ON-ORBIT FREQUENCY STABILITY ANALYSIS OF GPS NAVSTAR CESIUM AND RUBIDIUM CLOCKS

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Abstract

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 discontinuties, 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. Discontinuties 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 offset, 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 1×10^{-13}/day has a measurable effect on NAVSTAR one-day frequency stability. It is further demonstrated that uncorrected aging on the order of 1×10^{-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.

INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is a space–based navigation satellite system which, when operational in the early 1990's, will provide accurate navigation and time information to users anywhere on the Earth's surface, or in near–Earth orbit. A constellation of 21 satellites, with three on–orbit spares, will be tracked by a network of GPS Monitor Stations (MS) and controlled from the Master Control Station (MCS). GPS will provide a near–instantaneous navigation capability because each NAVSTAR Spacecraft Vehicle (SV) clock is synchronized to a common GPS time. Each NAVSTAR clock must then maintain GPS time until the next update by the MCS, therefore NAVSTAR clock performance is critical to the GPS mission.

The Naval Research Laboratory (NRL) determines on–orbit NAVSTAR GPS clock performance using a procedure as depicted by the Figure 1. The goal of the NRL NAVSTAR clock analysis is to separate the clock offset from the orbit and other system effects that are present in the GPS signal. Outputs from the clock analysis include frequency and aging histories, frequency–stability profiles, time–prediction uncertainty profiles, time–domain noise process analysis, spectral analysis, and anomaly detection. Events that perturb normal NAVSTAR or MS clock operation are of particular interest in the clock analysis.

The NRL on–orbit analysis[1] represents total system errors super–imposed on the NAVSTAR clock results. GPS system influences may either enhance or detract from actual clock performance. Therefore, deviations from a typical frequency–stability profile will be further analyzed to identify GPS clock, ephemeris, or other factors.

The following table presents the NAVSTAR number, SV number, clock identification, clock type and data span for each of the NAVSTAR clocks included in this analysis.

NAVSTAR CLOCK DATA
DATA SPAN: 1 Jan 1986 to 31 December, 1988

NAV #	SV #	CLOCK ID	CLOCK TYPE	DATA SPAN t1 MJD	t2 MJD	t2-t1 days
3	6	19	Rb	6431	7526	1095
4	8	18	Rb	6431	6678	247
6	9	14	Rb	6431	7526	1095
8	11	33	Rb	6431	6563	132
8	11	2	Cs	6569	7526	957
9	13	4	Cs	6431	7526	1095
10	12	5	Cs	6431	7526	1095
11	3	3	Cs	6431	7515	1084

The NAVSTARs are referenced by both NAVSTAR numbers (column #1) and NAVSTAR SV numbers (column #2). Column #3 presents the NAVSTAR clock indentification number. The clock type is abbreviated by **Cs** for a cesium clock and by **Rb** for a rubidium clock. The starting and stop dates for the data span are expressed in Modified Julian Days (MJD), and the data span is expressed in days.

Reference to the table shows that six of the eight NAVSTAR clocks have data spans that are close to

1000 days. The longer data spans will be used to evaluate clock performance with sample times of up to 100 days.

The NAVSTAR SVs included in this analysis are Block I models that do not have any degradation in the ephemeris or broadcast signal due to Selective Availability (SA). Three of the four NAVSTAR rubidium clocks are of the early models that have significant temperature coefficients; the fourth rubidium has additional temperature compensation. The four NAVSTAR cesium clocks are expected to have performance that is close to the Block II NAVSTAR cesium clocks.

PSEUDO–RANGE MEASUREMENT MODEL

Measurements of pseudo–range (PR) are taken between signals derived from the NAVSTAR SV clock and the MS reference clock using a single–frequency, spread–spectrum receiver. Each measurement is corrected for equipment delay, ionospheric and tropospheric delay, earth rotation, relativistic effects, and the ephemeris offset is computed from the broadcast NAVSTAR ephemeris. The clock offset measurements are then aggregated and smoothed once per 13 minutes.

The equation that relates the pseudo–range measurement to the time difference between the NAVSTAR clock and the reference MS clock is

$$PR = R + c(t_{SV} - t_{MS}) + ct_A + e$$

where

PR is the measured pseudo–range,
R is the slant range (also known as the geometric range) from the NAVSTAR at the time of transmission to the MS at the time of reception,
c is the speed of light,
t_{MS} is the reference MS clock time,
t_{SV} is the NAVSTAR clock time,
t_A is ionospheric, tropospheric, and relativistic delay, with corrections for antenna and equipment delays, and
e is the PR measurement error.

The NAVSTAR clock and the MS clock (or other reference clock) enters the PR measurement as the difference between NAVSTAR clock time t_{SV} and MS clock time t_{MS}. Because the reference MS clock t_{MS} enters directly into the measurement the stability of the MS reference clock must be considered in the NAVSTAR clock analysis. For the measurements that are referenced to the USNO Master Clock #2 the stability of the USNO time–scale is significantly better than that of an individual NAVSTAR clock for sample times of 1 to 100–days.

It should be noted that NAVSTAR clock time is used with the clock coefficients that are broadcast as part of each NAVSTAR navigation message to compute GPS time. The NAVSTAR clock time(for each NAVSTAR) is measured and controlled by the GPS MCS to be within plus or minus one millisecond of GPS time.

NAVSTAR CLOCK MODEL

The pseudo–range measurements that are taken between a NAVSTAR SV and a GPS monitor site (or by any GPS user) are normally sampled by the reference MS clock (or the user reference clock) at the discrete times $t_{MS} = t_k$. The *clock phase offset* between a NAVSTAR clock and the reference MS clock is obtained by solving the pseudo–range equation for the quantity $(t_{SV} - t_{MS})$, which is the difference between the NAVSTAR clock time and the MS clock time.

$$(t_{SV} - t_{MS}) = (R/c + t_A + e/c) - PR/c$$

The time difference between the NAVSTAR clock and the MS clock, $(t_{SV} - t_{MS})$, is usually expressed in microseconds; the pseudo–range is a measure of distance expressed in kilometers or meters, and c is the speed of light expressed in a consistent set of units.

The pseudo–range measurements are normally sampled at a uniform rate, therefore another variable $x(t_k)$ may be defined to denote the *clock offset*, sampled at time $t_{MS} = t_k$ by the MS clock.

$$x(t_k) = (t_{SV} - t_{MS})$$

where $k = 0, 1, 2, 3, \ldots, N$ (the number of clock measurements)

Given two clock measurements, $x(t_j)$ and $x(t_k)$, which were sampled at times t_j and t_k, the *sample time* τ is defined as

$$\tau = (t_k - t_j)$$

In *time-domain analysis*, the performance of a NAVSTAR clock will be analyzed as a function of τ, the sample time. In *frequency–domain analysis*, the independent variable is the Fourier frequency.

The average clock rate can now be computed using a variable known as the average *fractional–frequency offset*, as defined by the following equation.

$$\overline{y}(t) = \frac{x(t_k) - x(t_j)}{\tau}$$

The fractional–frequency offset $\overline{y}(t)$ will be analyzed as a function of time to determine NAVSTAR clock coefficients, and anomalies such as frequency discontinuities or environmentally induced frequency fluctuations.

TIME–DOMAIN STABILITY ANALYSIS

NAVSTAR clock performance in the time–domain is characterized through the use of a frequency–stability profile[2]. The time–domain measure of frequency–stability used in this analysis is the Allan variance[3]. Time–domain clock performance parameters can be related to the Allan variance by the following equation.

$$\sigma_y^2(\tau) = a\tau^{\mu}$$

In this equation, τ is the sample time, σ_y is the square root of the variance of the fractional–frequency measurements $\overline{y}(t)$, the coefficient a varies with each type of clock and the random noise process type, μ depends on the random noise process type. The variance $\sigma_y^2(\tau)$ is defined as an infinite average which is estimated using successive triplets of clock phase measurements or pairs of fractional frquency offset measurements separated by the sample time τ. Confidence intervals are then computed for each stability measurement according to the random noise process type and the number of samples.

