PERFORMANCE OF GLOBAL POSITIONING SYSTEM BLOCK II/IIA/IIR ON-ORBIT NAVSTAR CLOCKS

Jay Oaks, Thomas B. McCaskill, Marie M. Largay
U.S. Naval Research Laboratory

James A. Buisson
AEI

Abstract

Analysis of the performance of all on-orbit Navstar space vehicle clocks and Global Positioning System (GPS) monitor station reference clocks is performed by the Naval Research Laboratory (NRL), in cooperation with the GPS Master Control Station, under the sponsorship of the GPS Joint Program Office (JPO). The measurements used in the analysis are collected by multi-channel GPS receivers located at the Air Force and National Imagery and Mapping Agency (NIMA) monitor stations. The offset of each Navstar clock is computed with respect to the Department of Defense Master Clock. The resultant Navstar clock offsets are then used to compute frequency offset, drift offset, frequency stability profiles, and frequency stability histories.

The performance of selected cesium and rubidium atomic clocks will be presented. Frequency stability results are calculated using sample times that vary from 15 minutes to several days. The operational Navstar timing signals will be ranked (according to frequency stability) for sample times of 6 hours and 1 day. In addition, the Block IIR clocks will be compared to results from an ongoing NRL laboratory life-test on two flight-qualified Block IIR rubidium atomic frequency standards. Observed clock behavior and anomalies will be discussed.

INTRODUCTION

Performance of the on-orbit Navstar atomic clocks in the Global Positioning System (GPS) constellation is summarized using a multi-year database, including data collected to 1 October 2001. This ongoing work is sponsored by the GPS Joint Program Office (JPO) and is done in cooperation with the GPS Master Control Station (MCS). The measurements were collected from a network of Air Force (USAF) and National Imagery and Mapping Agency (NIMA) monitor stations. The NIMA Washington, D.C. monitor station is located at the United States Naval Observatory (USNO) and is referenced to the Department of Defense (DoD) Master Clock. The results from the NRL analyses of the Navstar spacecraft vehicle (SV) and monitor station (MS) atomic clocks are used by the GPS MCS to aid in the prediction of clock states in the Kalman filter. This aiding results in an improvement in navigation and time transfer performance [1]. The NRL results are reported to the GPS JPO and the MCS, and made available to the GPS working group community via a NRL Web site. Performance and lifetime evaluation tests are being conducted at NRL on Navstar flight-qualified candidate clocks. Currently, two Block IIR rubidium atomic frequency standards are undergoing life test in the NRL Precision Clock Evaluation Facility. The results of these analyses are compared with those of the on-orbit clocks and are also available on the NRL Web site.

METHODOLOGY

The current tracking network of monitor stations, depicted in Figure 1, consists of five Air Force MS, and 11 NIMA MS. The offset of each MS clock with respect to the DoD Master Clock is computed using Multiple-Path Linked Common-View Time Transfer (LCVTT) [2]. The network links used in the LCVTT computation are shown in Figure 2. The advantage of using multiple paths is that the loss of measurements from one station does not result in the loss of time transfer data for the remaining stations in the network. The offset of each MS clock is combined with the offset of the Navstar SV clocks, observed at each MS, to produce Navstar SV clock offsets with respect to the DoD Master Clock. This process results in multiple measurements of the Navstar SV clocks at each 15-minute epoch. The measurements are averaged at each epoch to get continuous coverage of each Navstar clock with respect to the DoD Master Clock [3]. The continuous coverage measurements are then used to compute the frequency offset, drift offset, frequency stability profiles, and frequency stability histories for the Navstar clocks using the NRL Clock Analysis Software System (CASS). CASS is a complex set of software analysis tools comprised of over 400,000 lines of code that was developed at NRL over the last 18 years. The current active database includes data for all Block II/IIA/IIR SV clocks for 34 Navstar SVs (out of a total of 44 launched). To date, 109 of the 167 Navstar clocks on orbit have been operated and 74 are Block II/IIA/IIR that are included in the active database. Archived data are maintained for all of the Block I Navstar clocks beginning with Navstar 1, which was launched in 1978.

CONSTELLATION OVERVIEW

A summary of the operational Navstar clocks in the GPS constellation as of 30 September 2001 is presented in Figure 3. Each Block II/IIA/IIR SV is shown by plane, position in the constellation, and type of clock that was operating on each SV. Fourteen of the 28 clocks operating were rubidium atomic frequency standards (RAFS) and 14 were cesium atomic frequency standards (CAFS). Of the 14 RAFS, six are on the new Block IIR SVs. The total operating time for each of the Navstar SVs since the SV was inserted into the constellation is shown in Figure 4. Twenty-three SVs have met or have exceeded the required Block II/IIA mean mission duration of 6 years. Eighteen SVs have exceeded 8 years of operation, and nine have exceeded 10 years of operation. Six Block II/IIA SVs, Navstars 14, 16, 18, 19, 20, and 28, have been decommissioned. Navstar 28 was the only space vehicle that did not meet the required mean mission duration before being decommissioned. The average lifetime of all SVs in the GPS constellation is 7.5 years. The numbers of clocks that have been placed in operation on each of the active SVs, since the SVs were inserted into the constellation, are shown in Figure 5. Of the active SVs, 10 are on the first clock, 12 are on the second clock, three are on the third clock, and three, Navstars 22, 24, and 32, are on the fourth clock. While Navstar 43 shows two clocks placed into operation, one was turned on for test purposes and then switched off. It was a good clock and can be reactivated when the need arises. The Block IIR SVs are equipped with only three clocks, all RAFS. The Block II and IIA SVs each have four clocks, two CAFS and two RAFS. The operating lifetime, or length of service, of the clocks that were operating as of 1 October 2001 is shown in Figure 6. The bars in the front row refer to rubidium clocks, and those in the back row refer to cesium clocks. Four clocks, cesiums on Navstars 13, 15, 23, and 27, have exceeded 8 years of continuous operation, and the cesium clock on Navstar 13 has exceeded 12 years of continuous operation. One of the Block IIR rubidium clocks, on Navstar 43, has exceeded 4 years of continuous operation. The average age of the currently active CAFS is 6.9 years and the RAFS is 2.0 years, as of 1 October 2001. The lifetime of the deactivated clocks ranked by relative order of lifetime is presented in Figure 7. Rubidium clocks are represented in the front row, and cesium clocks are represented in the back row. The notation SVN and SN on the horizontal axis denotes Navstar space vehicle number and clock serial number. The chart shows that the cesium clocks have an average lifetime that is almost three times that of the rubidium clocks, 3.9 years for the 41 cesium clocks compared to 1.4 years for the 30 rubidium clocks.

