GLOBAL POSITIONING SYSTEM CONSTELLATION CLOCK PERFORMANCE

Jay Oaks and Marie M. Largay
U.S. Naval Research Laboratory
Washington, DC 20375, USA

Wilson G. Reid
SFA, Inc.

James A. Buisson
AEI

Abstract

An overview of the Global Positioning System (GPS) constellation with respect to the lifetimes of space vehicles and space vehicle clocks, both active and deactivated, is presented. Analysis of clock performance with respect to frequency stability is reviewed. The operational Navstar timing signals are ranked according to frequency stability for a sample time of 1 day. In addition, the performance of the Block IIR clocks is compared to that of two flight-qualified Block IIR rubidium atomic frequency standards undergoing life tests in the NRL Precision Clock Evaluation Facility. This work was performed under the sponsorship of the GPS Joint Program Office.

INTRODUCTION

Performance of the Navstar space vehicle clocks is being summarized using a multi-year database, including data collected to 1 October 2002. This continuing work is sponsored by the GPS Joint Program Office and is done in cooperation with the GPS Master Control Station. The measurements were collected from a network of five Air Force, twelve National Imagery and Mapping Agency (NIMA), and one International GPS Service (IGS) 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 Master Clock. The results of the NRL analyses of the space vehicle and monitor station clocks are used by the GPS Master Control Station to set parameters in the Kalman filter, thereby improving navigation and time transfer performance **[1]**. The results of the NRL analyses are reported to the GPS Joint Program Office and to the Master Control Station and are made available to the GPS working group community via an NRL Web site. Currently, two flight-qualified Block IIR rubidium atomic frequency standards (RAFS) are undergoing life testing in the NRL Precision Clock Evaluation Facility. The performance of these two clocks in the laboratory is compared herein with that of the on-orbit clocks and is also available on the NRL Web site.

METHODOLOGY

The network of monitor stations, depicted in Figure 1, consists of five USAF, twelve NIMA, and one IGS monitor stations. The offset of each monitor station clock with respect to the Department of Defense (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 advantages of using multiple paths are that the absence of measurements at one station does not result in the loss of time transfer data for the remaining stations in the network and that the averaging of multiple, independent measurements results in a reduction of the measurement noise. The offset of each monitor station clock from the DoD Master Clock is combined with the offset of the space vehicle clocks from each monitor station to produce the offset of each space vehicle clock from the DoD Master Clock. This process results in multiple measurements of the space vehicle clock offset at each 15-minute epoch. The measurements are then 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 (CLASS). CLASS 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 75 of the 120 Block II/IIA/IIR clocks on 34 space vehicles. Archived data are maintained for 35 of the 37 Block I clocks on 10 space vehicles.

CONSTELLATION OVERVIEW

A summary of the operational Navstar clocks in the GPS constellation as of October 2002 is presented in Figure 3. Each Block II/IIA/IIR space vehicle is shown by plane, position in the plane, and type of clock that was operating on each space vehicle. Fifteen of the 28 clocks operating were rubidium atomic frequency standards (RAFS) and 13 were cesium atomic frequency standards (CAFS). Of the fifteen RAFS, six are on the new Block IIR space vehicles. The total operating time for each of the Navstar space vehicles since the space vehicle was inserted into the constellation is shown in Figure 4. Twenty-six space vehicles have met or have exceeded the required Block II/IIA mean mission duration of 6 years. Twenty-two space vehicles have exceeded 8 years of operation, 13 have exceeded 10 years of operation, and four have exceeded 12 years of operation. Six Block II/IIA space vehicles, 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 the Block II/IIA space vehicles is 9.6 years. The number of clocks that have been placed in operation on each of the active space vehicles, since the space vehicle was inserted into the constellation, are shown in Figure 5. Of the active space vehicles, nine are on the first clock, eleven are on the second clock, four are on the third clock, and four, Navstars 22, 24, 31, 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 space vehicles are equipped with only three clocks, all RAFS. The Block II and IIA space vehicles 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 2002 is shown in Figure 6. The unshaded bars refer to rubidium clocks while the shaded bars refer to cesium clocks. Five clocks, all cesium atomic frequency standards, have exceeded 8 years of continuous operation. The cesium clock on Navstar 13 has exceeded 13 years of continuous operation. One of the Block IIR rubidium clocks, on Navstar 43, has exceeded 5 years of continuous operation. The average age of the currently active CAFS is 7.3 years and that of the RAFS is 2.7 years as of 1 October 2002. The lifetime of the deactivated clocks ranked by relative order of lifetime is presented in Figure 7. The rubidium clocks are represented by unshaded bars and the cesium clocks by shaded bars. 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 which is more than three times that of the rubidium clocks, 4.2 years for the cesium clocks, compared to 1.3 years for the rubidium clocks.

