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ON-ORBIT FREQUENCY STABILITY ANALYSIS OF THE GPS NAVSTAR-1 QUARTZ CLOCK AND THE NAVSTARs-6 AND -8 RUBIDIUM CLOCKS

by

Thomas B. McCaskill
James A. Buisson
Marie M. Largay
Wilson G. Reid
Naval Research Laboratory
Washington, D.C. 20375-5000

ABSTRACT

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.

INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is a space-based navigation satellite system, which when operational in the late 1980's, will provide accurate navigation and time information to users anywhere in the world, or in near-Earth orbit. A constellation (1) of 18 to 24 satellites will be tracked and controlled by a network of Monitor Stations (MS).

GPS will provide a near-instantaneous navigation capability because each NAVSTAR Spacecraft Vehicle (SV) clock is synchronized to a common GPS time. The NAVSTAR clock offsets, orbital elements, and spacecraft health are periodically determined by the Master Control Station (MCS). These updated parameters are then uploaded to each NAVSTAR SV. Each NAVSTAR clock must then maintain GPS time until the next update by the MCS. Current system performance requires three updates per day to meet navigational requirements.

The Naval Research Laboratory (NRL) has recognized the importance of clock performance to the GPS mission (2,3), and is conducting the NRL GPS Clock Development Program. The on-orbit clock performance (4,5) was determined through the procedure depicted in Figure 1, and described in detail in reference 6. Key features of this technique are (1) use of a high-performance ground reference clock at each MS, and (2) use of a Naval Surface Weapons Center (NSWC) smoothed reference orbit to separate the orbital and clock signals from the pseudo-range and pseudo-range- rate measurements.

CLOCK PERFORMANCE MODELS

GPS on-orbit clock performance is characterized for both systematic and random effects. Systematic parameters include clock time and frequency offsets, and aging rate, all as function of time. The clock's random behavior, in the time domain, is characterized through use of the Allan variance (7,8). A typical frequency stability profile(9) is presented in Figure 2.

A time domain noise process analysis is performed to determine random noise process type. These time domain parameters may then be transformed to the frequency domain using conversion formulas detailed in reference (10).

Once a clock has been characterized through a frequency stability analysis, the frequency profile may then be used to estimate a clock's time prediction performance. Figure 3 presents a set of time prediction curves, as a function of frequency stability and clock update time, using optimal two point prediction (10,11). Other models for time prediction are presented in reference (7). Each of these optimal time prediction models has one thing in common -- namely that the long-term clock prediction performance is driven by the product of the clock update time and the frequency stability. The clock update time is determined by GPS requirements, hence improved clock stability is the parameter that will directly influence GPS time prediction. This analysis represents total system errors super-imposed on the clock results. GPS system influences either enhance or detract from actual clock performance. Therefore the apparent indication of slight deviations from normal clock behavior could be expected.

NAVSTAR-1 QUARTZ RESULTS

NAVSTAR-1 was launched on Feb 22, 1978, and the quartz clock was activated only after all on-board rubidium clocks failed. This quartz clock is still working as of this date, however its status is listed as "unhealthy" because more stable atomic clocks are now available in other NAVSTAR SVs. Of interest is the determination of the short- and long-term frequency stability of the NAVSTAR-1 quartz clock and its comparison with the NAVSTAR atomic clocks.

The clock offsets between the NAVSTAR-1 quartz clock and the Vandenberg Monitor Station (VMS) are presented in Figure 4. The data indicates a sequence of smooth quadratic curves, with occasional adjustments by the Master Control Station, to keep the quartz clock's time and frequency within prescribed limits. The concave shape of the quadratic curves is due to the negative aging rate of the NAVSTAR-1 quartz clock. The relative maximum clock offsets occur as the quartz clock's frequency offset passes through zero. The cusps in the quadratic curves occur because of step frequency adjustments, which keep the frequency offset between (+/-)1PP10(9). In addition to the frequency adjustments, several clock phase adjustments were made to align the clock offsets with respect to GPS time.

Frequency offsets for the NAVSTAR-1 quartz clock were computed, using clock offsets separated one day in time, and are presented in Figure 5. The time axis is labelled in units of Modified Julian Day (MJD), day-of-year, and calendar date. The frequency offsets decrease with time, with adjustments in frequency occuring as the frequency offset approaches (+/-)1PP10(9). Visual inspection of Figure 5 indicates small departures from a linear change in frequency, which are of primary interest in the on-orbit stability analysis.

Using the times of the frequency adjustments made by the GPS Master Control Station, the quartz frequency data was corrected to remove the effect of the frequency adjustments. These corrected frequency offsets are presented in Figure 6. These data were further analyzed to determine if the quartz clock aged at a constant rate. A constant aging rate is part of the clock model used by the GPS MCS for the quartz and rubidium clocks.

Assuming a constant aging rate for all of 1982, a linear frequency model was fitted to the data, and the frequency linear residuals are presented in Figure 7. The residuals indicate a change in aging rate near day 150, 1982. The data was segmented into two subsets, with a linear frequency model used for the first segment, and a quadratic model for the remainder of the year. The residuals for these two segments are presented in Figures 8 and 9.

Clock stability during a pass is determined by evaluating the Allan variance for sample times of 15-minutes to 2-hours. Stability results for 900-second and 2-hour sample times are presented by Figures 10 and 11. Note that the frequency stability values are plotted as a function of running time, rather than the sample time. The most interesting result evident in Figure 10 is a change that occurs near day 150, 1982. Inspection of the stability values indicates a small increase in the correlated noise after day 150. This decrease in stability is further supported by the prior results on aging rate, which indicate a change that occured near day 150, from a constant aging rate to a linear change in aging rate. This change can be seen by inspection of Figures 6, 7, and 9.

Long term frequency stability results for the NAVSTAR-1 quartz clock are computed after estimating and correcting the clock offsets for a constant aging rate. The effect of the aging rate errors on frequency stability will be explictly addressed later in this report.

A composite of short- and long-term frequency stability results for the NAVSTAR-1 quartz clock are presented by Figure 12. Uncharacteristic of a typical clock is the transition from random walk FM to flicker noise FM, which occurs at a sample time of about 3 days. Further conclusions will be made after comparing the quartz stability results with previous (6) on-orbit results for the NAVSTAR-6 cesium clock.

Parameteric frequency stability results are obtained by comparing the NAVSTAR-1 quartz stability with the NAVSTAR-6 cesium stability, which is presented by Figure 13. The results of this comparison are summarized in Table 1.

Table 1

NAVSTAR-1 QUARTZ CLOCK
COMPARISON WITH NAVSTAR-6 CESIUM CLOCK PERFORMANCE

SAMPLE TIME	IMPROVEMENT WITH CESIUM
900 seconds	FACTOR OF 2
2 hours	1 ORDER OF MAGNITUDE
1 day	2 ORDERS OF MAGNITUDE
10 days	FACTOR OF 300

NAVSTAR-6 RUBIDIUM RESULTS

On-orbit frequency stability results will be presented for one of the three rubidium clocks onboard the NAVSTAR-6 SV. The fourth clock, a cesium, was first activated, and operated from May, 1980 until early in 1984. The rubidium clock was activated in Feburary, 1984, and was operated for six months. This rubidium clock was deactivated because of degraded performance.

Frequency offsets for the NAVSTAR-6 rubidium clock are presented in Figure 14. Inspection of these data indicates an initial positive aging rate, which lasted for about 1-week, followed by a long trend with a negative aging rate. It is postulated that the initial positive aging rate is due to a transient.

The frequency data was edited to remove the transient and other outliers. The remaining data (Figure 15) was fitted with a linear frequency model. The residuals to this linear frequency model are presented in Figure 16. The aging rate value obtained was -8.2PP10(14)/day, which is lower than expected for the rubidium clocks. The RMS frequency noise was 1.4PP10(12), which is higher than expected.

Short- and long-term stability results are presented in Figure 17. The best after-the-fact aging term has been removed from the data for the long-term frequency stability determination. For the short-term analysis, the effect of the aging rate correction is small enough to be neglected. The short term stability results indicate 1.8PP10(12) for a 900-second sample time. For a 2-hour sample time, the stability was 1.3PP10(12). The long-term stability results indicate a 4.2PP10(13) stability for a 1-day sample time, which remains essentially constant for sample times from 2 to 10 days.

NAVSTAR-8 RUBIDIUM RESULTS

The NAVSTAR-8 spacecraft (SC) was launched on July 14, 1983, as part of the GPS Phase I constellation. NAVSTAR-8 is equipped with three rubidium clocks and one cesium clock. One of the three rubidium clocks was activated shortly after launch and has been the operational clock for NAVSTAR-8 from launch to the present time.

The rubidium clock currently in use onboard NAVSTAR-8 has additional temperature control which is provided by a Thermo Electric Device (TED). Preliminary analysis of temperature correlations for other NAVSTAR rubidium clocks has indicated a temperature coefficient on the order of 1.96PP10(12)/degree C.

The NAVSTAR-8 rubidium clock offset data analyzed is presented by Figure 18. Four adjustments in offset or clock frequency are present in the NAVSTAR-8 data. The first is a change in frequency which was a result of a C-field adjustment (September,1983). The second change was in clock offset as a result of a phase adjustment (Feburary, 1984). The third change (July, 1984) is another frequency adjustment with the fourth change (August, 1984) being a phase adjustment after the on-board cesium clock was cycled on and off for a period of hours.