NAVSTAR TIMING SIGNAL MEASUREMENTS

The phrase "Navstar Timing Signal" is used rather than "Navstar Clock Offset" because the AFS output is further modified by the electronics before being broadcast by each Navstar SV to the user. The Block II/IIA Navstars are equipped with a Frequency Standard Distribution Unit (FSDU), and the Block IIR Navstars are equipped with a Time Keeping System (TKS) [4]. The TKS provides the capability of tuning the output frequency and drift offset. This capability has been used to adjust the output frequency and drift of the Block IIR on-orbit RAFS to within a few pp10^{12} of the DoD Master Clock.

FREQUENCY STABILITY MODELS

NRL currently employs two models to measure the frequency stability performance of the Navstar clocks in the time domain. The Allan deviation is normally used in the analysis of cesium clocks that exhibit extremely low aging. The Hadamard deviation adaptively removes the very large drift characteristic of rubidium clocks. These frequency stabilities are computed as a function of sample time to determine the long-term and short-term characteristics of the clocks. Because the Navstar clocks are expected to operate on orbit for a period of years, an analytical method of determining frequency stability history was developed to detect non-stationary behavior and examine frequency stability as a function of time [5]. The frequency stability history is obtained by performing an N-day moving average of the sequence of squared first differences (Allan deviation) or squared second differences (Hadamard deviation) of frequency offset measurements separated by the sample time. The stabilities are computed for a selectable sample time, window width, and data span. The sample times of interest are usually 6 hours and 1 day, and the window width is chosen to be approximately ten times the sample time. The data spans may be over months or years, depending on the type of analysis being performed.

MONTHLY FREQUENCY STABILITY RANKING

Six-hour and 1-day frequency stabilities are calculated for each Navstar clock using 1 month of data. The stability ranking of all operational Navstar SV clocks for the month of September 2001 is presented in Figure 8. The chart shows ranking as determined by the 1-day frequency stability using the Hadamard deviation in the front row. The back row shows the corresponding 6-hour stability for comparison. The table is provided for quick reference to the stability values. The values are listed in order of SV number with the identified clock type and serial number. The Navstar 51 rubidium clock was the most stable clock in the GPS constellation, with a 1-day stability of 1.29 pp10^{14} for the month of September. The Navstar 35 cesium clock had the least stable 1-day performance, with a stability of 1.448 pp10^{13}. All Navstar SV clocks had a drift-corrected 1-day frequency stability of less than 1.5 pp10^{13}. The 6-hour frequency stability estimates are more sensitive to measurement noise and systematic effects that may be present in the data. Significant differences can be observed between the 6-hour frequency stability estimates for all Navstar SV clocks as compared to the 1-day estimates. The 6-hour frequency stability estimates varied from less than 6.5 pp10^{14} to 9 pp10^{13}.

FREQUENCY STABILITY HISTORY

The frequency stability history of the Navstar 23 cesium clock for a 6-hour sample time is presented in Figure 9. It is computed using the Hadamard deviation with a window width of 96 hours. The 6-hour stability shows a periodic degradation that correlates with the spacecraft vehicle eclipse seasons. A gradual degradation is also seen from a few pp10^{13} to almost 1 pp10^{12} over the span of 6 years. The 1-day sample time frequency stability history in Figure 10 shows a small degradation over the same span and in fact shows good performance of the clock with a stability better than 1 pp10^{13}. This implies there is some systematic behavior in the 6-hour case that is not present for a sample time of 1 day.

BLOCK IIR TIMING SIGNAL ANALYSIS

The 1-day average drift offset of Navstar 41 is presented in Figure 11 with the times of the TKS upload and four unknown frequency breaks labeled on the plot. In the spacecraft timing signal analysis, corrections are not made for unknown anomalies. Hence, no corrections were applied for the unknown frequency breaks in these data. Initially, the corrected 1-day average drift was –8.4 pp10^{14} per day, with a slope typical of rubidium clocks following activation. On 1 October 2001, the drift history approached a value near 2 pp10^{14} per day. Immediately following a frequency break of 9.1 pp10^{13}, which occurred on 27 October 2001, the drift history shows a small dip and then returns to its nominal drift value. The frequency stability history for Navstar 41 is presented in Figure 12, and was computed using the Hadamard deviation for a 1-day sample time with a 10-day window width. The 1-day stability history is well behaved, with all values less than 2 pp10^{14} from activation until the end of October 2001. The stability jumped almost an order of magnitude, degrading to a value near 1.2 pp10^{13}. Following the occurrence of the large frequency break of 9.1 pp10^{13}, the 1-day frequency stability recovered to a value near 1.5 pp10^{14}.

