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GPS NAVSTAR-4 and NTS-2 Long Term Frequency Stability and Time Transfer Analysis

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Washington, D.C.

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GPS (Global Positioning System)	Rubidium frequency standard	Frequency domain
NTS (Navigation Technology Satellite)	Cesium frequency standard	Satellite clock
Frequency stability	Reference ephemeris	(Continued)

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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-1 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

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19. KEY WORDS (Continued)

Time transfer
Frequency synchronization
Relativity
Flicker frequency noise
White frequency noise

20. ABSTRACT (Continued)

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.

A time domain estimate for the NAVSTAR-4 SV clock off-set 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.

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CONTENTS

GPS NAVSTAR-4 AND NTS-2 LONG TERM FREQUENCY STABILITY AND TIME TRANSFER ANALYSIS

INTRODUCTION

The navigation technology satellites (NTS) developed by the Naval Research Laboratory (NRL) have provided on-orbit test vehicles for the basic satellite navigation technology [1,2,3] currently used in the NAVSTAR Global Positioning System [4] (GPS). Two satellites, TIMATION I and TIMATION II, were flown in 1967 and 1969 to demonstrate the concept of using synchronized clocks to provide time ranging for time transfer [5,6] and navigational [7,8] purposes. Navigation Technology Satellite One (NTS-1), flown in 1974, introduced a rubidium [9] atomic clock and NTS-2 (Fig. 1), flown in 1977, introduced a cesium [10] clock. These spacecraft have demonstrated (Fig. 2) a two-order-of-magnitude improvement in timing precision from 300 ns in 1967 to a current value of near 3 ns!

Measurements from NTS-1 and NTS-2 will be presented that demonstrate the time-transfer [11] capability, frequency offset, and frequency stability [12] of the spacecraft clock. Measurements from NAVSTAR-4 (Fig. 3) will be presented that estimate the long-term frequency stability of the rubidium frequency standard from the pseudo-range measurements. Time-transfer results for the Hawaii, Guam, and Alaska monitor sites have been made using the Vandenberg monitor site as the central station. These time-transfer measurements are further processed to estimate the frequency stability of the Hawaii, Guam, and Alaska clocks.

PTTI (PRECISE TIME AND TIME INTERVAL) MEASUREMENTS

Two different types of time-interval measuring techniques are used to obtain the results reported in this paper. The first is a sidetone ranging technique in which a set of tones is generated in the spacecraft and then modulated onto the carrier; the receiver [13,14] synthesizes the same set of sidetones and, after detection and down conversion, compares the phase of the received tones to the phase of the synthesized tones. The set of phase difference measurements is then combined to produce observed range with progressively better resolution. Figure 2 presents the timing precision obtained as a function of time. The best precision [15] was less than 5 ns with a resolution of 1.5 ns employing a 6.4-MHz sidetone.

A spread-spectrum technique, first demonstrated on NTS-2 in 1977, is used for the Phase I NAVSTAR spacecraft. This ranging signal is comprised of two PRN [16] (pseudo random noise) codes, biphase modulated on the carrier frequency. A short 1.023-MHz C/A (coarse/acquisition) code is used for acquisition and a long 10.23-MHz P (precise) code is used for resolving range to at least 1.5 ns (46 cm). A navigation message [17] is also modulated onto the signal and is available upon acquisiton of the C/A code. Information exists in this message which enables acquisition of the P code. It also contains satellite ephemeris and health information.

Measurements of spacecraft doppler can be obtained by tracking the received carrier signal for a fixed amount of time or by counting a fixed number of cycles. The received frequency is

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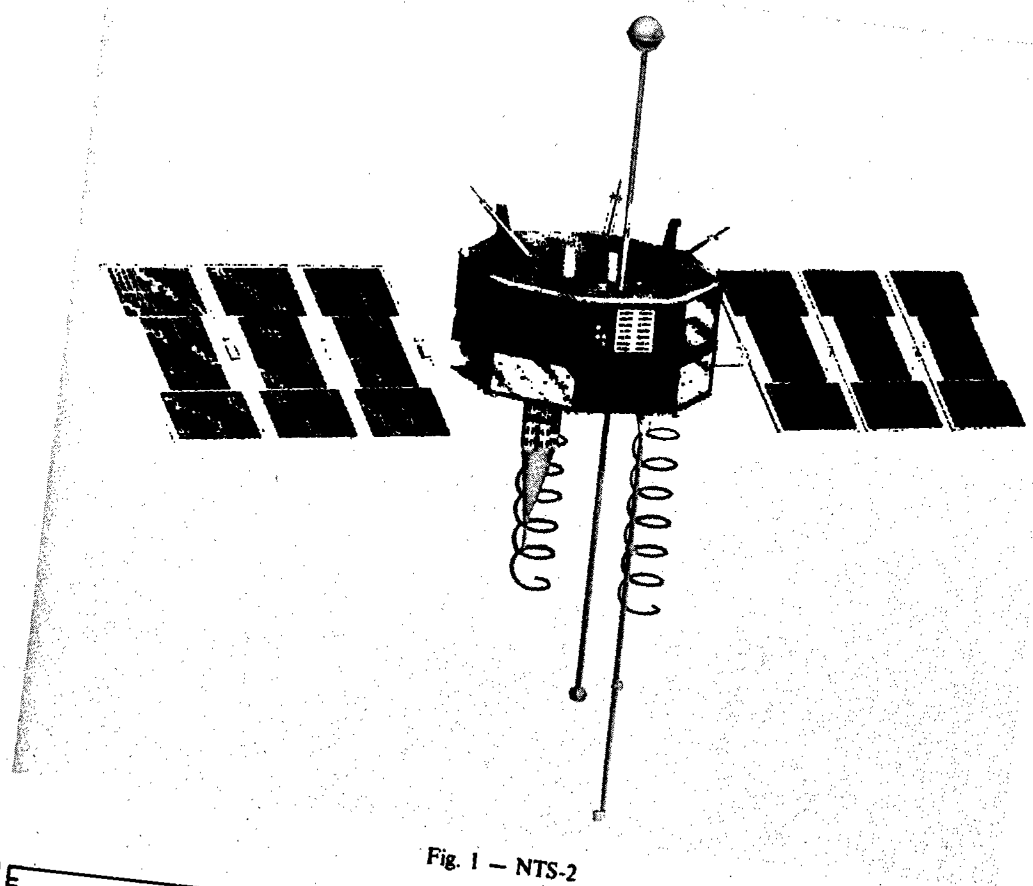

Fig. 1 — NTS-2

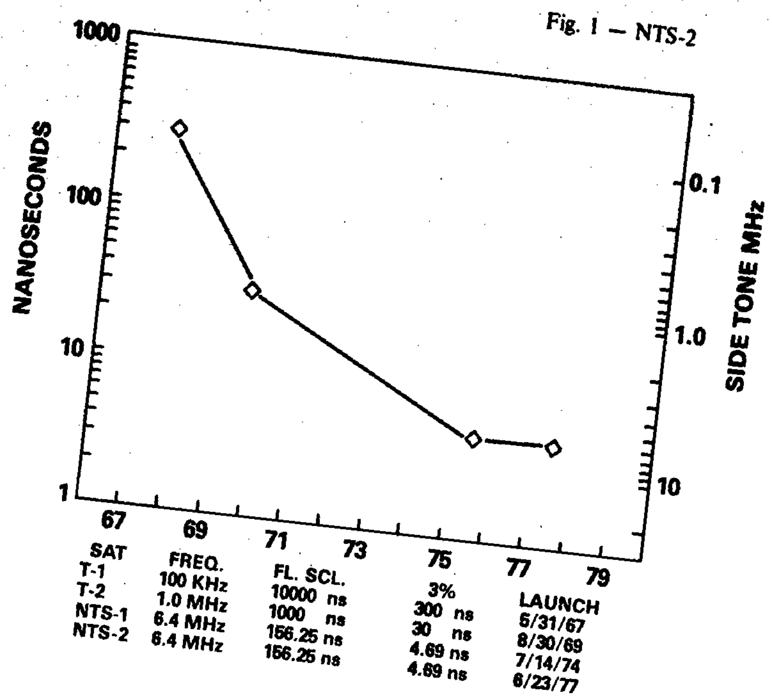

Fig. 2 — NTS timing precision history

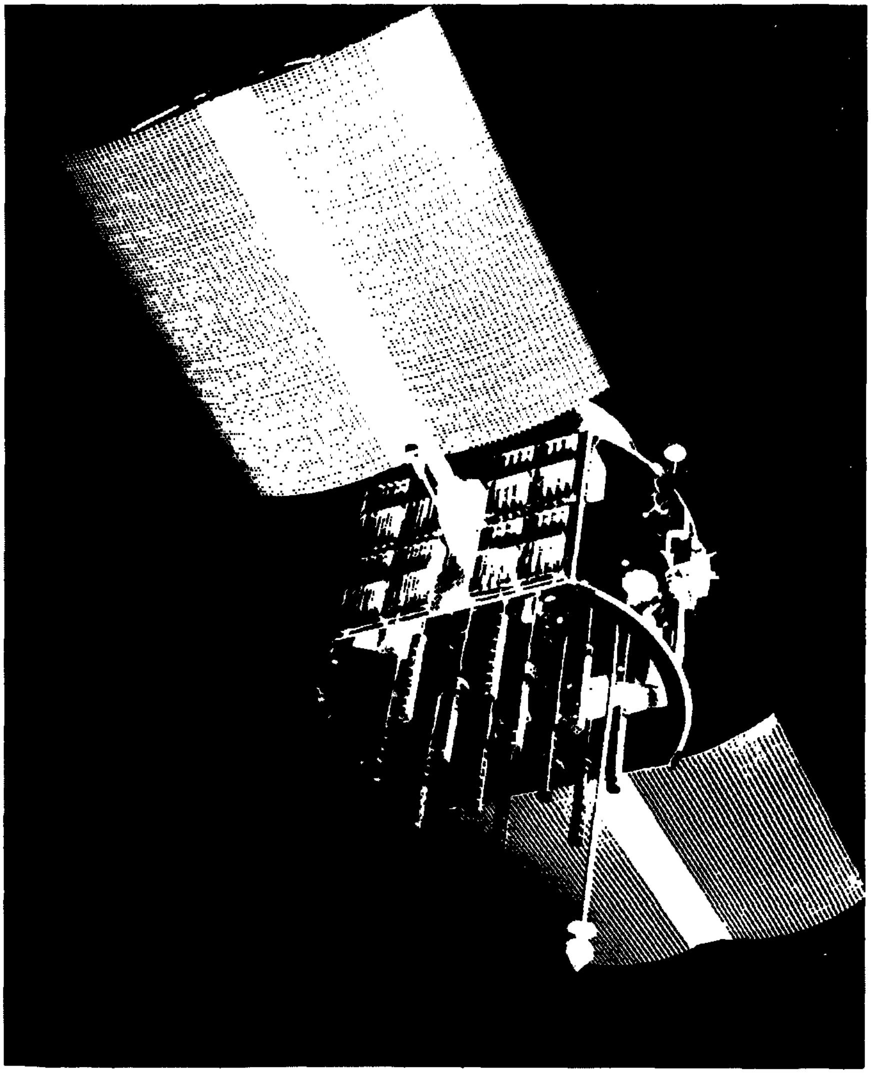

Fig. 3 — NAVSTAR-4

mixed with standard frequencies generated coherently from the user's frequency standard. The respective difference frequency then enters a phase-locked tracking filter. Measurements of doppler obtained from the PRN signal, called delta pseudo-range, are taken every 6 s.