By correcting for the adjustments in time and frequency, a continuous frequency is obtained as presented by Figure 19. A linear frequency model was fitted to the entire data span. This fit resulted in an average aging rate of -3.2PP10(13)/day for the entire span. Inspection of the residuals indicates the presence of a systematic behavior in the frequency. Careful analysis of the residuals indicated a change in aging rate near January, 1984. Because of this apparent change, a linear frequency model was fit to the data from January, 1984 until June, 1984. Then this model was back-dated to the beginning of the NAVSTAR-8 clock data. The residuals to the entire span of current data were computed and are presented by Figure 20.

The residuals to the data span from August, 1983 until June, 1984 indicate a possible long-term effect which lasted from August through December 1983. On July 12, 1984 an adjustment in TED temperature of three degrees was performed. Shortly thereafter a change in aging rate of the NAVSTAR-8 rubidium clock was measured.

NAVSTAR-8 rubidium frequency stability during a pass was evaluated using data from January, 1984 until September, 1984. The database was partitioned into 5-day sets for the stability calculations. This procedure is fully described in reference 6. The stability calculations were made for sample times of 900-seconds to 2-hours, in 900-second increments.

Frequency stability results for 900- and 2700-second sample times are presented in Figure 21 and 22. Analysis of these results indicates that an unexpected phenomena is occuring for the NAVSTAR-8 rubidium clock. The results indicate a two-state stability. This result is more evident for the 2700-second sample time than for the 900-second sample time. All checks to date have not produced a satisfactory explanation to this observed phenomena.

A short-term frequency stability profile for the NAVSTAR-8 rubidium clock is presented by Figure 23. This curve shows an uncharacteristic peak for a typical clock, at a 1-hour sample time.

Long-term frequency stability results for the NAVSTAR-8 rubidium clock are presented by Figure 24. A 280-day set was used for these stability results, which is more than a factor of 10 longer than the longest sample time. These results indicate a stability of 7PP10(14) for a 1-day sample time, which decreases to 5.5PP10(14) for a 3-day sample time, followed by an increase to 8PP10(14) for a 10-day sample time. These stability results were achieved assuming an accurate knowledge (after-the-fact) of the aging rate of the NAVSTAR-8 rubidium clock. In addition the assumption that the aging rate was constant is necessary. Occasional unpredictable changes in aging rate can occur, which will degrade long- and short-term rubidium clock performance.

A sensitivity analysis of the NAVSTAR-8 long-term frequency stability to aging rate was computed using a 95-day subset, and is presented by Figure 25. The stability analysis was computed with an increment of aging rate of 2 nanoseconds/day/day. The best stability was obtained using an aging rate of -28 nsec/day/day. Analysis of these results indicates a low sensitivity to aging rate errors for a 1-day sample time, with dramatically increasing sensitivity as the sample time increases to 10 days. The importance of this analysis is readily seen when GPS is used in a prediction mode. An aging rate value of some fashion must be assumed during the predicted span of time.

NAVSTAR 1/3/4/5/6/8 RESULTS

A composite of the NAVSTARs 1,3,4,5,6, and 8 results is presented in Figure 26, using previously presented results (6) in addition to those presented in this paper.

These results indicate that GPS NAVSTAR atomic clocks are stable to 2PP10(12) for a 900-second sample time, and improve with longer sample times, with better than 2PP10(13) for a 1-day sample time. For sample times longer than 1-day, the cesium clocks show a spread in stabilities from 8 to 10PP10(14). The rubidium clocks show a spread in stabilities from 5 to 25PP10(14). The long-term stability presentation has the best after-the-fact aging effect removed for all the rubidium clocks analyzed. This was not necessary for the cesium clocks since the aging term for cesium clocks is essentially zero.

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NAVAL RESEARCH LAB (NRL)