The 1-day average frequency offset history of Navstar 43, from activation on 19 August 1997 to 21 October 2001, is presented in Figure 13. Frequency and phase breaks of unknown origin that were detected in the analysis are shown on the graph. To date, a total of six phase breaks and 33 frequency breaks have occurred. The phase offset residuals to a 30th order regression for the Navstar 43 timing signal are presented in *Figure 14* using data from 22 January 1999 to 20 October 2001. A significant change in the phase-offset characteristics began with the first unknown frequency break of 7 pp10^{14} that occurred on 3 July 1999. The frequency breaks exhibit a sharp cusp in the phase-offset residuals at the time of the break and a rounded shape at the midpoint between successive breaks. The phase-offset residuals reached a maximum on 12 October 1999, which corresponds with a frequency break of –10 pp10^{14}. Figure 15 expands the portion of data from 21 May 2001 to 21 October 2001. Phase offset residuals to a quadratic show that the separation between successive breaks is fairly consistent with a period of 26 days. The period of the frequency breaks and a linear fit to the data is presented in Figure 16. The linear fit exhibits a negative trend, with an overall decrease in the period of 6 days. The cumulative magnitude of the 33 unknown frequency breaks is presented in Figure 17. The breaks began almost two years (688 days) after activation, and all but one has been positive with approximately the same magnitude. As of 21 October 2001, the sum of unknown frequency breaks is approximately 1.65 pp10^{12}.

Frequency breaks of unknown origin have also been observed in one of the two Navstar flight candidate RAFS that has been undergoing a life test in the Precision Clock Evaluation Facility at NRL. The life test for RAFS Serial Number 028 began in April 1997. A total of 76 frequency breaks have been detected since the life test began. The cumulative magnitude of the breaks is presented in Figure 18. The characteristics of the data here is similar to that of the Navstar 43 data. Until mid-year 2000, the frequency breaks were predominately positive and have roughly the same magnitude. From that time to present, the

RAFS SN028 clock has exhibited a few large negative frequency breaks with significant periods of no breaks at all. This is a dramatic change in the characteristics of the clock.

The 1-day average drift offset for Navstar 44 with respect to the DoD Master Clock is presented in Figure 19. The TKS drift upload that was made by the MCS on 1 March 2001 is indicated near the center of the plot. Periodic behavior with a deviation of about ±2 pp10^{13} per day is observed in the drift. A Power Spectral Density (PSD) of the 1-day average drift offset was computed monthly and is presented for periods of maximum and minimum drift deviation. Figure 20 is the PSD where the drift deviation is a maximum and shows a peak at 2.5 days. Figure 21 shows the PSD with a less predominant peak at 3 days for the span of time where the drift deviation is a minimum. The period of the drift deviation taken at monthly intervals is plotted in Figure 22 and is a good fit to a linear regression with an increasing trend. The data show an increase of almost 1 day in the period of drift deviation in the time span of about a year.

The 4-day average drift offset of the Navstar 46 timing signal with respect to the DoD Master Clock is presented in Figure 23 for the time span 25 December 1999 to 18 October 2001. A smaller drift deviation than was exhibited in Navstar 44 is seen with a period of about 12 days. The large increase in drift at turn-on is the activation transient that is typical in rubidium clocks. Figure 24 shows the drift deviation on an expanded scale, beginning with data after the activation transient. The drift deviation is ±2 pp10^{14}, an order of magnitude smaller than that of Navstar 44.

The Navstar 54 timing signal 1-day average drift offset with respect to the DoD Master Clock is presented in Figure 25. A TKS drift correction upload was made by the MCS as shown on 24 July 2001. A total of four frequency breaks of unknown origin have been detected in the Navstar 54 timing signal since activation. The first break occurred 218 days after activation on 17 September 2001. At that same time the drift exhibited changes from previous normal behavior. A drift variation can be seen in September and again in October of almost 1 pp10^{13} per day. This variation correlates with a degradation in the 1-day stability during that same time span, as shown in Figure 26. Initially, the 1-day frequency stability was near 1.9 pp10^{14} during the first month of operation and approaches 1 pp10^{14} until the onset of the unknown frequency breaks and drift anomalies. The frequency stability history performance degrades, with a peak that exceeds 4 pp10^{14} at the end of the data span.

The frequency-stability profiles using the Allan deviation are shown in Figure 27 for all 28 clocks in the GPS constellation, as of 1 October 2001. The effect of the large drift characteristic of the Block II/IIA rubidium clocks can be seen in the rapid degradation in stability after a 1-day sample time. Frequency-stability profiles are shown in Figure 28 for the same 28 Navstar clocks, but corrected for drift using the Hadamard deviation. The profiles vary by an order of magnitude for the different technology clocks. The best clocks are the Block IIR rubidium with a 1-day stability of about 2 pp10^{14}. The profiles for Navstar 22 and Navstar 30 at the top of the graph are poor because the clocks have been activated recently and they are probably still undergoing initial turn-on transitions. The stability profiles for the Block IIR Navstars are shown in Figure 29 for closer examination. Five of the six clocks (Navstars 41, 43, 46, 51, and 54) have frequency stability estimates at 1 day that are well below the GPS Block IIR specification of 6 pp10^{14}. The Navstar 44 rubidium clock, with a frequency stability of 6.4 pp10^{14} at 1 day, is close to the specification. The Navstars 44 and 46 rubidium clocks show a similar degradation in stability sample times of 3–6 days. The stability profile for Navstar 51 stands out as the best by far, with a 6-day stability approaching 5 pp10^{15}. A summary of the systematic behavior found in the Navstar Block IIR timing signals is presented in Figure 30.

CONCLUSIONS

The 1-day frequency stability of all of the Navstar clocks in the GPS constellation, as of 1 October 2001, was better than 1.5 pp10^{13}. The best clock was the Navstar 51 Block IIR rubidium, which had a 1-day stability of 1.3 pp10^{14}. The average lifetime for all currently activated Navstar atomic clocks is 4.4 years. The oldest active clock in the constellation is the Navstar 13 Block II cesium, which has been continuously operated for more than 12 years. The oldest Block IIR rubidium clock is the Navstar 43 rubidium (S/N 6), which has been operated for more than 4 years.