NTS Tracking Network

Figure 4 presents the four station network employed for tracking the NTS spacecraft. The limits of visibility for the NRL CBD (Chesapeake Bay Division), Panama, Australia, and England tracking stations are depicted by the symbols C, P, A, and E, respectively. Reference to Fig. 4 shows that the Panama station could track for 12 consecutive hours, or one complete revolution of the 2 rev/day NTS-2 orbit. This four-station network provided 97% coverage of the NTS-2 orbit, averaged over one day.

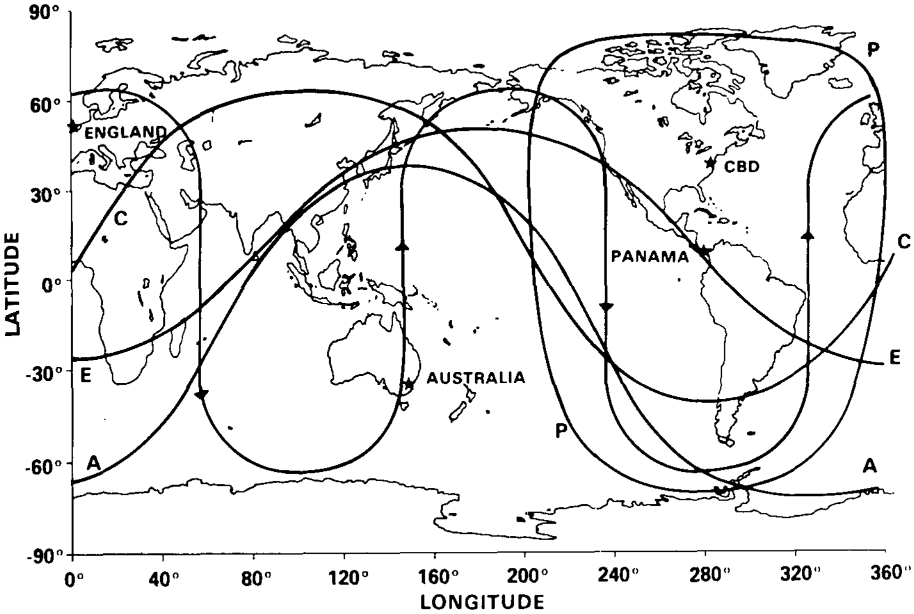

Fig. 4 — NTS network coverage

Ground station timing was provided by cesium clocks which were intercompared with other cesium clocks. Timing at the England NTS tracking station was coordinated with GMT and, in Australia, with the Division of National Mapping. The CBD tracking station had portable clock and TV links to the U.S. Naval Observatory DOD Master Clock. This arrangement provided control and timing checks for the time transferred by satellite.

Frequency Synchronization Results

Frequency tuning results from the first 150 days of NTS-2 operation are presented in Fig. 5. For the first segment, beginning at launch on 23 June 1977, the transmitted frequencies were derived from the quartz oscillator subsystem of one of the two on-board cesium frequency standards. Using time difference measurements from the NTS network, the frequency offset with respect to UTC(USNO,MC1) was estimated. The quartz frequency was then tuned close to the cesium resonance frequency and phase locked to the (nominal) cesium resonance at 9192 MHz.

The cesium resonators, which are primary standards, were expected to provide an absolute frequency reference to 1 part in 10^{12} while at rest on the earth's surface. The cesium frequency, in orbit, was expected to be influenced by the relativistic clock [18] effect, which is (nominal prediction) 445 parts in 10^{12} for the GPS constellation. The frequency offset of each frequency standard was measured with respect to the DOD Master Clock before launch. The second segment presents the results of on-orbit estimation of the frequency offset, which caused a (nominal) accumulation of time difference of 38,500 ns/day. By comparison of the theoretical and measured frequency offset, the Einstein relativistic clock effect was verified to less than one-half percent (0.5%).

Verification of this relativistic clock effect has resulted in a two-part correction for GPS. The first part of this correction is obtained by (hardware) offsetting the transmitted frequency by 445×10^{-12}. This hardware correction accounts for more than 99.6% of the relativistic

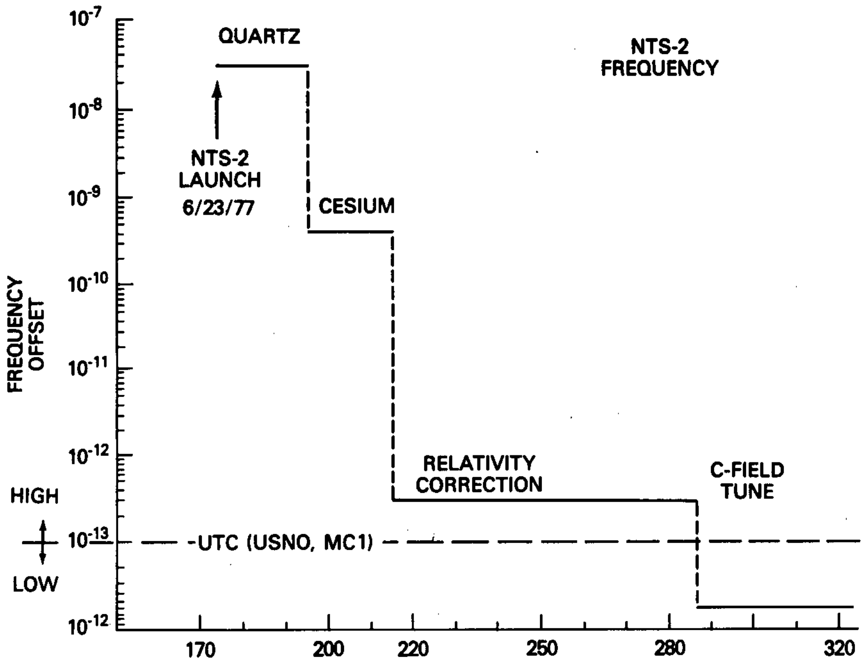

Fig. 5 — NTS-2 frequency history

effect. The remainder of the correction is provided by software, with the necessary coefficients included in the navigation message.

Time Transfer Theory

Time transfer via satellite (Fig. 6) is accomplished by measuring the time difference, beginning with the reference clock, for each of the time links and combining the results. Four links are necessary for GPS operation. These links are:

- From DOD Master Clock to Master Control Station (MCS),
- RF link from MCS to each GPS SV,
- SV clock update,
- SV to user RF link.

These four links, and subsets thereof, have been used to analyze time transfer, navigation, SV clock and frequency stability, and orbital accuracy for GPS.

The link from the DOD Master Clock, which is denoted as UTC(USNO,MC1), has been demonstrated via portable clock and a TV time link to the CBD station. Measurements are then made at CBD to the NTS satellites for the second link. The third "link" is that of the satellite clock, maintaining and carrying forward in time its measured offset with respect to the DOD Master Clock, through the CBD link. The fourth link is made by the user who makes the RF measurement to one or more satellites. Each satellite is synchronized by combination of hardware and software to a common time reference.

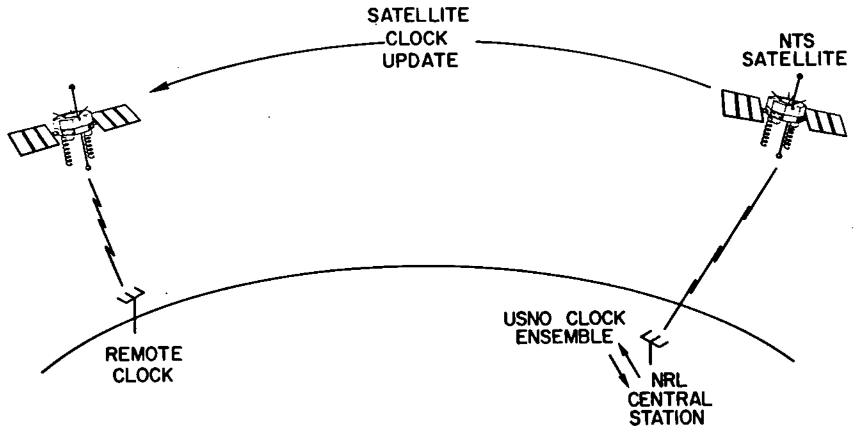

Fig. 6 — Time transfer via satellite

A GPS user who takes four simultaneous pseudo-range measurements to four GPS satellites can then use his assumed position and information in the navigation message to calculate four time-transfer values. If the four time-transfer values agree, his position is correct. If the four time transfers disagree, the four parameters (t, x, y, and z) can be solved for simultaneously. Calculation of the time-transfer value first requires a coarse time synchronization of the user's receiver to GPS time, as maintained by the satellite clock. The satellite ephemeris, which is a function of GPS time, can then be used to calculate the geometrical range from the satellite to the user's assumed position. Corrections must be applied for antenna and equipment delays, the effects of ionospheric delay, tropospheric delay, and earth rotation during the signal propagation time. The time transfer to the DOD Master Clock is obtained by a software correction which combines the offset of each GPS satellite clock with a relativity correction. This software correction is small because each GPS satellite clock is kept in near synchronization using an atomic frequency standard and most of the relativistic clock effect is hardware corrected.

The user's frequency offset and three-dimensional velocity can be solved for with four delta pseudo-range measurements to four GPS satellites. Alternately, frequency offset and three-dimensional velocity can be obtained using a sequence of time transfers and successive x, y, z position estimates.

NTS Time Transfer Results

Time-transfer techniques were first demonstrated by NRL in the formative development of GPS, by aircraft in 1964, by satellite in 1967, and on a worldwide [19,20] basis in 1978 to the submicrosecond level of accuracy. Figure 7 tabulates a summary of those results from a six nation campaign as compared with portable clock measurements from USNO. The average accuracy obtained was 60 ns. The primary source of error was the lack of an ionosphere delay correction.

Recent time-transfer results from South America, Japan [21], and Germany (Figs. 8 through 13) complement and confirm the previous time-transfer results. These figures present continuous satellite time-transfer results over a period of about 150 days through day 190, 1979. The entire worldwide net of stations participating since 1978 yields a history of worldwide submicrosecond satellite time transfer for the last two years.

STATION	DAY (1978)	PORTABLE CLOCK — NTS TIME TRANSFER (μS)
BIH	124	−.57
CERGA	117	.70
DNM	282	.09
IFAG	199	.03
NBS	221	.19
NRLM	299	−.53
RGO	115	.44
RRL	303	.13
USNO	186	.04