CLOCK ANALYSIS FLOW CHART FOR NAVSTAR GPS

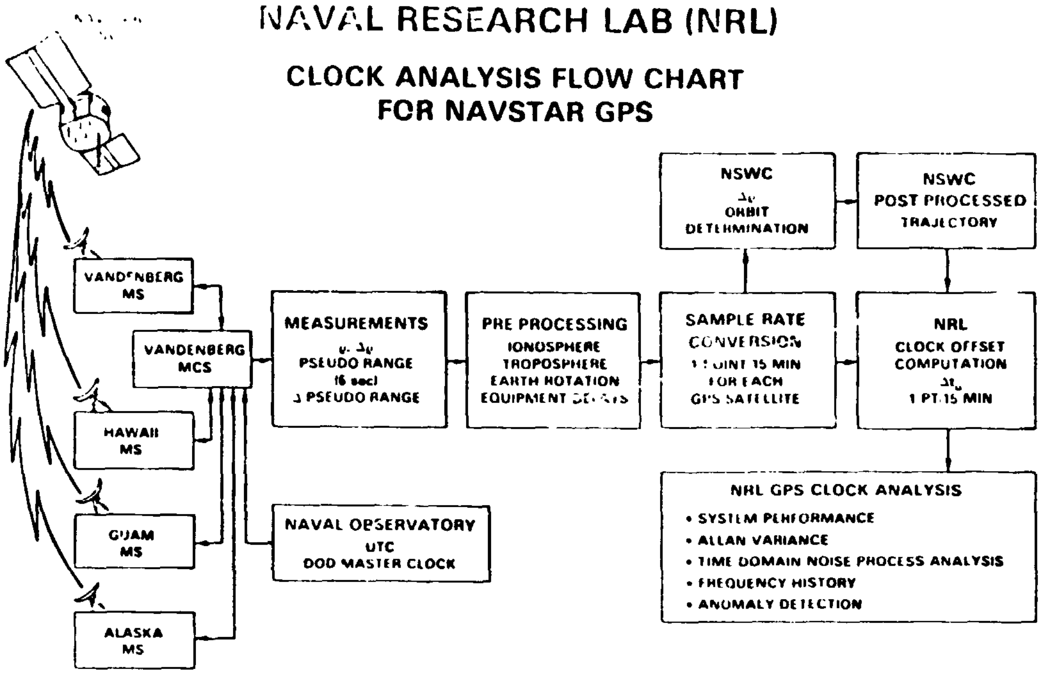

Figure 1

TIME DOMAIN FREQUENCY STABILITY PROFILE

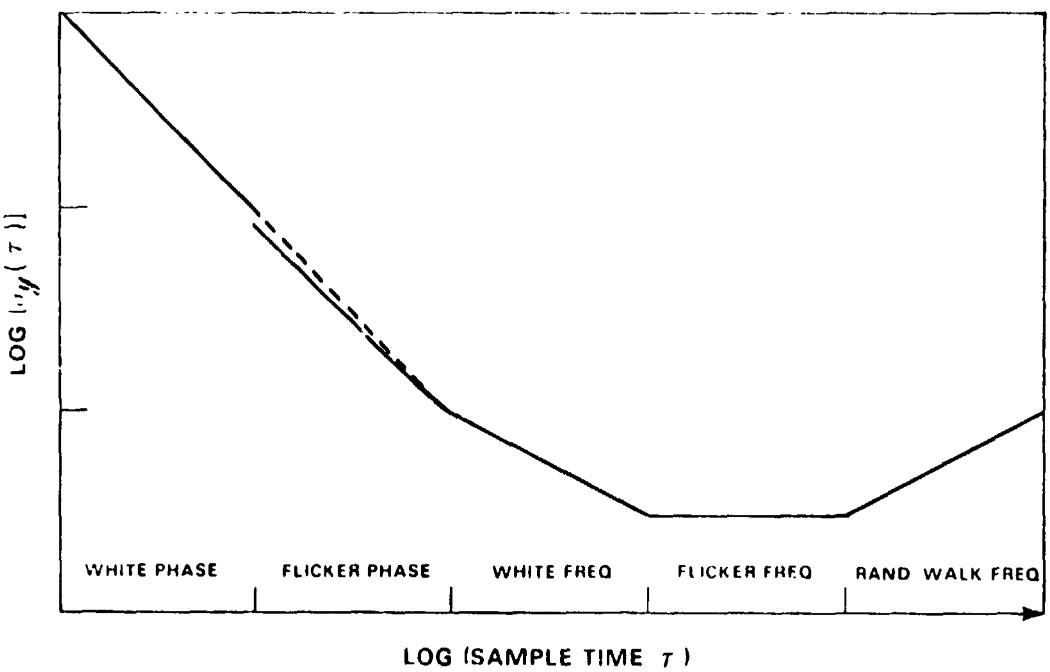

Figure 2

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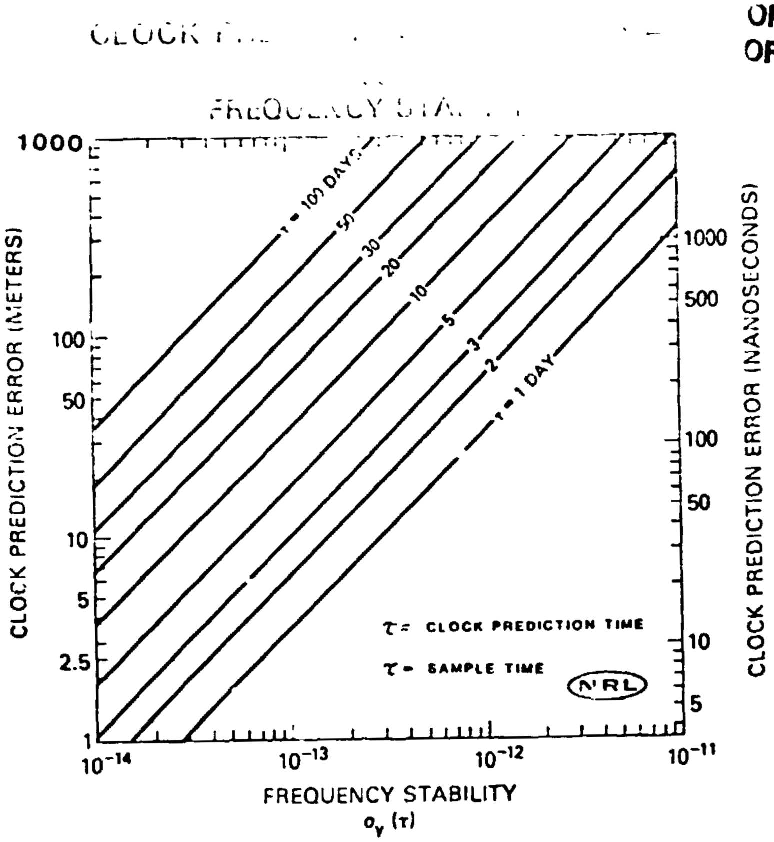


Figure 3

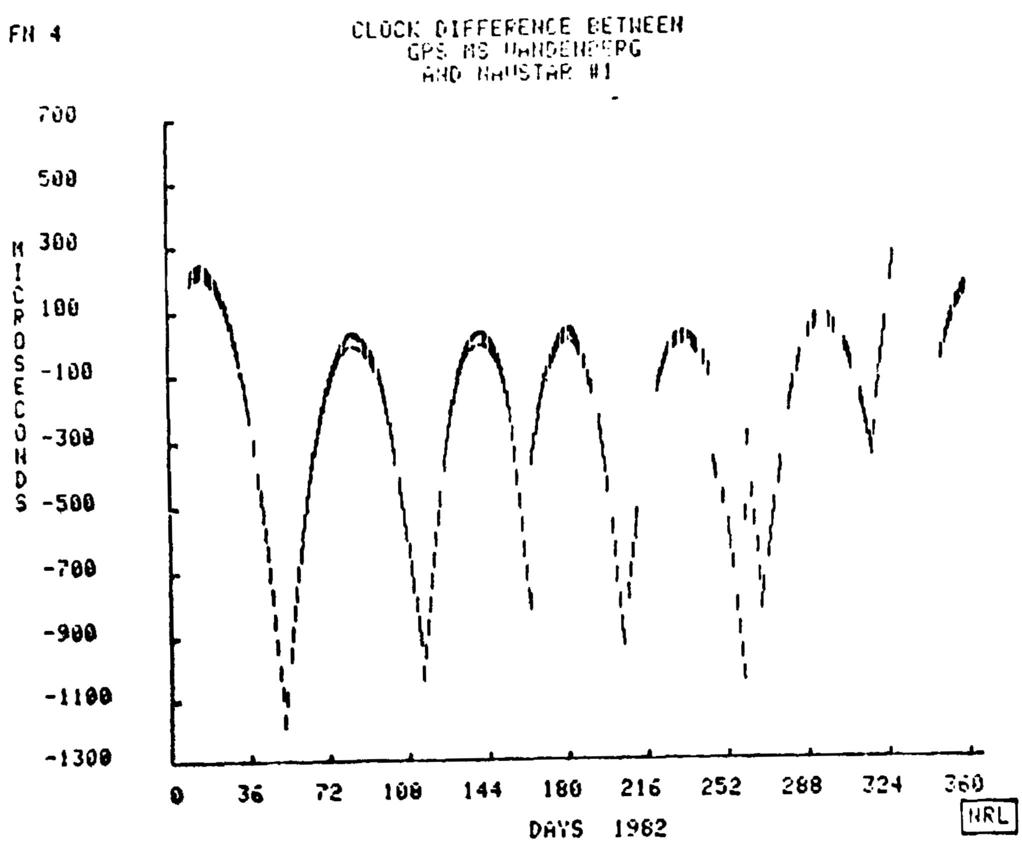


Figure 4

GPS QUARTZ FREQUENCY OFFSET
NAVSTAR 1
Vandenberg Monitor Station

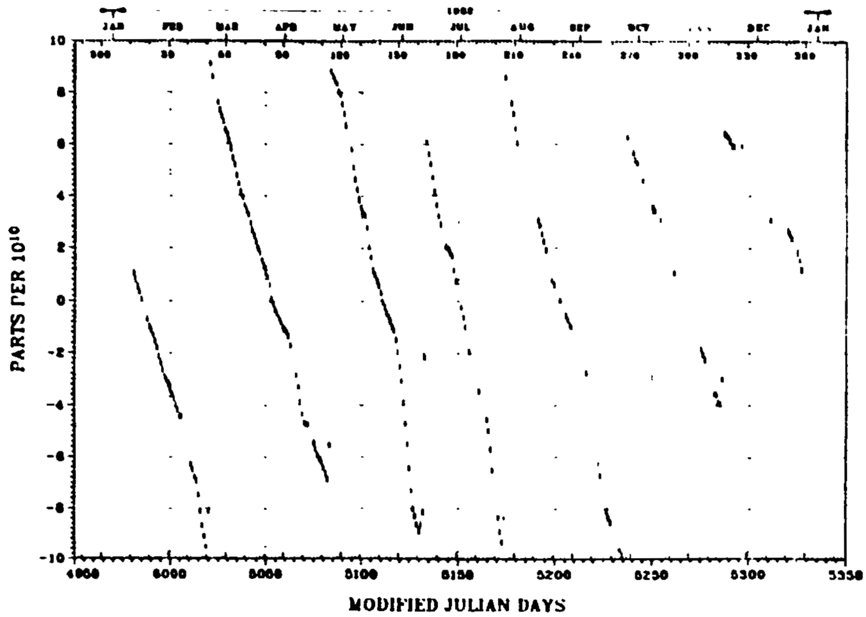


Figure 5

GPS QUARTZ FREQUENCY PURGED AND CORRECTED OFFSET
NAVSTAR 1
Vandenberg Monitor Station