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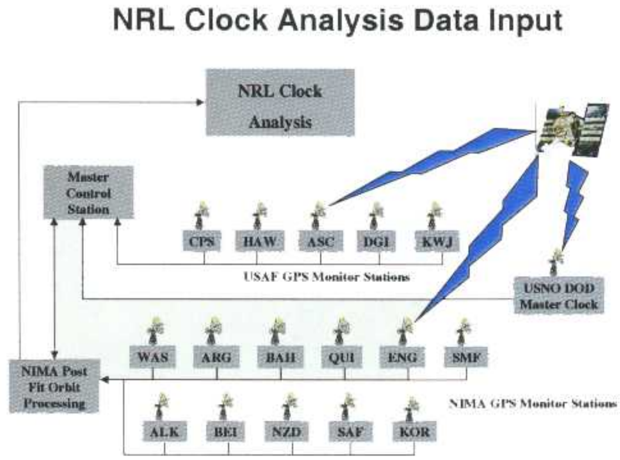

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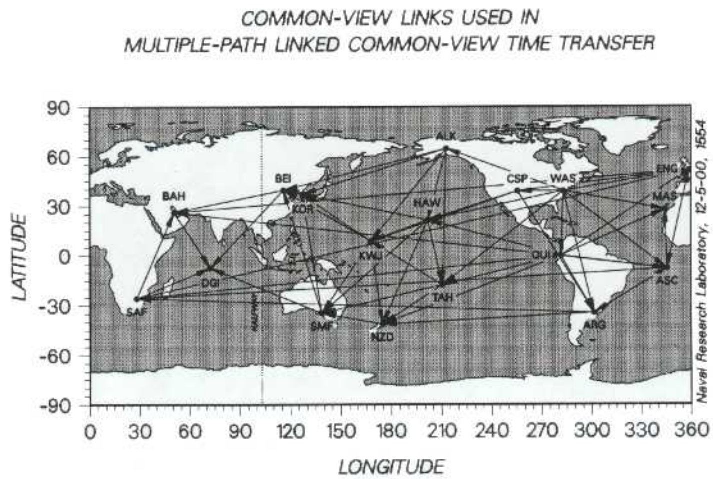

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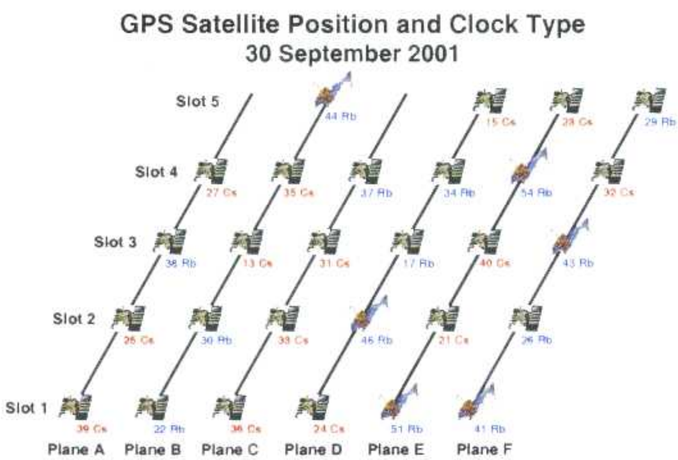

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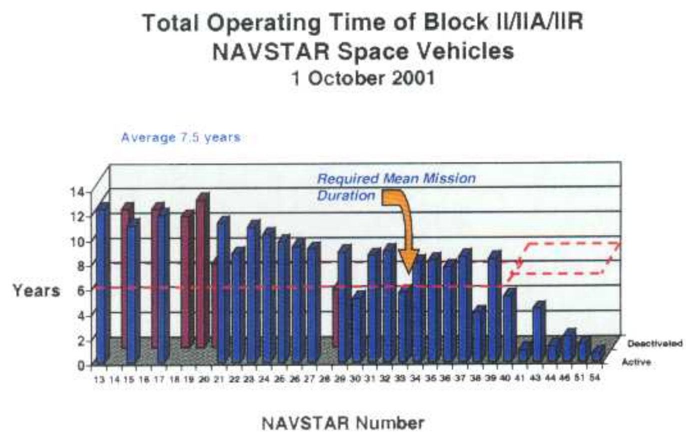

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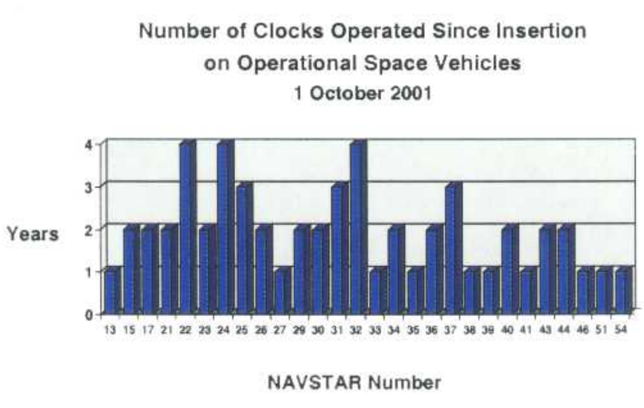

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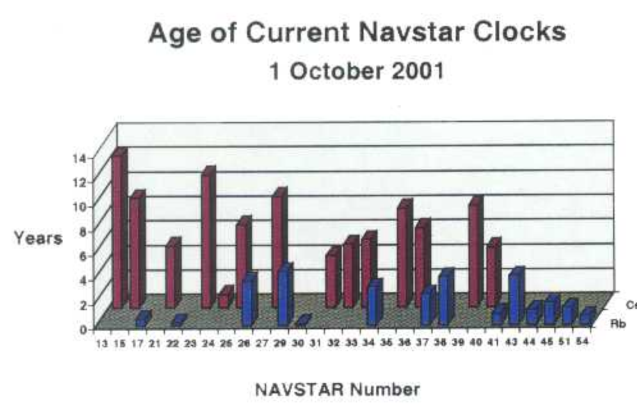

