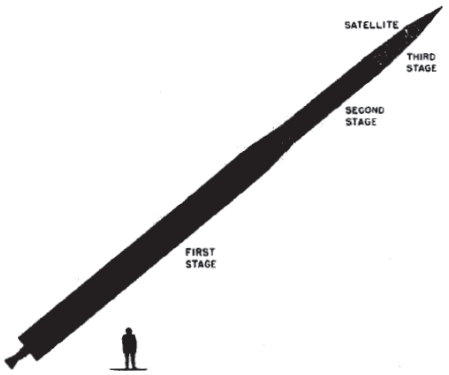


Vanguard satellite. (NRL Photo)

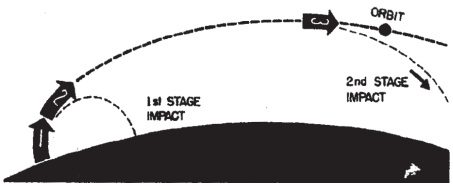
Takeoff of Viking 11, the heaviest Viking rocket ever fired, as it rose 158 miles to establish the altitude record for single-stage rockets. (Rosen-1955, p. 624)



Number of rocket stages versus relative burnout velocity. (Rosen-1955, p. 750)



The Vanguard launching vehicle. (Rosen-1955, p. 749)



VANGUARD launching vehicle trajectory. (Rosen-1955, p. 749)

of the first Vanguard satellite. An outgrowth out of that was system called "Mini-Track," which was developed to track Vanguard and later expanded to do other things. Mini-Track grew into a system that became known as the "Naval Space Surveillance System". That all started around 1960 or so. "SpaceSur" is not well known in the community, but in fact if you look at NORAD's list of what's flying around in space today, most the items on that list, I think something like 75 or 80%, come out of SpaceSur. It's a system that's still going, still growing, and Roger is one of the people that made SpaceSur happen.

Roger also, shortly after SpaceSur, invented a one-way ranging concept that became a Navy program that was known as "Timation". For those of you that know the history of GPS, Timation was one of two programs, that and the Air Force 621B project, which became GPS. That's about the time I went to work for Roger. The things that make GPS work so well, the clocks, the orbits, a lot of the concepts all came from Roger. We owe him a great debt of gratitude for the work he did there.

As I say, Roger retired from NRL around 1980; however, that was by no means the end of his career. He did a number of other things after that, including politics. Roger was elected twice to the New Hampshire General Court, which I believe is roughly the same thing as the State Assembly. And in 1986 he actually ran for Governor. He was beaten by an upstart by the name of John Sununu, and we understand that it had to do with the irregular voting in the southern part of the state and dimpled ballots. But he came close.

Roger has also received a number of awards over the years. I would like to list a few of those in 1960, back in the SpaceSur days, as that started up; he won NRL's Distinguished Civilian Achievement Award. Roger was one of several people involved in the Collier Award, which is shared between NRL, Aerospace, the Air Force, and Rockwell for GPS.

Another award that I thought was very interesting was the Magellanic Premium Award from the American Philosophical Society. And I'll read the description to you of what this is: "a medal to be awarded from time to time to the author of the best discovery or most useful invention relating to navigation, astronomy, or natural philosophy." Roger is also a Fellow of the Institute of Navigation.

Sometimes, though as you look through the list of people, a lot of people have won awards. One of the things that kind of gets your attention, as to how well recognized they are, is how may awards have been named after them. I know there are at least two in Roger's case: There's the Roger L. Easton Science and Engineering Award, which was out of Naval Space Surveillance, and the NRL Roger L. Easton Award for Engineering Excellence. I'm particularly interested in the NRL award because NRL, like most laboratories, is a hard science laboratory, but we have a group that does engineering. In hard science groups, the engineering people often get ignored. So it's very nice to see that award came for Roger and recognized not only his achievements, but also the achievements of the people who have followed.

So Roger, if I could you up here please, I'd like to make the award. You have to be aware of boxes that tick. I don't know how you are going to get this back on the airplane. This is the clock that is awarded as the PTTI Distinguished Service Award. Its inscribed "Distinguished PTTI Service Award 2000 to Roger Easton."

J. B. L. Rao and W. M. Waters, "Voltage-controlled oscillator with time-delay feedback," in *32nd Annual Frequency Control Symposium*, held at Atlantic City, NJ, 31 May - 2 June 1978, 378-384.

A voltage-controlled oscillator with time-delay feedback is analyzed. The results indicate that by properly choosing system parameters, both low noise from the degeneration and frequency agility from the periodic response can be obtained in one source. The conditions for system stability and the amount

of noise degeneration are expressed in terms of system parameters. Effects of different parameters on system stability and noise degeneration are discussed in detail. It is shown that the open-loop gain should be chosen as large as possible for good noise degeneration, and the amplifier-filter bandwidth should be chosen to meet the stability condition.

L. Raymond, J. Oaks, J. Osborne, G. Whitworth, J. Buisson, P. Landis, C. Wardrip and J. Perry, "Navigation Technology Satellite (NTS) Low Cost Timing Receiver Development," in *Eighth Annual Precise Time and Time Interval (PTTI) Meeting*, held at US Naval Research Laboratory, Washington, D.C., 30 November - 2 December 1976, 85-103.

A compact timing receiver which receives and processes NTS ranging side tones has been developed. In its prime operating mode, the receiver outputs a space-craft-receiver range measurement in time units once each minute. The format of the output is compatible with NTS data processing system, which determines the time difference between the user's clock and a reference clock at the Naval Observatory. The receiver, which operates at P-band (335 MHz), is designed to used a minimum of RF and analog circuitry. The received ranging signals are quickly converted to low frequency, digital signals for processing under the control of INTEL-8080 microprocessor. Receiver operation is primarily automatic, requiring only initial operator setup via front panel controls.

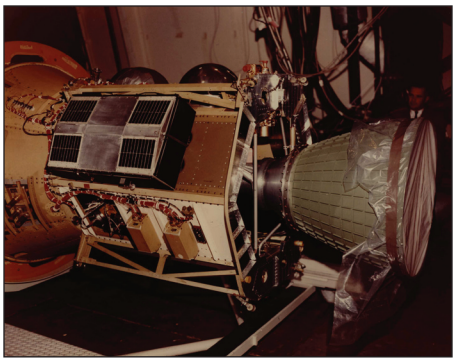
This paper describes the receiver and its operation, points out its advantages to a user requiring precise time at remote site at an economical price, and describes a typical application

W. G. Reid, T. B. McCaskill, O. J. Oaks, J. A. Buisson and H. E. Warren, "Effect of Space Vehicle Temperature on the Frequency of On-Orbit NAVSTAR Clocks," in *Proceedings of the 48th IEEE International Frequency Control Symposium*, held at Boston, Massachusetts, 1-3 June 1994, IEEE, 782-790.

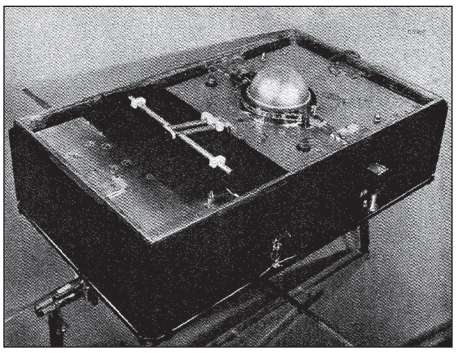
Analysis of the frequency of on-orbit Navstar clocks is performed by the Naval Research Laboratory using both broadcast and post-processed precise ephemerides. The phase offset between the Navstar clock and the reference clock is computed from pseudo-range measurements obtained by the five GPS monitor sites and by the U.S. Naval Observatory, Washington, D.C., precise-time site using precise-positioning-service dual-frequency, receivers which correct for selective availability. The frequency offset of the early Block I rubidium clocks was found to be highly correlated with the temperature of the space vehicle and consequently with the earth eclipse seasons. By providing subsequent space vehicles with rubidium clocks having additional temperature control this correlation was suppressed. The Block I cesium clocks, on the other hand, showed no sensitivity to the space vehicle temperature. Recently, however, two Block I cesium clocks and a Block I rubidium clock with the additional temperature control have evidenced temperature sensitivity and have shown strong correlation with the onset of the eclipse seasons. Frequency-offset histories show this correlation for the cesium clocks for the first time. Scatter diagrams used to measure the degree of correlation of the frequency with temperature yield temperature coefficients larger than those measured in the laboratory prior to launch.

W. G. Reid, T. B. McCaskill, O. J. Oaks, J. A. Buisson and H. E. Warren, "Common view time transfer using worldwide GPS and DMA monitor stations," in *27th Annual Precise Time and Time Interval (PTTI) Meeting*, held at San Diego, California, 29 November - 1 December 1995, NASA Conference Publication 3334, 145-157.

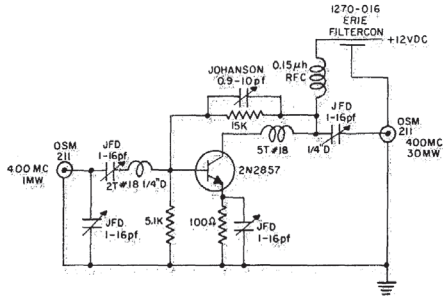
Analysis of the on-orbit Navstar clocks and of the GPS monitor station reference clocks is performed by the Naval Research Laboratory1 using both broadcast and post processed precise ephemeredes. The precise ephemeredes are produced by the Defense Mapping Agency (DMA)



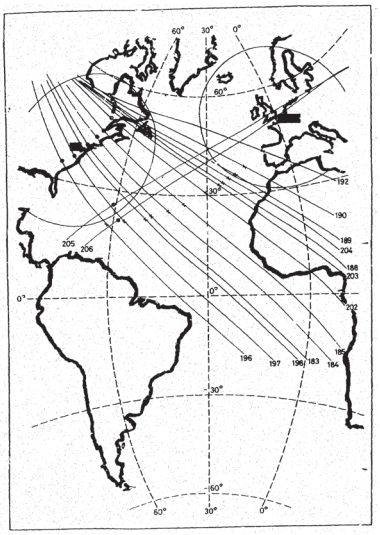
TIMATION I satellite on launch vehicle. (Space Applications Branch-1968, p. 2)



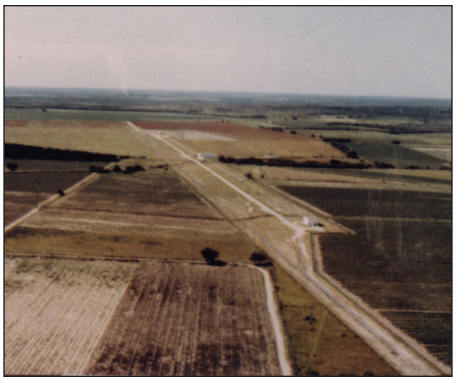
Dipole of TIMATION I satellite in its folded position. (Space Applications Branch-1968, p. 5)



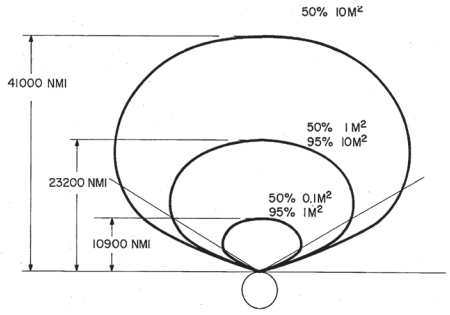
One of the 400-MHz amplifiers for the TIMATION I satellite. (Space Applications Branch-1968, p. 17)



Subsatellite positions for corresponding TCA at NRL (o) and RGO (x). (Smith-1975, p. 352)



Rio Grande transmitting station for Space Surveillance System. (NRL Photo)



Geometry of Space Surveillance System coverage. (Space Surveillance Branch-1961 NRLmr1147, p. 14)

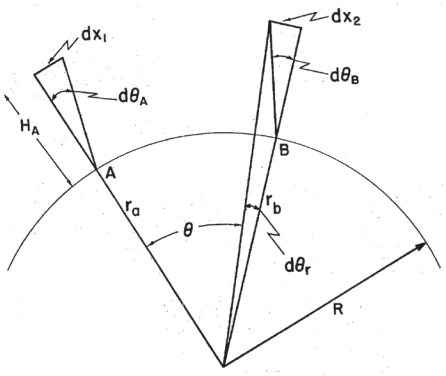
for each of the GPS space vehicles from pseudo-range measurements collected at five GPS and at five DMA monitor stations spaced around the world. Recently, DMA established an additional site co-located with the U.S. Naval Observatory precise-time site. The time reference for the new DMA site is the DoD Master Clock. Now, for the first time, it is possible to transfer time every 15 minutes via common view from the DoD Master Clock to the 11 GPS and DMA monitor stations. The estimated precision of a single common-view time transfer measurement taken over a 15-minute interval was between 1.4 and 2.7 nanoseconds. Using the measurements from all Navstar space vehicles in common view during the 15-minute interval, typically 3-7 space vehicles, improved the estimate of the precision to between 0.65 and 1.13 nanoseconds. The mean phase error obtained from closure of the time transfer around the world using the 11 monitor stations and the 25 space vehicle clocks over a period of 4 months had a magnitude of 31 picoseconds. Analysis of the low-noise time transfer from the DoD Master Clock to each of the monitor stations yields not only the bias in the time of the reference clock, but also focuses attention on structure in the behavior of the reference clock not previously seen. Furthermore, the time transfer provides a uniformly sampled database of 15-minute measurements that makes possible, for the first time, the direct and exhaustive computation of the frequency stability of the monitor station reference clocks. To lend perspective to the analysis, a summary is given of the discontinuities in phase and frequency that occurred in the reference clock at the Master Control Station during the period covered by the analysis.