NAVSTAR TIMING SIGNAL MEASUREMENTS

The phrase "Timing Signal" is used rather than "Clock Offset" because the output of the atomic frequency standard is further modified by the electronics before being broadcast by the space vehicle. The Block II/IIA space vehicles are equipped with a Frequency Standard Distribution Unit (FSDU), and the Block IIR space vehicles are equipped with a Time Keeping System (TKS) **[4]**. The TKS provides the capability of adjusting the frequency and drift of the timing signal. This capability has been used to adjust the output frequency and drift of the Block IIR on-orbit timing signals to within a few $pp10^{12}$ of the DoD Master Clock.

FREQUENCY STABILITY MODELS

NRL currently employs two time-domain models to estimate the frequency stability of the timing signals. The Allan deviation is normally used in the analysis of cesium clocks, which exhibit extremely low values of drift. The Hadamard deviation adaptively removes the drift and is, therefore, applied to rubidium clocks, which are typically characterized by very large values of drift. The frequency stability is 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 nonstationary behavior and to 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 10 times the sample time to achieve confidence in the estimates. The time 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 space vehicle clocks for the month of September 2002 is presented in Figure 8. The chart shows, in the front row, the ranking of the 1-day frequency stability estimates based on the Hadamard deviation. The back row shows for comparison the corresponding frequency stability estimates for a sample time of 6 hours. The table shows for each space vehicle the clock type, the clock serial number, and the value of the stability estimates for sample times of 1 day and 6 hours. The values are listed in order of space vehicle number. The Navstar 54 rubidium clock was the most stable clock in the GPS constellation, with a 1-day stability of 1.3 $pp10^{14}$ for the month of September. The Navstar 21 cesium clock had the least stable 1-day performance, with a stability of 1.64 $pp10^{13}$. 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 space vehicle clocks as compared to the 1-day estimates. The 6-hour frequency stability estimates varied from less than 7.5 $pp10^{14}$ to 9.50 $pp10^{13}$. In Figures 9 to 12 are shown the 1-day monthly stability estimates for all of the active clocks in the constellation for the 12 months ending with September 2002. Figure 12 shows the stability of the Navstar 44 timing signal to have degraded beyond the specification of 6 $pp10^{14}$ after January 2002 and to continue to degrade.

FREQUENCY STABILITY PROFILE

In Figures 13 and 14 are shown the frequency stability profiles for all active clocks in the constellation and for the six Block IIR rubidium clocks respectively for sample times of 1 to 18 days for the 6 months ending 1 October 2002. The Navstar 27 timing signal originating with RAFS Serial No. 66 activated in June is the least stable in the constellation. The three most stable timing signals originated with the Block IIR RAFS on Navstars 41, 51, and 54 and showed stability estimates for a sample time of 1 day of less than 2 pp10^{14}. Figure 14 shows the stability profile for the Block IIR Navstar 44 timing signal to be the least stable of the six Block IIR timing signals. Its stability estimate of 7.2 pp10^{14}, for a sample time of 1 day, fails to meet the specification of 6 pp10^{14}.

BLOCK IIR RAFS LIFE TEST COMPARISON

Two flight-qualified Block IIR rubidium atomic frequency standards have been undergoing life tests in the NRL Precision Clock Evaluation Facility for more than 5 years. Serial No. 28 has suffered 79 breaks in the frequency of unexplained cause during that time. The cumulative effect of these breaks on the frequency of this clock is shown in Figure 15. The breaks were roughly repetitive until the large negative break occurred in August 2000. The effect of these breaks on the 1-day stability of the clock can best be appreciated by comparing the stability history, for the uncorrected data, in Figure 16 with that for the corrected data in Figure 17, which shows a stability almost an order of magnitude better—measurable predominantly in pp10^{15}. The stability profiles for the uncorrected and corrected data are shown on the same set of axes in Figure 18. The same analysis was done for Serial No. 30 and is shown in Figures 19 to 22. For the same period of time as Serial No. 28, Serial No. 30 experienced only 16 breaks in the frequency of unknown cause. Generally, the breaks were smaller and had minimal impact on the stability as evidenced by the comparison of the stability histories for the uncorrected and corrected data in Figures 20 and 21. The effect on the stability of the one break of –2.5 pp10^{13} in June 2002 is clearly seen in Figure 20. The stability profile in Figure 22 shows that the few breaks in frequency had no effect on the stability for sample times greater than about 43 days.