The random clock phase or frequency fluctuations for quartz, rubidium, cesium, and hydrogen clocks can be modeled by an appropriate combination of five types of random noise processes. A typical frequency–stability profile is presented in the Figure 2. The dependent variable presented is $\sigma_y(\tau)$ (the square root of the Allan variance) as a function of sample time, τ.

Once a clock has been characterized through a frequency–stability analysis, the frequency–stability profile may then be used to estimate a clock's time–prediction performance. The time–prediction uncertainty is computed using optimal two–point prediction that can be related to the frequency–stability by the following equation.

$$\sigma_x(\tau) = \sqrt{2}\tau\sigma_y(\tau)$$

In this equation $\sigma_x(\tau)$ represents the NAVSTAR clock phase time–prediction uncertainty, $\sigma_y(\tau)$ represents the NAVSTAR frequency–stability, and τ represents the sample time or the NAVSTAR clock update time.

This time–prediction model indicates that the long–term time–prediction performance is driven by the product of the clock update time and the frequency–stability. Therefore, the frequency–stability is also related to time–prediction uncertainty. The length of time between NAVSTAR clock updates is determined by GPS performance requirements, hence improved frequency–stability is the parameter that will improve GPS time–prediction performance.

Sets of clock measurements may now be analyzed to determine both deterministic and random components of NAVSTAR clock performance. These clock measurements also contain residual ephemeris, environmental, and system effects.

NAVSTAR PHASE/FREQUENCY DISCONTINUITY ANALYSIS

The primary reason for applying the phase or frequency discontinuity corrections is so that sample times from 1 day up to 100 days, or more, may be used in the stability analysis. Otherwise the clock data would have to be partitioned at every discontinuity, which would in turn reduce the longest possible sample time that could be computed.

Clock phase offset measurements computed from smoothed pseudo–range measurements taken between the NAVSTAR–03 and USNO are presented in Figure 3. Each measurement is time–tagged using three related time scales which are:

(a) Modified Julian day (MJD) for the lower time axis
(b) the day–of–year is on the upper time axis
(c) the calendar month and year are on the upper time axis

The clock data is nominally sampled at a rate of once per sidereal day at the point of closest approach of the NAVSTAR to the ground MS. This choice results in sampling the NAVSTAR–SV clock offset at the same place in the 12–sidereal hour GPS orbit. This procedure also insures that the NAVSTAR–SV clock parameters and stability are determined, except for missing observations, using a uniformly sampled database.

Analysis of the NAVSTAR–03 phase data indicates piecewise continuous clock data with three phase discontinuities and a negative slope for each segment. These discontinuities in the clock data can be caused by normal GPS operations such as NAVSTAR time or frequency adjustments or MS clock resets, therefore these discontinuities do not represent the normal unperturbed clock behavior. As part of the NAVSTAR clock analysis the amount of each discontinuity is estimated and a search is made to find a reason for each discontinuity in the clock data. The phase discontinuity correction procedure will now be presented for a typical phase discontinuity that was present in the (USNO vs NAVSTAR–03) clock data.

The NAVSTAR–03 vs USNO clock data in the neighborhood of one phase discontinuity that was detected is presented by the Figure 4. The time of the phase discontinuity was estimated to be MJD 6525.483 (5 April, 1986). The clock phase data was partitioned into subsets delineated by the discontinuity. The clock phase offset was then predicted at the time of the discontinuity using the two subsets; the difference between these two predictions yields the clock phase discontinuity. The corrected clock phase data is presented by the Figure 5. The time of the discontinuity is indicated on the figure with an arrow. The values of the phase correction (0.444E03 microseconds) and frequency correction which in this case is zero, are plotted adjacent to the arrow. The clock phase data is now continuous within the interval analyzed.

All data prior to the discontinuity has been corrected, which can be seen by comparing the NAVSTAR–03 clock data before and after the discontinuity correction. This discontinuity correction procedure is repeated until all significant phase discontinuties have been detected and corrected. The error in the clock phase discontinuity correction procedure can be related to the clock prediction performance at a sample time of $\tau/2$ days.

The fractional–frequency offset was computed using pairs of clock phase measurements separated in time by one sidereal day. Figure 6 presents the NAVSTAR–03 fractional–frequency as a function of time.

Analysis of the NAVSTAR–03 frequency offset data indicates an overall negative slope with large frequency fluctuations that appear to be periodic. Previous NRL analyses have determined that the NAVSTAR–03 rubidium clock frequency was sensitive to temperature changes that occur in the NAVSTAR spacecraft. The temperature coefficient was determined to be 1.96×10^{-12} per degree Celsius. The onset and departure of each NAVSTAR–03 eclipse cycle has been plotted using two vertical lines with a shaded fill during the eclipse season. A total of six eclipse cycles occured during the three year data span. Analysis of the frequency data that ended in May, 1986 and the following eclipse cycle (beginning in late September, 1986) indicated that a frequency discontinuity occured on MJD 6613. The observation that a frequency discontinuity had occured was determined by extracting subsets of data during 1986, 1987, and 1988 that are partitioned using a nominal one–year partition size.

The amount of the NAVSTAR–03 frequency discontinuity was determined by iteratively analyzing the frequency offset data for the value of the discontinuity, applying the correction, and then analyzing the corrected frequency offset data. The total amount of the frequency discontinuity determined was -1.75×10^{-12}.

Closer examination of the NAVSTAR–03 frequency data indicates rapid changes in frequency offset occurs at the onset of the NAVSTAR-03 eclipse season. Rapid changes in frequency also occur at the end of the eclipse seasons. The observed frequency changes are on the order of 1.0×10^{-12} to 3.5×10^{-12}. Because of the correlation with the eclipse season and the temperature sensitivity of the NAVSTAR–03 rubidium clock, these data are treated as normal behavior and will be included in the subsequent NAVSTAR–03 stability analysis.

Additional frequency corrections were made for a series of small rate corrections that were made by the USNO to coordinate their Universal Time Coordinated (UTC) time scale with an international time scale. These rate corrections affect all NAVSTAR clock measurements made by USNO. The

NAVSTAR–03 versus USNO clock data that includes the USNO rate corrections is presented by Figure 7.

The NAVSTAR–03 versus USNO clock offset with all corrections applied is presented by Figure 8 and the fractional frequency offset presented by Figure 9. The corrected data will be used to compute long term clock coefficients and frequency–stability.

The NAVSTAR–10 versus USNO raw phase offsets is presented by Figure 10. No phase or frequency discontinuities were detected in this data during the entire three year data span. The USNO rate corrections were the only corrections that were made to the NAVSTAR–10 versus USNO data. The NAVSTAR–10 frequency offset data is presented by Figure 11 with the eclipse cycles highlighted. It is clear that a significant improvement exists between the earlier NAVSTAR rubidium clocks and the NAVSTAR–10 cesium clock. The corrected NAVSTAR–10 versus USNO clock is presented by Figure 12. Comparsion of the data without the USNO rate corrections (Figure 10) and with the USNO rate corrections indicates no detectable difference for this scale factor. The corrected NAVSTAR–10 versus USNO clock data was used to compute the long term clock parameters, frequency–stability, and time–prediction uncertainty results.

NAVSTAR LONG TERM AGING RATE ANALYSIS

Each NAVSTAR spacecraft carries atomic clocks that are used as time and frequency references for GPS and to determine the epochs of the transmitted waveforms. The physics of atomic clocks indicates that the frequency of these clocks should remain invariant, ie, not change with time. The clock aging parameter gives a measure of how quickly a NAVSTAR clock departs from a reference clock.

The departure of a NAVSTAR clock from an initial frequency that is within GPS specifications impacts GPS operation in at least two ways.