W. G. Reid, "Continuous Observation of NAVSTAR Clock Offset from the DoD Master Clock Using Linked Common-View Time Transfer," in *28th Annual Precise Time and Time Interval (PTTI) Meeting*, L. A. Breakiron, ed. held at Reston, Virginia, 3-5 December 1996, 397-408.

Analysis of the on-orbit NAVSTAR clocks and of the Global Positioning System (GPS) and National Imaging and Mapping Agency (NIMA) monitor station reference clocks is performed by the Naval Research Laboratory (NRL) using both broadcast and postprocessed precise ephemerides. The precise ephemerides are produced by NIMA for each of the GPS space vehicles from pseudorange measurements collected at the five GPS and seven NIMA monitor stations spaced around the world. That the time reference for the NIMA Washington, D.C., monitor station is the DoD Master Clock has enabled synchronized time transfer every 15 minutes via Linked Common-View Time Transfer from the DoD Master Clock to the other eleven monitor stations. Summing the offset of a space vehicle clock from a monitor station time reference with the offset of the monitor station time reference from the DoD Master Clock yields the offset of the space vehicle clock from the DoD Master Clock for the period during which the space vehicle was in view of the monitor station. Repeating this procedure for each of the monitor stations produces continuous overlapping observations of the offset of the NAVSTAR clock from the DoD Master Clock. Following this procedure for the NAVSTAR 29 cesium clock for 118 days during which there were no anomalies in either the space vehicle clock for the Washington, D.C., monitor station time reference yielded a measurement noise with a standard deviation of 1.1 nanoseconds. This was reduced to an estimated measurement precision of 641 picoseconds by averaging overlapping measurements from multiple monitor stations at each observation time. Analysis of the low-noise clock offset from the DoD Master Clock yields not only the bias in the time of the space vehicle clock, but focuses attention on structure in the behavior of the space vehicle clock not previously observable. Furthermore, the uniformly sampled database of 15-minute measurements makes possible for the first time the exhaustive computation of the frequency stability of the space vehicle clocks.

W. G. Reid and O. J. Oaks, "Fourier transform for non-uniformly sampled data in the study of systematic errors in common-view time transfer," in *1998 IEEE International Frequency Control Symposium*, 27-29 May 1998, 254 -259.

A new mathematical formulation for the Fourier transform applicable to non-uniformly sampled data has been derived. The importance of this to the Global Positioning System (GPS) is identification of harmonics of the orbital period in the frequency of both the space vehicle and the ground reference clocks relative to the DoD Master Clock. The presence of such a periodicity was discovered in doing the exhaustive computation of frequency stability, i.e., in estimating the stability at sample times equal to every multiple of the basic sample period of the data as opposed to the common method of under-sampling the stability at a canonic set of sample times equally spaced along a logarithmic axis. Analysis of the frequency stability of the time reference at the Air Force GPS ground tracking station at Colorado Springs showed a pronounced periodic component at 2.99 hours --the fourth harmonic of the operational GPS space vehicle orbital period of 11.97 hours.



Geometry of the two-fence velocity determination. (Space Surveillance Branch-1961 NRLmr1147, p. 19)

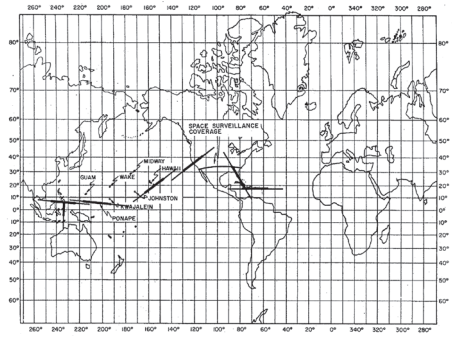
W. Reid, "Multiple-Path Linked Common-View Time Transfer (LCVTT)," in *31st Annual Precise Time and Time Interval (PTTI) Meeting*, 7-9 December 1999, 43.

Analysis of the on-orbit Navstar clocks and of the GPS monitor station reference clocks is performed by the Naval Research Laboratory [1] using both broadcast and post-processed precise ephemerides. The precise ephemerides are produced by the National Imagery and Mapping Agency (NIMA) for each of the GPS space vehicles from pseudorange measurements collected at five Air Force and at ten NIMA GPS monitor stations spaced around the world. The time reference at the NIMA Washington, D.C. site, colocated with the U.S. Naval Observatory precise-time site, is the DoD master clock. Hence, it is possible to transfer time via linked common-view every fifteen minutes from the DoD master clock to the remaining fourteen Air Force and NIMA GPS monitor stations. Linking stations serially, although computationally efficient, was found to suffer several disadvantages. The most serious of these was the accumulation of gaps in the time transfer to a remote site. A secondary disadvantage of the serial linking was the dominance in the linking process of the short-term noise from a single noisy site. Using multiple common-view paths overcomes both of these defects by supplementing the link that propagated the gap in the data and by providing multiple independent measurements that can be averaged to reduce the measurement noise. An additional benefit of the multiple-path method is an improvement in the continuous coverage of the Navstar space vehicle clocks; i.e., in referencing the observations of a space vehicle clock by each of the monitor stations back to the DoD master clock. Improvement was manifested by an increase in the number of estimates obtained of the offset of the space vehicle clock from the DoD master clock and by a decrease in the short-term noise of these estimates.

Receiving station for Space Surveillance System. (NRL Photo)

W. Reid, T. McCaskill, M. Largay, O. J. Oaks and J. Buisson, "Performance of GPS Block IIR Rubidium Clocks," presented at the ION GPS 2000, 13th International Technical Meeting of the Satellite Division of the Institute of Navigation, Salt Lake City, Utah, 19-22 September 2000, Institute of Navigation, 937-46.

The objective of this paper is to report to the community the performance of the Global Positioning System (GPS) Block IIR rubidium clocks. The performance of the on-orbit Block IIR rubidium clocks is, in general, superior to that of all other clocks in the constellation. The performance of some of these clocks has, however, been characterized by repetitive anomalies. For example, while the drift of most of these clocks smoothly and asymptotically approaches zero, the drift of the Navstar 46 timing signal shows a pronounced oscillation with a period of approximately 12 days. The Navstar 43 timing signal has shown small repetitive

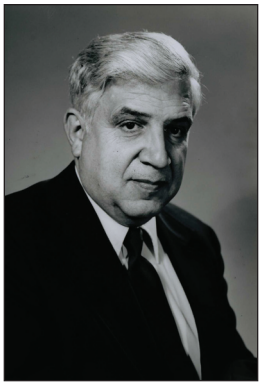


Complete space surveillance system with 180 degree longitudinal coverage and equitorial coverage. (Space Surveillance Branch-1961 NRLmr1147, p. 6)

discontinuities in the frequency, as has been the performance of Serial Number 28 under test at the Naval Research Laboratory. But unlike either of the two clocks in the laboratory, or unlike any of the 59 GPS Block II/IIA on-orbit clocks activated thus far, the timing signal originating with Serial Number 6 on Navstar 43 shows repetitive spiking in the phase. There have been four episodes which occurred in February and August 1999 and in February and May 2000, which do not appear to be correlated with the occurrence of the eclipse seasons. But in spite of the reported anomalies, the frequency stability of the Block II rubidium clocks is superior to that of all other atomic frequency standards in the GPS constellation. Estimation of the frequency stability of the on-orbit Block II rubidium clocks for a sample time of one day is limited by receiver noise. However, results from the laboratory testing of this type of clock suggest that the stability for a sample time of one day may well be measurable in parts per l0^15.

V. H. Ritz, V. M. Bermudez and V. J. Folen, "Analysis of Degraded Hydrogen Dissociator Envelopes by AES," in *Ninth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held at Washington, D.C., 29 November - 1 December 1977, NASA Technical Memorandum 78104, 353-369.

The performance of hydrogen dissociators used in atomic clocks is known to degrade after prolonged operation, requiring large increases in rf power to maintain a constant output of atomic hydrogen. Auger electron spectroscopy (AES) has been used to characterize the inner surfaces of Pyrex dissociator envelopes obtained from NASA Goddard Space Flight Center and Smithsonian Institution Astrophysical Observatory hydrogen masers. Prolonged operation of the dissociators leads to buildup of a dark film incorporating large quantities of carbon in its amorphous and carbide forms and smaller amounts of nitrogen. Possible mechanisms by which the film could interfere with the operation of the dissociator are given which involve its electrical conductivity and its role as a catalyst in the recombination of atomic hydrogen.



Roger Easton, Branch Head, Space Applications Branch. (NRL photo)

Rocket Development Branch, *A Scientific Satellite Program*, NRL Memorandum Report 466, Naval Research Laboratory, Washington, D.C., 13 April 1955.

This is a proposal for an earth satellite program. It proposes (1) a useful purpose for the satellite, (2) a method of achieving that purpose, and (3) an organization capable of implementing the method.

Rocket Development Branch, Rocket Sonde Branch and Electron Optics Branch, *A Scientific Satellite Program*, NRL Memorandum Report 487, Naval Research Laboratory, Washington, D.C., 5 July 1955.

This is a proposal for an earth satellite program. It proposes (1) a useful purpose for the satellite, (2) a method of achieving that purpose, and (3) an organization capable of implementing the method.

T. Rodilosso, "NRL alumnus Roger Easton to speak at Sigma Xi's upcoming lecture," *Labstracts*, 22 October 2001, 8.

NRL alumnus Roger Easton will be at the Laboratory to speak on "Time Synchronization and GPS"..

M. W. Rosen, *The Viking Rocket Story* (Harper & Brothers, New York, 1955).

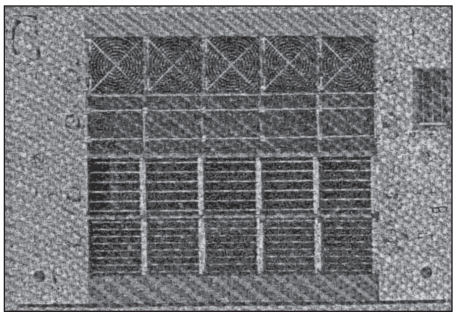
M. W. Rosen, "Twenty-Five Years of Progress Toward Space Flight," *Jet Propulsion*, November issue, 623-6 (1955).

By the year 1930, in which the American Rocket Society (then called the American Interplanetary Society) was established, the advance toward space flight had entered its second phase, the period of experimental preparation.

M. W. Rosen, "Influence of Space Flight on Engineering and Science," *Nature* **176** (4495), 1190-3 (1955).

Within the past few years many scientists have predicted seriously and confidently that human beings from the Earth would, in the foreseeable future, travel to the Moon and the nearer planets. The ranks of those who would dispute this prospect are diminishing rapidly. Although much of the progress is still guarded military necessity, space flight is emerging as an activity in its own right-- one that can command the efforts of many engineers and scientists.

In the United States the exploration of the upper atmosphere, the frontier to space, is being confuted vigorously. Pilots of rocket aircraft have experienced conditions approximating to those in free space, if only for a few minutes. The effect of space flight upon the human organism is being investigated---the US Air Force maintains a Department of Space Medicine. There is an international organization devoted to the promotion of space travel, and there are space flight societies in twenty-three countries.



Solar cell experiments 1 through 4 on TIMATION III satellite. (Statler-1974, p. 374)

M. W. Rosen, "Placing the Satellite in Its Orbit," *Proceedings of the Institute of Radio Engineers* **44** (6), 748-751 (1956).

The VANGUARD satellite launching vehicle is a three-stage rocket of which the first two stages are guided and the third stage is maintained in a fixed orientation while its firing. The first stage, an improved Viking, serves primarily to raise the remaining stages to altitude . The second stage, another liquid-propellant rocket, contains the guidance for the three-stage vehicle and, in addition, supplies some of the propulsive energy. The third stage, a solid-propellant rocket, is ejected from the second stage at orbital altitude and provides about half of the required orbital velocity.

The VANGUARD launching vehicle system was chosen from a number of possible two- and three-stage vehicle combinations. It represents the smallest satellite launching vehicle consistent with the present state of rocket development.