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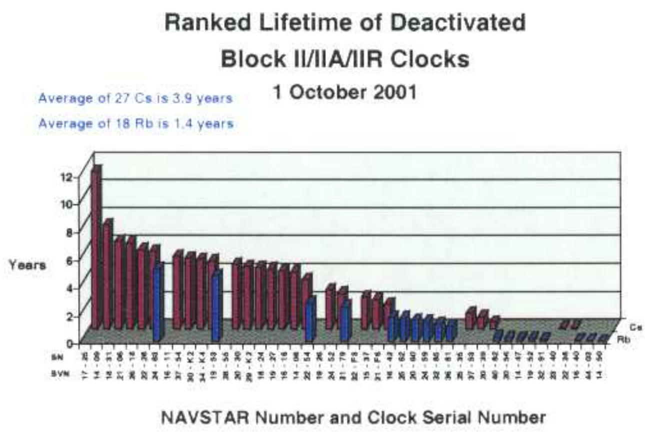

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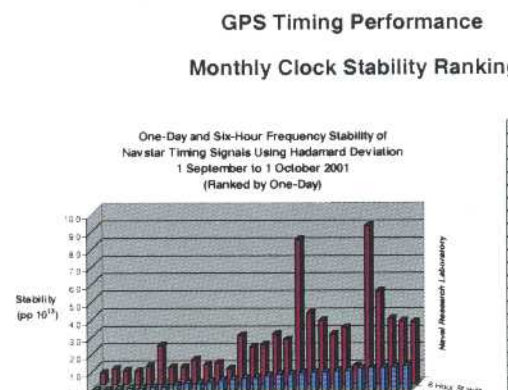
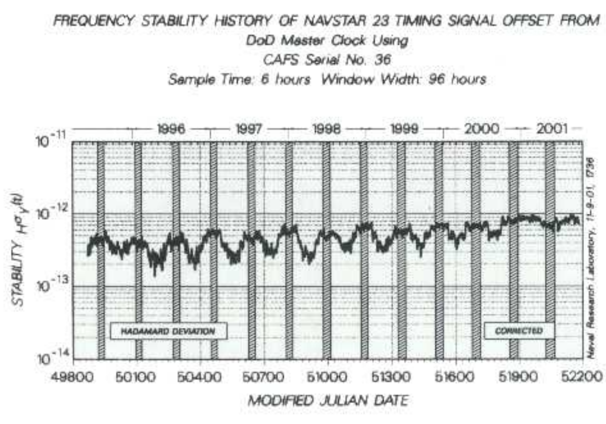


Navstar/Type/SN	1 Day Stability	6 Hour Stability
	(pp10^{13})	(pp 10^{13})
SVN 13 Cs 14	0.913	2.821
SVN 15 Cs 17	1.372	3.706
SVN 17 Rb 44	0.271	2.212
SVN 21 Cs 10	1.191	3.213
SVN 22 Rb 78	0.600	1.197
SVN 23 Cs 36	1.017	8.222
SVN 24 Cs 48	1.111	2.862
SVN 25 Cs 20	0.792	2.119
SVN 26 Rb 67	0.473	1.351
SVN 27 Cs 19	1.344	5.287
SVN 29 Rb 73	0.386	0.968
SVN 30 Rb 38	1.191	1.027
SVN 31 Cs 41	1.397	3.565
SVN 32 Cs 43	1.075	4.025
SVN 33 Cs 48	0.834	2.253
SVN 34 Rb 84	0.284	0.963
SVN 35 Cs 32	1.448	3.543
SVN 36 Cs 46	1.328	9.016
SVN 37 Rb 83	0.473	1.106
SVN 38 Rb 30	1.079	3.623
SVN 39 Cs 58	0.992	2.543
SVN 40 Cs 42	0.708	2.737
SVN 41 Rb 28	0.150	0.850
SVN 43 Rb 6	0.203	0.739
SVN 44 Rb 9	0.662	0.856
SVN 46 Rb 21	0.170	0.777
SVN 51 Rb 34	0.129	0.654
SVN 54 Rb 44	0.209	1.024

Figure 8.



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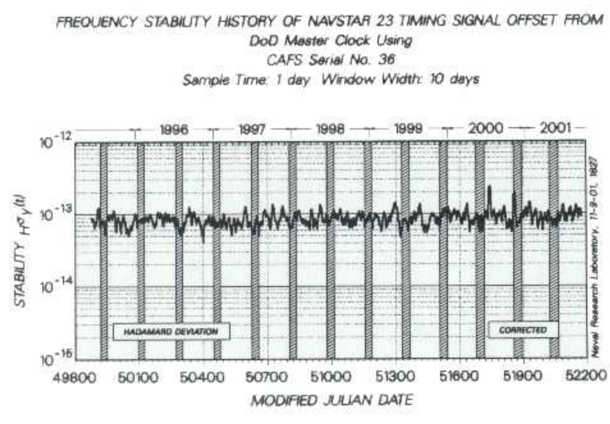

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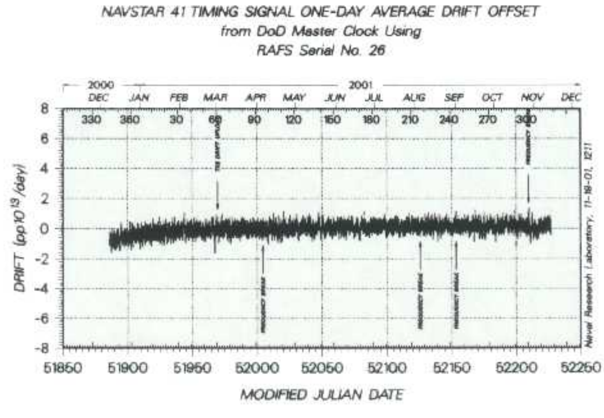