The first way NAVSTAR clock aging impacts GPS operation depends on how well the aging rate parameter has been estimated. Stability results indicate that an uncorrected aging rate term on the order of 1×10^{-13}/day can have a measurable impact of clock performance. This can be seen by comparing (Figure 13) the NAVSTAR–08 rubidium frequency–stability results with and without an aging rate correction. The uncorrected aging rate of -1.3×10^{-13}/day results in a measured stability of 1.4×10^{-13} for a 1–day sample time. The aging–rate corrected stability is 8.9×10^{-14} for a 1–day sample time. It follows that an uncorrected aging rate on the order of 3×10^{-13}/day would drive the stability over the GPS 1–day specification and cause unacceptable performance.

For an uncorrected aging rate term on the order of 1×10^{-15}/day the impact of aging rate on stability is significantly reduced. This can be demonstrated using the NAVSTAR–10 cesium frequency–stability results with and without an aging rate correction (Figure 14). There is no measurable difference up to a sample time of 15–days between the measured 1–day stability without an aging rate correction and with an aging rate correction for the NAVSTAR–10 long term aging rate of -1.1×10^{-15}/day. The impact of the -1.1×10^{-15}/day aging rate is so small that the frequency–stability values are still less than 1×10^{-13} for a 100–day sample time.

The second way aging impacts GPS operation is that a relatively large aging rate causes any initial frequency offset to drift away from the GPS time and frequency limits. Furthermore each NAVSTAR clock reset by a Z–adjust or C–field tune requires a re–estimation of the all clock parameters. The amount of time required to accurately determine the NAVSTAR aging rate parameter is on the order of one week or more.

The NAVSTAR long–term aging performance was further analyzed by computing the aging as a function of sample length. The NAVSTAR 30–day sample length aging results will be presented using the same scale factor for the NAVSTAR–08 rubidium clock and the NAVSTAR–10 cesium clock.

The NAVSTAR–03 rubidium clocks shows significant periodic changes in aging that are presented by the Figure 15. The amplitudes of the 30–day aging for this rubidium clock are on the order of 1.3×10^{-13}/day. The periodic changes in aging are (probably) driven by the rubidium clock's sensitivity to temperature as has been previously noted.

The NAVSTAR–10 one–day corrected frequency offset data is presented in Figure 16. The slope of this frequency data is the long term aging.

The NAVSTAR–10 cesium 30–day aging results without the eclipse cycles highlighted are presented by Figure 17. By comparison with the NAVSTAR–03 data it is clear that there is a significant improvement in temperature changes that occur during the NAVSTAR eclipse cycles.

Comparison between the NAVSTAR rubidium results and the NAVSTAR cesium results indicates a significant improvement in aging performance for the cesium clocks.

NAVSTAR STABILITY ANALYSIS

The frequency–stability was computed using sample times that varied according to the amount of clock data available during the three year data span. Six of the (USNO vs NAVSTAR) clock pairs had close to 1000 days of data. The remaining two clock pairs had a limited amount of data that restricted the sample times that could be computed with high confidence.

The composite frequency–stability profile plot (Figure 18) includes stability results for eight clocks pairs. All of the eight clock pairs had frequency–stabilities that are better than the GPS Block I one–day frequency–stability specification limit of 2×10^{-13}.

Time–prediction uncertainty results were computed using the aging–corrected frequency stability profile for each clock pair. The clock times evaluated are the same as the sample times used for each clock pair.

All clock pairs evaluated indicate a time prediction uncertainty that was in the 11 to 21 nanoseconds range for a 1 day clock update time. The time–prediction uncertainty for longer clock update times indicated significant differences between the NAVSTAR cesium and rubidium clocks.

Ensemble cesium frequency–stability and time–prediction uncertainty results were computed for the NAVSTAR cesium clocks by averaging the individual stability–variances and the time–prediction results. The ensemble NAVSTAR cesium frequency–stability and time–prediction uncertainty results are as follows.

* 1.6×10^{-13} for a 1–day sample time
* 4.0×10^{-14} for a 10–day sample time
* 6.0×10^{-14} for a 100–day sample time

* 19 nanoseconds for a 1–day sample time
* 52 nanoseconds for a 10–day sample time
* 577 nanoseconds for a 100–day sample time

NAVSTAR CLOCK ANALYSIS CONCLUSIONS

On-orbit (USNO vs NAVSTAR) clock analysis results were obtained using a three year database of clock data that covers from 1 Jan, 1986 through 31 December, 1988. The results are summarized by the following table.

NAVSTAR ON-ORBIT RESULTS
DATA SPAN: 1 Jan, 1986 to 31 December, 1988

NAV	CLOCK	frequency stability			time-prediction			data span
ID	TYPE	$\times 10^{-13}$	$\times 10^{-14}$	$\times 10^{-14}$	ns	ns	ns	days
		1 day	10 days	100 days	1 day	10 days	100 days	
3	Rb	1.5	34.0	74.0	19	417	8982	1095
4	Rb	1.6	54.0	-	19	655	-	247
6	Rb	1.7	34.0	160.0	19	414	20072	1095
8	Rb	0.9	4.8	-	11	58	-	132
8	Cs	1.4	4.0	6.0	18	49	658	957
9	Cs	1.7	4.5	5.0	20	55	555	1095
10	Cs	1.6	4.4	4.0	20	53	543	1095
11	Cs	1.6	4.7	3.0	19	51	360	1084

* All NAVSTAR clocks are better than the GPS Block I frequency-stability specification of 2×10^{-13} for a 1-day sample time.

* The NAVSTAR-08 rubidium clock shows a significant improvement over earlier model rubidium clocks with respect to stability and reduced temperature sensitivity.

* All NAVSTAR cesium clocks show excellent frequency-stability performance that varies from 1.7×10^{-13} for a one-day sample time to 6.0×10^{-14} or less for a 100-day sample time. The ensemble cesium time-prediction uncertainty results are from 19 nanoseconds for a 1-day clock update to 577 nanoseconds for a 100-day clock update.

REFERENCES

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2. Luck, J.Mc., "Construction and Comparison of Atomic Time Scale Algorithms", TR 32, Division of National Mapping, Canberra, Australia, 1983.

3. Allan, D.W., "Clock Characterization Tutorial", Proceedings of the Fifteenth Annual Precise Time and Time Interval(PTTI) Applications and Planning Meeting, December 6-8, 1983.