Figures 23 to 26 show the same analysis for the Block IIR Navstar 43 timing signal, which suffered 56 breaks in the frequency of unknown cause and six breaks in the phase of unknown cause. Most of the frequency breaks were very repetitive and of small amplitude so the effect on the stability was minimal, except for the one frequency break of –3.9 pp10^{13} that occurred on 16 May 2002. The effect of this and the three phase breaks of 9, 12, and 16 nanoseconds can be seen as spikes in the stability history in Figure 24. Both stability histories appear to average about 2 pp10^{14}, which is close to the measurement noise threshold. The stability profiles for both the uncorrected and corrected data appear in Figure 26, which shows the 1-day stability to be relatively unaffected by the breaks. Rather, it is the stability estimates for sample times of two to 50 days that are most affected.

Figure 27 compares the frequency stability profiles for the two Block IIR flight-candidate rubidium atomic frequency standards undergoing life testing in the laboratory with those for the six Block IIR on-orbit Navstar timing signals. As expected, the two flight-candidate clocks show the best stability at 1 day. But the long-term stability is better for the Navstar 43 and 51 timing signals. In all cases, breaks of unknown cause were removed. The facts that the stability estimates at 1 day for the two flight-candidate rubidium clocks in the laboratory are measurable in pp10^{15} and that the stability estimate at 1 day for the best of the on-orbit Block IIR timing signals was 1.3 pp10^{14} suggest the latter number to be the measurement noise floor for the on-orbit timing signals.

CONCLUSIONS

The 1-day frequency stability of all of the Navstar clocks in the GPS constellation, as of 1 October 2002, was better than 1.6 pp10^{13}. The best clock was the Navstar 54 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 clock, which has been continuously operated for more than 13 years. The oldest active rubidium clock in the constellation is the Navstar 43 Block IIR rubidium clock (Serial No. 6), which has been operated for more than 5 years. The average age of the 13 cesium clocks operating on 1 October 2002 was 7.3 years, compared to an average age of 2.7 years for the 15 rubidium clocks operating on 1 October 2002. The 29 deactivated cesium clocks had an average lifetime of 4.2 years, compared to 1.3 years for the deactivated rubidium clocks.

REFERENCES

[1] S. T. Hutsell, W. G. Reid, J. D. Crum, H. S. Mobbs, and J. A. Buisson, 1997, *"Operational Use of the Hadamard Variance in GPS,"* in Proceedings of the 28th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 3-5 December 1996, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 201–214.

[2] W. G. Reid, 2000, *"Multiple-Path Linked Common-View Time Transfer,"* in Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Dana Point, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 43-53.

[3] W. G. Reid, 1997, *"Continuous Observation of Navstar Clock Offset from the DoD Master Clock Using Linked Common View-Time Transfer,"* in Proceedings of the 28th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 3-5 December 1996, Dana Point, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 397-408.

[4] M. Epstein, and T. Dass, 2002, *"Management of Phase and Frequency for GPS IIR Satellites,"* in Proceedings of the 33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 November 2001, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 481-492.

[5] T. B. McCaskill, 1997, *"Analysis of the Frequency Stability History of GPS Navstar Clocks,"* in Proceedings of the 1997 IEEE International Frequency Control Symposium, 28–30 May 1997, Orlando, Florida, USA (IEEE Publication 97CH36016), pp. 295–303.

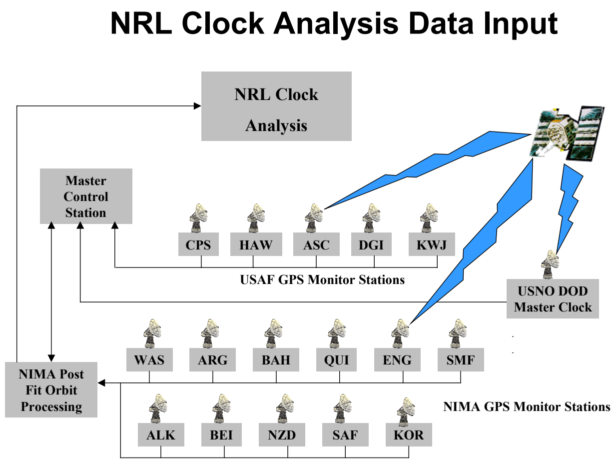


Figure 1.