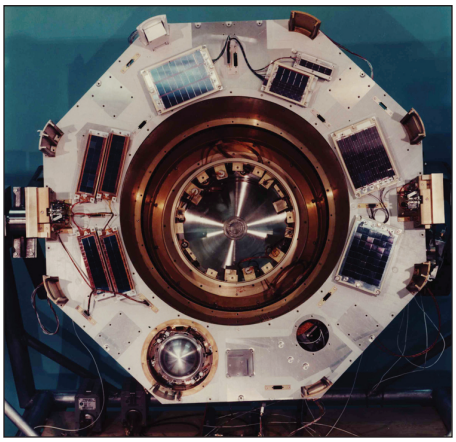
M. W. Rosen, "October 4, 1957: Sputnik Beeps, America Responds," *Astronautics & Aeronautics* (October), 20-23 (1977).

A Soviet engineering triumph, orbiting the first Earth satellite, shakes up Americans and puts them on the move.

Satellite Applications Branch, *The Timation I Satellite*, NRL Report 6781, Naval Research Laboratory, Washington, D.C., 18 November 1968.

An experimental navigation satellite was launched on May 31, 1967, by NRL under a program sponsored by the Naval Air Systems Command. A passive ranging technique has been used both for the navigation of fixed and moving vehicles and for the accurate transfer of time between separated points.

This report discusses the navigation principles involved but is primarily concerned with the components of the satellite.



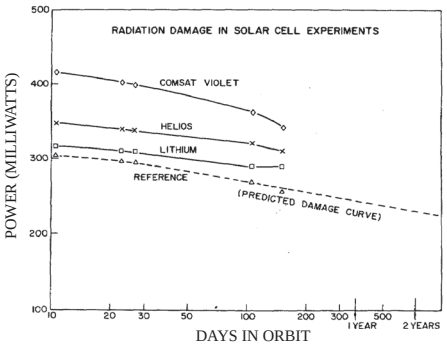
Solar cell experiments on the top deck of NTS-1. (Statler-1974, p. 509)

H. S. Satz, D. B. Cox, Jr., R. L. Beard and G. P. Landis, "GPS Inertial Attitude Estimation Via Carrier Accumulated-Phase Measurements," *Navigation: Journal of The Institute of Navigation* **38** (3), 273-84 (1991).

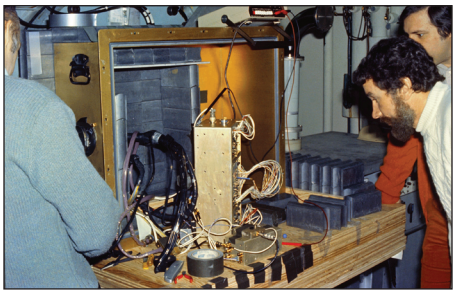
This paper describes the design and simulation of an integrated GPS/INS that accomplishes space vehicle navigation and attitude estimation. The simulation contains models of an inertial measurement unit (IMU), a GPS receiver processing signals from an array of antennas placed on the spacecraft placed on the spacecraft structure, and an integrated navigation.

Interferometric equations are employed to process GPS carrier accumulated-phase measurements from precise antenna locations in the user vehicle. Vehicle orientation in inertial space is then obtained by relating baseline-difference phase measurements to orientations of antenna baselines relative to satellite line-of-sight vectors.

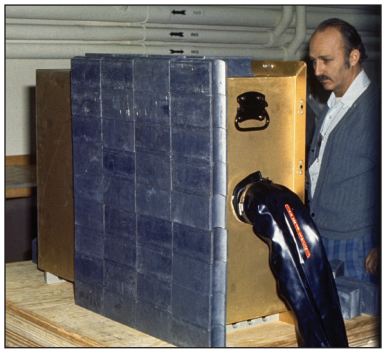
The method of GPS-aided attitude estimation described herein is distinguished from other methods in that it does not employ search algorithms to resolve



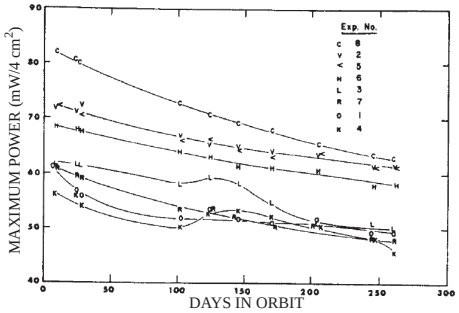
The effect of trapped radiation damage on the maximum power output of the solar cell experiments on NTS-1. (Statler-1974, p. 511)



Setting up for a radiation exposure experiment. (NRL photo)



Shielding in place for radiation exposure. (NRL photo)



Maximum power values normalized to four cm^2 for the TIMATION III (NTS-1) solar cell experiments. (Statler-1975, p. 193)

the carrier phase cycle ambiguity is modeled as a random process and is included as an error state of a statistical filter. As a result, the attitude estimation time history evolves directly for any dynamic environment.

C. A. Schroeder, C. H. Looney, Jr. and H. E. Carpenter, Jr., *Project Vanguard Report No. 18: Minitrack Report No. 1 - Phase Measurement*, 4995, Naval Research Laboratory, 26 July 1957.
NRL4995 LIMITED DISTRIBUTION

H. M. Smith, N. P. J. O'Hora, R. L. Easton, J. A. Buisson and T. B. McCaskill, "International Time Transfer Between USNO and RGO via NTS-1 Satellite," in *Seventh Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held at Washington, D.C., 2-4 December 1975, 341-355.
Time transfer data was taken at NRL and RGO during July-August 1975. The NRL station was reference to USNO via portable clock and Loran-C. The data indicates continuous sub-microsecond clock, synchronization during the experiment.

H. M. Smith, R. L. Easton, J. A. Buisson and T. B. McCaskill, "Sub-Microsecond Intercontinental Time Comparisons by Satellite," in *Euromeas 77: European Conference on Precise Electrical Measurement*, IEE Conference Publication No. 152, 5-9 September 1977, Institution of Electrical Engineers, 87-89.
Navigation Technology Satellite Number 1 (NTS-1) was launched July 14, 1974 as part of the NAVSTAR Global Positioning System (GPS) program. The orbit is near circular at an altitude of 13610 ± 137 kilometers with an inclination near 125 degrees.
The satellite contains two rubidium frequency standards and a high performance crystal oscillator for generating ranging signals transmitted to suitable receiving stations located in the U.S., Canal Zone, England and Australia. Orbits are generated at NSWC, Dahlgren, VA from data derived from these signals so one can know the past, present and future positions of the satellite.

Space Applications Branch, *Ranging and Velocity Experimental Equipment*, NRL Report 6633, Naval Research Laboratory, Washington, D.C., 18 April 1968.
NRL6633 LIMITED DISTRIBUTION

Space Applications Branch, *Timation Development Plan*, NRL Report 7227, Revised Edition, Naval Research Laboratory, Washington, D.C., 2 March 1971.
TIMATION (Time Navigation) is a technological development program designed to study, identify and develop the critical components and make measurements necessary to describe a navigation system which meets JCS requirements.
The purpose of the Timation navigation system development plan is to describe the technical parameters, tradeoffs, experiments, and costs encompassing the implementation of a satellite position fixing and navigation system that meets the requirements promulgated by the Joint Chiefs of Staff (JCS) Navigation Study Panel in 1968. This navigation system provides continuous all weather instantaneous readout to an un1imited number and variety of users on a worldwide basis.

Space Surveillance Branch, *An Advanced Space Surveillance System*, NRL Memorandum Report 1147, Naval Research Laboratory, Washington, D.C., 8 February 1961.
Requirements for a space surveillance system are now being generated by the various unified and specified commands. While details remain to be determined, in general it may be stated that the requirements express a need for three categories of coverage: (a) early detection, (b) coverage of low inclinations, and (c) coverage at extreme altitudes.
A minimum-cost, space surveillance system which provides early orbit

determination of all satellites out to nearly 30,000 nautical miles is described. The system consists of U.S. installation, to provide refined orbital data on most known satellites, and special installations, to provide data on orbital elements of new satellites and special orbits. The special installations would be located on islands in the Pacific and Caribbean to provide extended longitude coverage and to provide equatorial coverage for both low-period and 24-hour-period orbits.

The detection device described utilized high-powered, continuous-wave transmitters, fixed antennas, a nonambiguous ranging technique, and precise determination of angles to give a good orbit (error in period approx. 0.1%) for satellites above 350 nautical miles (seen by two stations) and a less accurate orbit for satellites below that altitude seen by one station (error in period 0.1% to 1%).

The proposed initial installation at Truk-Ponape and in Florida provides 30,000 mile coverage for the island installation and lower latitude coverage for the U.S. experimental installation.

Space Technology Hall of Fame, "R.L. Easton, 1998 Inductee – Global Positioning System (GPS) Technology," http://www.spacetechhalloffame.org, 1998, captured 23 September 2003.

Technology Innovators:

Dr. Malcolm R. Currie, Roger L. Easton, Dr. Ivan A. Getting, Col. Gaylord B. Green, James R. Henry, Dr. Richard B. Kerschner, Walter C. Melton, Dr. (Col.) Bradford Wells Parkinson, Richard Schwartz

Innovating Technology Companies:

The Aerospace Corporation, General Dynamics, Johns Hopkins University, Applied Physics Laboratory, Magnavox, Naval Research Laboratory, NAVSTAR GPS Joint Program Office, Space & Missile System Center, Rockwell-Collins, Rockwell International, Texas Instruments, U.S. Army Yuma Proving Ground

Technology Overview

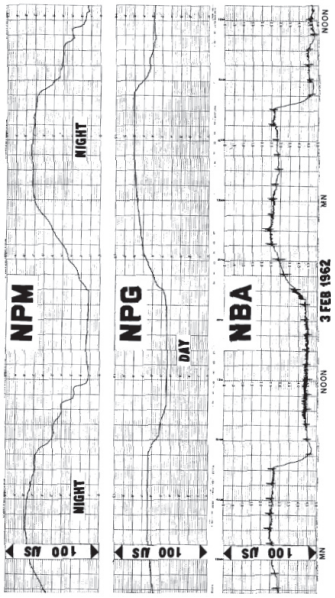
The Global Positioning System (GPS) program began in 1973 when the U.S. military services and the Defense Mapping Agency combined resources to develop a highly accurate space-based navigation system. Functions not originally envisioned, such as communications system synchronization, search and rescue, precision approaches and landings, and GPS-assisted munitions, have come into common usage within the military community.

GPS is managed by the NAVSTAR GPS Joint Program Office at the Space and Missile Systems Center near Los Angeles. This multinational organization develops, acquires, and sustains the 24-satellite constellation, a worldwide satellite control network, and more than 120,000 receiver systems that provide positioning data and other services to users worldwide. As a dual use (military and civil) space-based radionavigational signal jointly controlled by the Department of Defense and Department of Transportation, Headquarters Air Force Space Command champions GPS requirements from concept to capability to meet validated and approved civil and military needs. This includes maintaining the Standard Positioning System (civil signal) and the Precise Positioning System (military and authorized signal) on a continuous, worldwide basis.

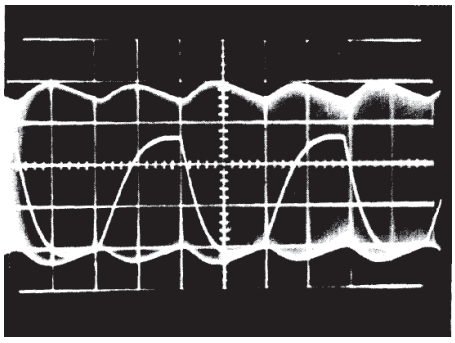
Ever-growing commercial applications increasingly impact everyone as this technology continues to mature. These ever-expanding uses include applications in land, sea and air transportation; surveying and geodesy; mapping, charting, and geographic information systems; geophysical applications; meteorological applications; agriculture; scientific research; and recreational uses.

Spacecraft Engineering Department, "Webpage of the SED," http://code8200.nrl.navy.mil, 2005, captured 3 March.

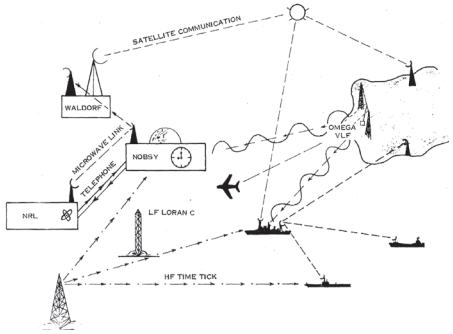
Web pages of the Spacecraft Engineering Department (SED) of the Naval Research Laboratory, 3 March 2005, http://code8200.nrl.navy.mil.