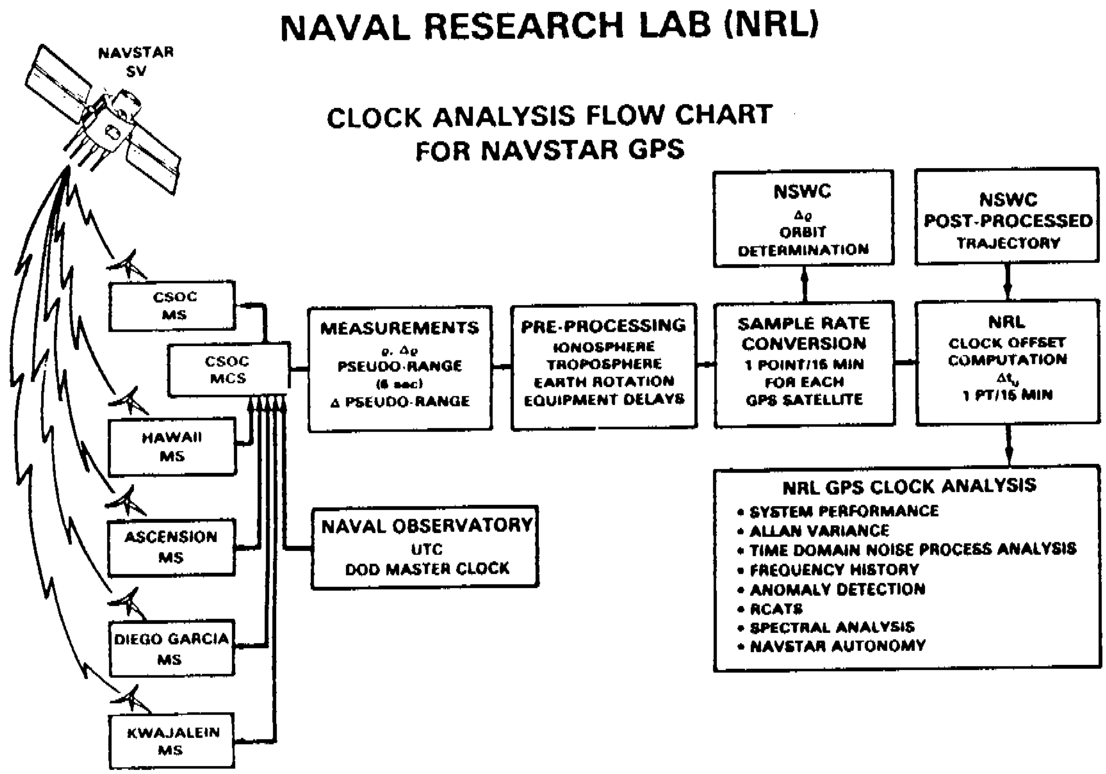

FIGURE 1

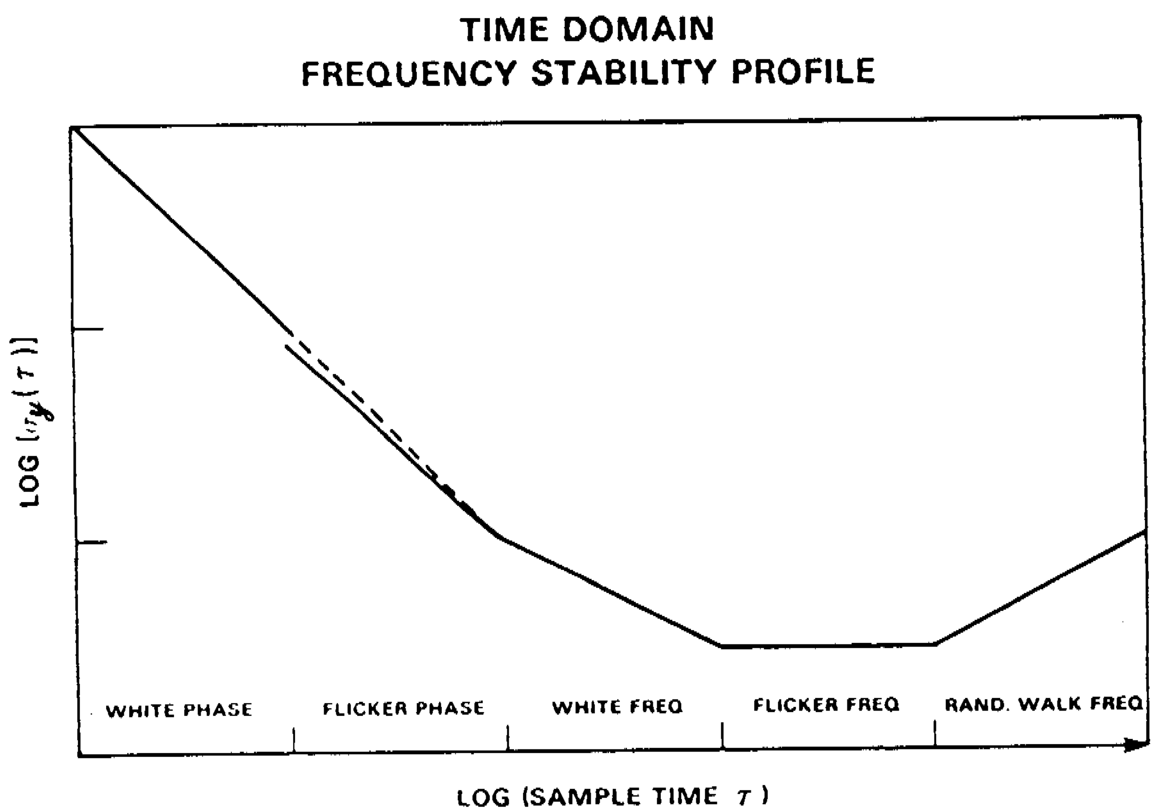

FIGURE 2

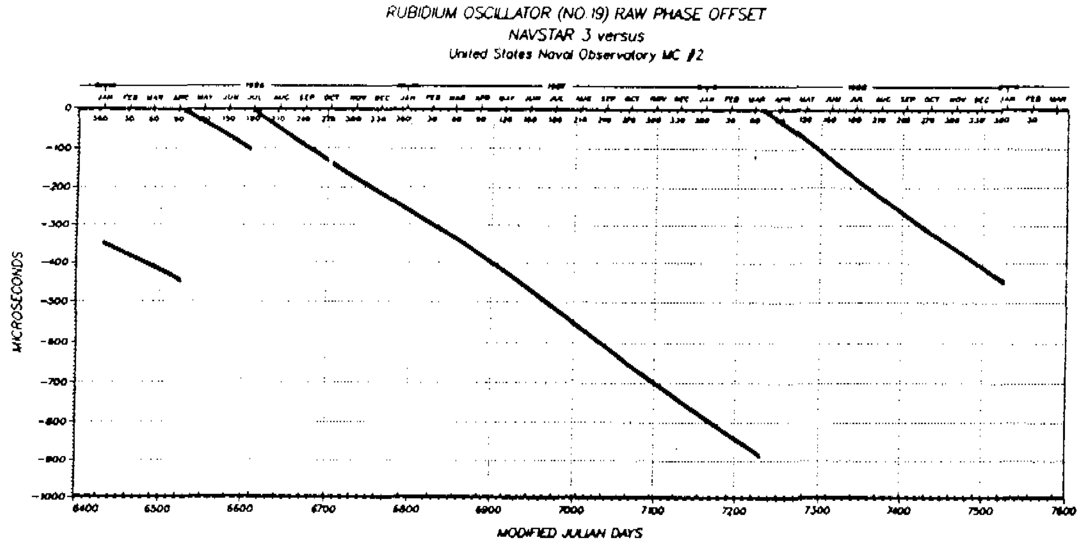

FIGURE 3

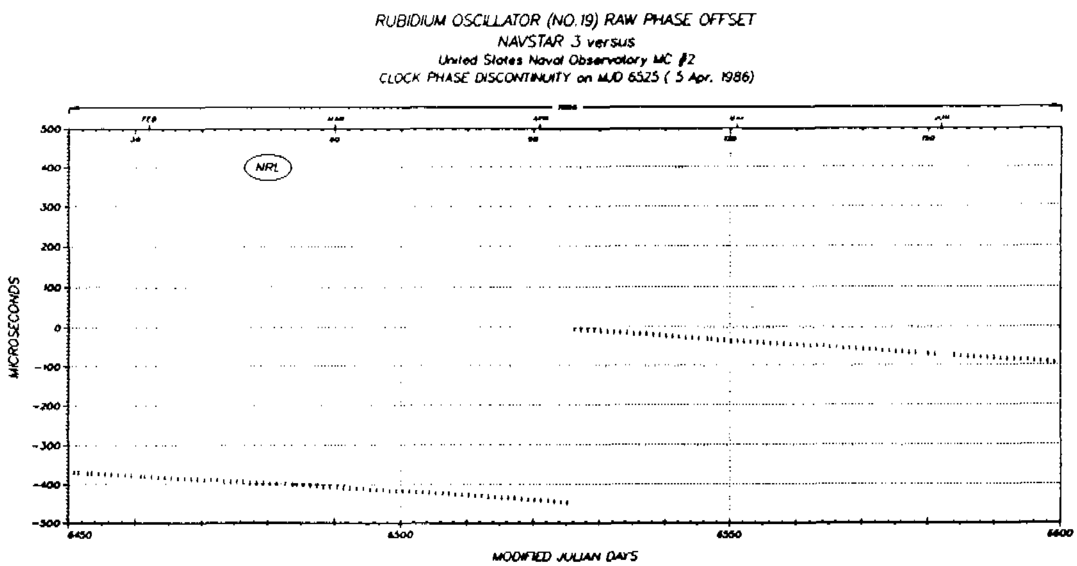

FIGURE 4

RUBIDIUM OSCILLATOR (NO. 19) CORRECTED PHASE OFFSET
NAVSTAR 3 versus
United States Naval Observatory MC #2
CORRECTED PHASE DISCONTINUITY @ MJD 6625 (5 Apr. 1986)