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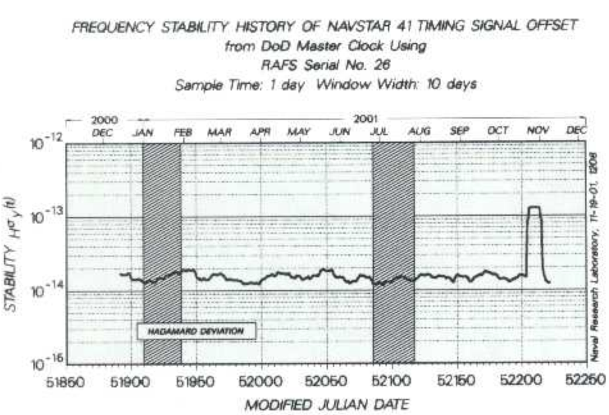

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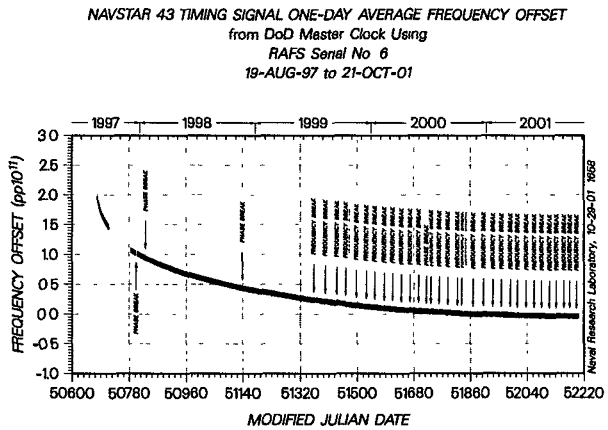

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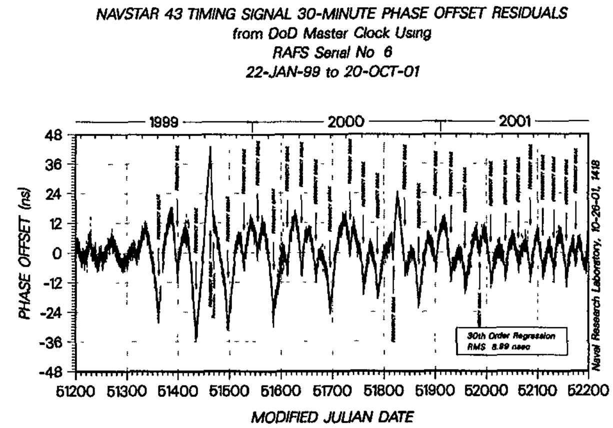

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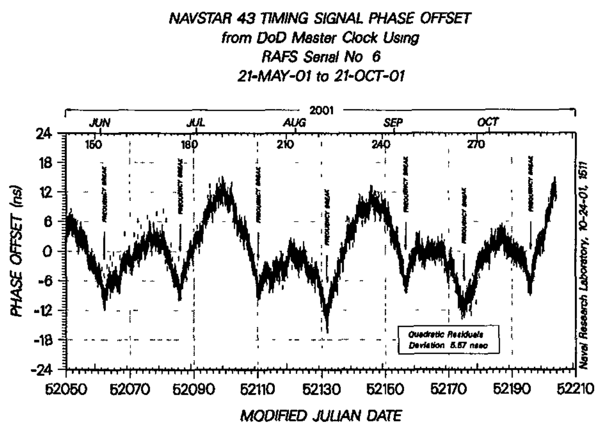

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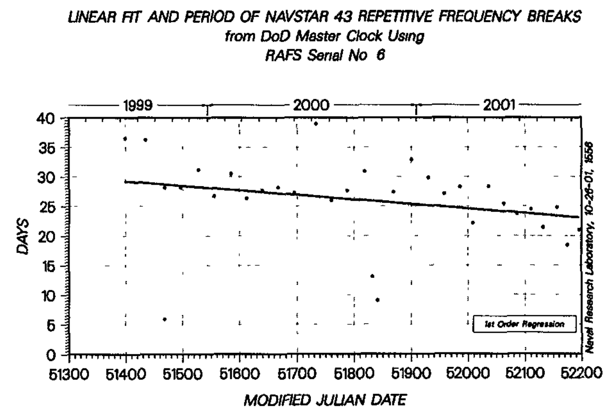

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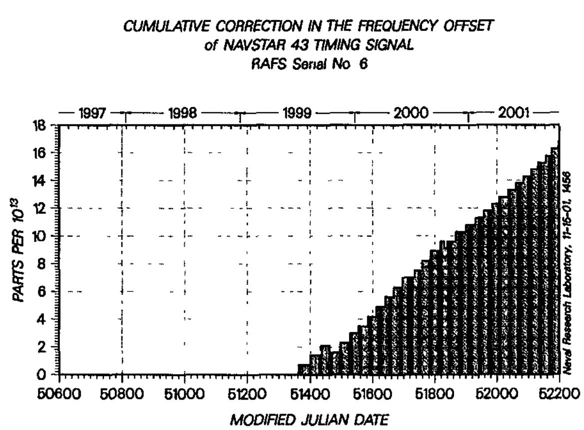

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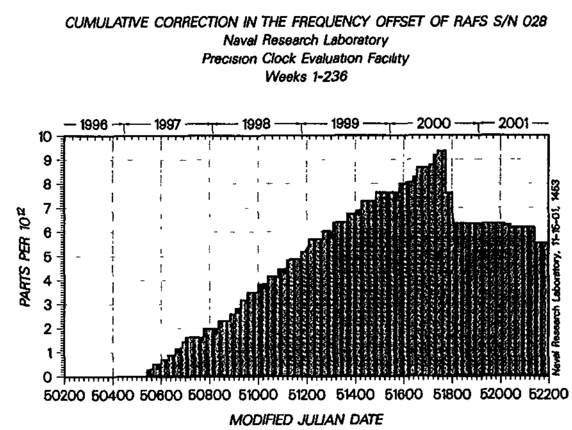