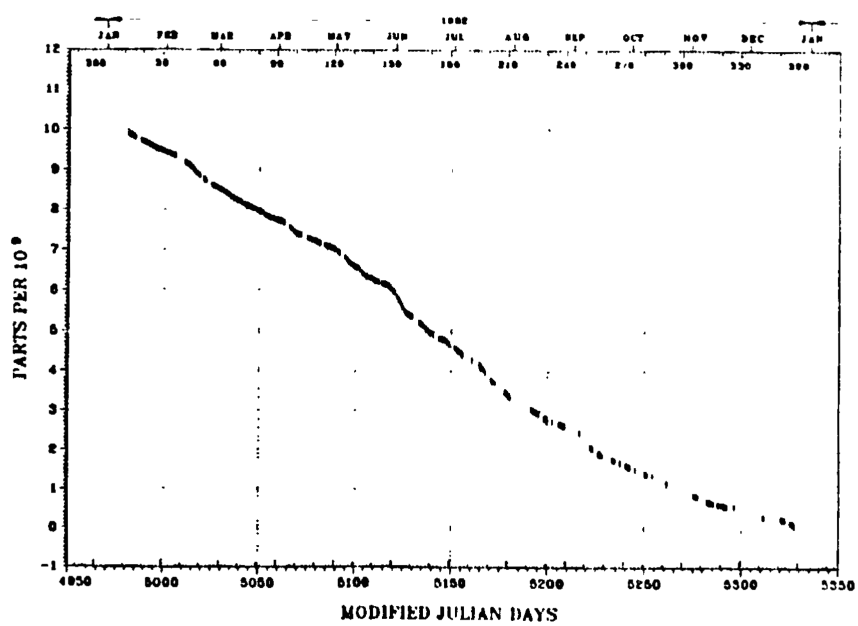


Figure 6

GPS QUARTZ FREQUENCY LINEAR RESIDUALS
NAVSTAR 1
Vandenberg Monitor Station

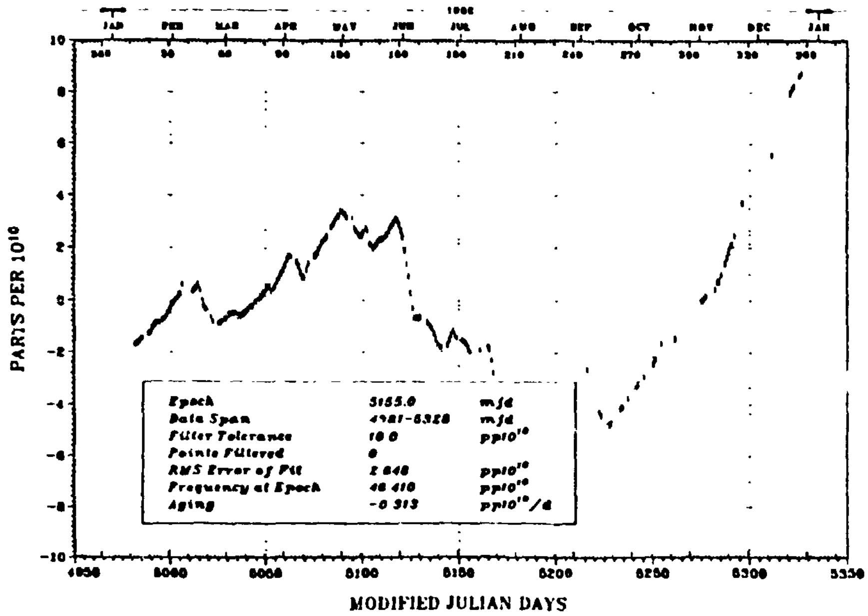


Figure 7

GPS QUARTZ FREQUENCY LINEAR RESIDUALS
NAVSTAR 1
Vandenberg Monitor Station

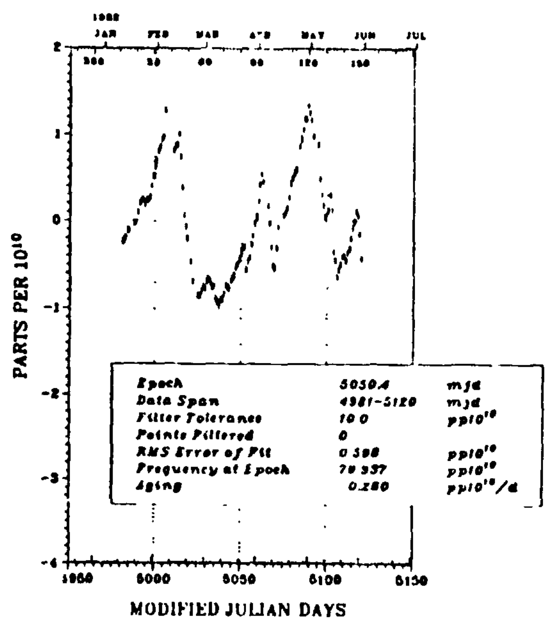


Figure 8

GE - QUARTZ FREQUENCY QUADRATIC RESIDUALS
NAVSTAR 1
Vandenberg Monitor Station

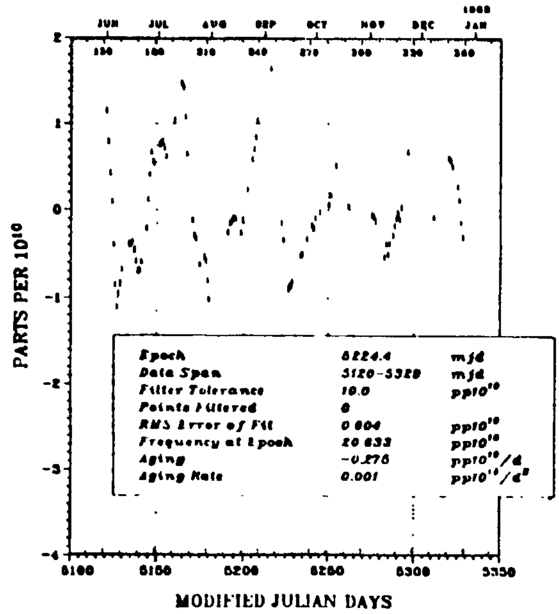
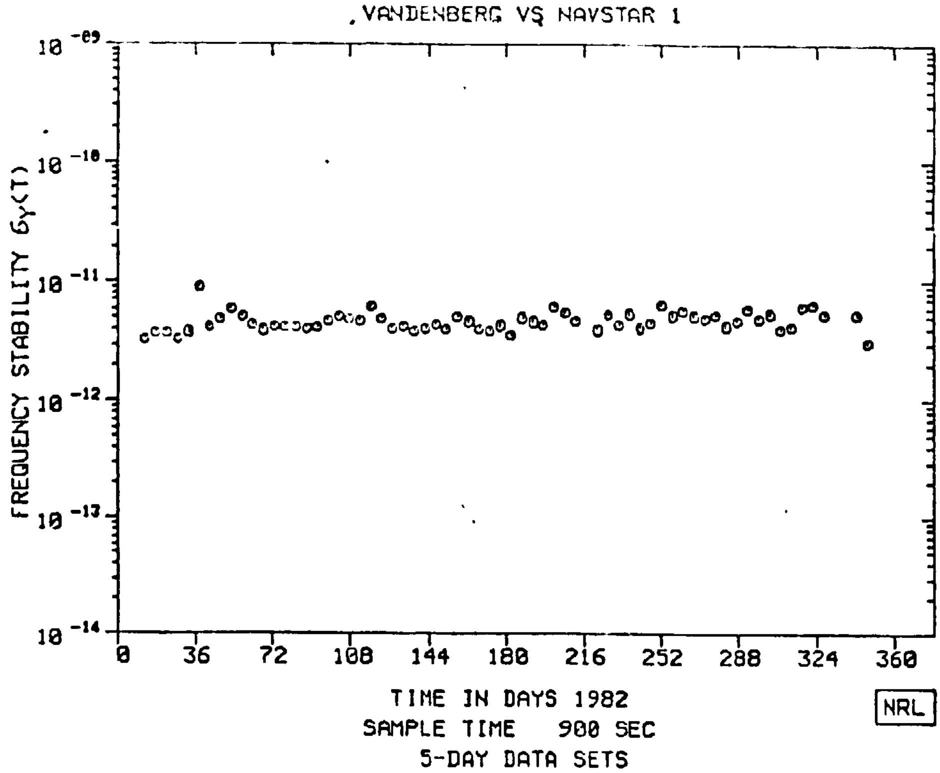