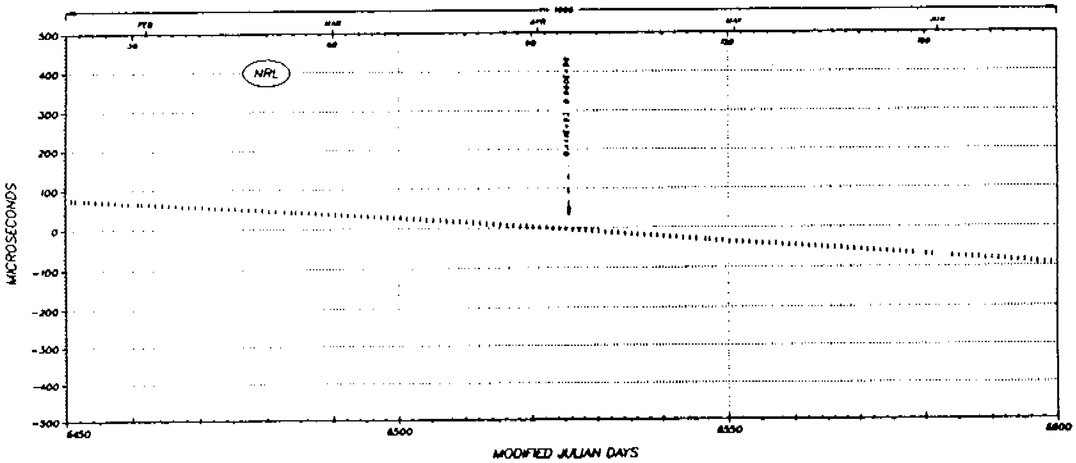

FIGURE 5

RUBIDIUM OSCILLATOR (NO. 19) FREQUENCY OFFSET
NAVSTAR 3 versus
United States Naval Observatory MC #2
−175 pp10(14) FREQUENCY BREAK @ MJD 6613