Fig. 7 — NTS Time transfer vs portable clock closures

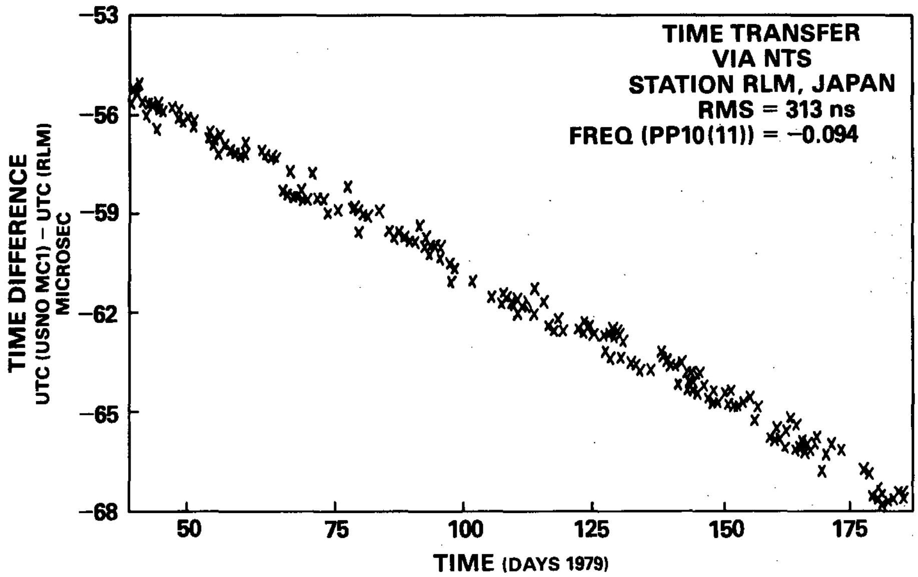

Fig. 8 — NTS-1 time transfer to RLM, Japan

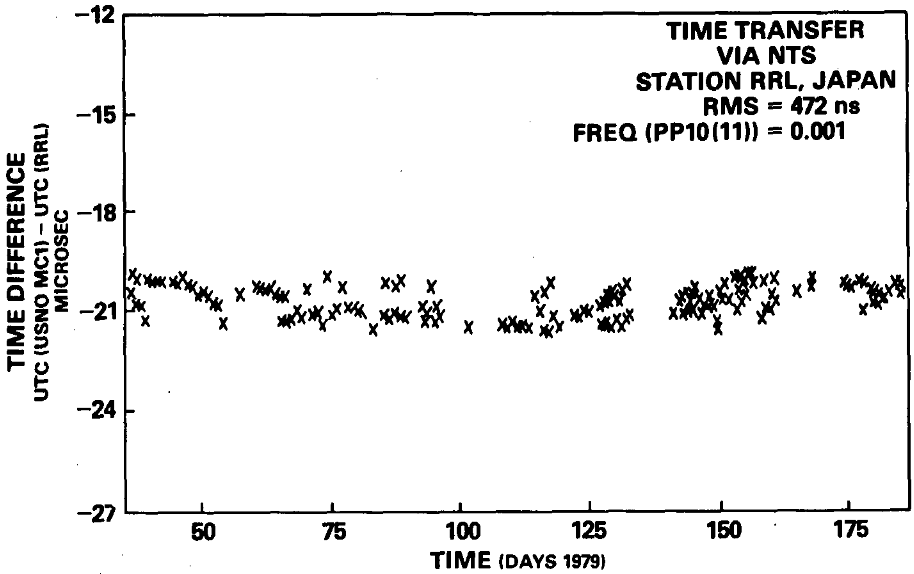

Fig. 9 — NTS-1 time transfer to RRL, Japan

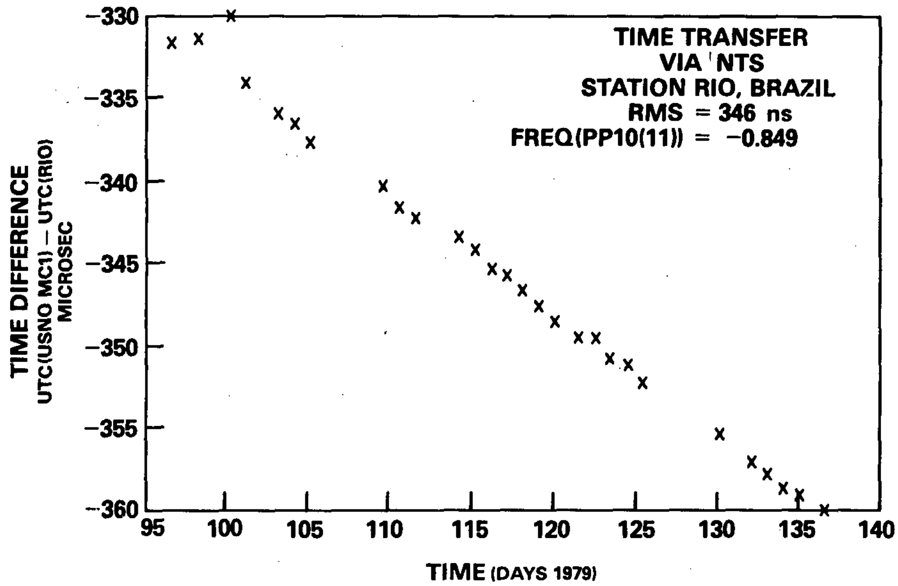

Fig. 10 — NTS-1 time transfer to Rio, Brazil

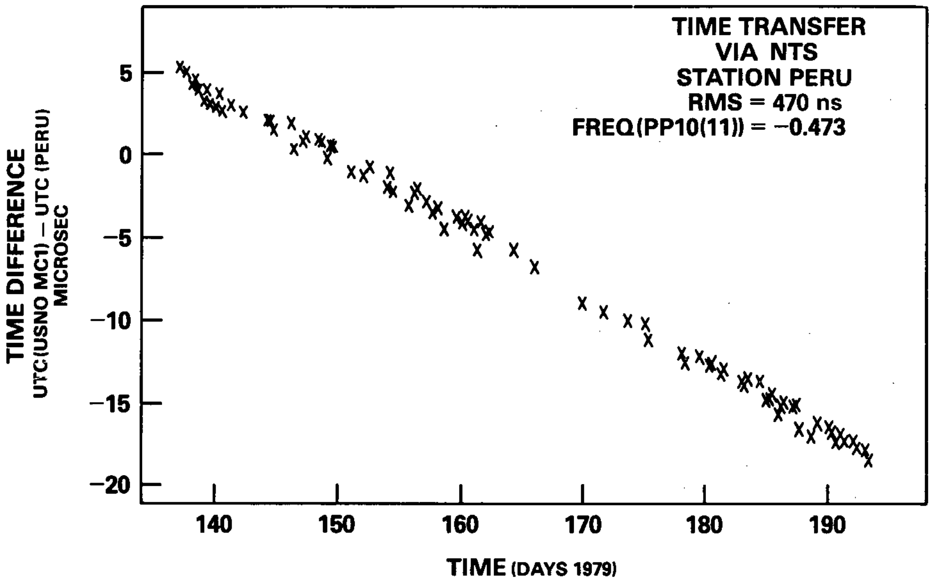

Fig. 11 — NTS-1 time transfer to Peru

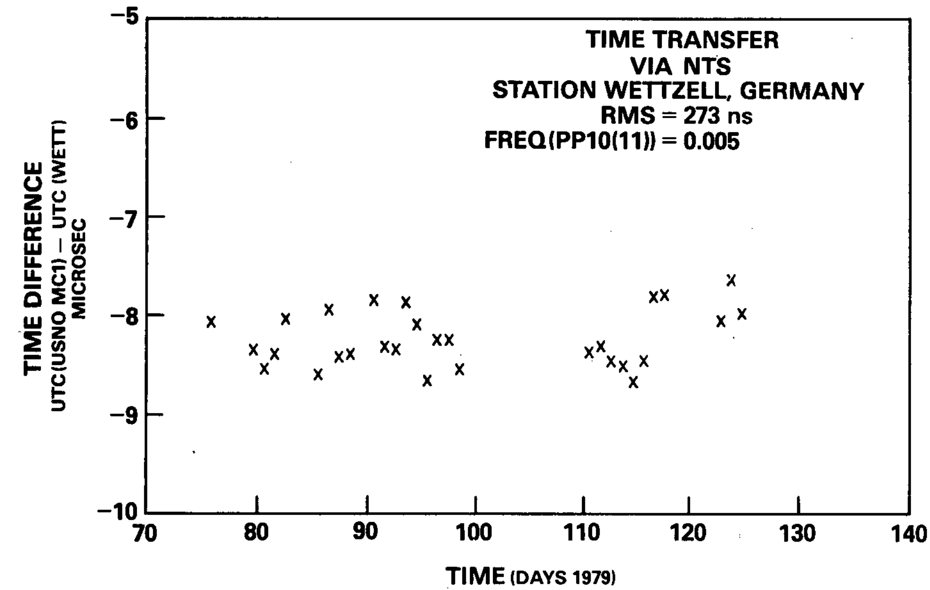

Fig. 12 — NTS-1 time transfer to Wettzell, Germany

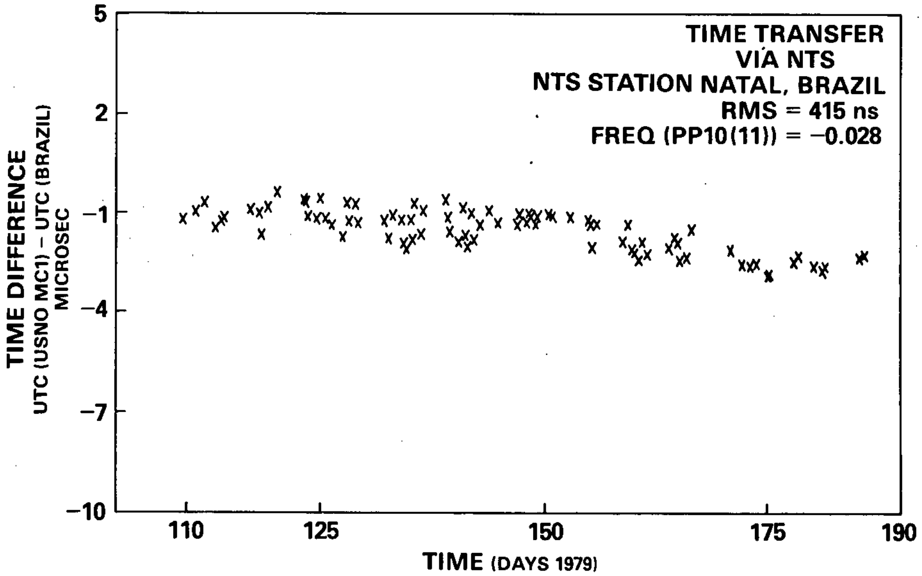

Fig. 13 — NTS time transfer to Natal, Brazil

Figure 14 presents time transfer to the NTS Panama Station over a 100-day span. During the first segment, NTS-1 was used to transfer time without the aid of an ionospheric correction. The last segment presents the NTS-2 results which had the benefit of an ionospheric correction and a cesium clock in the satellite. Figure 15 presents an 11-day segment of NTS-2 time-transfer data. The 9-ns precision of these measurements indicates the potential of GPS to transfer time.

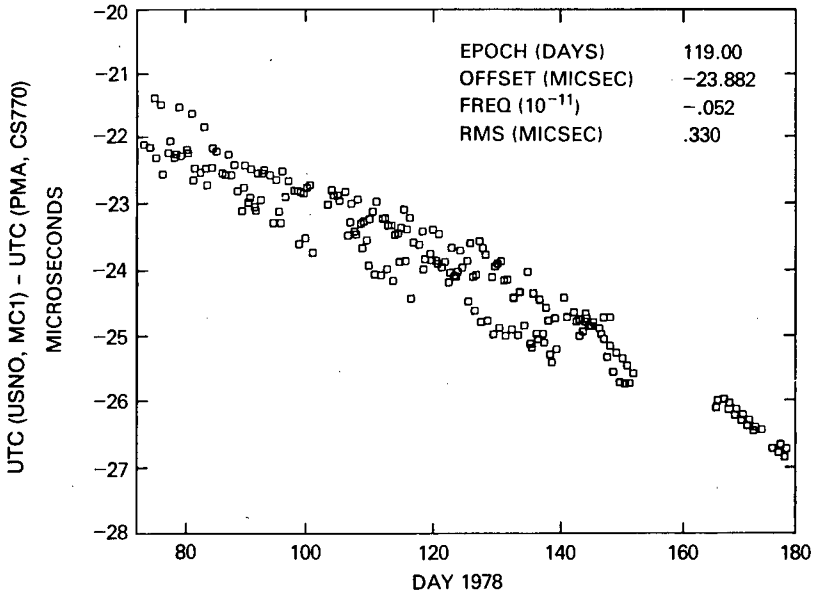

Fig. 14 — NTS-1/NTS-2 time transfer to NTS Panama tracking station

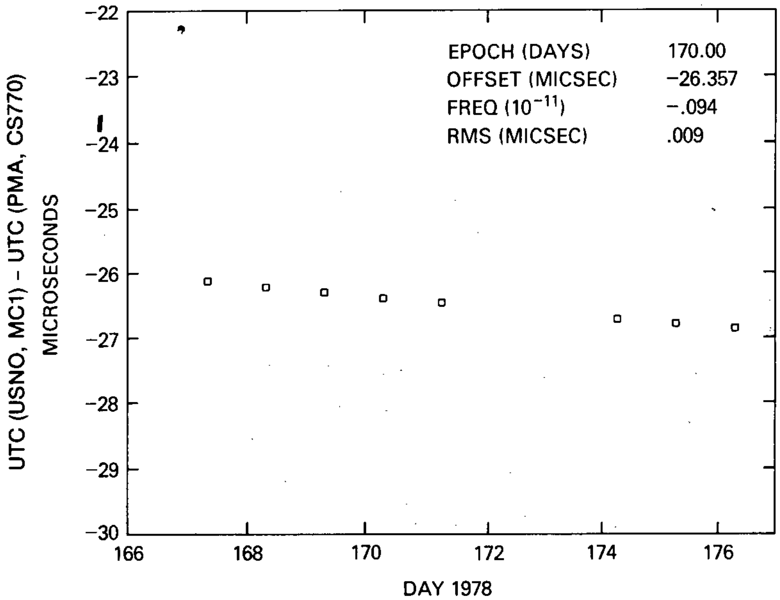

Fig. 15 — NTS-2 time transfer to NTS Panama tracking station

Long Term Frequency Stability

The Allan Variance was adopted by the IEEE as the recommended measure of frequency stability. Reference 22 presents a theoretical development which results in a relationship between the expected value of the standard deviation of the frequency fluctuations for any finite number of data samples and the infinite time average of the standard deviation. Equation (1) presents the Allan Variance [23] expression for M frequency samples with sample period T equal to the sampling time,