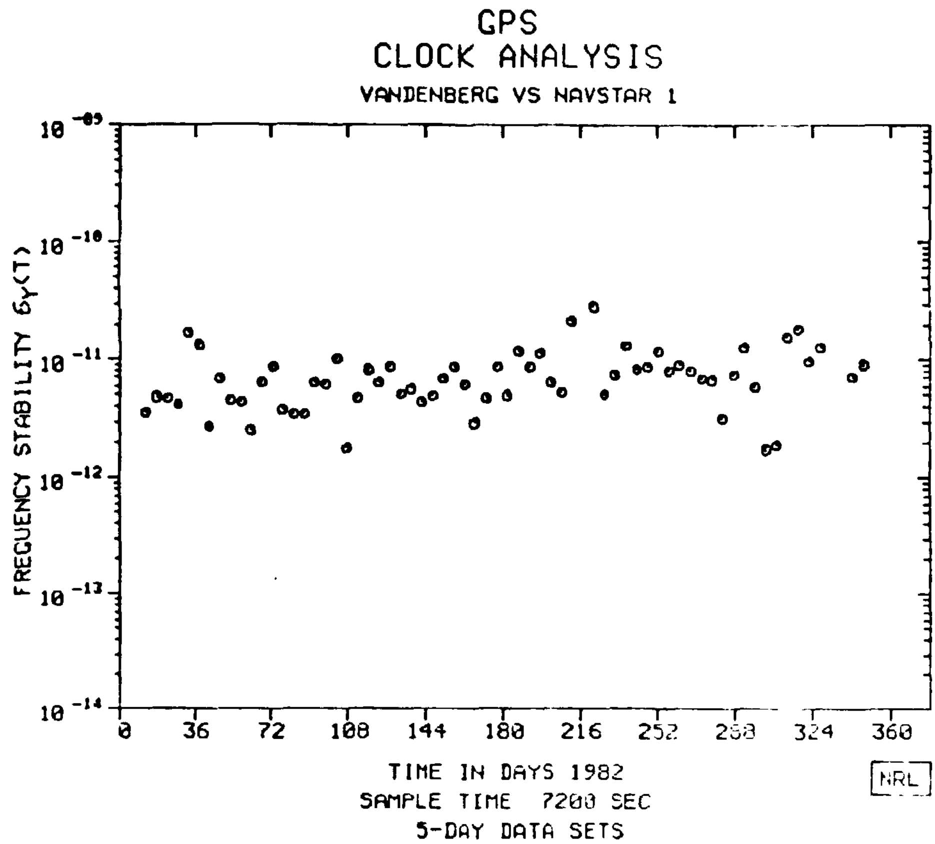
Figure 9

GPS
CLOCK ANALYSIS
VANDENBERG VS NAVSTAR 1



31-MAY-84

Figure 10



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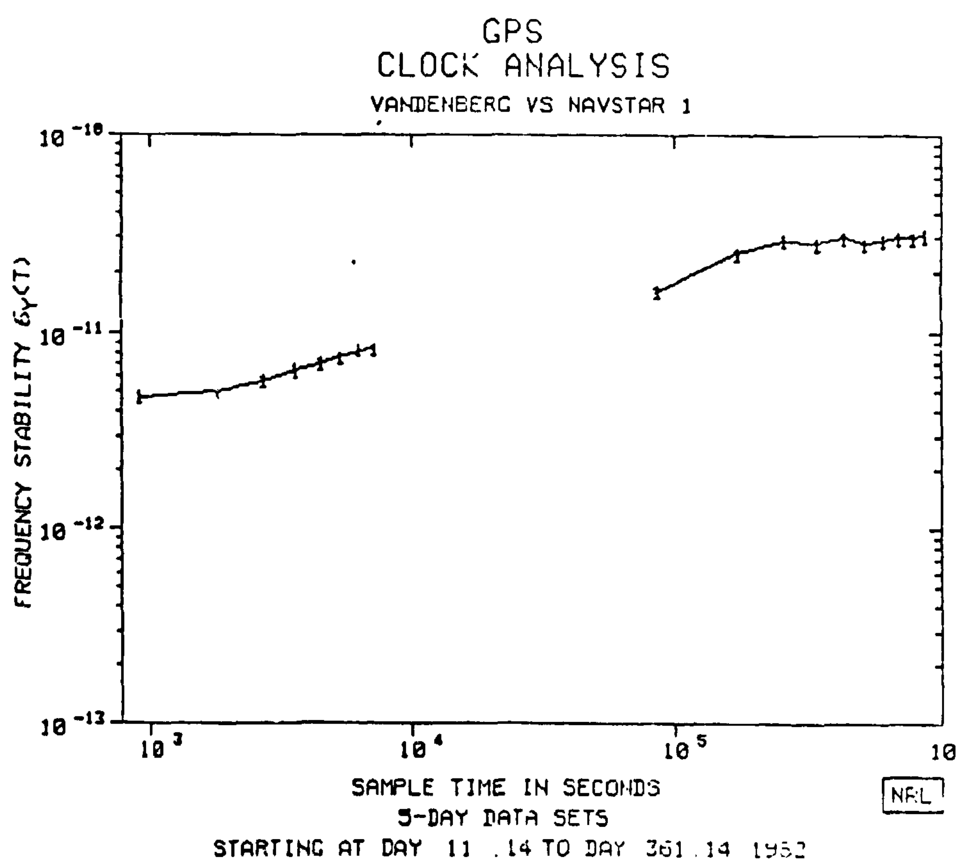