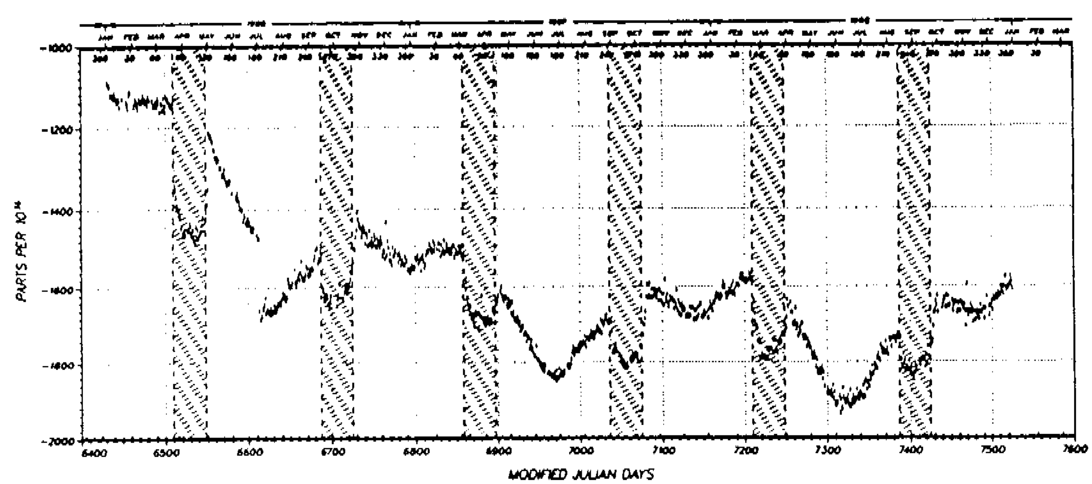

FIGURE 6

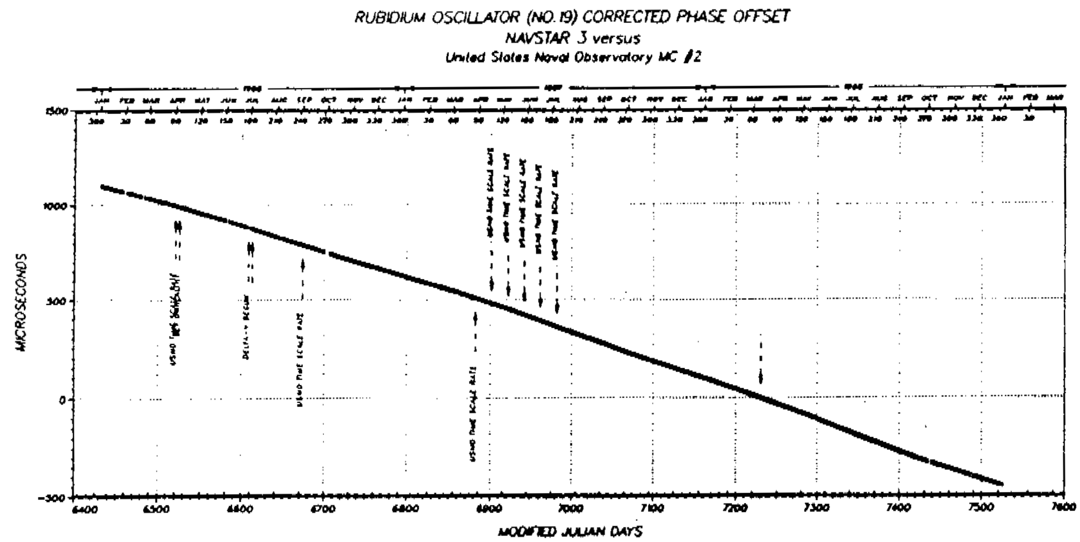

FIGURE 7

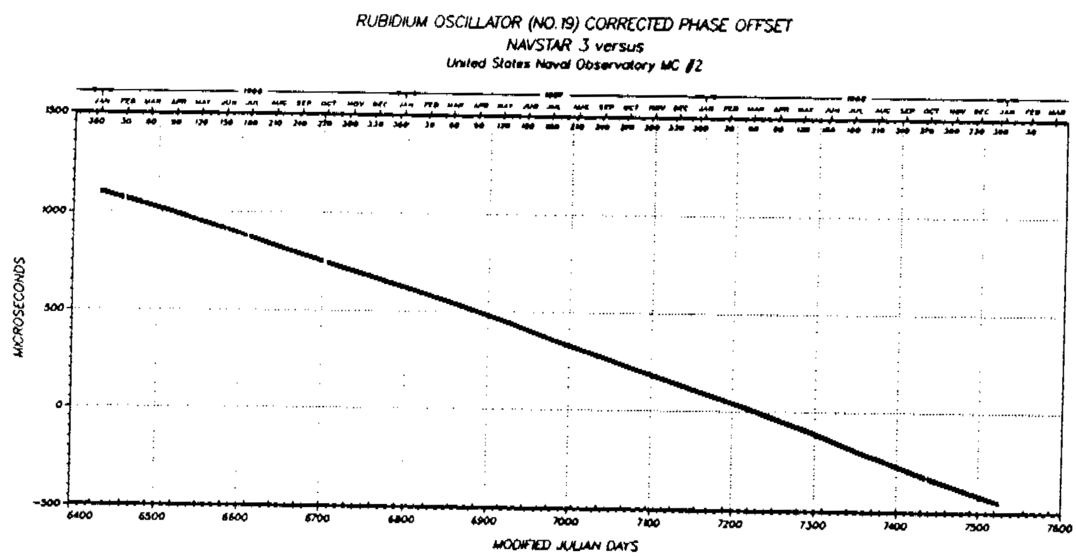

FIGURE 8

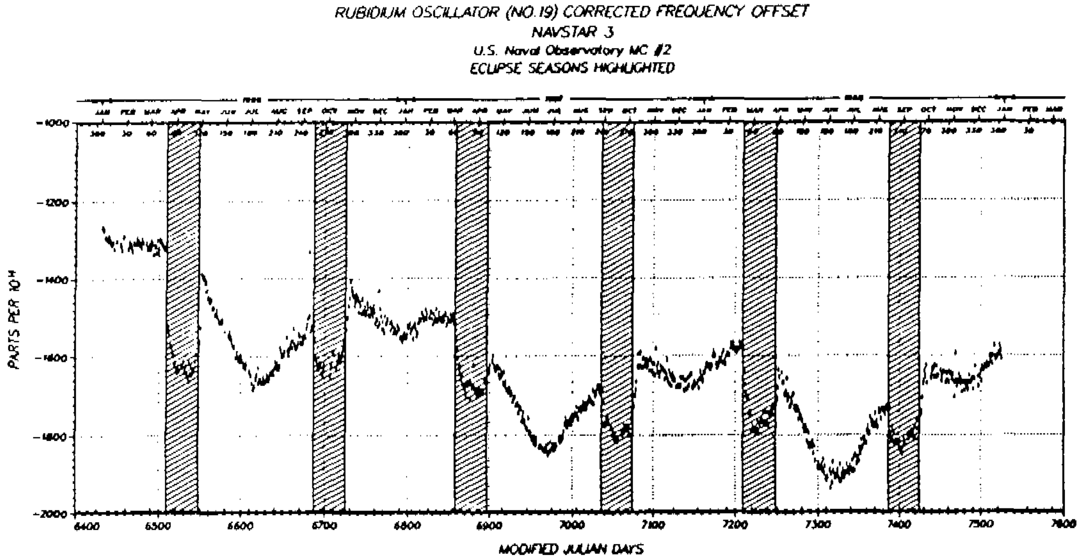

FIGURE 9

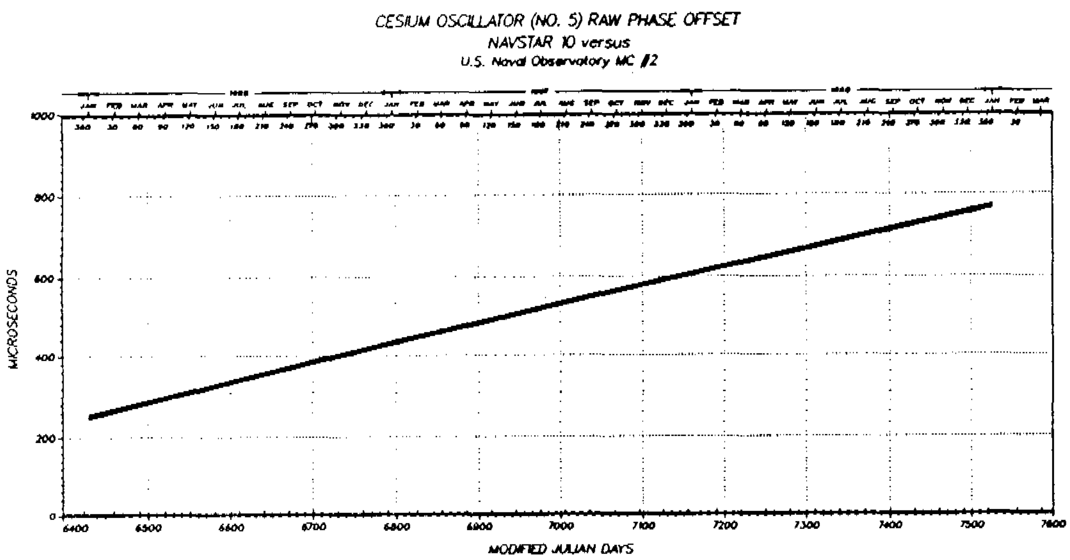

FIGURE 10

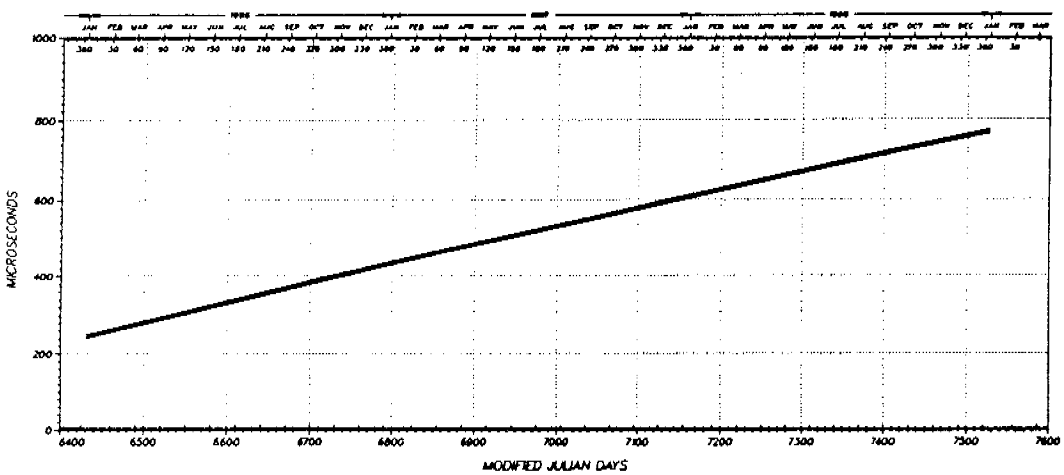

FIGURE 11

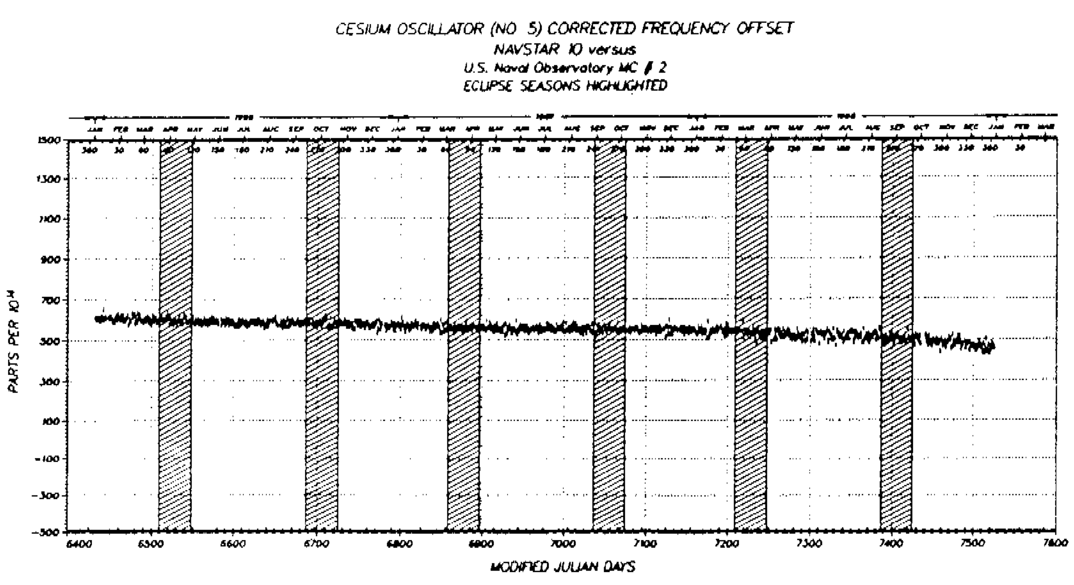

FIGURE 12

FREQUENCY STABILITY OF
NAVSTAR–SV–08 RUBIDIUM versus
U.S. Naval Observatory MC #2
PRESENTS EFFECT OF AGING vs NO–AGING CORRECTION