$$\sigma_y^2(2,\ \tau) = \frac{1}{M-1} \sum_{k=1}^{M-1} \frac{(\bar{y}_{k+1} - \bar{y}_k)^2}{2}. \quad (1)$$

The average frequency values $\bar{y}_k$ are calculated from pairs of clock offsets, Δt, separated by sample time, τ, as given by

$$\bar{y}_k = \frac{\Delta t_{k+1} - \Delta t_k}{\tau}. \quad (2)$$

The clock offset is not directly observable from a pseudo-range measurement; other variables must be measured or estimated. Figure 16 presents smoothed pseudo-range measurements that are evaluated at the Time of Closest Approach (TCA) of NAVSTAR-4 to the Vandenberg MS on day 177, 1979. Figure 17 presents the Long Term Frequency Stability [24] Analysis Flowchart which outlines the steps required to obtain estimates of $\sigma_y(2,\ \tau)$ for the NAVSTAR-4 rubidium clock. Pseudo-range and delta pseudo-range measurements, taken between NAVSTAR-4 and each Monitor Site, are transmitted to the Vandenberg Master Control Station (MCS) and are processed in real time to keep track of the NAVSTAR-4 clock and ephemeris. The measurements are collected and sent daily [25] to the Naval Surface Weapons Center (NSWC); once per week a reference ephemeris is calculated using the delta pseudo-range measurements in the CELEST [26] orbit determination program. Copies of the reference

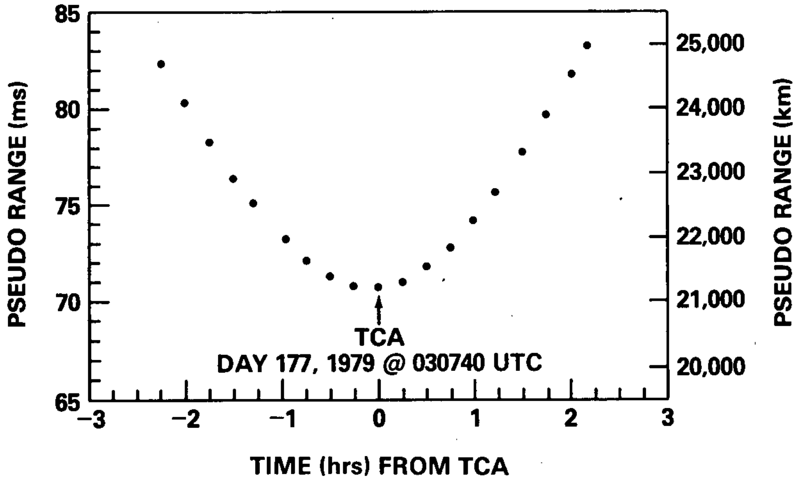

Fig. 16 — Pseudo range vs time, Vandenberg MS

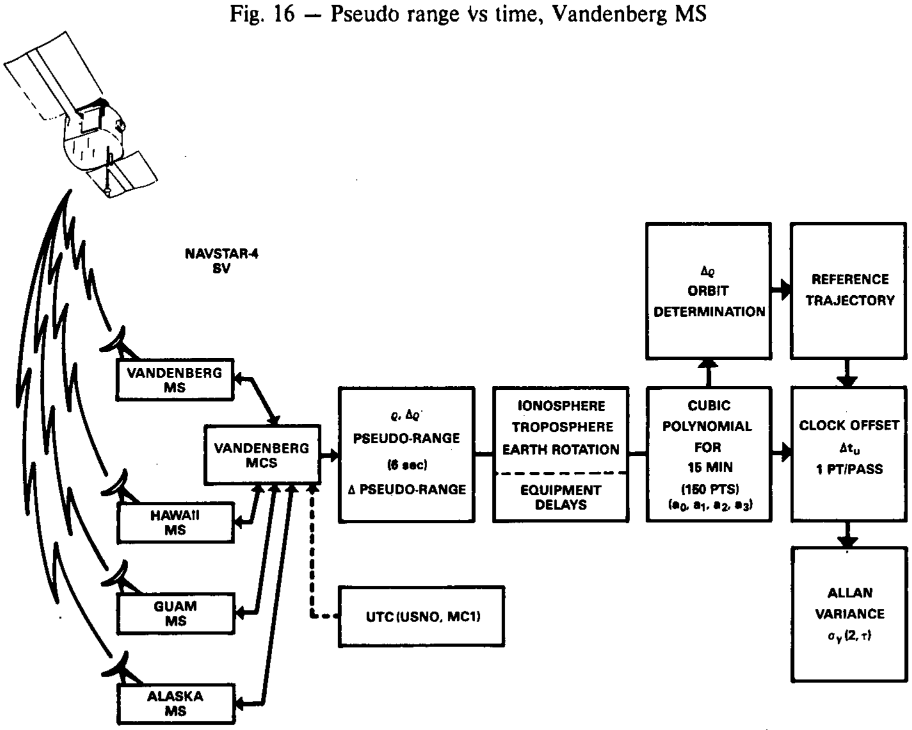

Fig. 17 — Long term frequency stability analysis flowchart

ephemeris are then transmitted to the Master Control Station, NRL, and other GPS users. NRL then calculates the NAVSTAR-4 clock offset at the TCA for each monitor site pass, using the reference ephemeris and a smoothed value of pseudo-range. This smoothed value of pseudo-range, named SRTAP, is obtained from a 15-min segment of 6-s pseudo-range and delta pseudo-range measurements which are used to sequentially estimate coefficients of a cubic equation. Corrections are applied for equipment delays, ionosphere, tropospheric delay, earth rotation, and a small relativity correction. The significant effects which are not corrected are spacecraft orbit, clock offset, and random effects remaining in the measurement.

The clock offset is estimated using the reference ephemeris and the a_0 coefficient from the cubic coefficients (a_0, a_1, a_2, a_3), which are reevaluated every 15 min of the NAVSTAR-4 pass. For a typical 6-h pass, this procedure results in 24 values of clock offset; a subset of these values is used to estimate the clock offset at TCA.

Figures 18 through 21 depict the actual amount of information collected from each MS. Reference to Fig. 18 presents 90 days (from day 036, 1979 through day 126, 1979) of observations from the Vandenberg MS. Figures 22 through 25 present the NAVSTAR-4 ground track as observed at each MS on 4 Mar. 1979.