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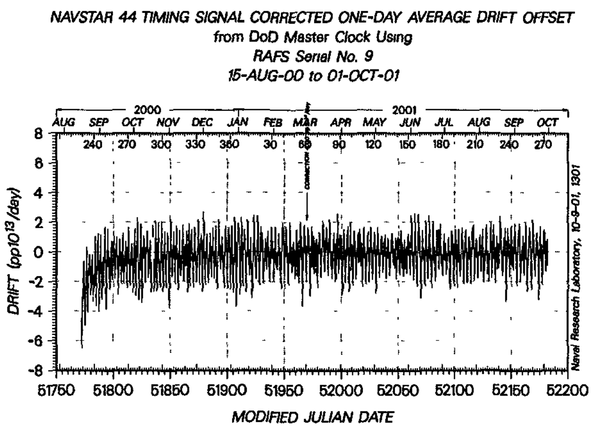

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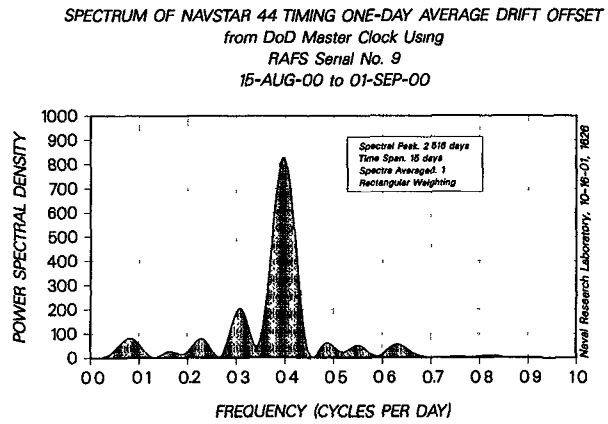

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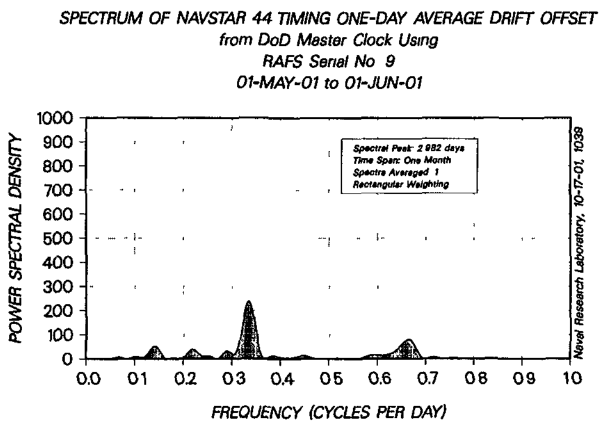

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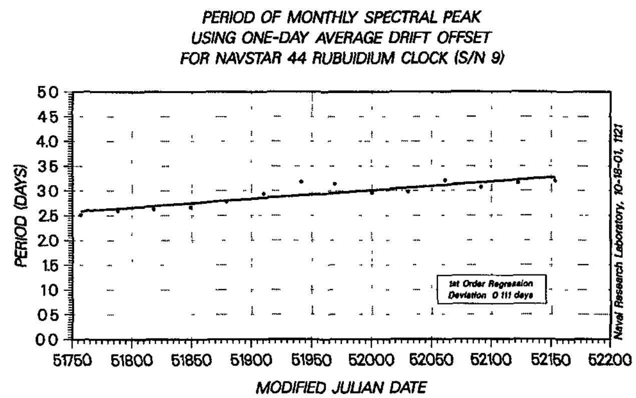

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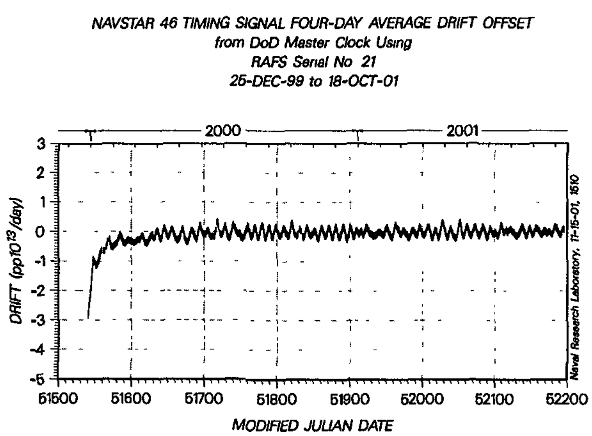

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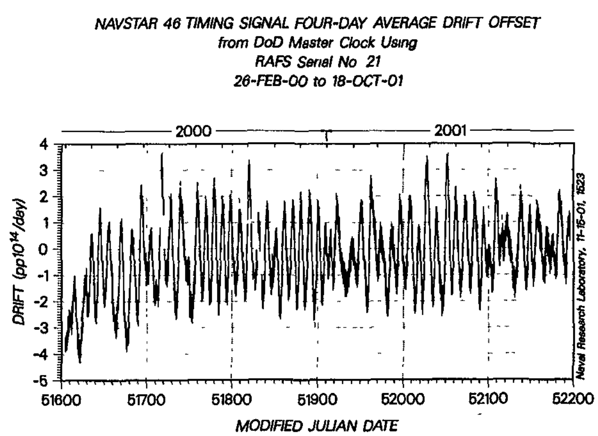