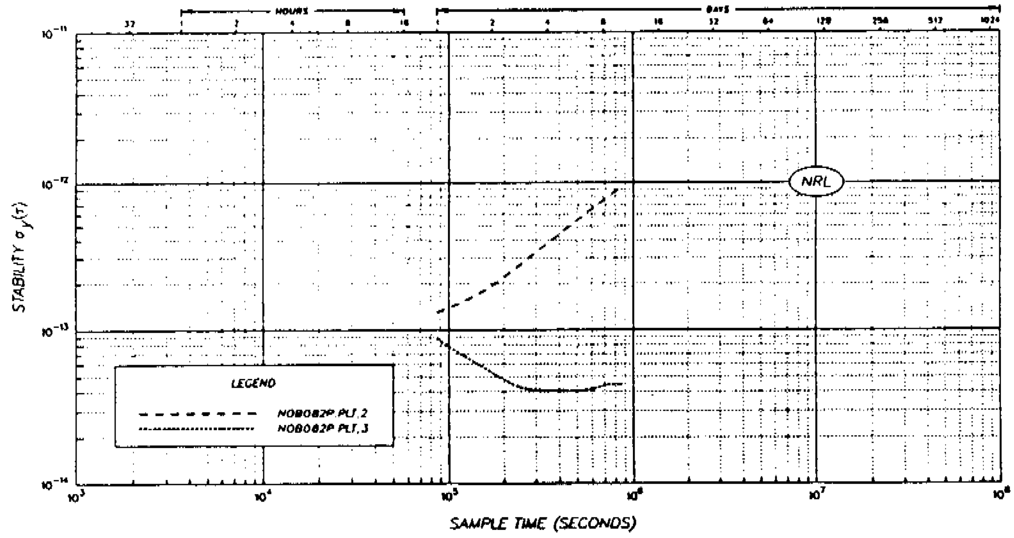

FIGURE 13

FREQUENCY STABILITY OF
NAVSTAR–SV–10 CESIUM CLOCK versus
U.S. Naval Observatory MC #2
PRESENTS EFFECT OF AGING vs NO–AGING CORRECTION