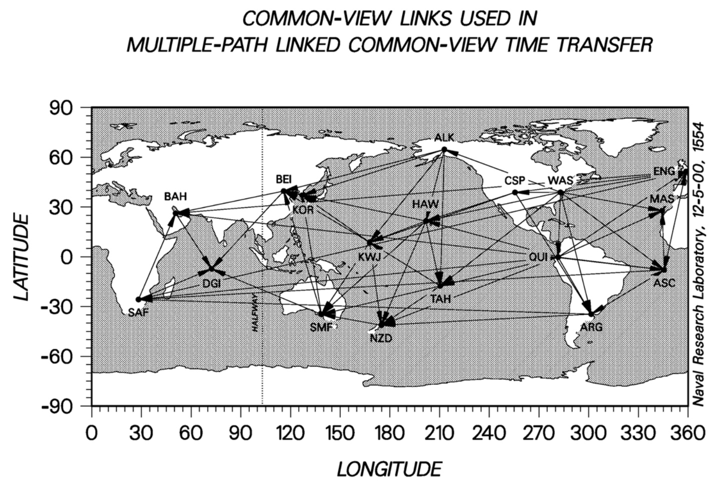


Figure 2.

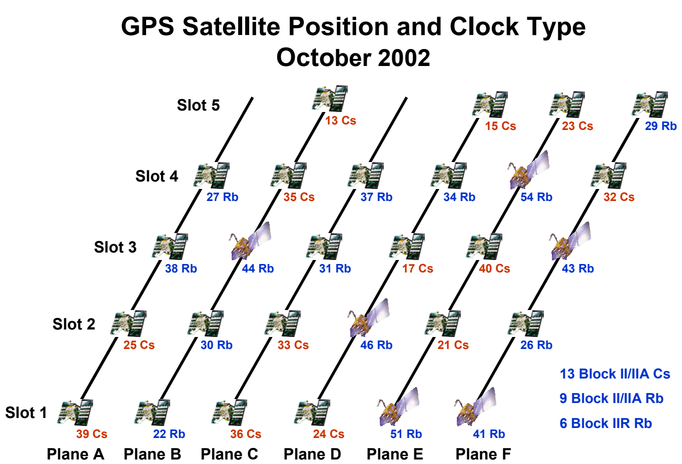


Figure 3.

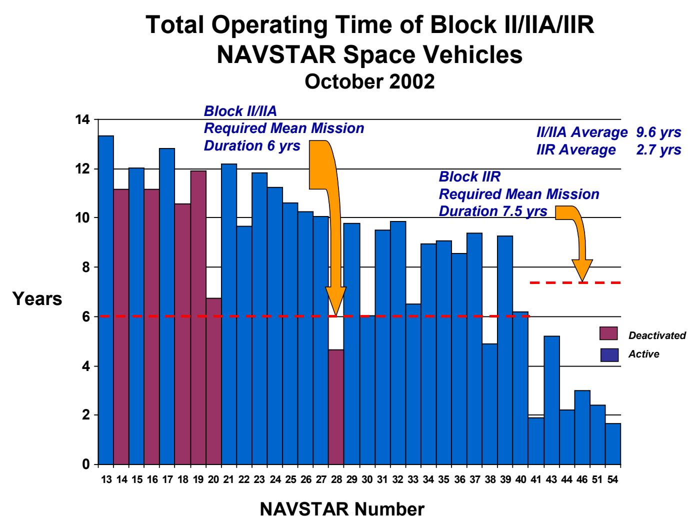


Figure 4.