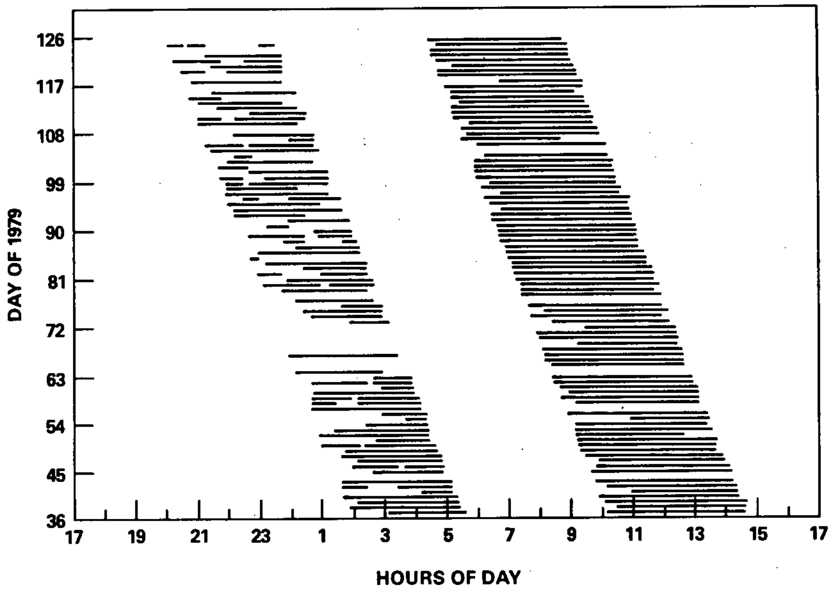

Fig. 18 — NAVSTAR-4 observed time span, Vandenberg MS

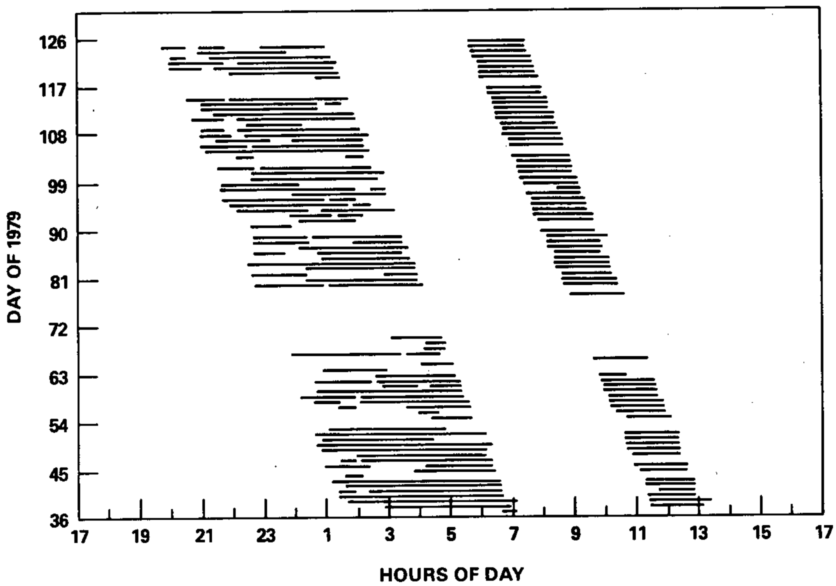

Fig. 19 — NAVSTAR-4 observed time span, Hawaii MS

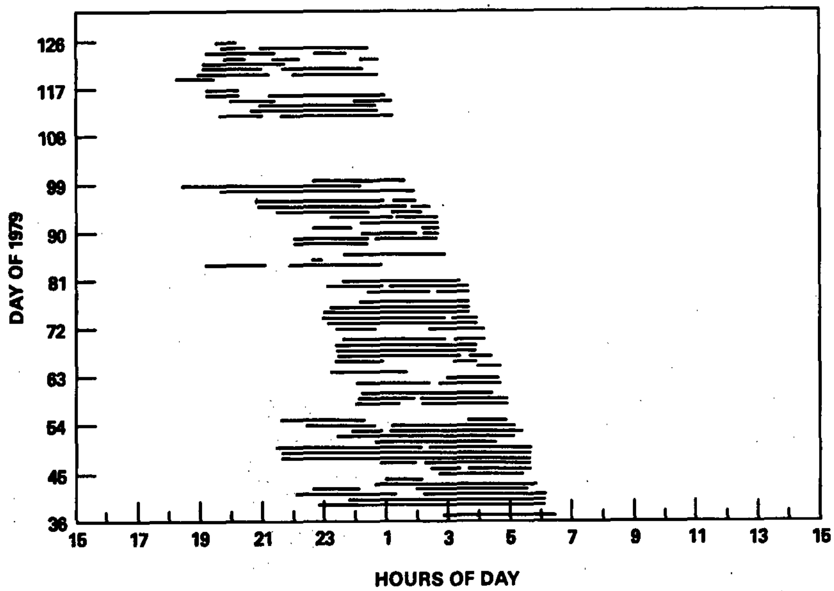

Fig. 20 — NAVSTAR-4 observed time span, Guam MS

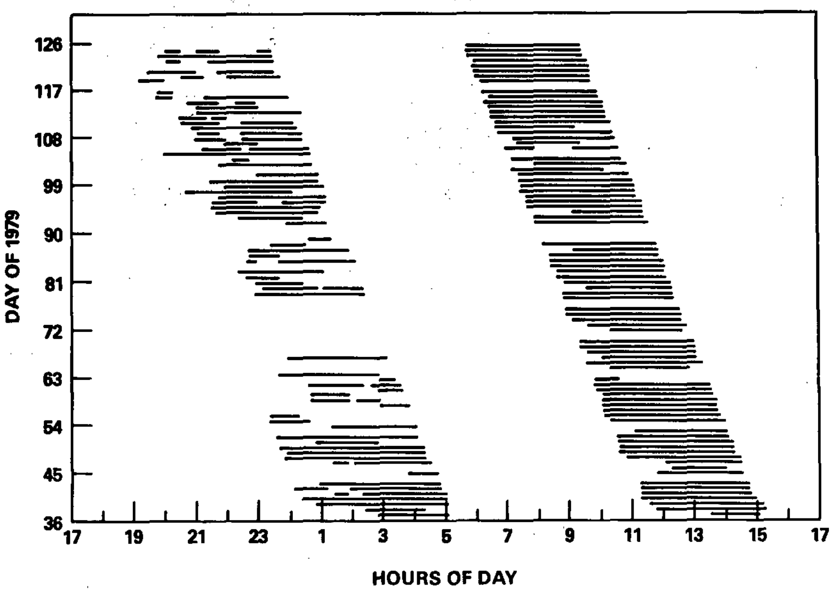

Fig. 21 — NAVSTAR-4 observed time span, Alaska MS

Reference to Fig. 22 shows that NAVSTAR-4 rose above the horizon at 2350 UTC on 3 Mar. 1979 and set at 0410 on 4 Mar. 1979. Consequently, NAVSTAR-4 could be observed for a maximum of 4 h and 20 min for the first pass. The second pass is longer, with a pass duration of 5 h and 20 min. In Fig. 22 the dots along the SV ground track are placed at 10-min intervals; the short bars perpendicular to the ground track are placed at 1-h intervals. The TCA for each pass occurs approximately mid-way in the pass; the clock offset is calculated at this time. Reference to Fig. 24 for the Guam MS shows that NAVSTAR-4 has only one pass each day, with a possible maximum pass time of 9 h and 50 min. Reference to Figs. 22 through 25 shows that the tracking network can track NAVSTAR-4 for as much as 66% of the time, averaged over the 2 rev/day orbit.

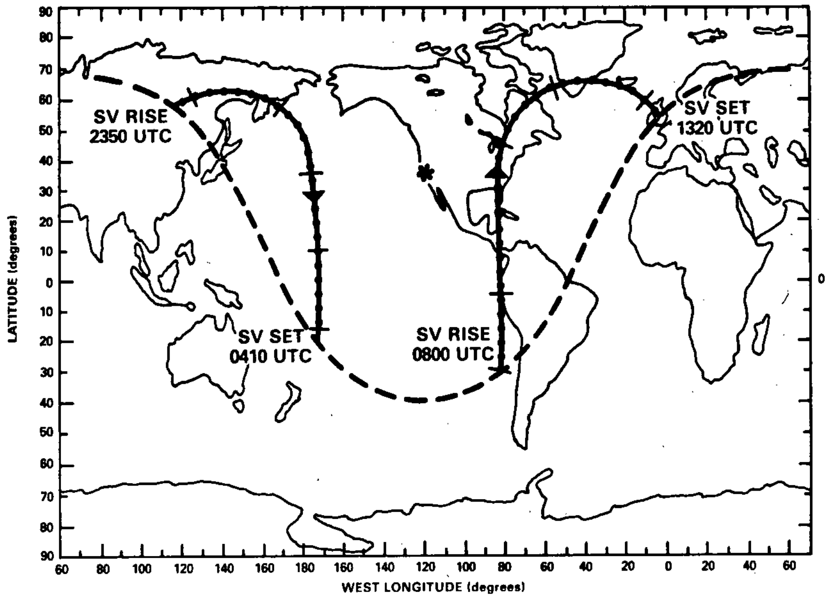

Fig. 22 — NAVSTAR-4 ground track on 4 Mar. 1979, Vandenberg MS

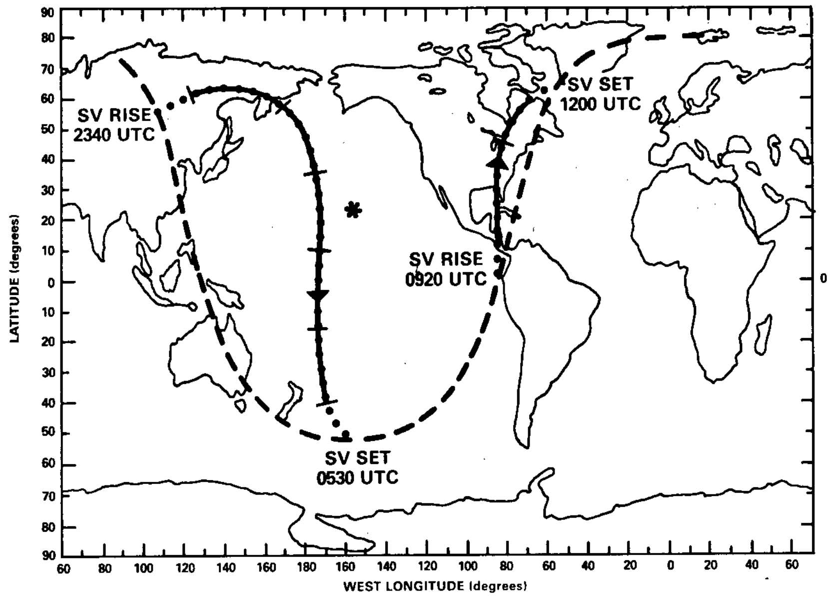

Fig. 23 — NAVSTAR-4 ground track on 4 Mar. 1979, Hawaii MS

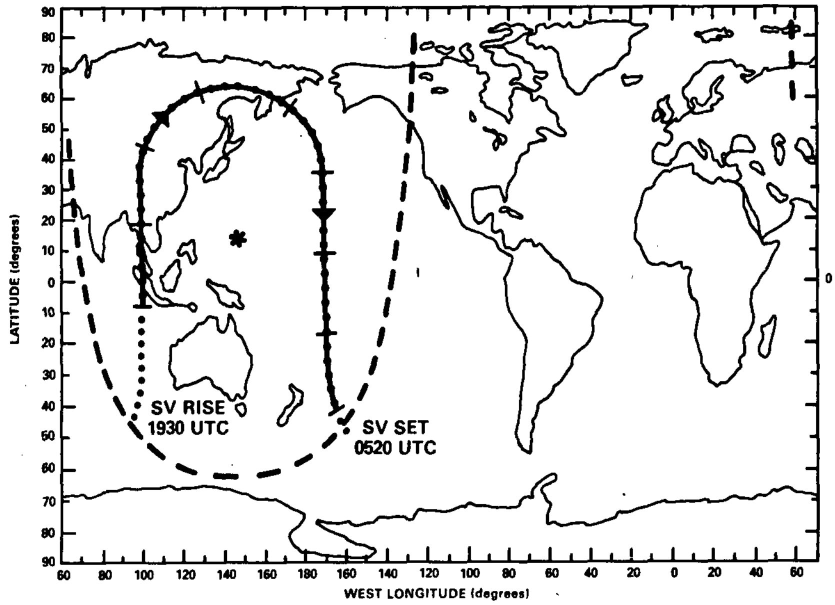

Fig. 24 — NAVSTAR-4 ground track on 4 Mar. 1979, Guam MS

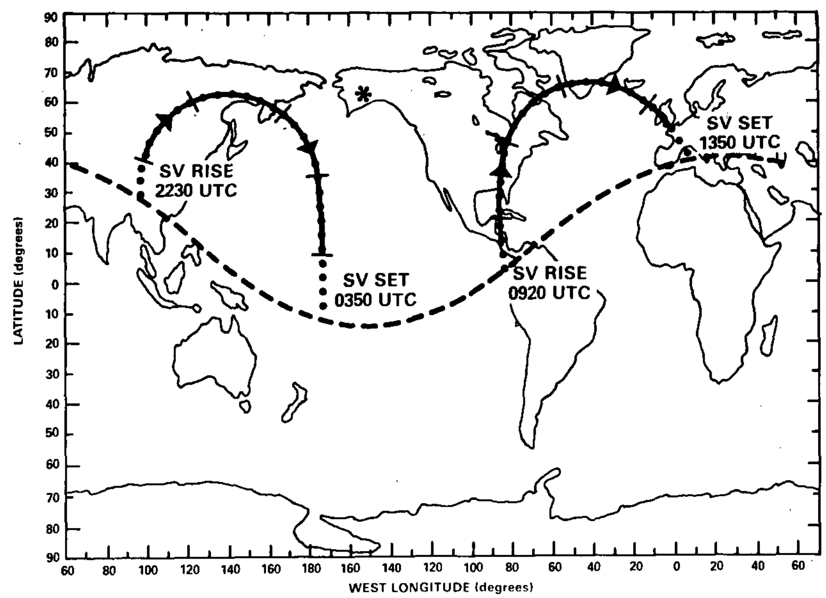

Fig. 25 — NAVSTAR-4 ground track on 4 Mar. 1979, Alaska MS

The SV pass time is a critical parameter in the orbit estimation; the $\Delta\rho$ (integrated pseudo-range rate) reference trajectory orbit estimation assumes that the frequency offset (between the monitor site clock and the SV clock) will be constant for sample times varying from $\tau = 0.11$ days (Fig. 23, Hawaii MS, second pass) to $\tau = 0.41$ days (Fig. 24, Guam MS). Reference trajectory calculations are made once per week, using data collected for 7 days. The four monitor sites collect (typically) 49 passes per week: 7 passes from the Guam MS and 14 passes each from Vandenberg, Hawaii, and Alaska.

The clock offset calculation at TCA produces a result that is independent of (small) along-track orbit errors. This can be seen by reference to Fig. 16; the pseudo-range rate is zero at TCA. A similar statement applies for (small) normal-to-the-orbit track errors. Radial (between the SV and the user) orbit errors behave differently; they look exactly like clock errors. Therefore, the capability of this technique to give significant $\sigma_y(2, \tau)$ estimates depends on the orbit smoothing to separate orbit errors from clock errors. The satellite dynamics have been extensively modeled; hence, the results are ultimately determined by the quality of the observations which are obtained by measurements between the spacecraft clock and the monitor site clocks.