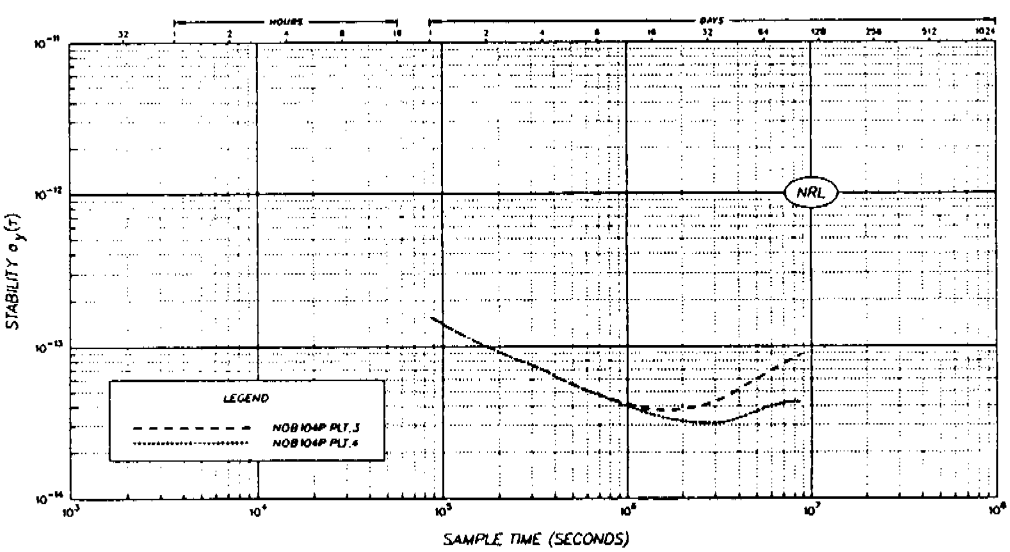

FIGURE 14

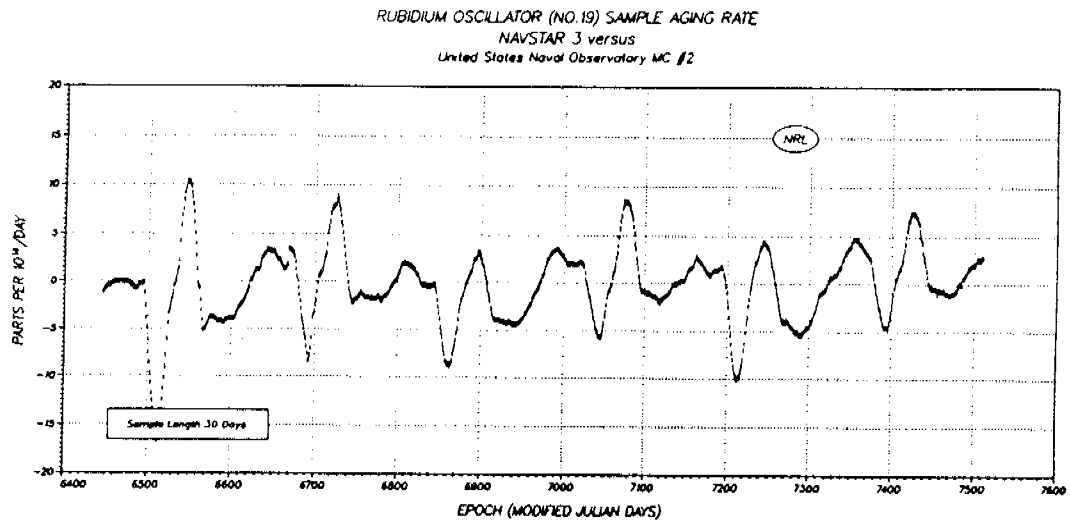

FIGURE 15

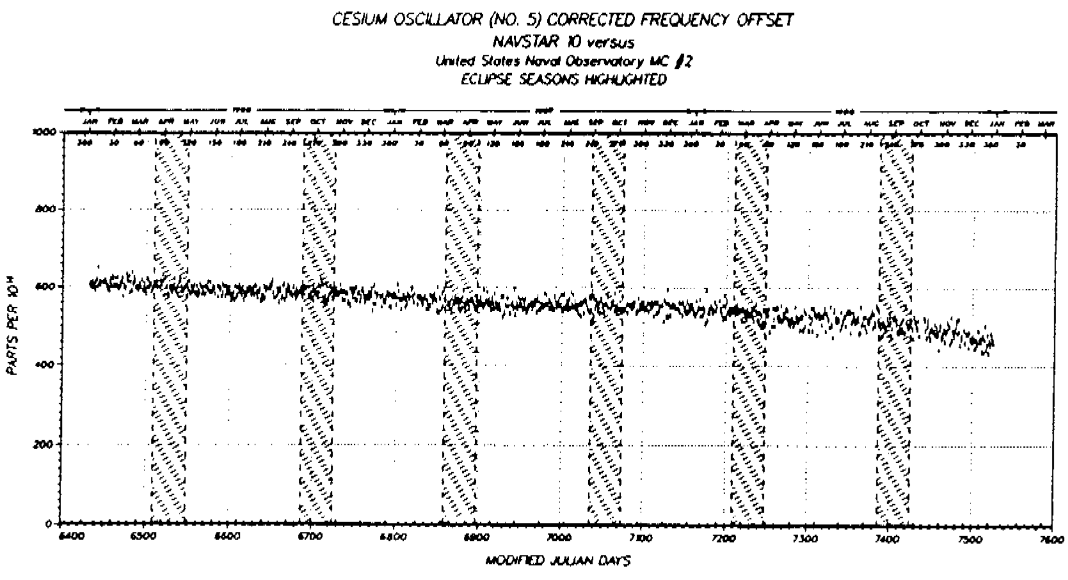

FIGURE 16

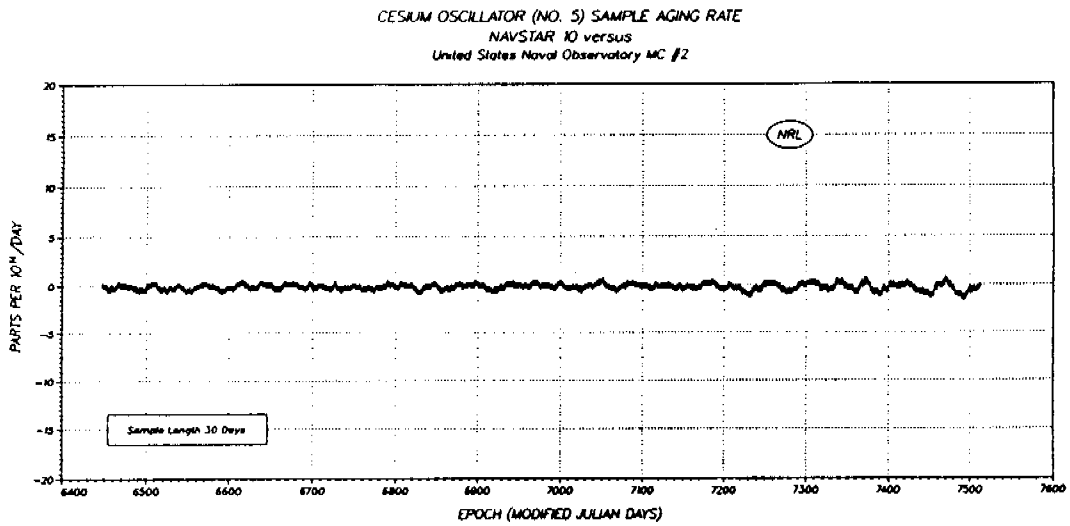
CESIUM OSCILLATOR (NO. 5) SAMPLE AGING RATE
NAVSTAR 10 versus
United States Naval Observatory MC #2
PARTS PER 10^14/DAY
EPOCH (MODIFIED JULIAN DAYS)
NRL
Sample Length 30 Days

FIGURE 17

NRL NAVSTAR TIME PREDICTION UNCERTAINTY ANALYSIS
REFERENCE GROUND CLOCK: USNO

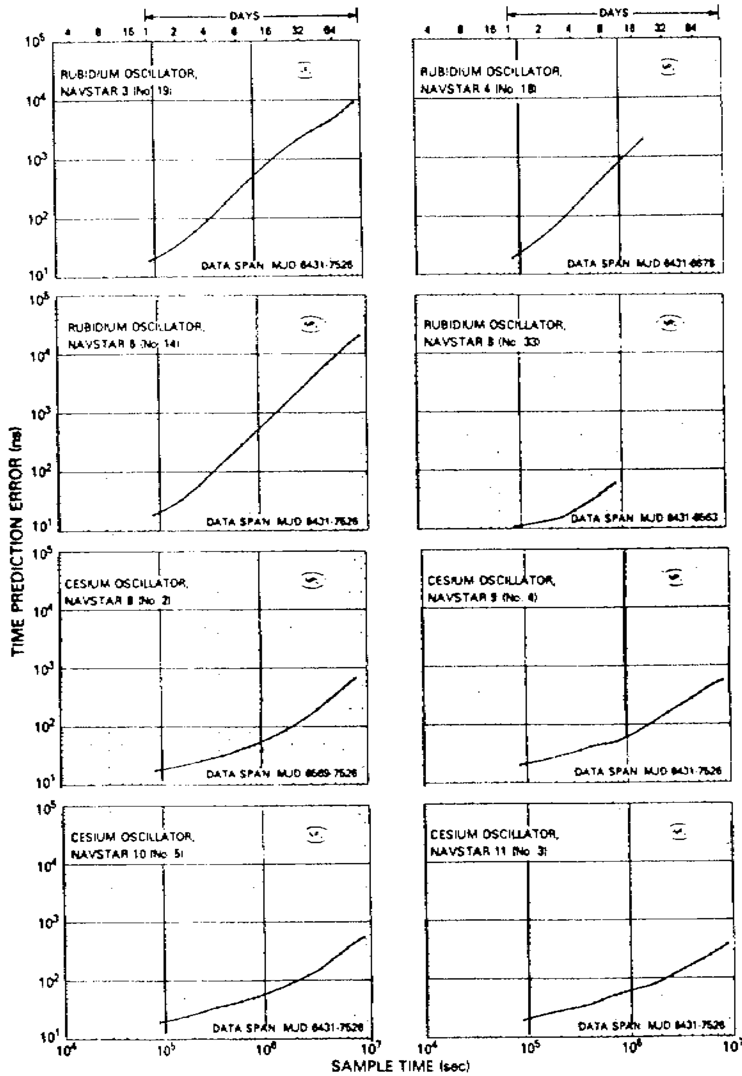

FIGURE 19

NRL NAVSTAR FREQUENCY STABILITY ANALYSIS
REFERENCE GROUND CLOCK: USNO
AGING CORRECTED

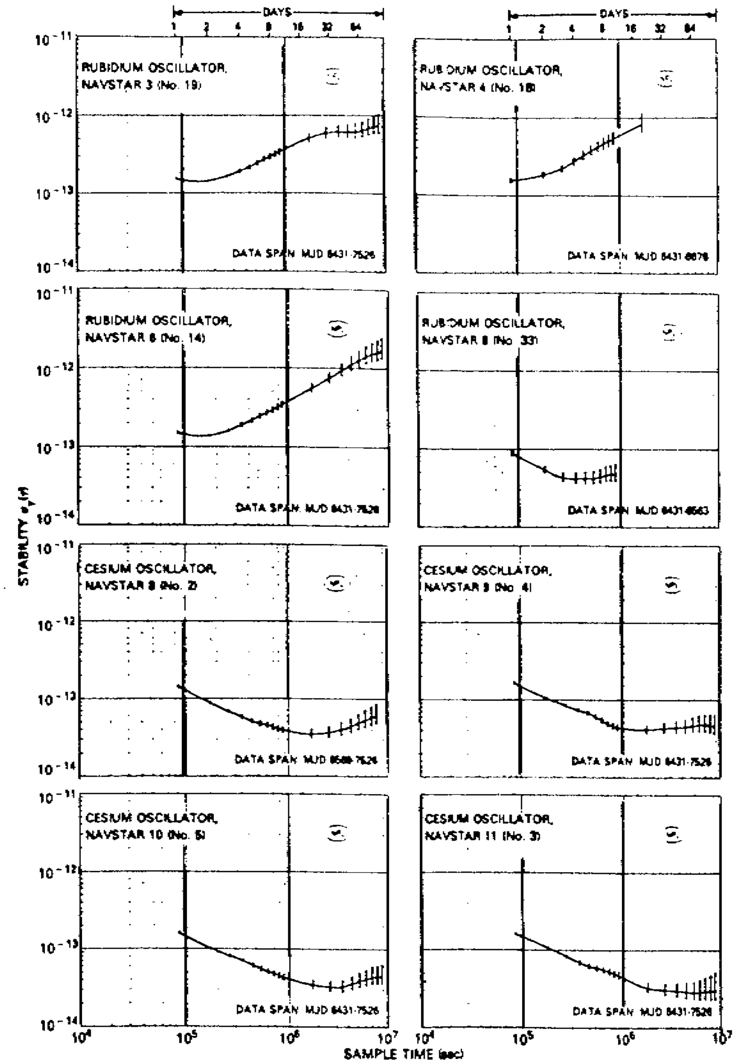

FIGURE 18