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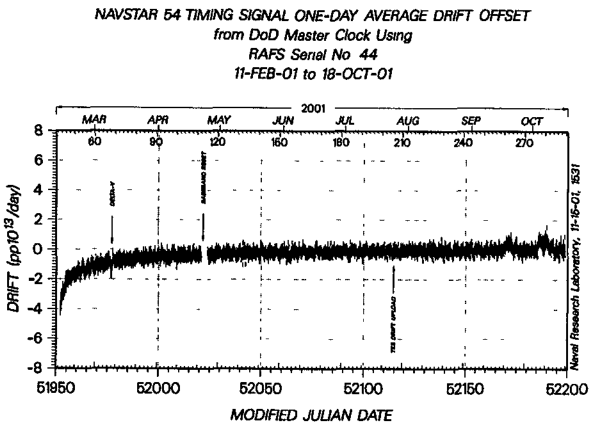

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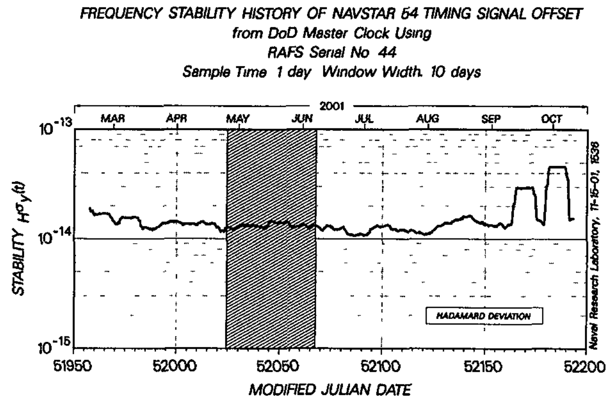

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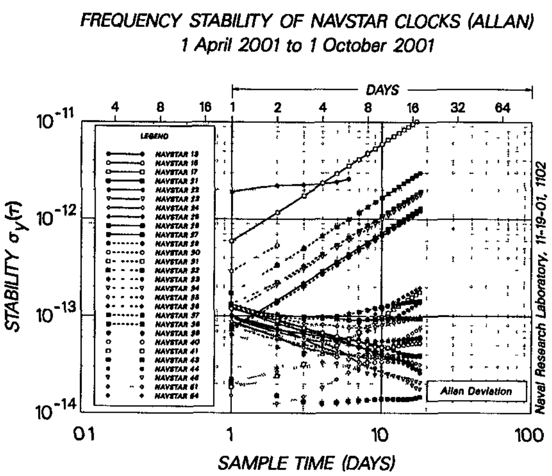

Figure 27.

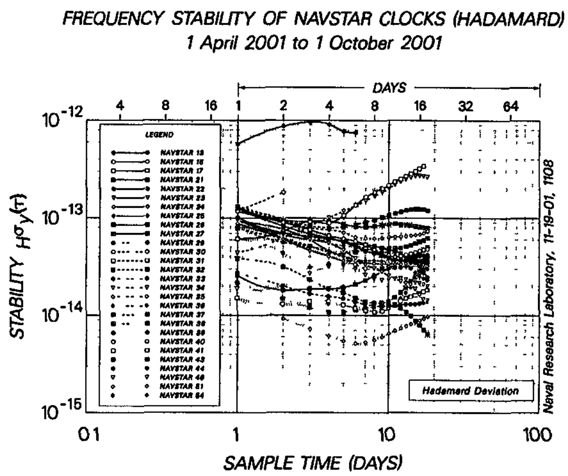

Figure 28.

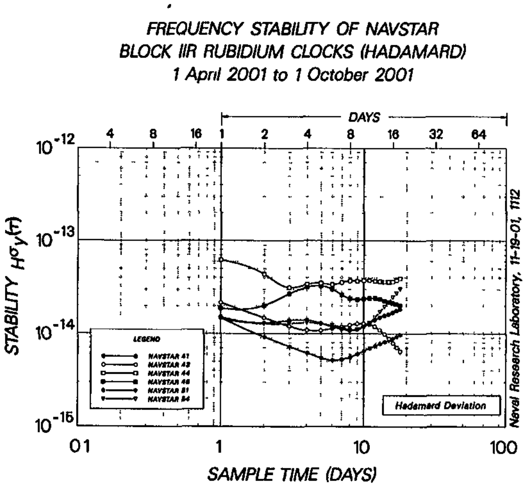

Figure 29.

Block IIR Timing Signal Systematics

Satellite	Anomaly	Periodic	Total Breaks
SVN 41	Drift	12.07 days	NA
SVN 43	Frequency	26.06 days	33
SVN 44	Drift	2.52 days	NA
SVN 44 ATP	Drift	2.32 days	NA
SVN 46	Drift	11.62 days	NA
SVN 51	None	NA	NA
SVN 54	None	NA	NA
SN 28 (Lab)	Drift / Frequency	47 days / NA	NA / 76
SN 30 (Lab)	None	NA	NA

Figure 30.

QUESTIONS AND ANSWERS

JIM CAMPARO (The Aerospace Corporation): Do you have any idea what those anomalies might be due to that you are seeing?

JAY OAKS: No. We present all the data and try to correlate it with things that we know about, but we have not come up with anything, and we presented it more or less to the working community to try to come up with reasons. Again, most of these things that we are seeing are below what the operational people care about. But they are interesting to us because there are things that if we want to improve clocks, if we can figure out what's causing them, maybe we can make clocks better in the future.

VICTOR REINHARDT (Boeing Satellite Systems): Do you have access to the telemetry data from the spacecraft to see if it is correlating with environmental things?

OAKS: We have been off and on about trying to get the telemetry data. One of the problems with the current telemetry data is granularity or resolution – we cannot really correlate very well. With the laboratory clocks, we get that down pretty well, and we can correlate, the anomalies that we see in the clock to all of the different things that are monitored. But for the most part, when we've tried to look at the telemetry data, it is too coarse to do a lot of good.

REINHARDT: Yes, most telemetry data are okay if you don't have to use them.