Recordings of the phase variation from three VLF stations, as received in Washington, D.C. NPM at 19.8 kc in Hawaii, NPG at 18.6 kc in Washington State, and NBA at 18 kc in the Canal Zone. (Stone-1962, p. 237)

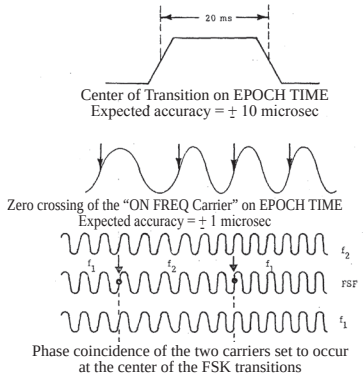


Antenna voltage and the transient effect resulting from frequency shift when the phase is controlled and no phase discontinuity exists. Phase shift appears as a sloping line. (Stone-1964, p. 405)



The worldwide dissemination of precise time, at present. NRL has been active in the field of time and frequency since the early 1920's. (Stone-1970, p. 120, 126)

Isidor I. Rabi, Nobel Laureate in Physics, speaks at the presentation of NRL's Hydrogen Maser I to the Smithsonian Institution. (NRL Photo)



New time signal format. (Stone-1970, p. 14)

J. H. Spencer, E. B. Waltman, K. J. Johnston, N. J. Santini, W. J. Klepczynski, D. N. Matsakis, P. E. Angerhoger and G. H. Kaplan, "Comparison of VLBI, TV, and Traveling Clock Techniques for Time Transfer," in *Thirteenth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, NASA Conference Publication 2220, held at Naval Research Laboratory, Washington, D.C., 1-3 December 1981, 231-41.

A three part experiment was conducted to develop and compare time transfer techniques. The experiment consisted of: I. a VLBI between Maryland Point Observatory at Riverside, Maryland and NRAO at Green Bank, West Virginia; II. a high precision portable clock time transfer system between the two sites coordinated by the U. S. Naval Observatory in Washington, D. C.; and III. a television time transfer between the U. S. Naval Observatory and the Maryland Point Observatory using a local Washington, D. C, television station, WTTG.

A comparison of the VLBI and traveling clock shows each technique can perform satisfactorily at the five nsec level. There was a systematic offset of 59 nsec between the two methods, which we attributed to a difference in epochs between VLBI formatter and station clock.

The VIBI method had an internal random error of one nsec at the three-sigma level for a two-day period. Thus, the Mark II system performed well, and VLBI shows promise of being an accurate method of time transfer.

The TV system, which had technical problems during the experiment, transferred time with a random error of about 50 nsec.

W. Stapor, B. Henson, M. Frank, P. McDonald, G. Snyder and J. Nelson, "On-orbit Fractional Frequency Shifts of Precision Crystal Oscillators," in *Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Meeting*, 29 November 2000, (Presentation abstract only. Not included in published proceedings.) The combination of Solar activity and the Earth's own geomagnetic shielding modulates the energetic proton environment. Over the past three years, the ambient integral proton flux with energy greater than 10 MeV in the free space between the Earth and the Sun has been small and even declining from 2 to 1 particles/(cm2×s×sr). However, during the same period, there have been at least ten times when the integral flux of protons with energy greater then 10 MeV has greatly exceeded 10 particles/(cm2×s×sr) by two to three orders of magnitude for periods of time ranging from hours to days. These periods of increased proton flux are a concern to space missions with precision timing applications using crystal oscillators. We present a look at some crystal oscillator on orbit performance during the last three years concentrating on the known high flux times and compare to ground measurements.

Quartz crystal oscillators are arguably the most widely used timing and synchronization sources for microelectronics applications. In general, crystal oscillators have many features which make them very desirable for use in space applications including relatively stable performance, inherent rugged design, low cost, small size, and low power requirements. Over the past 30 years or so, crystal oscillators have been successfully used in many space applications, and we anticipate their use to continue. However, future space applications will demand more timing and synchronization performance to meet mission needs and requirements.

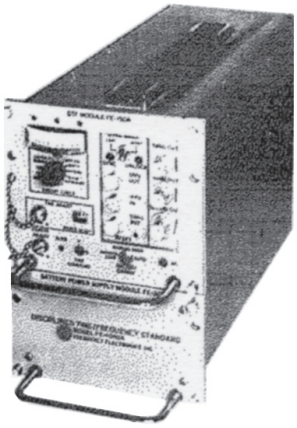
It has been observed that proton radiation introduces fractional frequency drift in measurable amounts that may exceed not only long term system timing drift requirements but also the instantaneous timing drift requirements usually expressed as the fractional frequency drift, Df/f, per minute. Therefore in precision timing and synchronization space applications that use crystal oscillators, it becomes important to understand the crystal response to proton radiation.

This is a first look at on-orbit crystal oscillator performance directly correlated with known times of increased proton flux. While oscillator performance has been reasonably acceptable, we anticipate the future timing and

synchronization requirements to challenge crystal oscillator performance in the proton radiation environment for space applications.

R. L. Statler and F. C. Treble, "Solar Cell Experiments on the TIMATION III Satellite," presented at the International Conference on Photovoltaic Power Generation, Hamburg, Germany, 25-27 September 1974, 369-377.

Twelve solar cell experiments were on the Naval Research Laboratory TIMATION III (NTS-1) satellite launched on 14 July 1974, into a 13,620 km circular orbit at an inclination of 125 degrees. The experiment comprises: 2 ohm-cm n/p, lithium-diffused p/n, violet n/p, p+ back surface field, and ultra-thin wrap-around contact cells. The short-circuit current of the experiments ranges from 2 to 12 percent higher in space than under solar simulators. During the 5 year life of the satellite, the experiments will be exposed to radiation equivalent to 2 x 10^5 1-MeV electron cm^-2 and to nearly 5500 thermal cycles.



Disciplined time/frequency standard. (Stone-1971, p. 214)

R. L. Statler, "Results of the First 150 Days of the NTS-1 Solar Cell Experiments," in *Proceedings of the Sixth Precise Time and Time Interval (PTTI) Planning Meeting*, X-814-75-117, held at U.S. Naval Research Laboratory, 3-5 December 1974, NASA, 503-11.

Twelve solar cell experiments were on the Naval Research Laboratory NTS-1 satellite launched on 14 July 1974, into a 13,620 km circular orbit at an inclination of 125 (degrees). The experiment comprises: 2 ohm-cm n/p, lithium-diffused p/n, violet n/p, p+ back-surface field, and ultra-thin wrap-around contact cells. The short-circuit current of the experiments ranged from 2 to 12 percent higher in space than under solar simulators. During the 5 year life of the satellite, the experiments will be exposed to radiation equivalent to 2 x 10^15 1-MeV electron cm^-2 and nearly 5500 thermal cycles.

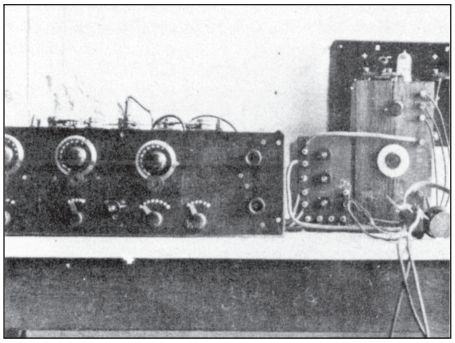
Captain Edward E. Henifin, NRL Commanding Officer, with Dr. Rabi and Dr. Alan Berman, NRL Director of Research, at the Smithsonian presentation. (NRL Photo)

R. L. Statler and D. H. Walker, "Solar Cell Experiments on the NTS-1 Satellite," presented at the 11th IEEE Photovoltaic Specialists Conference, Scottsdale Arizona, 6-8 May 1975, 190-193.

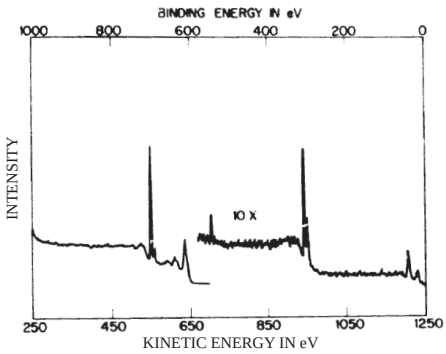
Twelve solar cell experiments were on the Naval Research Laboratory TIMATION III (NTS-1) satellite on 14 July 1974, into a 13,620 km circular orbit at an inclination of 125 degrees. This experiment comprises: two ohm-cm n/p, lithium-diffused p/n, violet n/p, p+ back surface field, and ultra-thin-wrap-around contact cells. During the five year life of the satellite the experiments will be exposed to radiation equivalent to 2 x 10^15 1-MeV electron cm^-2 and to nearly 5500 thermal cycles. After 261 days in orbit the loss in power ranged from 15.0 to 24.4 percent. Some of the radiation damage in the two lithium cell panels annealed temporarily between days 100 and 200 as the panel temperatures warmed up. The power degradation rate of the two ohm-cm solar panel can be fitted by a fluence of ~1.2 x 10^14 1-MeV e/cm^2 -day.

R. L. Statler, D. H. Walker and R. J. Lambert, "The NTS-1 Solar Cell Experiment After Two Years in Orbit," presented at the 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, 15-18 November 1976, 208-215.

Twelve experimental solar cell modules were placed on the Naval Research Laboratory Navigation Technology Satellite One (NTS-1) which was launched on 14 July 1974 into a 13,529 km circular orbit with an inclination angle of 125 degrees. The experimental cell configurations include: typical flight-quality two ohm-cm n/p cells, lithium diffused p/n cells with aluminum metallization, enhanced uv response (violet) solar cells, shallow-junction n/p cells with p+ back surface field, and ultra-thin wraparound contact cells. During the first two years in space, the experiments have been exposed to particle radiation fluence which is calculated to be equivalent to 8 x 10^14 1-MeV electron cm^-2 and to



First crystal-controlled high-frequency transmitter - 1924. (Taylor-1948, p. 18)



X-ray photoelectron spectrum of the brown portion of the FEP Teflon from a used hydrogen maser. (Turner-1977, p. 377)

2500 thermal cycles, with solar panel temperatures rising to 98oC. The loss in maximum power after 753 days ranged from 32.4 percent to 47.5 percent.

S. Stebbins, A. Gifford and R. L. Beard, "A Comparison of Time Transfer Techniques," in *21st Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Redondo Beach, California, 28-30 November 1989, 215-22.

In the development of timing systems for the Global Positioning System (GPS), a clock ensemble has been installed at the Master Control Station for GPS at Falcon Air Force Station, Colorado Springs, Colorado. A single-frequency, Clear/Acquisition (C/A) GPS receiver is integrated into that system to perform time comparisons with the U. S. Naval Observatory (USNO). Having data from these two sites provided an opportunity to compare different techniques for time transfer and to examine their relative merits and performance. Three basic techniques were examined: common-view, melting-pot, and non-simultaneous common-view. The results and a comparison of the different techniques will be presented.

S. R. Stein and G. A. Gifford, "Software for two automated time measurement systems," in *38th Annual Frequency Control Symposium*, held at Philadelphia, PA, 29 May - 1 June 1984, 483-6.

The purpose of this paper is to inform the frequency control community of the availability of several computer programs which will assist anyone who needs to make automated time and frequency measurements and analyze the data. The text below summarizes the capabilities of the equipment and the programs. A reader who feels that this approach may be useful for his application can find more details on the equipment in earlier papers. (1, 2) A detailed description of the programs, an operations manual, and source code may be obtained by writing to one of the authors (Gifford) and enclosing a blank data cassette.(3)

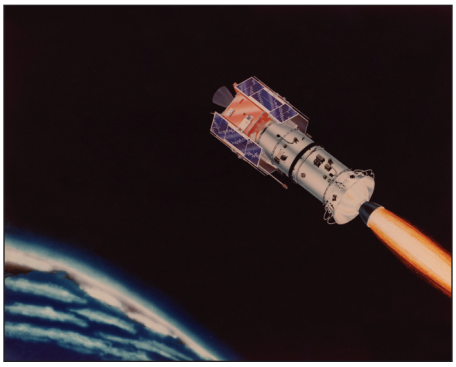
R. R. Stone, Jr., "Synchronization of Local Frequency Standards with VLF Transmissions," in *Sixteenth Annual Symposium on Frequency Control*, held at Atlantic City, New Jersey, 25-7 April 1962, 227-40.

Five US Navy VLF transmitters have been stabilized in frequency by the US Naval Research Laboratory and are being controlled by the Naval Observatory to within several parts in 10^10 of their assigned frequencies. Station NBA in the Canal Zone is the primary station for this service, and the only one, which, at present, transmits precise time signals at constant frequency.

By monitoring its phase relative to the received VLF signals, a local standard may be maintained in frequency to within a part in 10^10. Account must be taken of propagation time delay changes caused by the diurnal shifts and other disturbances of the ionosphere.

Several techniques for monitoring the VLF signals are available. The best choice depends on the degree of precision required of the measurement, the received signal strength, the location of the receiver, and the allowable expense. For maintaining synchronism of local frequency standards with the received signal, the receiver must incorporate certain design features which pertain to the i-f bandpass characteristics, frequency doubling in the RF or IF sections, synthesizer type used, provision of servo and phase shifter capability, etc.

Current NRL designs include the features found desirable through the Laboratory's experience over the past several years. Capabilities include 100 cycle step tuning and means to shift receiver resonance from one signal to another and return without the loss of phase continuity of either signal.