NAVSTAR-4 Rubidium Frequency Stability Results

The clock offsets from the Vandenberg MS for a 90-day span are presented in Fig. 26. During this time span, the clock offset of NAVSTAR-4 was within 100 μs of the Vandenberg MS clock, except for a short time near day 055 when the cesium standard was activated. Two other clock resets are present, one near day 095 and another near day 118. The clock offsets for the other three monitor sites exhibit more frequent receiver resets.

The frequency stability of the NAVSTAR-4 rubidium frequency standard, referenced to the Vandenberg MS, is presented in Fig. 27 for sample times from 1 to 10 days. A value of 6.1×10^{-13} was measured for $\tau = 1$ day. The frequency stability remains constant for up to τ

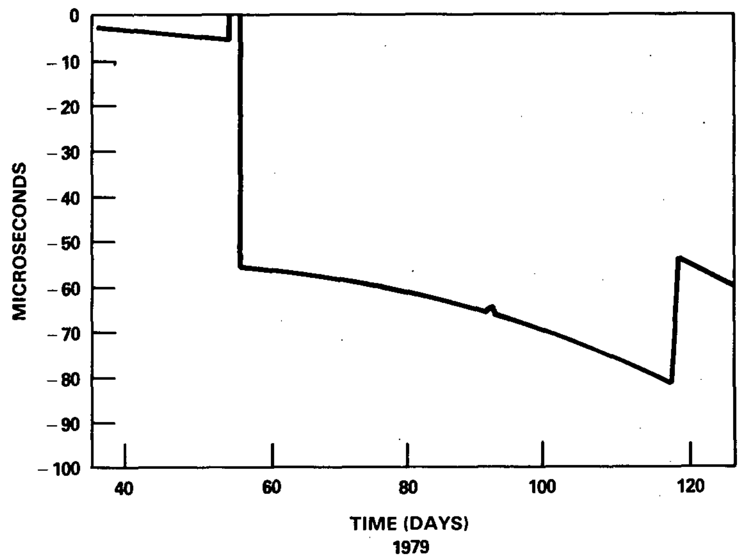

Fig. 26 — NAVSTAR-4 clock offset vs time, Vandenberg MS

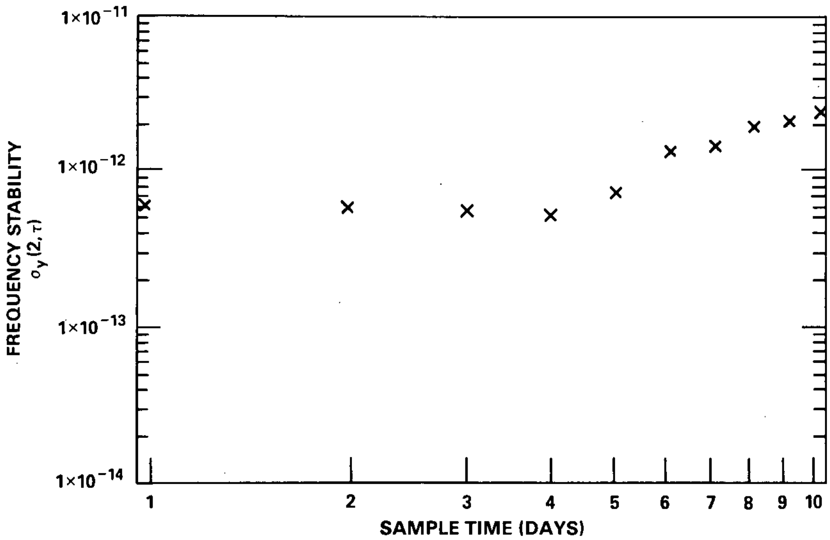

Fig. 27 — NAVSTAR-4 rubidium frequency stability (no aging correction), Vandenberg MS

= 4 days, followed by an increase in frequency instability. These results were not corrected for aging rate, which averaged -8.7×10^{-14}/day for the 154-day span. Aging rate corrections were applied to each data segment and the $\sigma_y(2, \tau)$ was recalculated; the frequency stability with respect to the Vandenberg MS is presented in Fig. 28.

For $\tau = 1$ day, $\sigma_y(2, \tau) = 6.1 \times 10^{-13}$;

for $\tau = 10$ days, $\sigma_y(2, \tau) = 2.4 \times 10^{-13}$.

Frequency stability calculations were made for all four monitor sites; the results are presented in Fig. 29. The influence of aging rate, which is quite evident in the Vandenberg MS

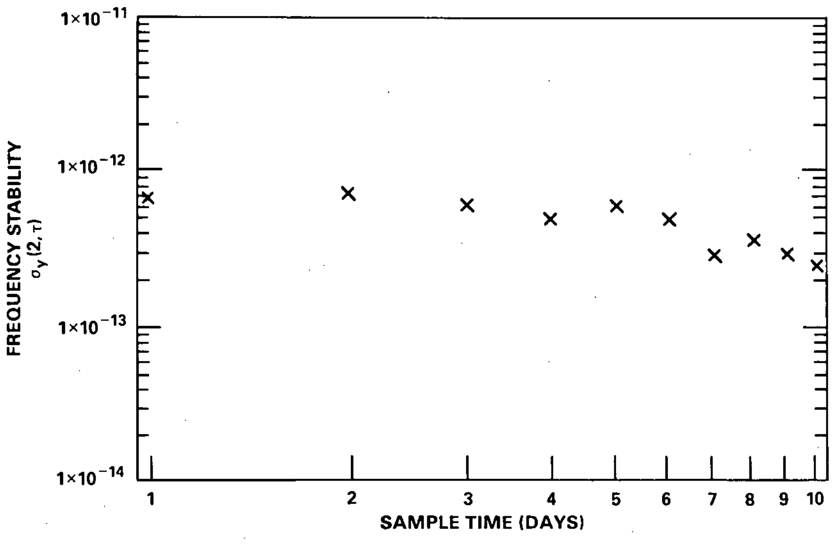

Fig. 28 — NAVSTAR-4 rubidium frequency stability (aging removed), Vandenberg MS

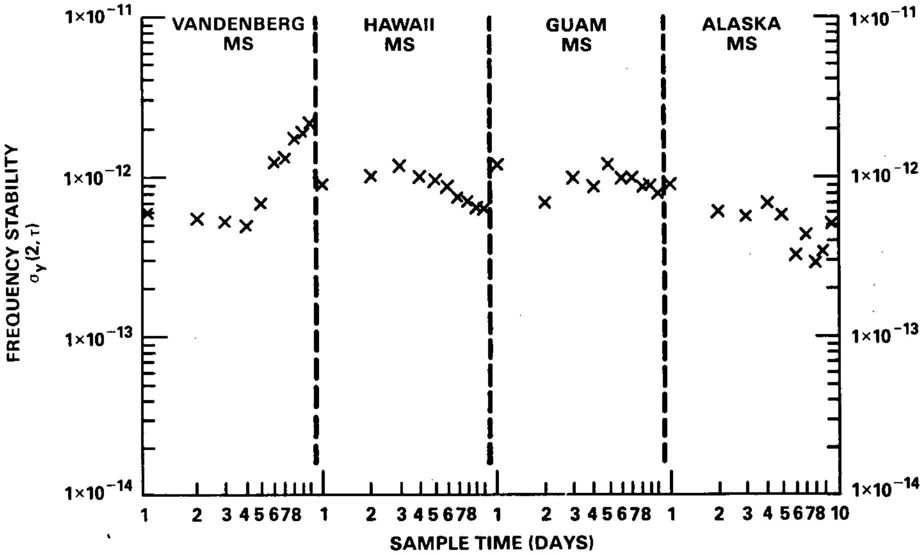

Fig. 29 — NAVSTAR-4 rubidium frequency stability, four monitor stations (no aging correction)

measurements, is not as apparent in the Hawaii, Guam, and Alaska monitor-site data. Aging rate corrections were applied and the results are presented in Fig. 30. These measurements indicate a constant trend for $\tau = 1$ day to $\tau = 6$ days, followed by an abrupt change for $\tau = 7$ days.

The frequency stability values from each monitor site were averaged; the four-station average is presented in Fig. 31 with no aging correction. Figure 32 presents the four-station frequency stability corrected for aging rate.

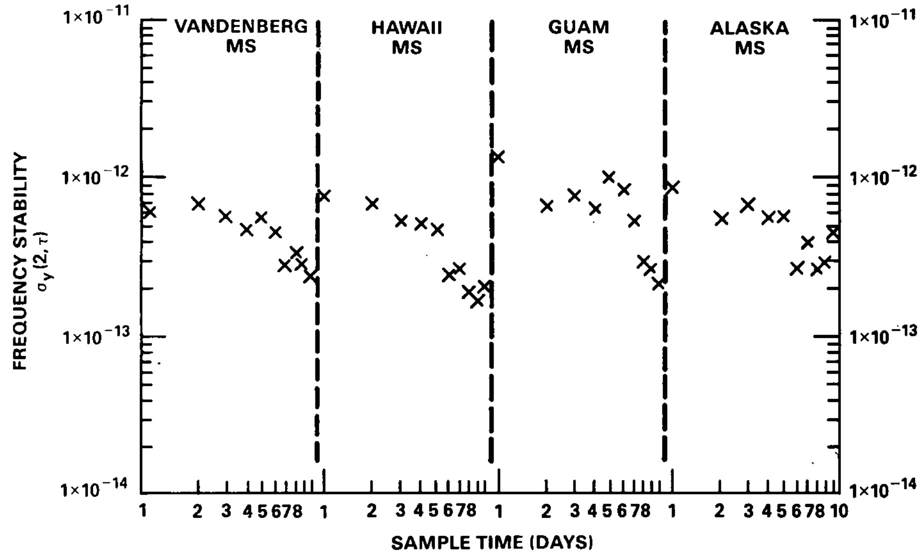

Fig. 30 — NAVSTAR-4 rubidium frequency stability, four monitor stations (aging removed)

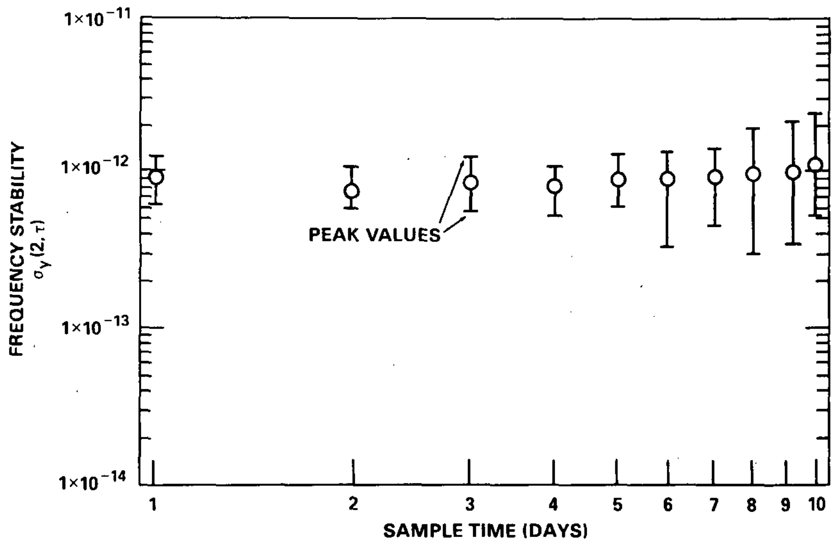

Fig. 31 — NAVSTAR-4 rubidium frequency stability four station average, (no aging correction)