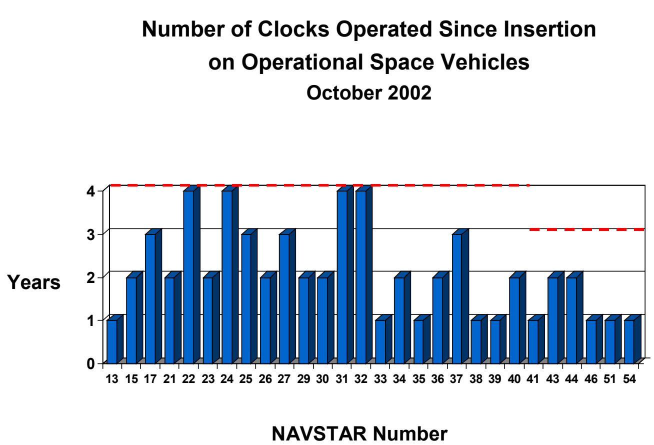


Figure 5.

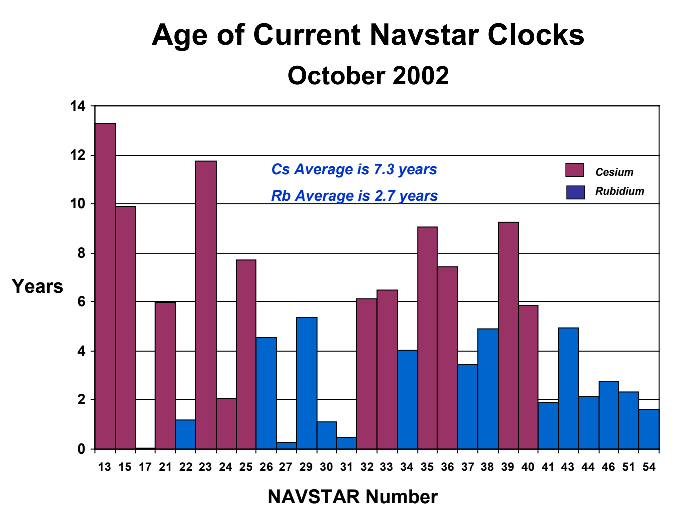


Figure 6.

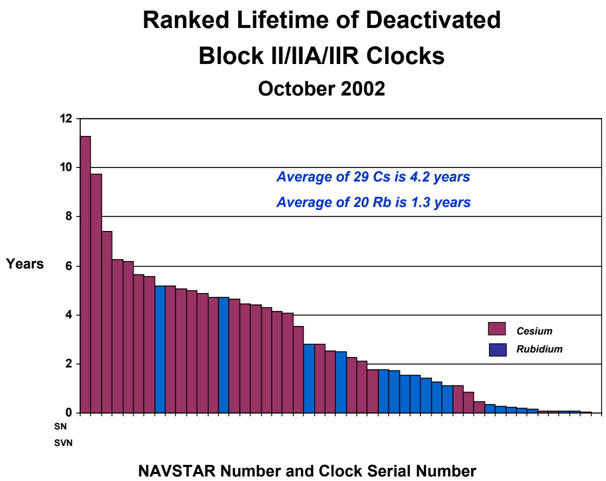
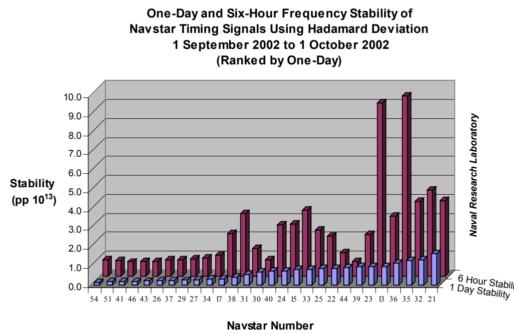


Figure 7.

GPS Timing Performance
Monthly Clock Stability Rankings



Navstar/Type/SN	1 Day Stability	6 Hour Stability
	(pp10^{13})	(pp 10^{13})
SVN 13 Cs 14	0.967	3.173
SVN 15 Cs 17	0.800	3.467
SVN 17 Rb 44	0.297	2.234
SVN 21 Cs 10	1.638	3.998
SVN 22 Rb 78	0.880	1.236
SVN 23 Cs 36	0.955	9.122
SVN 24 Cs 49	0.731	2.769
SVN 25 Cs 20	0.848	2.109
SVN 26 Rb 67	0.215	0.851
SVN 27 Rb 66	0.278	0.957
SVN 29 Rb 73	0.242	0.926
SVN 30 Rb 72	0.667	0.883
SVN 31 Rb 76	0.527	1.477
SVN 32 Cs 43	1.305	4.528
SVN 33 Cs 48	0.808	2.414
SVN 34 Rb 84	0.289	1.099
SVN 35 Cs 32	1.282	3.932
SVN 36 Cs 46	1.132	9.502
SVN 37 Rb 83	0.225	0.844
SVN 38 Rb 30	0.417	3.304
SVN 39 Cs 58	0.948	2.219
SVN 40 Cs 42	0.713	2.684
SVN 41 Rb 26	0.173	0.751
SVN 43 Rb 6	0.196	0.761
SVN 44 Rb 9	0.906	0.768
SVN 46 Rb 21	0.188	0.768
SVN 51 Rb 34	0.151	0.820
SVN 54 Rb 44	0.134	0.859

Figure 8.