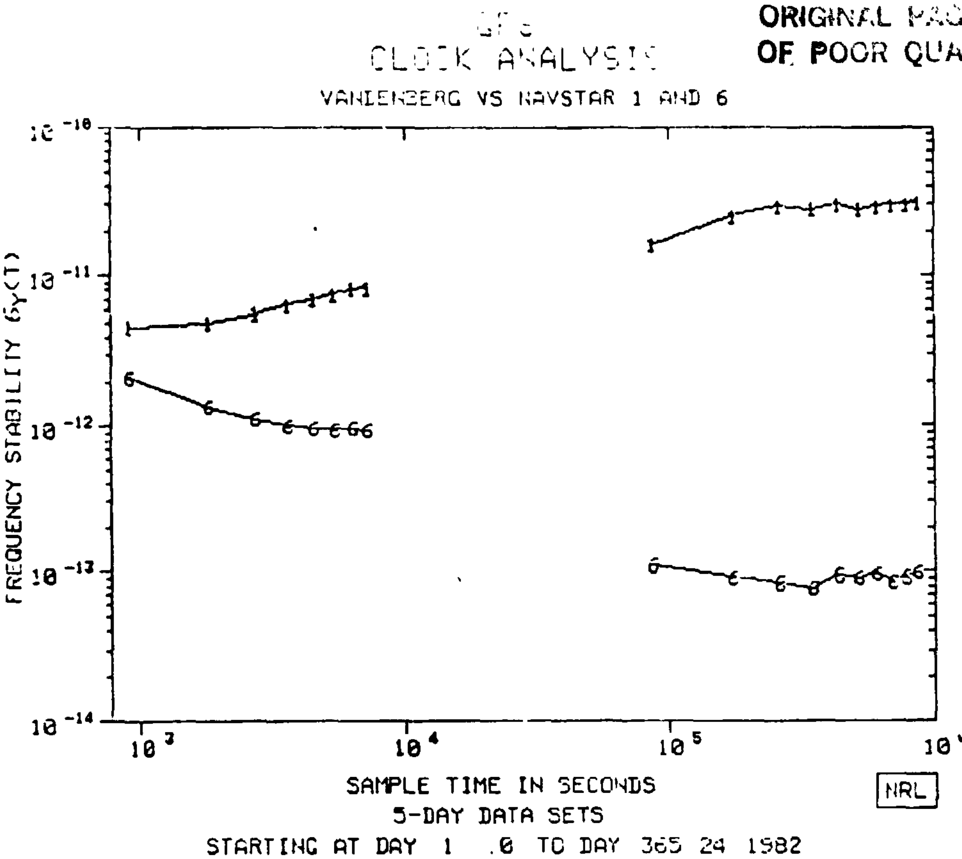

Figure 13

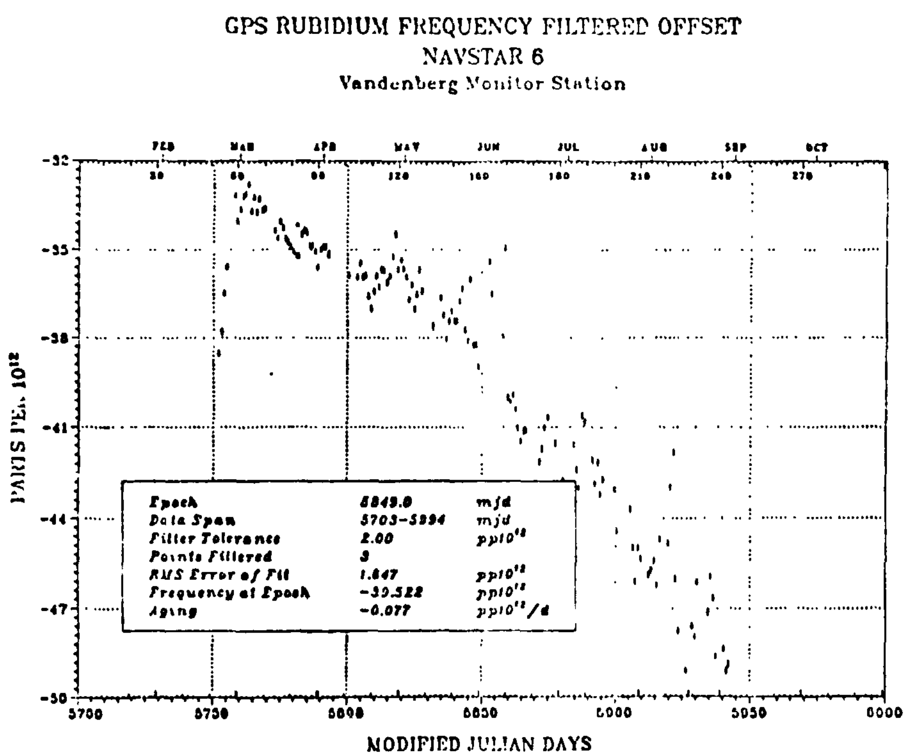

Figure 14

GPS RUBIDIUM FREQUENCY FILTERED OFFSET

NAVSTAR 6

Vandenberg Monitor Station

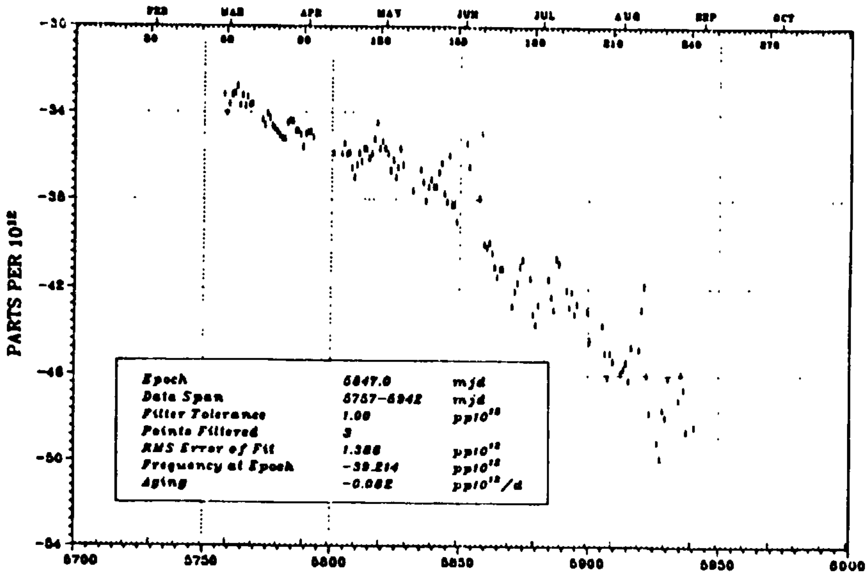

Figure 15

GPS RUBIDIUM FREQUENCY LINEAR RESIDUALS

NAVSTAR 6

Vandenberg Monitor Station

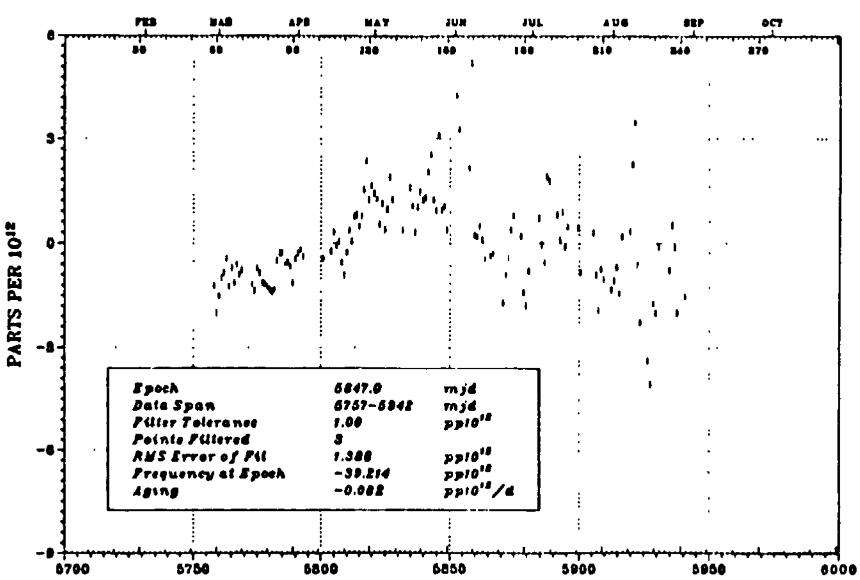

Figure 16

GPS
CLOCK ANALYSIS

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NAVSTAR.6 (RUBIDIUM) VS MONITOR STATIONS

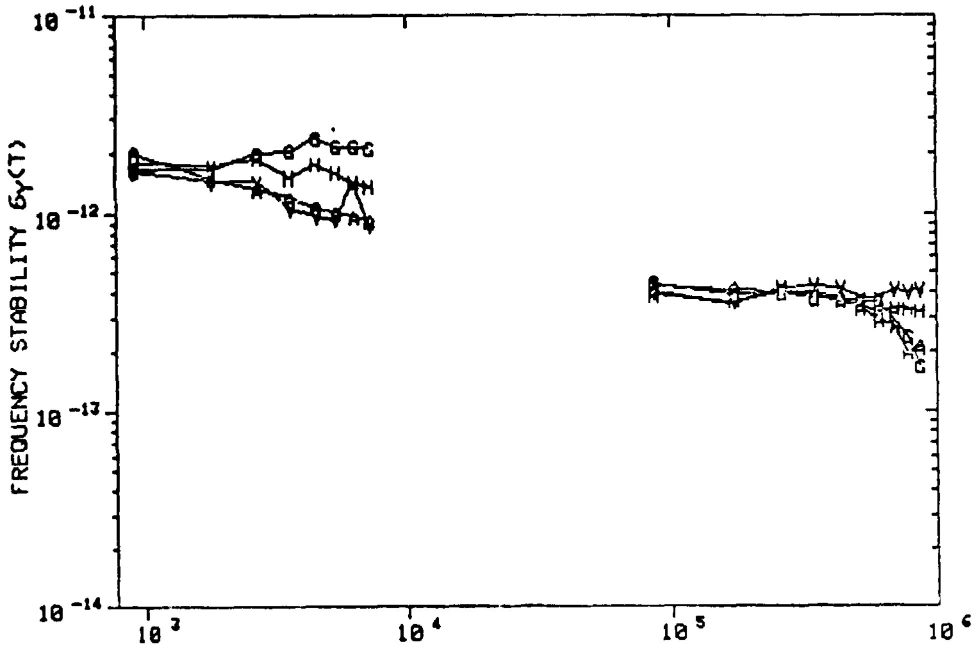

Figure 17

GPS RUBIDIUM PHASE OFFSET
NAVSTAR 8
Vandenberg Monitor Station

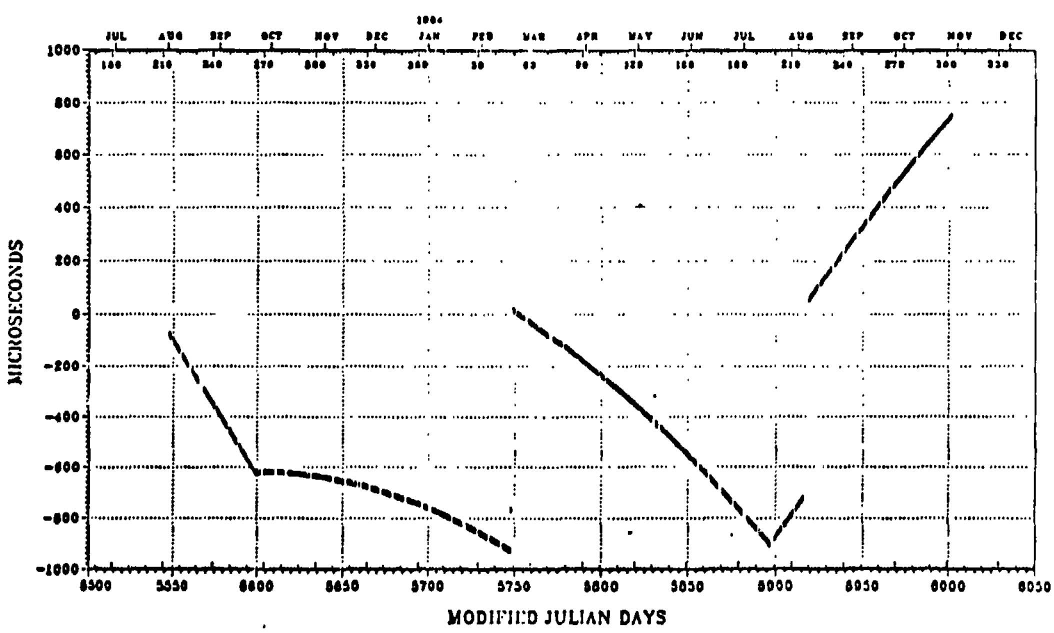

Figure 18

GPS RUBIDIUM FREQUENCY CORRECTED AND PURGED OFFSET
NAVSTAR 8
Vandenberg Monitor Station

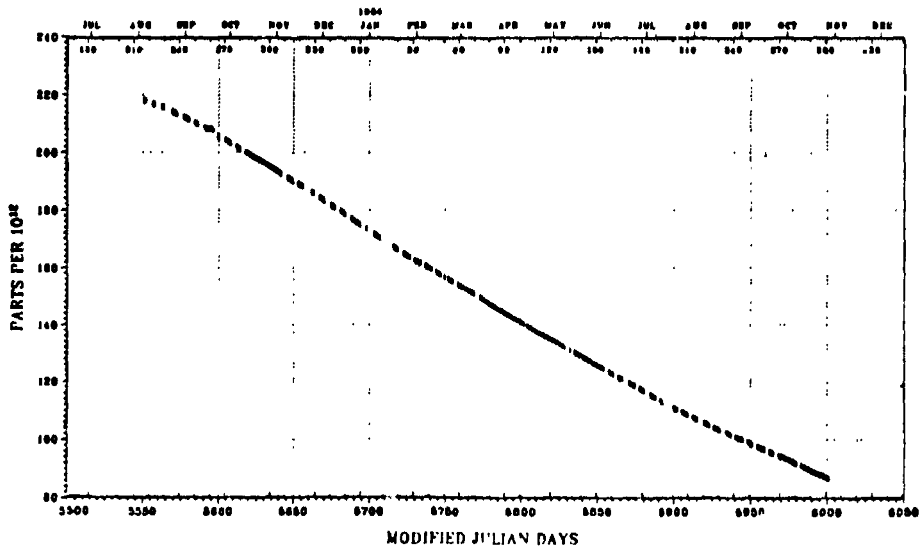

Figure 19

GPS RUBIDIUM FREQUENCY ASYMPTOTIC LINEAR RESIDUALS
NAVSTAR 8
Vandenberg Monitor Station