The NTS-2 satellite with solar paddles folded during launch. (Walker-1979, p. 5)

R. R. Stone, "Frequency synthesizing techniques permitting direct control and rapid switching," in *17th Annual Frequency Control Symposium*, held at Fort Monmouth, NJ, 27-29 May 1963, 587-601.

The use of precisely controlled frequency is increasing. A necessary item in the use of the available stability is the frequency synthesizer. A synthesizing system, developed at NRL, is described in this paper. A number of desirable characteristics is provided.

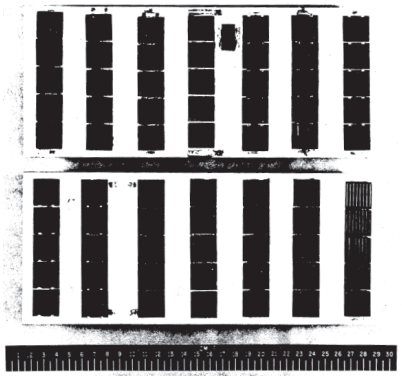
R. R. Stone and T. H. Gee, "VLF frequency synchronization provided with FSK capability," in *18th Annual Frequency Control Symposium*, held at Fort Monmouth, NJ, 4-6 May 1964, 395-406.

The U.S. Navy has established a system for worldwide synchronization of frequency through the stabilization of the carriers of its high power VLF transmitters. Local oscillators at remote points may be synchronized to within one part in 10^10 by monitoring the relative phase between a locally derived signal at the signals received from these transmitters.

At present, these stations are transmitting in the interrupted or keyed continuous wave mode. In the future, it is contemplated that they will be operated in a frequency shift mode using two closely spaced frequencies (carriers). The high Q, narrow band transmitting antenna system which must be employed at VLF to obtain good efficiency limits the magnitude and speed of the frequency shift. To be useful for phase comparison, the phase of successive intervals of at least one of the two frequencies must be continuous. Consequently, the possibility of phase discontinuity due to switching presents a major problem.

A frequency-shift system has been developed which synchronizes the time of switching with the zero crossing of the difference frequency (beat) between the two carriers and thereby precisely controls the rate of shift. The side-bands produced are within the limits allowed by the passband of the antenna system. Phase discrepancies between the keying rate and the beat frequency of the two carriers are compensated by servo adjustment of the nonstabilized carrier.

At present, the 7.42 teletype code is used. However, exact phase synchronism is not available under these conditions. In a solution to this problem, the carrier is allowed four possible phase positions (one at each 90 degrees). A multiplication of the received signals by four is necessary to allow phase comparison. The need for such measures will be eliminated when an equal-length code is adopted.

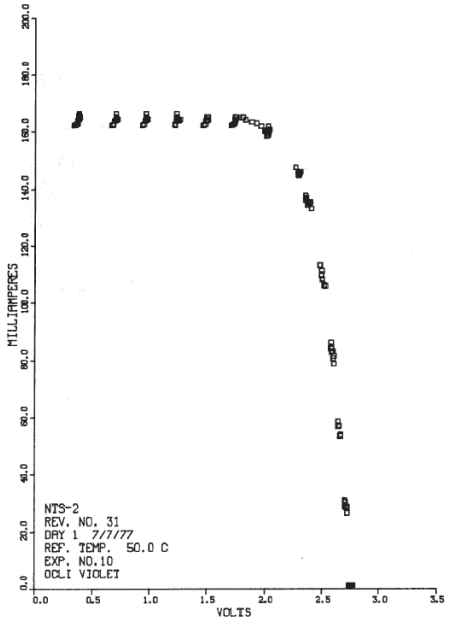


The NTS-2 solar cell experiment modules as mounted on the flight panels. (Walker-1979, p. 9)

R. R. Stone, "Frequency Synthesizers," in *21st Annual Frequency Control Symposium*, held at Fort Monmouth, NJ, 24-26 April 1967, 294-307.

The use of frequency synthesizers has greatly increased in the past decade. They have now assumed an essential role in communication and automatic testing systems. Many systems have been developed and as a result certain practical guidelines for the development of new systems have emerged.

Several techniques of frequency synthesis have been more successful and more widely used than others, particularly, the re-entrant mixer type, the digital divider type, and the repetitive mixing and dividing type. Practical applications and limitations of these techniques are discussed, and some of the design criteria for new instrumentation considered.



Typical current-voltage data curve as received from the NTS-2 satellite, corrected for solar intensity, sun angle and to a temperature of 50 degrees C. (Walker-1979, p. 6)

R. Stone, "Microwave, Optics, Lasers, and Other Exotic Systems," in *Proceedings from (the Second) Precise Time and Time Interval (PTTI) Strategic Planning Meeting*, Vol. 1, held at Naval Research Laboratory, Washington, D.C., 10-11 December 1970, 120-8.

It is good to work in a real world if possible, and the real world in time and frequency has had a look over the years as shown in Figure 1. NRL has been active in this field since the early 1920's. The solid curve represents what the real need has been over the years in precision time and frequency, and the dotted curve represents the state-of-the-art. In the beginning years of electronics, time and frequency were thought of separately. Tuning forks, crystals, etc. were used to control frequency; pendulums and other similar devices were used to control time. For the greater part of the time,

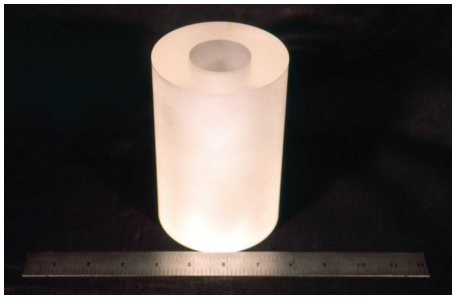
the state-of-the-art in time and frequency has been a factor of 10 greater in accuracy than was actually needed. Communication during this period was very simple and the time/frequency problems could be very easily met.

A major breakthrough in time/frequency techniques occurred with the advent of the ring crystal in 1930…

About 1960, frequency synthesizers were developed which allowed a much more precise control of transmission frequencies…

About 1950, things began to change. More and more precision was being required in frequency and time…

The aim of the time and frequency program at NRL is to provide a practical path by which users of precision time and frequency can refer to a common worldwide standard at the Naval Observatory…



Sapphire maser cavity. (White-1980, p. 505)

R. Stone, "VLF," in *Proceedings from (the Second) Precise Time and Time Interval (PTTI) Strategic Planning Meeting*, Vol. 1, held at Naval Research Laboratory, Washington, D.C., 10-11 December 1970, 6-18.

Since 1960 the Navy has employed its high-powered VLF system as a means of rating precision frequency oscillators at remote points. The wavelengths of these frequencies (15 KHz to 30 KHz) are sufficiently long, compared to variations in the length of the propagation path, that phase tracking of the received carrier at remote points, even after several reflections, can easily be accomplished. Atomic standards at the transmitter provide frequency control of better than one part in 10^11 and permit the rating of oscillators at the received point to better than one part in 10^10. Prior to this system, HF radio time signals were employed which had an accuracy of about 1 msec. This system was capable of rating oscillators to about one part in 10^8 on a day-to-day basis. At the present time, there are seven of these high-powered VLF transmitters as shown in Figure 1. (A recent installation has been made, NDT, in Yosami, Japan.) New antenna systems are being installed in Hawaii and Annapolis. Some of these stations have been operating since the mid-1930's, at which time they employed tuned circuits at the input and intermediate stages. At the present time, all stations have been updated with broadband amplifiers and they employ tuning only at the output/antenna. The newer system greatly simplifies the transmission of time signals.

R. R. Stone, T. H. Gattis, R. C. Petit and T. N. Lieberman, "Time control of frequency shift keyed transmissions at VLF," in *25th Annual Frequency Control Symposium*, held at Fort Monmouth, NJ, 26-8 April 1971, 152-8.

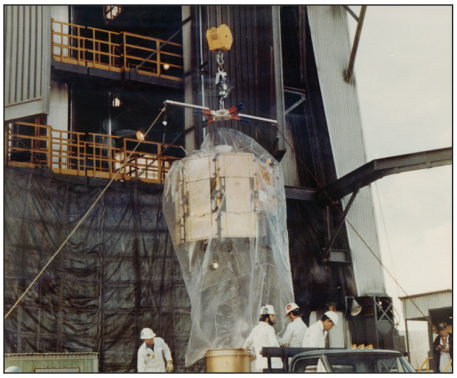
Since 1960, the Navy has provided phase stabilized transmissions from its high powered VLF communications stations as a means for rating precision frequency oscillators at remote points. Recently, emphasis has been placed upon adding precision time reference capabilities to these transmissions.

A system has been developed by which the point of transition of the frequency shifted signal can be controlled at a precise rate and a defined time during normal communications periods. Means have also been developed to permit the transmission of scheduled time signals.

The time of the frequency shift transition, the phase coincident point between the MARK and SPACE frequencies and the zero crossing of the positive slope of the "ON frequency" carrier are controlled to +/- 1 microsecond of the station clock. Cesium beam standards and the associated clocks at the station are referenced to the U.S. Naval Observatory via "flying clocks" or the DSCS satellite time transfer system.

The first installation of this system has been made at station NWC at the Harold E. Hold Communications Station at North West Cape, Australia.

This paper discusses techniques, instrumentation and problems involved in the development of the system for the transmitters. Data on the operation of the system at the remote receive end will be presented and discussed at a later date when the system has been operated sufficiently long to permit evaluation.

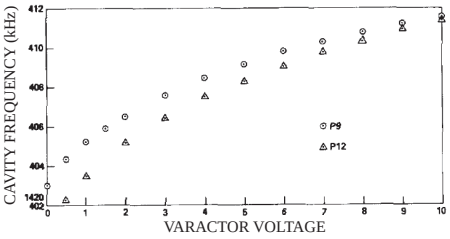


NTS-2 being lifted to the Atlas launch vehicle. (NRL Photo)

R. Stone, "Disciplined Time and Frequency Oscillator," in *Proceedings of The Third Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Washington, D.C., 16-18 November 1971, 211-23.

The aim of the PTTI Program is to provide to the user a coordinated time system that can be referenced to the Naval Observatory. Long-range transfers will be accomplished via the Defense Satellite Communications System satellite link, and short-range transfers will be accomplished by microwave links, UHF links, or any other suitable system.

In concept, a centralized area (in as ship or a shore station) will contain the reference atomic standards (see Figure 1). Cables throughout the station will connect the reference standard to units called Disciplined Time Frequency Oscillators (DTFO). The DTFO is an important part of the concept; it separates the timekeeping function from the user-operator function and eliminates the necessity for frequent calibration, which aids considerably in maintenance. It is also much less expensive to use the DTFO than to employ atomic standards in each of the user spaces.



Cavity tuning for masers P9 and P12. (White-1981, p. 661)

R. R. Stone, Jr., T. H. Gattis and T. N. Lieberman, "Utilization of FSK Communications for Time," in *Proceedings of the Fourth Annual Precise Time and Time Interval (PTTI) Planning Conference*, held at Goddard Space Flight Center, 14-16 November 1972, NASA Report X-814-73-72, 213-224.

The original purpose of this paper was to present off-the-art data on the recovery of a time stream transmitted by the VLF station NBA at Summitt, Canal Zone. Due to unforeseen difficulties in the procurement of some critical components required in the antenna portion of the system, the commencement date for transmission was delayed until January 1973. No actual data has been received from the station at this time; however, the system has been simulated in the laboratory.

This presentation will be divided into two parts:

The first part discusses the method of time control employed at NBA for time-signal transmission. It also describes methods of extracting a "recovered clock" at the receiver and presents data derived in an experiment at the Naval Research Laboratory (NRL) and from a signal received from NLK/NPG, located at Oso, Washington.

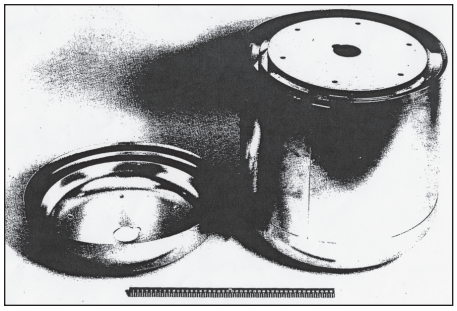
The second part of the presentation discusses requirements for adapting PTTI control to Naval Communications Systems. It describes a method for reducing the time required for synchronization or identification of messages and the fallout from the communication system to passive timekeeping users.

R. L. Swanson and S. A. Nichols, "Flight and Ground Tests of a GOES Satellite Time Receiver for Satellite Communications Applications," in *Twelfth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Greenbelt MD, 2-4 December 1980, NASA Conference Publication 2175, 351-76.

A satellite time receiver has been tested by the Air Force Wright Aeronautical Laboratories in various environmental conditions during the past year. The commercial receiver which was designed to work with the National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellites (GOES) was purchased from Arbiter Systems, Inc. The test program included operation at low elevation angles (less than five degrees), operation during flight in a military cargo aircraft and long term comparison with laboratory standards.