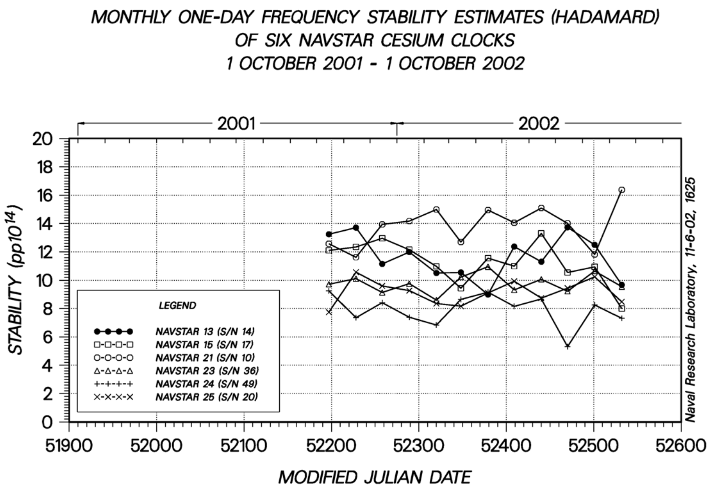


Figure 9.

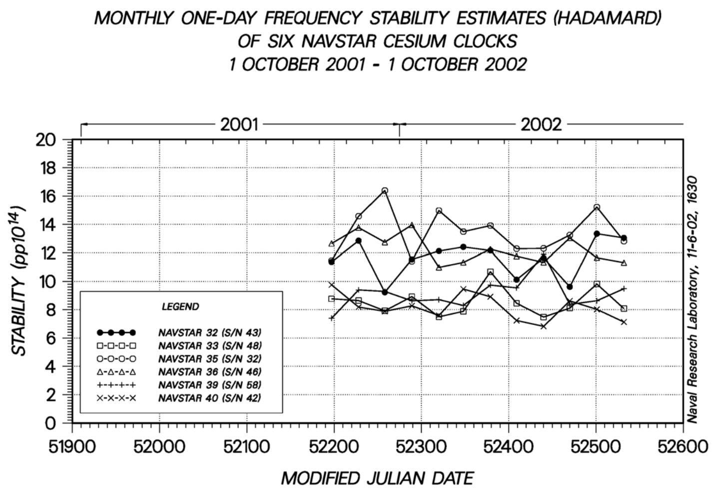


Figure 10.

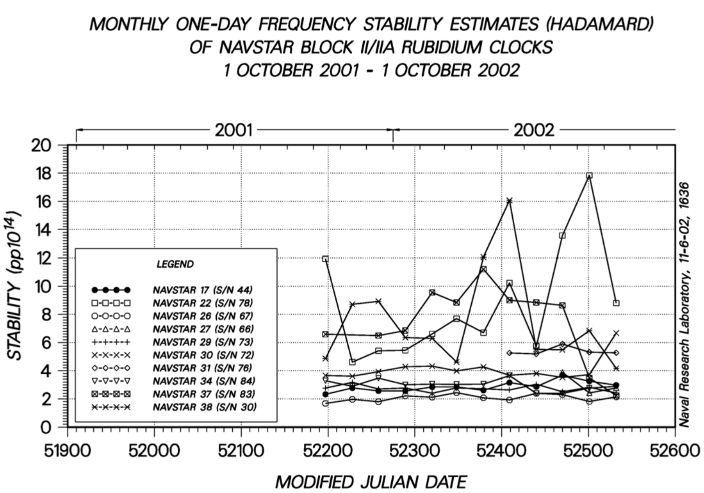


Figure 11.