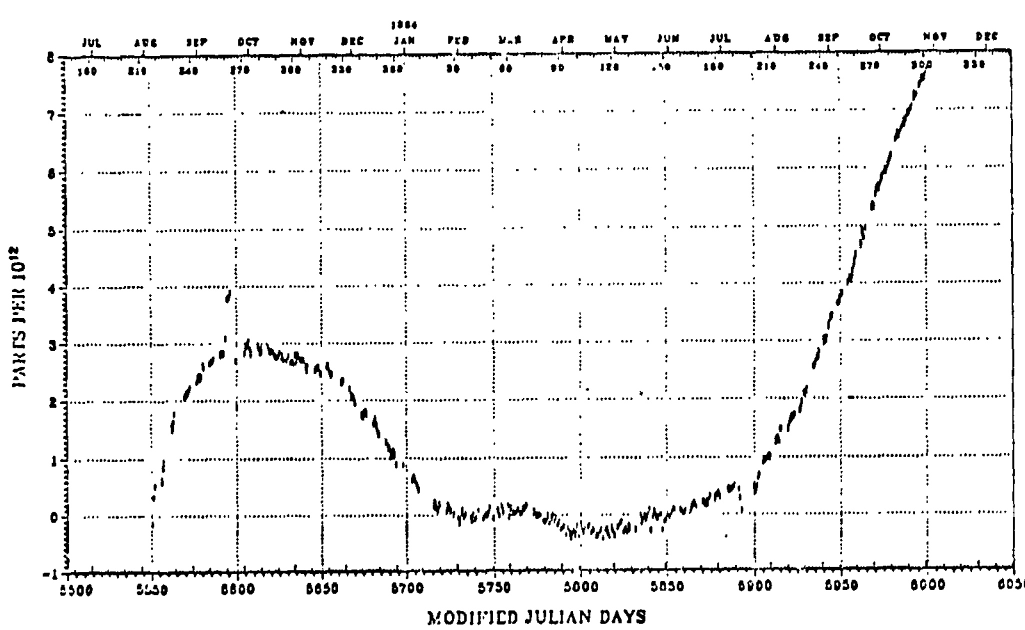

Figure 20

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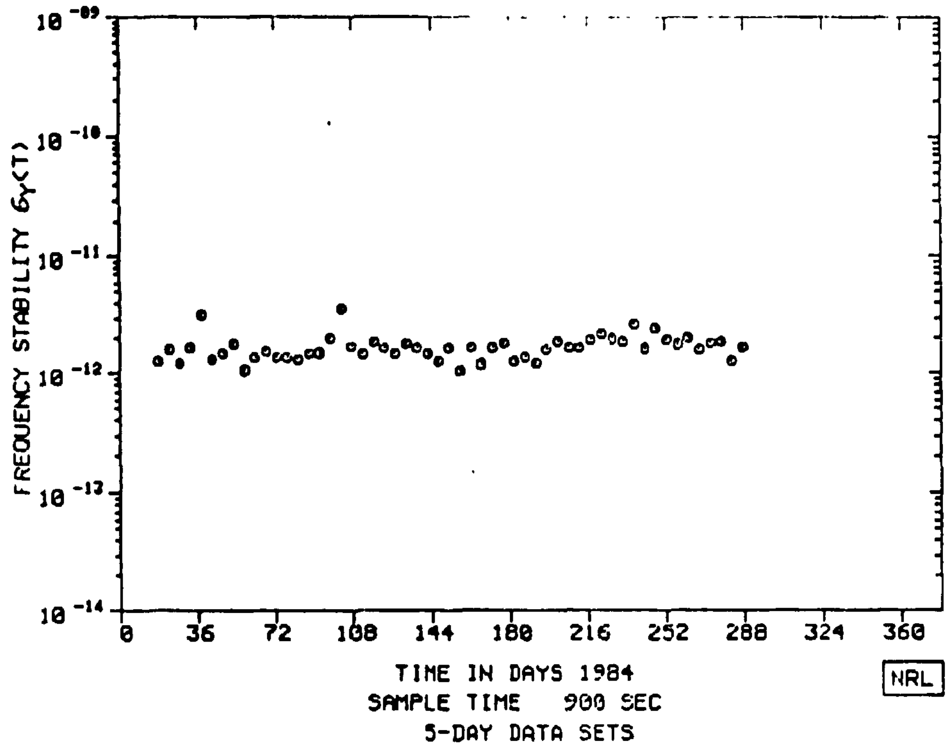