Modern military spread spectrum communications systems require accurate timing to achieve synchronization. These systems will be deployed on various mobile platforms with attendant startup problems at remote locations. The GOES satellite time receiver offers an opportunity to provide easy wide area coverage synchronization at low cost.

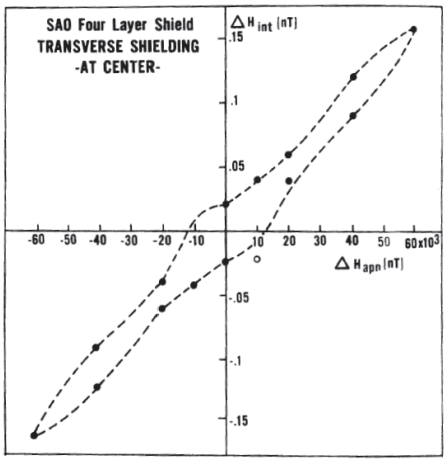
Two receivers were delivered in December 1979. One was carried to Thule, Greenland in March 1980 where the elevation angle was less than five degrees. Comparisons were made at Thule, Greenland and Goose Bay,



Four-shield nested array for magnetic shielding of maser. (Wolf-1977, p. 392)

Labrador with a Hewlett Packard Rubidium Traveling Clock. Test results from this trip will be presented. The results of long term testing which has been performed at Wright-Patterson Air Force Base to determine the reliability and accuracy for use in testing of potential military communication systems will be presented. The test phase which involves integration into the test aircraft and related test results will be described.

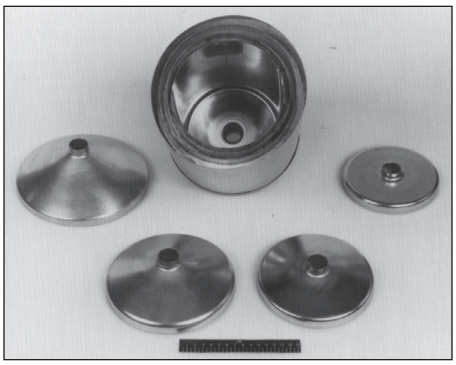
A. H. Taylor, *The First 25 Years of the Naval Research Laboratory*, NAVEXOS P-549, Naval Research Laboratory, Washington, D.C., 1948.
Pamphlet commemorating the Laboratory's 25th year.



Internal fields of a 4 layer nested Moly Permalloy shield set as a function of applied transverse field. (Wolf-1977, p. 398)

N. H. Turner, "An Investigation of Polymer Coatings used in Hydrogen Maser Storage Bulbs," in *Ninth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held at Washington, D.C., 29 November - 1 December 1977, NASA Technical Memorandum 78104, 371-380.
X-ray photoelectron spectroscopy has been used to investigate the surface composition (top 50 Å) of some fluorinated polymers that either have been, or could be, used to coat the storage bulbs in hydrogen masers. The results indicate inadequacies of some of the coatings, and the long-term effect of exposure to hydrogen atoms. Recently developed fluorinated polymers have been investigated also as possible coating materials.

D. H. Walker and R. L. Statler, *Results of the Solar Cell Experiments Aboard the NTS-2 Satellite After 447 Days in Orbit*, NRL Memorandum Report 3935, Naval Research Laboratory, Washington, D.C., 9 March 1979.
Results after 447 days in orbit of the solar cell experiments aboard the NTS-2 satellite are presented. The objective of the solar cell experiment, consisting of 15 separate experiments of five cells each, is to evaluate the performance of state-of-the-art solar cells in the space environment. Telemetered data from the 14 silicon and one gallium arenside modules indicate a more severe radiation environment in the 63 degree, 20,190 km circular orbit than was predicted. Based on the NTS-2 data, the solar power array containing Spectrolab Helios cells will degrade 27 percent in maximum power over the three-year mission. Solar cell panel temperatures have reached 104 degrees C providing ideal conditions for annealing of the radiation-induced damage in the gallium arsenide cells. After 15 months of operation these cells have suffered the least power degradation, with a maximum power loss of 14.0 percent. After 447 days in orbit, the loss in power ranged from 14.0 percent to 59.5 percent with the exception of the Solarex "low-cost space cell" which became open-circuited on the 69th day. The average value of Isc measured in space on the first day of exposure agreed with prelaunch solar simulator values to within 1.41+ 0.99 percent. The agreement between Voc in space and solar simulator values was 1.24+ 1.08 percent. Results are summarized of the changes in the photovoltaic parameters of each of the experiments.



Photograph of a nested set of maser magnetic shields and their end caps. (Wolf-1978, p. 141)

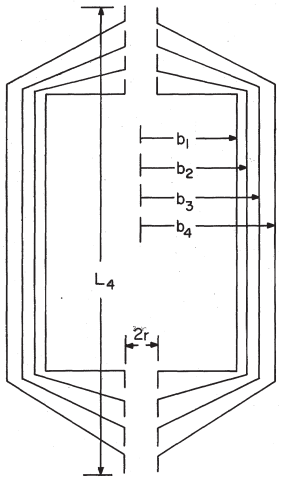
W. B. Waltman, S. H. Knowles, W. H. Cannon, D. A. Davidson, W. T. Petrachenko, J. L. Yen, J. Popelar, D. H. Fort and J. Galt, "A Phase-Coherent Link Using the Anti-B Satellite for Geodetic VLBI (Abstract only)," in *Thirteenth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, NASA Conference Publication 2220, held at Naval Research Laboratory, Washington, D.C., 1-3 December 1981, 801.
(Paper not presented.)
A joint U.S.-Canada experiment is in progress to demonstrate the capabilities of phase-coherent VLBI for the measurement of Universal Time and Polar Motion. This paper was to present the results of the satellite link evaluation experiments. The 12/14 GHz transponder of the ANIK-B synchronous communications satellite has been used to provide a phase-coherent link between radio observatories in Maryland, Ontario and British Columbia. The system operates in a shared-user mode with

television transmissions and makes only modest power and bandwidth demands on the satellite channel. A two-tone scheme is used with two-way transmissions on each path. The performance of the link can be separated from that of the frequency standards by use of the phase closure relationship for the three stations. The measured phase stability of the link is 2 X 10^-15 for a period of one day. This result is comparable to that of the best separated hydrogen masers. When combined with the VLBI results the error in the UT measurement is ± 200 microseconds.

C. Wardrip, J. Buisson, O. Oaks, M. Lister, S. Stebbins, B. Guinot, M. Granveaud, G. Freon, B. Dubois, W. Schluter, K. Nottarp, V. Reinhardt, R. Kruger, P. Dachel, E. Detoma, J. Ingold, R. Roloff and T. Stalder, "An International Time Transfer Experiment," in *37th Annual Frequency Control Symposium*, held at Philadelphia, Pennsylvania, 1-3 June 1983, 61-6.

This paper presents data obtained during an international time transfer experiment between the Bureau International de l'Heure (BIH), Paris, France; the Institut Fur Angewandte Geodasie (IFAG), Wettzell, Germany and the Bendix Field Engineering Corporation (BFEC) ,Columbia, Maryland utilizing GPS timing receivers developed for the NASA-Goddard Space Flight Center (GSFC) by the Naval Research Laboratory. The purpose of the experiment was to determine the accuracy of the GPS time transfer receivers for the NASA laser ranging network and to intercompare geographically separated atomic frequency standards.

Two NASA-GSFC hydrogen masers and a high performance cesium beam frequency standard in thermally controlled chambers were used for the frequency baseline at BFEC. The IFAG frequency baseline was established using EFOS-1 hydrogen maser and two Oscilloquartz cesium beam frequency standards. The data from France is comprised of a high performance cesium beam frequency standard at BIH and a hydrogen maser at the Centre National d'Etudes des Telecommunications (CNT). Data is presented on the intercomparison of masers and cesiums using direct comparison to the Naval Observatory (USNO), BFEC, BIH, CNT and IFAG via portable clocks, Loran-C and TV line 10. Data on the GPS NAVSTAR satellites, with typically rms values of less than 50 nanoseconds, is also presented. A discussion of the time transfer technique and frequency measurements is included.



A schematic design of the two smaller sets of shields. (Wolf-1978, p. 141; Gubser-1979, p. 754)

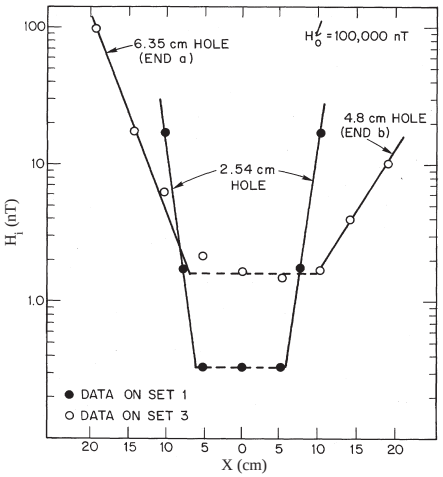
S. C. Wardrip, P. L. Wedding and W. D. Dahl, *Space Surveillance System - Observations of the Satellite 1959 Alpha 2*, NRL Report 5402, Naval Research Laboratory, Washington, D.C., October 1959.
NRL5402 LIMITED DISTRIBUTION

S. C. Wardrip, J. Buisson, O. J. Oaks, M. Lister, E. Detoma, P. Dachel, T. Stalder, H. Warren, G. Winkler, G. Luther, S. Leschiutta, P. G. Galliano, F. Cordara, V. Pettiti, R. Azzarone and F. Fedele, "International Time Transfer and Portable Clock Evaluation Using GPS Timing Receivers: Preliminary Results," in *Fifteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Naval Research Laboratory, Washington, D.C., 6-8 December 1983, 283-330.

Four portable cesium clocks and two single channel Global Positioning System (GPS) timing receivers were deployed in Italy during October 1983 at the Naval Base in La Spezia, onboard the Italian Navy hydrographic ship "Magnaghi," and at the Istituto Elettrotecnico Nazionale (lEN) in Torino.

The experiment was a joint effort between the following U.S. and Italian agencies and organizations: the NASA Goddard Space Flight Center (GSFC) with the support of the Bendix Field Engineering Corporation (BFEC), the Italian Navy, the U.S. Naval Research Laboratory (NRL), the U.S. Naval Observatory (USNO), the Istituto Elettrotecnico Nazionale (lEN) "G, Ferraris," and the Politecnico of Torino, Italy,

The timing data collected in this effort provided mutual synchronization between the U.S. Naval Observatory and other international time-keeping

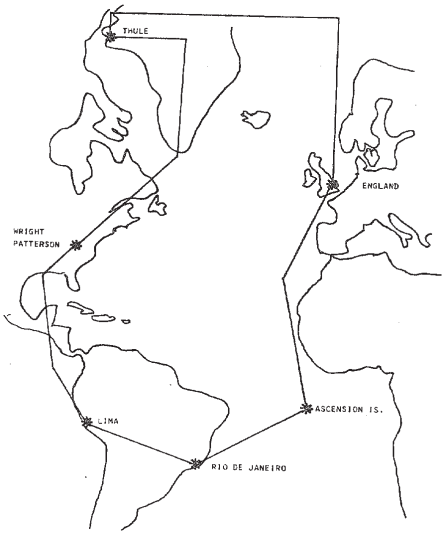


Axial field profiles for shield sets 1 and 3. (Wolf-1978, p. 143; Gubser-1979, p. 756)

institutions and laboratories to within an accuracy of +/- 50 nanoseconds (ns).

In addition, the experiment provided an excellent opportunity to perform field tests of portable cesium standards during actual trip conditions. Onboard the hydrographic ship was an ensemble of three cesium clocks, which were intercompared via an automated measurement system. Two external time references, Loran-C and GPS, and one additional cesium standard were continuously available on shore, providing a redundant and reliable reference time base. Similar portable clock and GPS data was taken at the lEN, while performing a GPS synchronization for a period of one week.

P. L. Wedding, W. D. Dahl and S. C. Wardrip, *Space Surveillance System - Observations of the Satellite 1959 Alpha 1*, NRL Report 5382, Naval Research Laboratory, Washington, D.C., September 1959.
NRL5382 LIMITED DISTRIBUTION



Two Rubidium atomic frequency standards were flown around the Atlantic, one as clock and the other as frequency standard, to ensure successful phasing of a spread spectrum modem under test. (Woodring-1979, p. 73)

K. W. Weiler, "Report on a Stable New Pulsar," in *Seventeenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Washington, D.C., 3-5 December 1985, 23-32.

A pulsar has been discovered which not only has a very rapid pulsing period of 1.6 milliseconds and a narrow pulse width of ~70 microseconds, but also appears to be an isolated and very stable object. Monitoring has so far shown no signs of the instabilities or "glitches" which reduce the utility of many pulsars as precise time references. Study of this "millisecond pulsar" therefore yields, in principle, a time reference of greater stability than any other known. However, its utility as a possible laboratory reference is presently limited to about 1 microsecond due to systematic errors in the corrections for numerous time transfer and solar system effects. The prospects for improving these corrections and for using the millisecond pulsar both as a time reference and to improve our knowledge of solar system parameters appear very good.