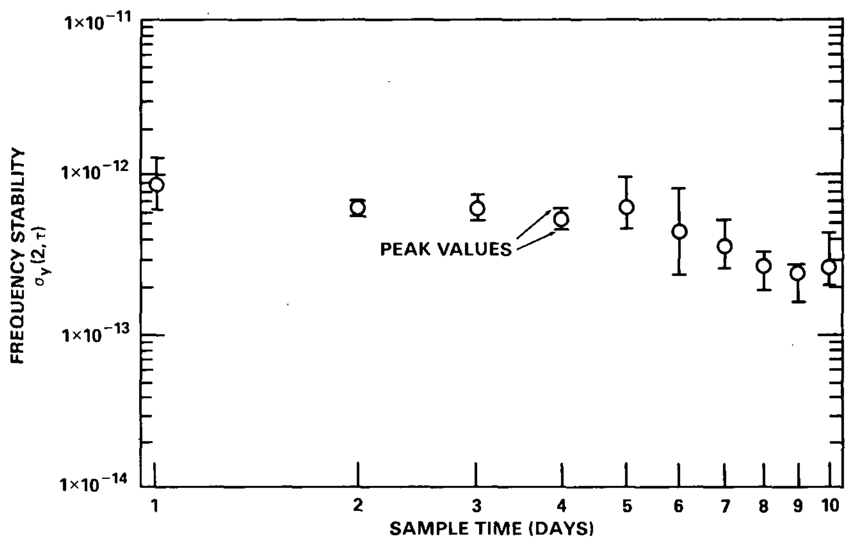

Fig. 32 — NAVSTAR-4 time transfer to Hawaii MS four station average (aging removed)

The four-station average frequency stability for

$$\sigma_y(2,\ 1\ \text{day}) = 9.1 \times 10^{-13}.$$

The peak departure of any monitor site average from the four-station average is indicated by the error bars. The frequency stability improves up to $\tau = 4$ days, followed by an increase with an apparent change in slope for $5 \leqslant \tau \leqslant 9$ days. The flicker floor is reached at $\tau = 9$ days, with $\sigma_y(2,\ 9\ \text{days}) = 2.5 \times 10^{-13}$. The coefficient for white frequency noise is estimated to be $(8.3 \times 10^{-13})/\sqrt{\tau}$, for $1 \leqslant \tau \leqslant 9$ days. Other factors are present in the data with the most notable being the change in $\sigma_y(2,\ \tau)$ slope for $\tau \geqslant 5$ days.

NAVSTAR-4 Time Transfer Results

Time-transfer calculations for the three remote GPS monitor sites (Hawaii, Guam, and Alaska) were made using the Vandenberg MS as the central station. The Vandenberg MS clock was linked to UTC(USNO,MC1) [27] by a series of portable clock trips. The SRTAP pseudo-range measurements were used to obtain monitor station clock offsets with respect to NAVSTAR-4; the Vandenberg MS pseudo-range measurements were used to obtain the NAVSTAR-4 clock and clock rate values. Measurements were available from day 036, 1979 through day 189, 1979, a 154-day time span. The internal receiver delay was not available; a value of zero was assumed.

Time-transfer results from the Hawaii MS are presented in Fig. 33 for a 25-day time span with an epoch of day 175, 1979. A time-transfer value of 75031.121 μs was obtained for day 175 with a slope of -4.80×10^{-12} and a noise level of 17 ns. Each point in Fig. 33 denoted by the symbol "X" was obtained using smoothed values for each of the four links involved in time transfer. The time transfer is given as the clock difference (UTC(USNO,MC1)-UTC(HAWAII)) which includes a 1-leap second correction since GPS time is not reset for leap seconds. The average frequency offset computed over the entire 154-day span was $[-4.05 \pm 0.41] \times 10^{-12}$.

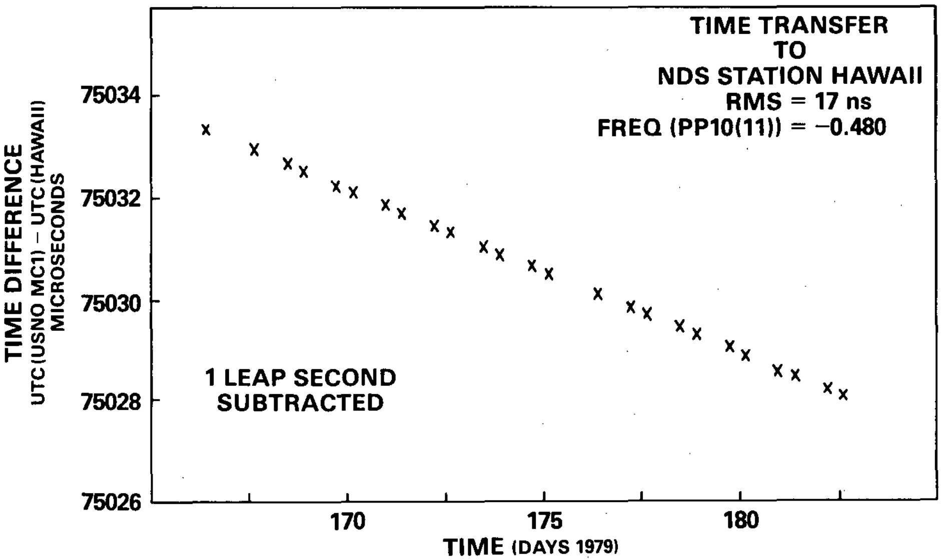

Fig. 33 — NAVSTAR-4 time transfer to Hawaii MS

Time-transfer results from the Guam MS are presented in Fig. 34 for a 25-day time span with an epoch of day 070, 1979. A time-transfer value of 65660.025 μs was obtained for day 070 with a slope of 4.24×10^{-12} and a noise level of 72 ns. Inspection of Fig. 34 shows an effect is present that increases the noise level of the Guam MS time transfers when compared to the Hawaii MS time transfers. The average frequency offset computed over the 154-day span was $[4.73 \pm 0.14] \times 10^{-12}$

Time-transfer results from the Alaska MS are presented in Fig. 35 for a 20-day time span with an epoch of day 162, 1979. A time-transfer value of 69314.634 μs was obtained for day 162 with a slope of -0.56×10^{-12} and a noise level of 55 ns. The average frequency computed over the 154-day span was $[-0.14 \pm 0.11] \times 10^{-12}$

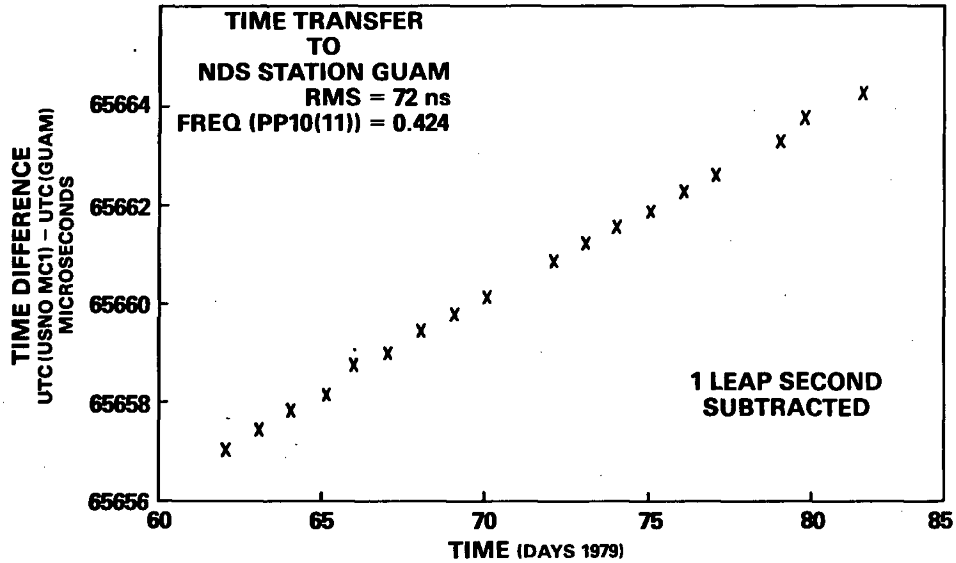

Fig. 34 — NAVSTAR-4 time transfer to Guam MS

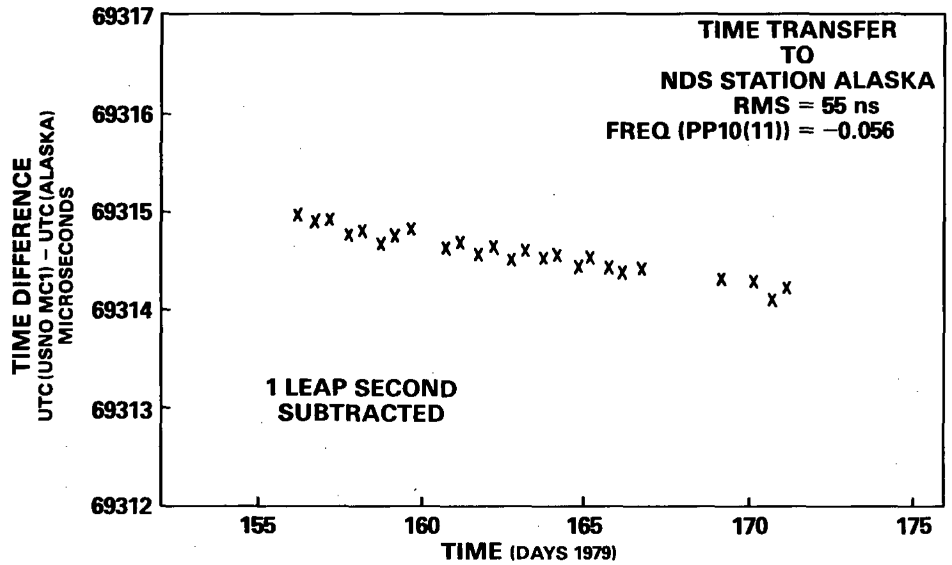

Fig. 35 — NAVSTAR-4 time transfer to Alaska MS

Further analysis indicates that the Alaska MS time-transfer values change by 75 ns every 12 h. Reference to the ground track (Fig. 25) illustrates that this change corresponds to successive NAVSTAR-4 passes over the Alaska MS. This 75-ns change is responsible for the increased (55 ns for Alaska MS) noise level as compared to the Hawaii MS noise level of 17 ns.

The remote monitor site offsets, determined via NAVSTAR-4, vary from 65 to 75 ms. These values indicate that the remote monitor site clock offsets approximate the 65- to 85-ms delay required for the signal to propagate from NAVSTAR-4 to the surface of the earth, assuming that the internal delay is small with respect to 85 ms (85,000,000 ns).

The monitor site frequency offsets for the Guam MS and the Hawaii MS differ from those expected of the cesium standards. The ground station cesium frequency standard manufacturer quotes an absolute frequency reference of 7×10^{-12}; however, user experience indicates that this is a conservative value. The difference frequency between the Guam MS and the Hawaii MS of 8.8×10^{-12} is slightly larger than the expected value.

Remote Monitor Site Frequency Stability

The time-transfer results were further analyzed by calculating the frequency stability of each remote MS (Hawaii, Guam and Alaska) cesium frequency standard, as determined through the time-transfer measurements. This procedure involves all four links, similar to those given in Fig. 6. Due to the relative position of the four monitor sites, the NAVSTAR-4 clock was required for an update of no more than 2 h. In these calculations, the clock update time was from TCA at Vandenberg MS to TCA at each monitor site. This procedure involves NAVSTAR-4 clock and the orbital trajectory for a segment equal to the arc of the orbit traversed during the clock update time. Hence, the $\sigma_y(2, \tau)$ values computed via time transfer are sensitive to the short term stability of the NAVSTAR-4 clock and the difference in radial orbit error over a fraction of a revolution.