Figure 21

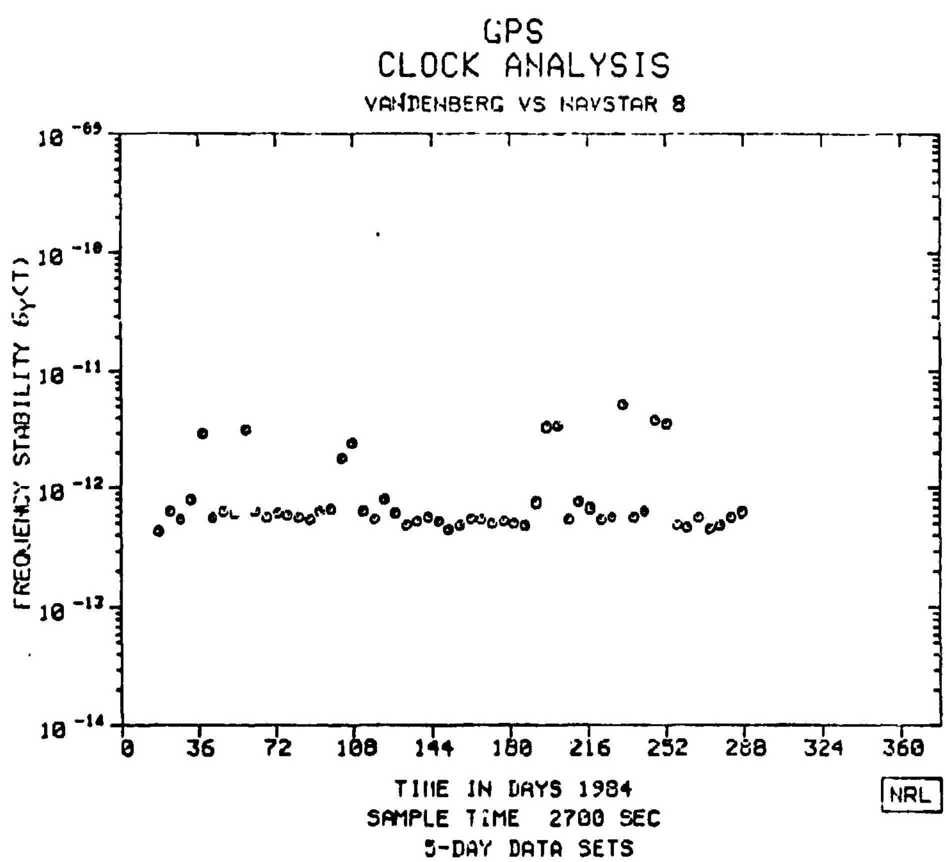

Figure 22

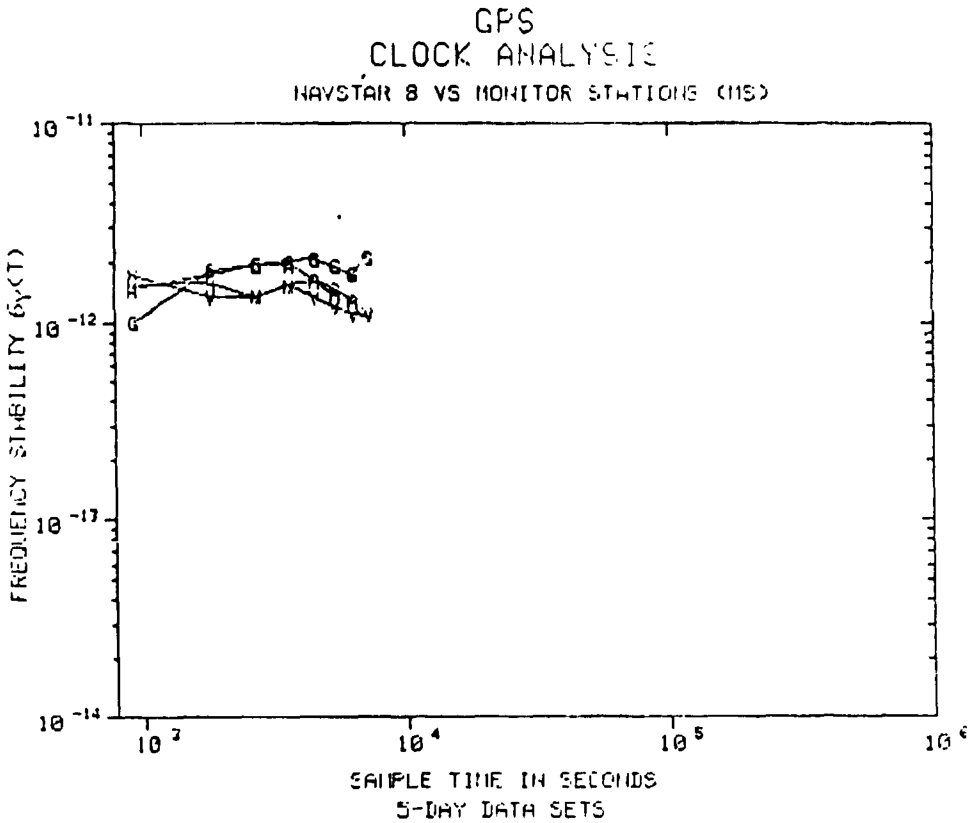

Figure 23

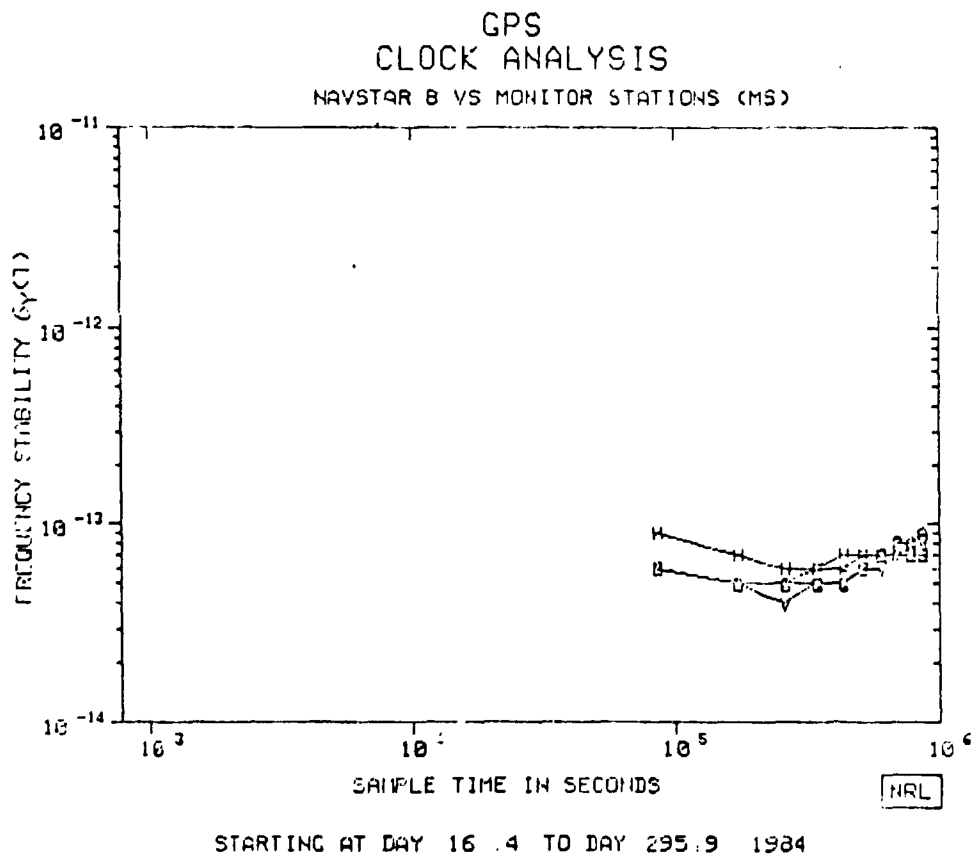

Figure 24

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NAVSTAR 8 RUBIDIUM - VANDENBERG MS
DAY 270-365 1983

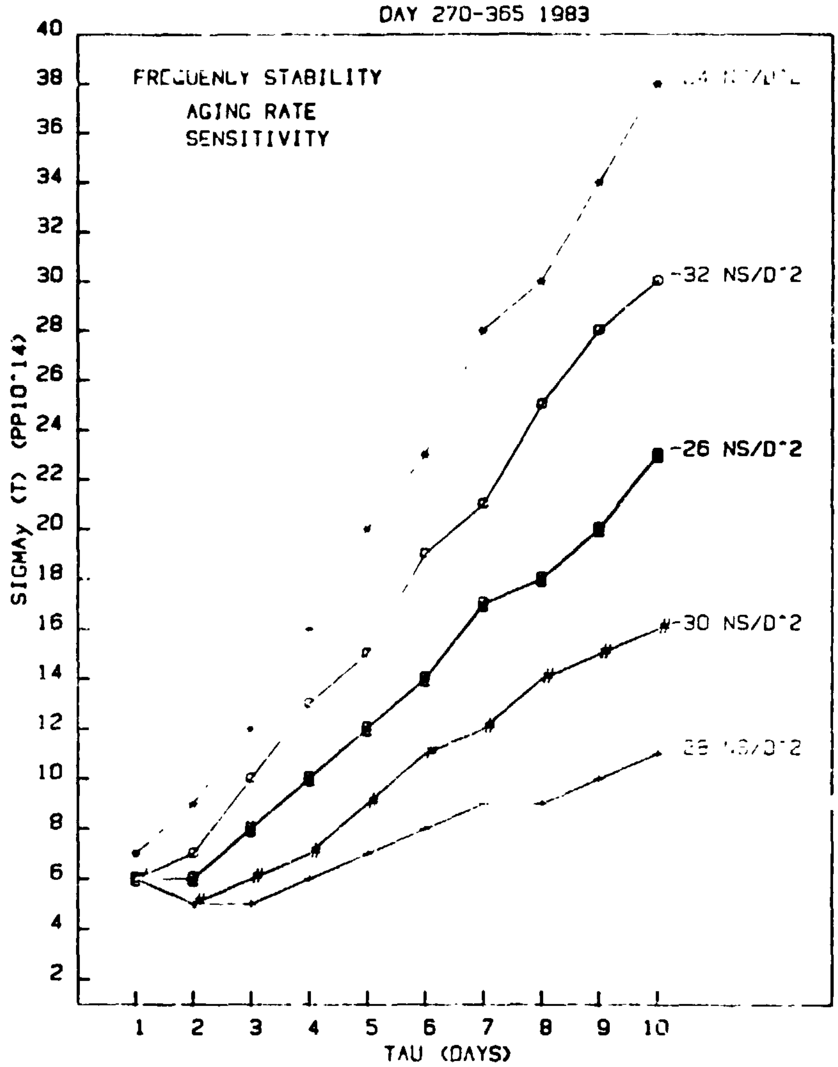

Figure 25

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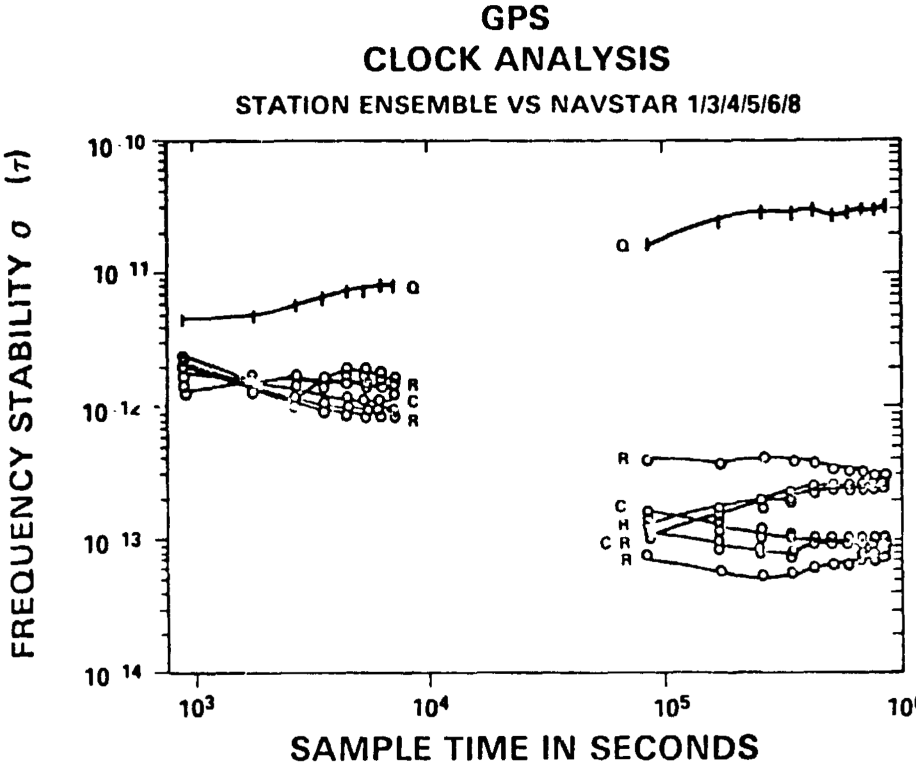

Figure 26

QUESTIONS AND ANSWERS

PHIL TALLEY, AEROSPACE CORPORATION: I would like to comment that there is a post-correlation for those variations in the frequency that you can see with solar activity, and I have looked at that in some depth, and every time there is a significant case that's being noted, there will be, within the next twenty-four hours, a significant change in the aging rate, and they correlate very closely with the changes in aging rate that you showed in your curve. I mentioned it to Jim Buisson earlier, but we can discuss that in some depth later. That is not an inherent quartz characteristic. It is induced, and we think we know to what extent.

MR. McCASKILL: Thank you for your comments, Phil.

DAVID ALLAN, NATIONAL BUREAU OF STANDARDS: There was a question earlier in my mind with regard to the deviations in sigma at 900 seconds. I wondered if those could be induced by a deviation in one of the other spacecrafts, since the Kalman filter forces the error somewhere in the system. If you have a problem in another part of the system, it can show up on another spacecraft, and not be on that spacecraft. It might be worth looking at the correlations of some bad performance on other spacecrafts at those times when those events occurred.

MR. McCASKILL: That would, of course, be true if we were using the orbital elements that were generated by the GPS master control station. We are not. We are using an after-the-fact smoothed orbit, which is determined for each of the spacecraft, the NAVSTAR 8 Rubidium in this case.

The fluctuations on NAV 8 showed up first at about 900 seconds, and they seem to increase as you go out to around 2,700 seconds sample time. We have looked, but at the moment we have still not been able to isolate the cause.

GERNOT WINKLER, NAVAL OBSERVATORY: Would you repeat the performance concerning one day and ten days? It appears that the Rubidium clock is better than the Cesium clock. Is that correct?

MR. McCASKILL: The NAVSTAR 8 Rubidium clock with the additional thermal control does give a better stability at a one day sample time. That's assuming that you know what the aging rate is going to be. We have determined the aging rate after the fact. If you do not know what the aging rate is, you can get results that don't look like this, but they follow an apparent random walk FM process.

Please keep in mind that we are determining, on the rubidium clocks, and on the quartz, the aging rate after the fact. On the cesium clocks, the stability measurements were made without any aging correction at all. Cesiums don't age.