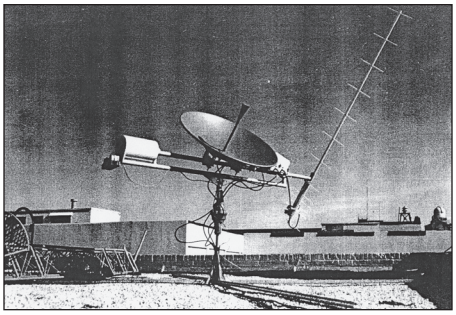
J. White, F. Danzy, S. Falvey, A. Frank and J. Marshall, "NTS-2 Cesium Beam Frequency Standard for GPS," in *8th Annual Precise Time and Time Interval (PTTI) Meeting*, 1 December 1976, 637-48.

NTS-2 is being built by the Naval Research Laboratory. It is scheduled for launch in mid 1977 and will be a part of the demonstration phase of the NAVSTAR Global Positioning Program (GPS). NTS-2 and Air Force Navigational Development Satellites will form a six-satellite demonstration system, which will permit a thorough evaluation of GPS.

NTS-2 will have two cesium beam frequency standards and will be the first satellite application for this type of atomic standard. Utilizing experience gained from the successful launch of rubidium frequency standards on NTS-1 in 1974 NRL has defined operating specifications for atomic standards in the space environment.

Flight standards are being delivered to NRL for testing. Each unit was subjected to environmental and stability testing at NRL. The temperature qualification range is -10 degrees C to +50 degrees C in vacuum. The standards are required to pass random vibration. Phase noise and short-term stability tests have also been performed.

Additional equipment has been designed and constructed to synthesize the 10.23 MHz signal required to drive the GPS navigation system electronics. In order to compensate for the relativistic effects a device was developed to offset the frequency of the cesium standard.



Receiver site near Ancon, Peru. (Zirm-1976, p. 5-12)

J. White, A. Frank and V. Folen, "Passive Maser Development at NRL," in *Twelfth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Greenbelt MD, 2-4 December 1980, NASA Conference Publication 2175, 495-513.

The Naval Research Laboratory investigating the application of passive hydrogen

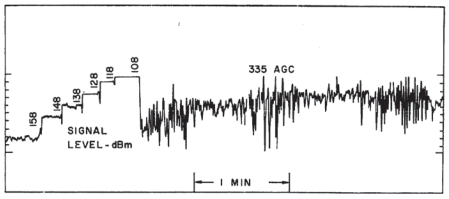
masers to satellites. This effort has included development of a working small maser at NRL and contractual support of work at Hughes Research Laboratory and the National Bureau of Standards.

The NRL maser is of compact design suitable for the space environment. It is based on a dielectrically loaded sapphire cavity and uses a computer optimized set of four shields. The mechanical structure was developed in a cooperative effort with the Smithsonian Astrophysical Observatory. The servo design is a novel phase sensitive method, which directly measures the phase dispersion of the interrogating signal as it passes through the cavity. Test results will be presented.

A brief synopsis of the results of the contractual work will also be presented.

J. White and K. McDonald, "Long Term Performance of VLG-11 Masers," in *35th Annual Frequency Control Symposium*, held at Philadelphia, Pennsylvania, 27-9 May 1981, 657-61.

There has recently been increased interest in active hydrogen masers for use in timekeeping applications for space and military programs. Most of the published data on masers has related to their short-term stability. The VLC-11 maser, one of two generally available, has been produced since 1977 but no long term stability or reliability information has been available to potential users. The US Naval Research Laboratory (NRL) has over three years experience with Smithsonian Astrophysical Observatory's (SAO) VLC-11 masers. NRL purchased two of the first three masers built in this series in the fall of 1977. An additional maser was delivered in January, 1980. This paper documents the performance of these three masers and also an NRL owned VLC-10, the predecessor of the VLC-11 series.



Example of amplitude scintillation at Ancon on 18 May 1975. (Zirm-1976, p. 5-13)

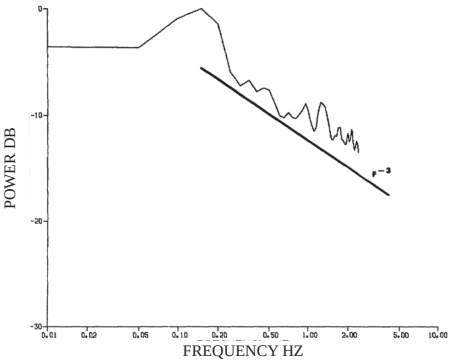
J. White, "Specifying performance for atomic standards," in *37th Frequency Control Symposium*, held at Philadelphia, Pennsylvania, 1-3 June 1983, 513-15.

As the needs for precise time, time interval and frequency continue to increase the demand for atomic frequency standards has also grown. This paper is designed to aid those whose program requirements now include these devices. There are several areas where specifications of atomic clocks vary significantly from crystal oscillator specifications. These include stability, environmental sensitivity, reliability, and testing. At this time, there is no general military specification for atomic standards.

The Naval Research Laboratory has extensive experience in procuring atomic standards in GPS and other programs. Examples based on experience are included. The level of detail required for particular applications is discussed.

J. D. White and D. D. McCarthy, "PTTI Opening Address: The Future of the PTTI Meeting," in *29th Annual Precise Time and Time Interval (PTTI) Meeting*, 2-4 December 1997, 1.

(no abstract)



Power spectrum of scintillating signal, observed with NTS-1 near the magnetic equator. (Zirm-1976, p. 5-19)

J. D. White, Chairman, "Panel Discussion: The Future of Military Receivers," in *31st Annual Precise Time and Time Interval (PTTI) Meeting*, held at Dana Point, CA, 7-9 December 1999, 339-46.

Joe White (NRL): Good afternoon. This session is about the future of military GPS receivers, and when we say "military GPS receivers" in this context, of course, we're talking about timing GPS receivers.

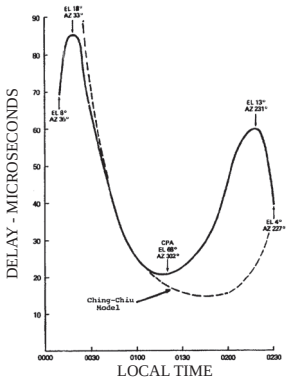
So what we're going to try to do in the next hour or two is fill you in on what the new technology is, what some of the administrative issues are, and a lot of what the panel is going to discuss here shortly will deal with that. And, just in general, give you an overview of where the program is going.

So with that, I'd like to go ahead and start this panel. It's Mihran Miranian from the Naval Observatory, Steven Hutsell from the Naval Observatory Alternate Master Clock, and Don Mitchell from TrueTime. And we kind of picked

this group to give a representative sample of the user community, the high-precision users and the manufacturers. So, Mihran.

J. White, R. Beard, G. Landis, G. Petit and E. Powers, "Dual Frequency Absolute Calibration of a Geodetic GPS Receiver for Time Transfer," presented at the 15th European Frequency and Time Forum, Neuchatel, Switzerland, 6-8 March 2001, 167-170.

The use of geodetic quality Global Positioning System (GPS) receivers for time transfer offers the possibility of excellent low noise measurements. This paper describes an approach to making high accuracy, low noise, independent calibrations of the internal delays in such receivers. Typical noise levels are around one nanosecond with comparable bias uncertainties. Calibration results for several current receivers are presented and compared with results from other calibrations of the same receivers.



Differential delay curve obtained on 24 May 1975 showing anomalous pattern for pass number 968. (Zirm-1976, p. 5-16)

J. White and R. Beard, "Space Clocks -- Why They're Different," in *33rd Annual Precise Time and Time Interval (PTTI) Meeting*, 27-29 November 2001, 7-17.

Atomic clocks for use in operational satellites such as GPS and MILSTAR are a breed apart from their terrestrial cousins. Like most space electronic packages, clocks will seem to be a generation behind the technology used in other applications. The reasons for this include the need for high reliability parts, radiation hardness, and mechanical design. Other key drivers in the designs include zero gravity, unattended operation, limited monitoring bandwidth, and limits on weight size and power. Clocks used in short-term space experiments can be closer in design to ground clocks, but are generally not usable for operational systems without extensive modifications.

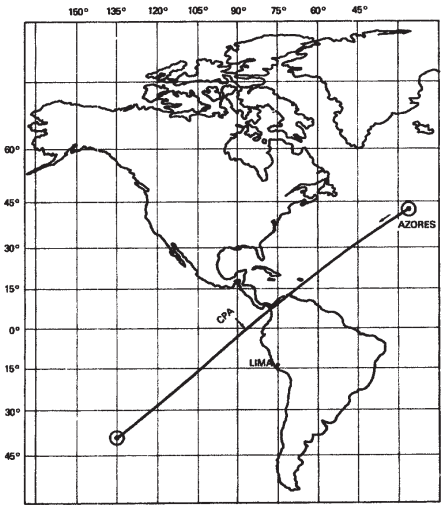
J. White, "Closing Remarks," in *34th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston VA, 3-5 December 2002, 551-3.

(no abstract)

J. White, Moderator, "The Future of Clock Technology for Space," in *34th Annual Precise Time and Time Interval (PTTI) Meeting*, held at Reston, VA, 3-5 December 2002, 215-42.

The topic this morning is about the future of clock technology for space. You have seen a lot this morning in the earlier papers about things that will happen hopefully in the future of GPS and Galileo. We saw some things yesterday about GLONASS. And we decided that it was worth a little more discussion with some of the principles in it, let people kind of argue with each other about which way things are going and what it is going to take to make it all work. We have an all-star panel here this morning: Ron Beard (U.S. Naval Research Laboratory), Martin Bloch (Frequency Electronics, Incorporated), Lt. Jason Bolger (GPS Joint Program Office, USAF); Mike Garvey (Symmetricom, formerly Frequency Time Systems and Datum), Professor Leschiutta (Istituto Elettrotecnico Nazionale, Italy), and finally Pascal Rochat (Temex Neuchâtel Time SA).

What I would like to talk about here today is the nature of the problem. I did a paper last year where we talked about what made space clocks different than ground clocks. And the last thing I mentioned in that paper was the fact that GPS is, in a way, its own worst enemy. GPS has fantastic clocks in the satellites; it does very well. And that is really the problem: it makes atomic clocks unnecessary in some applications. So the concern is, are we necessarily going to have atomic clocks when we need them for various space programs? The first thing that comes to mind is how many people actually need atomic clocks. And the list is fairly short.



Geometry for NTS-1 pass number 968. (Zirm-1976, p. 5-16)

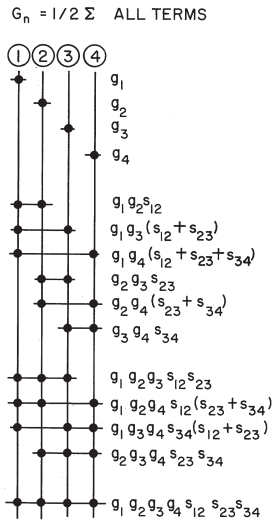
S. A. Wolf and J. E. Cox, "An Investigation of the Shielding Properties of Moly permalloy Shields Designed for use with a Hydrogen Maser," in *Ninth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*,

held at Washington, D.C., 29 November - 1 December 1977, NASA Technical Memorandum 78104, 381-401.

Hydrogen masers are being considered for use as the frequency standard in the next generation of navigational satellites (NAVSTAR GPS). For these masers to achieve the required frequency stability (1 part in 10^14), the magnetic field environment in which the maser operates must be accurately known and stable to 1nT for ambient magnetic field changes of 100,000 nT. (The earth's magnetic field is approximately 50,000 nT). The usual procedure is to surround the hydrogen maser by one or more concentric magnetic shields. The objective of this study is to verify the shielding characteristics of the magnetic shield system (Fig. 1) that has been designed for use with the VLG-11 ground based hydrogen maser.

Measurements were made in the 11.3-meter diameter Braunbek coil system at the Spacecraft Magnetic Field Site, Goddard Space Flight Center, Greenbelt, MD, (See Fig. 2). This coil system actively compensates for changes in the Earth's magnetic field and is capable of nulling the earth's field to better than 1 nT over a 1.3 m diameter sphere. In addition, this system has the capability of applying a field, known to an accuracy of 1 nT over this volume, with a magnitude as large as 60,000nT.

Both the transverse and axial shielding factors of a single layer shield and a four layer nested shield were determined using a fluxgate magnetometer with 0.1 nT resolution and a Superconducting Quantum Interference Device (SQUID) magnetometer with 0.001 nT resolution. Attenuation was studied as a function of external magnetic field, position within the shield, zero field magnetic moment (perm), and thermal cycling.