The frequency stability of the Guam MS cesium frequency standard, as determined by NAVSTAR-4 time transfer, is presented in Fig. 36 for sample time varying from $\tau = 1$ to 10 days. For $\tau = 1$ day, a value of $\sigma_y(2, \tau) = 1.0 \times 10^{-12}$ was measured. The measured frequency stability decreases to a value of $\sigma_y(2, \tau) = 3.4 \times 10^{-13}$ for $\tau = 5$ days. For $\tau = 6$ through $\tau = 9$ days, a significant increase occurs; a peak value of 1.1×10^{-12} was measured at $\tau = 8$ days.

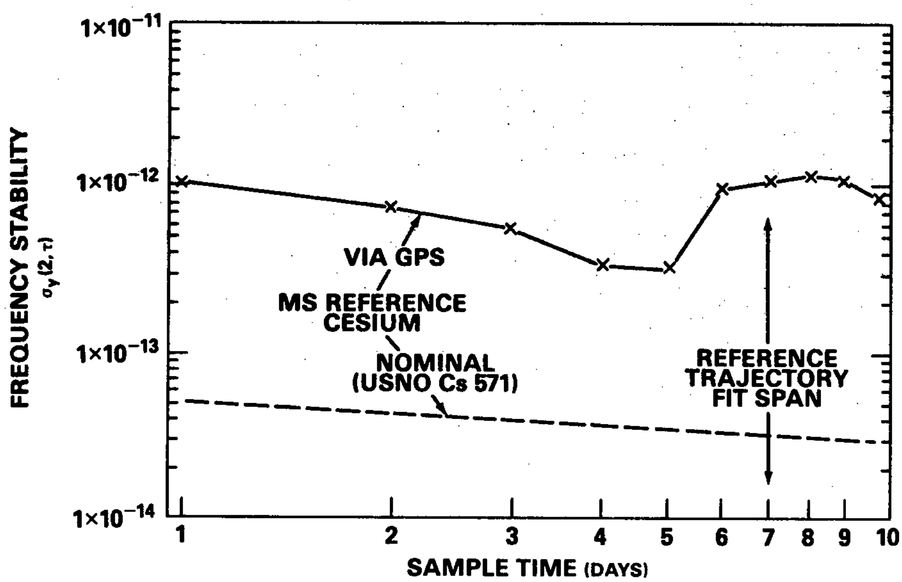

Fig. 36 — Guam MS frequency stability via NAVSTAR-4 time transfer

The frequency stability of the Alaska MS cesium standard is presented in Fig. 37. For $\tau = 1$ day, a value of $\sigma_y(2, \tau) = 7.9 \times 10^{-13}$ was measured. A behavior similar to the Guam MS results (Fig. 36) was noted with a peak value occurring at $\tau = 7$ days. The results for $\tau = 3$

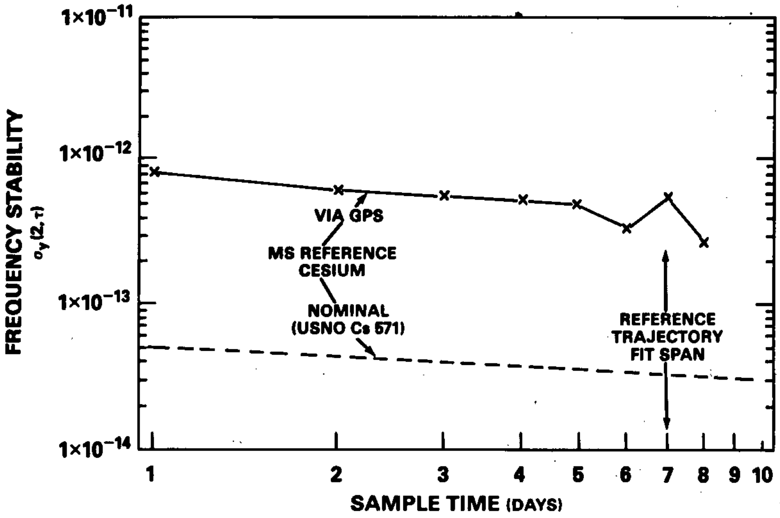

Fig. 37 — Alaska MS frequency stability via NAVSTAR-4 time transfer

days are less significant than the results from the Guam MS. A shorter arc of the orbit was required; also, more equipment resets resulted in a smaller sample.

The frequency stability of the Hawaii MS cesium frequency standard are presented in Fig. 38. For

$$\tau = 1 \text{ day, a value of } \sigma_y(2, \tau) = 6.7 \times 10^{-13}$$

was measured. An increase in $\sigma_y(2, \tau)$ which is less than that observed at the Guam MS, occurs for $\tau = 5$ days. The results from the Hawaii MS are the best of the three remote monitor sites.

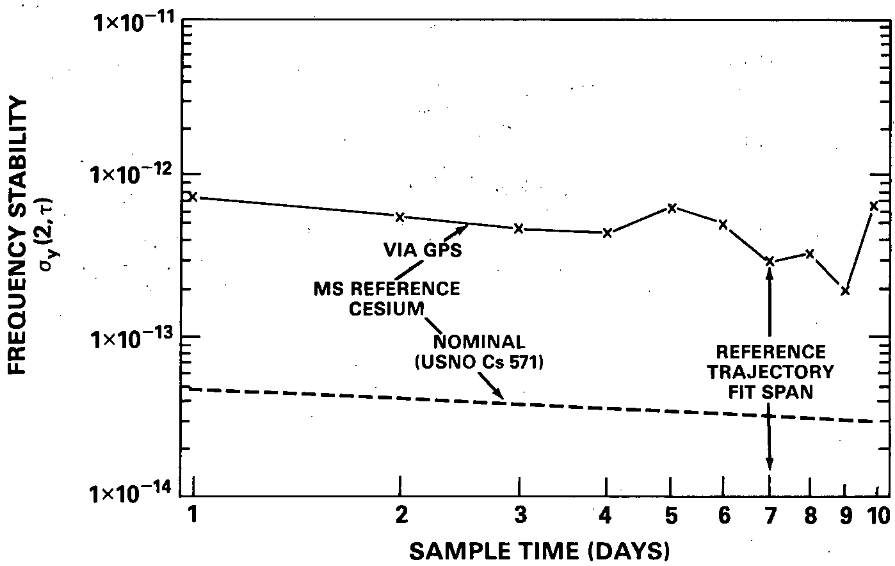

Fig. 38 — Hawaii MS frequency stability via NAVSTAR-4 time transfer

The $\sigma_y(2, \tau)$ values for Guam MS reach a maximum at $\tau = 8$ days of 1.1×10^{-12}. The Alaska MS $\sigma_y(2, \tau)$ reach a relative maximum at $\tau = 7$ days; Hawaii shows an increased frequency $\sigma_y(2, \tau)$ value at $\tau = 5$ days as shown in Figs. 37 and 38, respectively.

Two factors were considered as possible causes of this increased frequency instability. The first factor is the seven-day-reference-trajectory-orbit fit spans. A total of 22 seven-day orbits were made during the 154-day data span. The time-transfer results from Guam (see Fig. 34) indicate small changes from the average slope that correspond exactly with the seven-day-orbit fit spans. The second factor considered was the once-per-week P code resets for the pseudo-random code transmitter [28]. If this was the factor, it would have appeared at the same amplitude (1.1×10^{-12}) for the single station $\sigma_y(2, \tau)$ results presented in Figs. 27-32. Therefore, it is concluded that "orbit mismatch" is present for the longer sample times of 5 days or more.

The average value of the $\sigma_y(2, \tau)$ values for the Hawaii, Guam and Alaska frequency standards is 7.8×10^{-13} for $\tau = 1$ day. This value is considerably larger than the expected frequency stability for the HP5061A, Opt 004 standards. However, it is close to the 9.1×10^{-13} value measured for the NAVSTAR-4 rubidium frequency standard. These results indicate that NAVSTAR-4 rubidium is slightly less stable than the average remote MS frequency stability, as measured by time transfer.

CONCLUSIONS

- Worldwide time transfer to the major time standards laboratories has been demonstrated with NTS-1 for the past 2 years. The average accuracy achieved was 60 ns. Ionospheric delay was the most significant uncorrected error source.

- A time-transfer precision of 9 ns has been demonstrated for an 11-day span with the NTS-2 spacecraft using a cesium clock and a first order ionospheric delay correction.

- The NAVSTAR-4 rubidium frequency standard has a measured frequency stability, with aging corrected, of

$$\sigma_y(2, 1\ \text{day}) = 9.1 \times 10^{-13},$$
$$\sigma_y(2, \tau) = 8.3 \times 10^{-13}/\sqrt{\tau} \quad 1 < \tau < 9\ \text{days},$$
$$\sigma_y(2, 9\ \text{days}) = 2.5 \times 10^{-13},$$

referenced to a smoothed reference ephemeris calculated over 22 seven-day orbits using delta pseudo-range measurements. For $\tau \geqslant 5$ days a change in the $\sigma_y(2, \tau)$ versus τ curve is present which correlates with the orbit fit span.

- Time transfer to the three remote monitor sites indicates clock offsets near 65 to 85 ms. Time-transfer noise levels of 17 to 55 ns were measured for the reported data span over a 154-day observed data span.

- The frequency stability of the three remote GPS monitor sites has been calculated for $1 \leqslant \tau \leqslant 10$ days using NAVSTAR-4 time-transfer results with the Vandenberg MS as the central station, linked by portable clock to UTC(USNO,MC1). These measurements indicate a seven-day orbital effect.

- Comparison of the on-orbit frequency stability of a rubidium frequency standard versus a cesium frequency standard indicates $\sigma_y(2, 1\ \text{day}) = 9.1 \times 10^{-13}$ for rubidium and $\sigma_y(2, 1\ \text{day}) = 3.7 \times 10^{-13}$ for cesium as presented in Fig. 39, details of which are in Ref. 12.

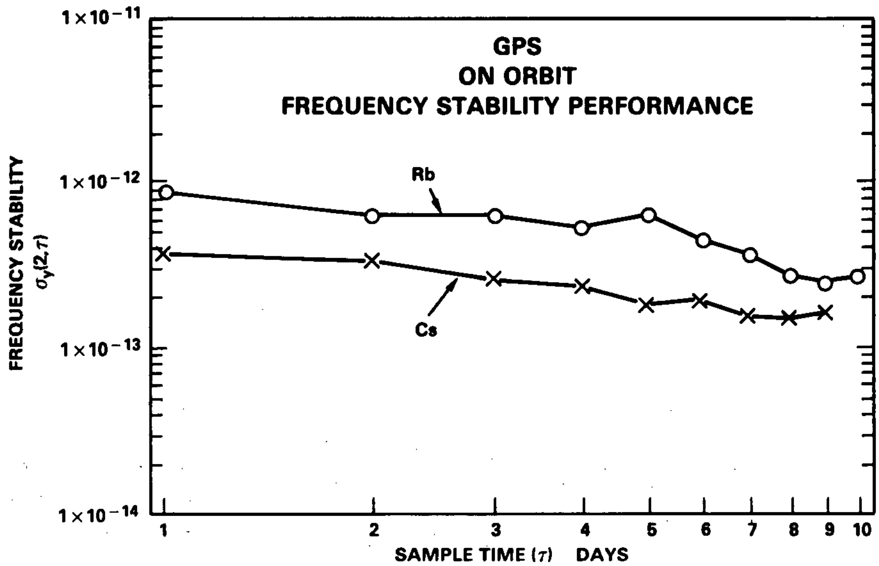

Fig. 39 — GPS on-orbit frequency stability performance

NRL, along with other agencies and contractors, is continuing development of advanced cesium and hydrogen maser frequency standards for use in future GPS spacecraft. Other proposed work includes a study to investigate the seven-day orbit effect.

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