Diagrammatical representation for a general shielding effectiveness formula. (Gubser-1979, p. 751)

S. A. Wolf, D. U. Gubser and J. E. Cox, "Shielding of Longitudinal Magnetic Fields with Thin, Closely Spaced, Concentric Cylindrical Shells with Applications to Atomic Clocks," in *Tenth Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held at Washington, D.C., 28-30 November 1978, NASA Technical Report 80250, 131-46.

Formulae for the longitudinal shielding effectiveness of thin, closely, spaced concentric cylindrical shells have been developed and experimentally tested. For shields which cannot be oriented, or which change their orientation in the ambient field, the shielding effectiveness for longitudinal fields is generally the limiting criteria and no design formulae have been presented for more than two shields. In this paper a general formula is given for the longitudinal shielding effectiveness of N closed concentric cylinders. The use of these equations is demonstrated by application to the design of magnetic shields for hydrogen maser atomic clocks. Examples of design tradeoffs such as size, weight, and material thickness will also be discussed.

Experimental results on three sets of shields fabricated by three manufacturers have been obtained. Two of the sets were designed employing the techniques described above. Agreement between the experimental results and the design calculations is then demonstrated.

Nested magnetic shields for hydrogen maser undergoing pre-flight shake testing at NRL. (NRL Photo)

S. A. Wolf, D. U. Gubser and L. D. Jones, "Vacuum Pumping System for Spaceborne Passive Hydrogen Masers," in *Twelfth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, held at Greenbelt MD, 2-4 December 1980, NASA Conference Publication 2175, 581-9.

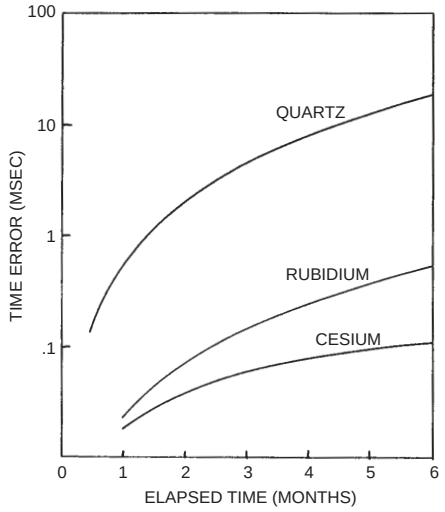
The ultimate utility of hydrogen masers as highly accurate clocks aboard navigation satellites depends on the feasibility of making the maser lightweight, compact, and capable of a 5-7 year unattended operation. We have designed and fabricated a vacuum pumping system for the SAO-NRL Advanced Development Model (ADM) maser that we believe meets these criteria.

The pumping system was fabricated almost completely from 6AL-4V Titanium alloy and incorporates two (three years minimum) or four (six years minimum) sintered zirconium carbon getter pumps with integral activation

heaters. These pumps were designed in collaboration with SAES getters and fabricated by them for these systems. In addition to these pumps, small getter ion pumps (~1 l/sec) are also appended to the system to pump the inert gases.

In this paper we will illustrate the manner in which the getter pumps were mounted to insure that they will stand both the activation (900 deg C for 10 minutes) and the shock of launch.

Data on the total hydrogen capacity and pumping speed of this system will also be presented.



Time error versus elapsed time, for various standards. (Nichols-1978, Fig. 11)

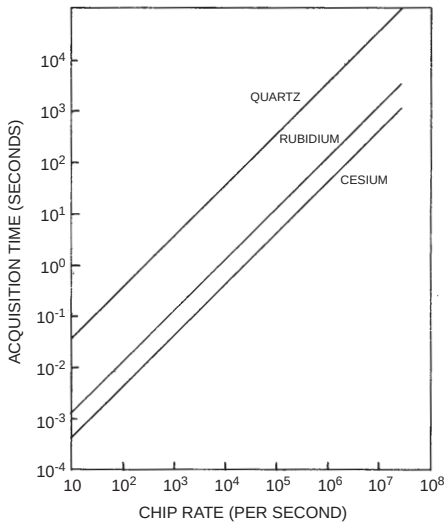
D. G. Woodring, S. A. Nichols and R. Swanson, "Timing and Frequency Considerations in the Worldwide Testing of a Spread Spectrum Communication System," in *Eleventh Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, Conference Publication 2129Q, held at Goddard Space Flight Center, Greenbelt MD, 27-29 November 1979, NASA, 65-78.

During 1978 and 1979, an Air Force C-135 test aircraft was flown to various locations in the North and South Atlantic and Pacific Oceans for satellite communications experiments by AFAL. A part of the equipment to be tested on the aircraft was the SEACOM spread spectrum modem developed for NRL by Raytheon.

Test results achieved in the program will be presented. The SEACOM modem operated at X band frequency from the aircraft via the DSCS II satellite to a ground station located at NRL. This modem incorporated the concepts of wide bandwidths, autonomous operation, high frequency multiplication factor and design-to-cost. For data to be phased successfully, it was necessary to maintain independent time and frequency accuracy over relatively long periods of time (up to two weeks) on the aircraft and at NRL.

To achieve this goal, two Efratom atomic frequency standards were used. One of these has been in service at NRL since 1973. One standard was used as a portable clock and the other was used as the modem frequency standard.

This paper will discuss the performance of these frequency standards as used in the spread spectrum modem, including the effects of high relative velocity, synchronization and the effects of the frequency standards on. data performance. The aircraft environment, which includes extremes of temperature, as well as long periods of shutdown followed by rapid warmup requirements, will also be discussed. The limitations of maintained time in remote locations such as Thule, Greenland, Ascension Island, Lima, Peru, Hawaii and Dayton, Ohio will also be addressed.



Acquisition time versus chip rate (hopping rate) for various standards modem programs. (Nichols-1978, Fig. 6)

R. R. Zirm, R. E. Brescia and R. S. Rovinski, "Space Surveillance System," Report of NRL Progress, 44-45, 30 July 1965.

Two smooth-polished, 14-inch-diameter, aluminum spheres weighing 2.2 and 22 lb have been simultaneously injected into nearly identical 600-naut-mi circular polar orbits. They will provide (1) standard radar targets and (2) observations of the relative change in the orbital parameters with time.

R. R. Zirm, R. E. Brescia and C. Morris, *Transionospheric Differential Delay Measurements from TIMATION II at 150 MHz and 400 MHz*, NRL Report 7419, Naval Research Laboratory, Washington, D.C., 24 August 1972.
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R. R. Zirm and J. M. Goodman, "Propagation Effects Observed in Connection with NTS-1 Observations Near the Magnetic Equator," presented at the Advisory Group for Aerospace Research and Development (AGARD) Specialists Meeting of the Electromagnetic Wave Propagation Panel on Propagation Limitations of Navigation and Positioning Systems, 1976, Advisory Group for Aerospace Research and Development (AGARD), 5-1 to 5-20.

During a two-week period in May 1975 near the magnetic equator, the Naval Research Laboratory measured amplitude and differential propagation

delay scintillation of the 335 and 1580 MHz transmissions from NTS-1 satellite. NTS-1 is an experimental test vehicle in support of the NAVSTAR-GPS and was launched on 14 JUL 1974 into a 7,277 by 7,444 nautical mile orbit having an inclination of 125 degrees. The measurements which are described in this paper are part of Operation Antarqui, named for Inca god, and was a joint NASA Instituto Geoficisco del Peru campaign with specific experiments by the universities of Illinois, Pittsburgh, Denver, and Penn State, the Dudley Observatory, and NRL.

In this paper we will discuss the results obtained through analysis of amplitude and differential propagation delay data at 335 and 1580 MHz and observed at the former mini-track station at Ancon, 25 miles north of Lima. Data were also taken during this experiment in support of the NTS-1 orbit improvement and time transfer research effort.

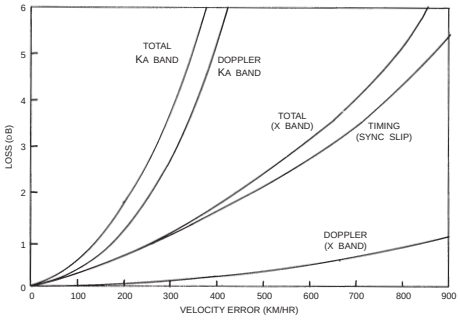
These results also have immediate applications in resolving such practical system problems as the contribution of propagation delay scintillation to error budgets of satellite navigation systems such as NAVSTAR/GPS, and the power margins necessary to overcome the effects of amplitude scintillation in the equatorial region. For example, the data taken on this campaign (which is only representative of the two week data span) show amplitude fading greater than 30 dB below the mean at 335 MHz, but little or no affect on 1580 MHz. These data have been scaled for SI and have been compared with the Fremouw-Pope-Rino Model. Differential propagation delays at these frequencies during time of scintillation activity were observed to be two nanoseconds peak-to-peak.

Experimental receivers designed for NTS-1 were used with special Doppler converters to generate convenient analogue data displays of the differential delay and amplitude variables. A special transportable antenna system was designed and deployed and data was recorded on chart and magnetic tape recorder.

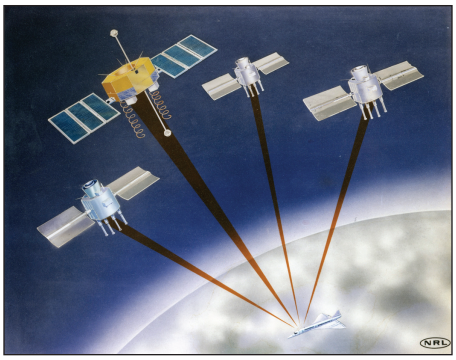
Several conclusions have been reached on the basis of our analysis.

1. Severe scintillation activity was observed at 335 MHz for approximately four days out of a two-week interval and varied from a few dB to over 30dB.
2. No apparent scintillation was observed at 1580MHz.
3. The differential delay scintillation was not observed to exceed two nanoseconds peak-to-peak. The smoothed differential delay information suggested the existence of an anomaly in the total electron content as the satellite passed over the magnetic equator. This feature is not inconsistent with currently accepted models of electron redistribution near the equator.

It is emphasized that these data were obtained over a limited span of time and the conclusions are valid for equatorial-equinox conditions only.



Loss due to velocity error. (Nichols-1978, Fig. 11)



Artist's rendering of NTS-2 and three subsequent Navigation Development Satellites forming the first GPS constellation, giving users longitude, latitude, altitude, and time. (*Labstracts* 15 October 2007)

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2 March 1971

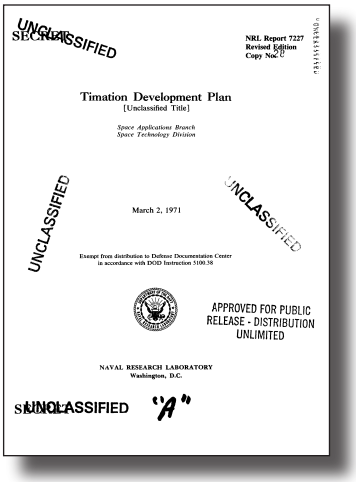
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Table 3-1 lists typical modes of operation in order of decreasing cost and complexity of user equipment. It should be noted that in categories 3 and 4, a precision clock could be used with two satellites, with little change in accuracy or operation. Category 5 and 6 users make sequential measurements on a set of three satellites, and they require an inexpensive clock to correlate the measurements.

Table 3-1
Modes of Operation

Categories of Potential Users	Number of Satellites Used				
	Range-Only Mode	Range-Difference Mode	Fix Accuracy (feet)	External Data Required	Type of Data From Fix
1. Military (strategic and tactical) aircraft, carrier operations, and gun placement	3	4	50	None	Position and velocity (3 dimensions)
2. Submarines, search and rescue, and logistic support	2	3	50	Altitude	Position (2 dimensions)
3. Land operations (vehicle)	3	4	50	None	Position (3 dimensions)
4. Land operations (foot)	3	4	50	None	Position (3 dimensions) Velocity (3 dimensions)
5. General air navigation	-	3	1000	Altitude	Position (2 dimensions)
6. General marine	-	3	1000	Velocity	Position (2 dimensions)

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14. ABSTRACT

The broad utility of GPS is widely recognized and appreciated. Less well known is the critical role played by the Naval Research Laboratory in its invention, concept demonstration, operational configuration, inception, and continued development. Perhaps this is in part due to the quiet way the Laboratory goes about pursuing scientific and technical excellence. Although ample documentation on the NRL role in GPS still remains, it is largely in the form of memoranda, technical reports, series of proceedings from specialized technical conferences, and a relatively few widely published articles. Many of the key technical reports were classified when originally produced, were not declassified until the mid 1990s, and were not disseminated at that time.

This bibliography is offered as an aid to those who are interested in better understanding the NRL role in the origins of GPS. Bibliographic citations, primarily of published works, are presented. These are annotated with abstracts, photos, and figures, to facilitate selecting which of the referenced papers to examine more closely. A timeline is provided to aid in setting the citations in their context of historical development.

15. SUBJECT TERMS

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Time navigation	Passive ranging	Navigation	NAVSTAR	

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