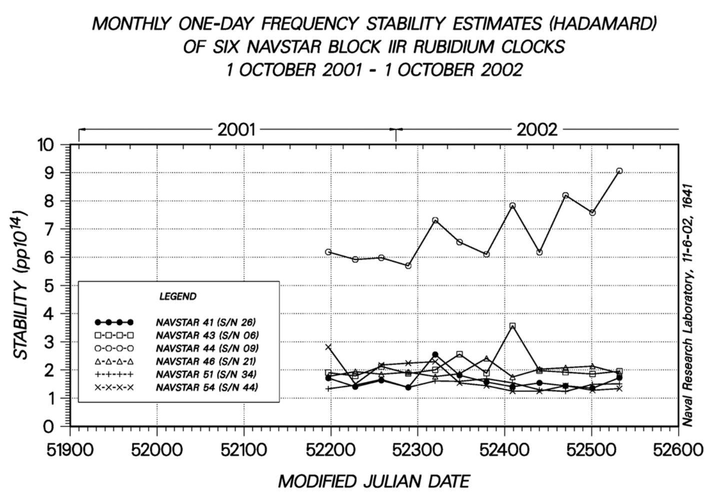


Figure 12.

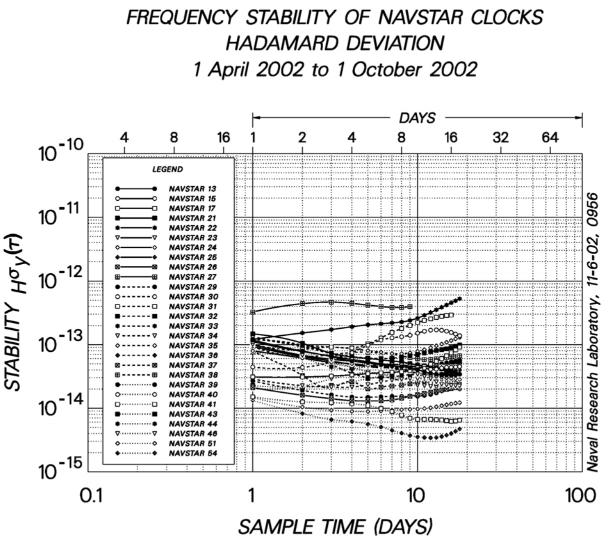


Figure 13.

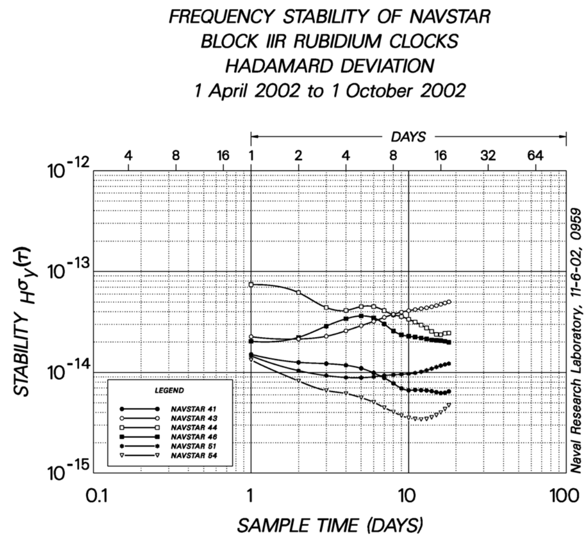


Figure 14.

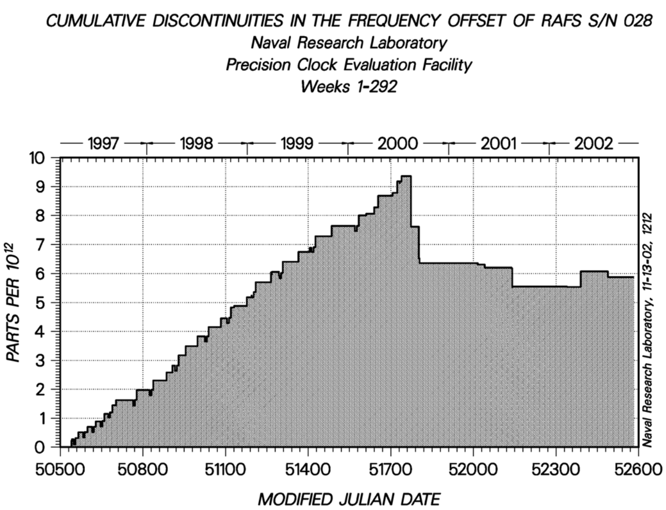


Figure 15.

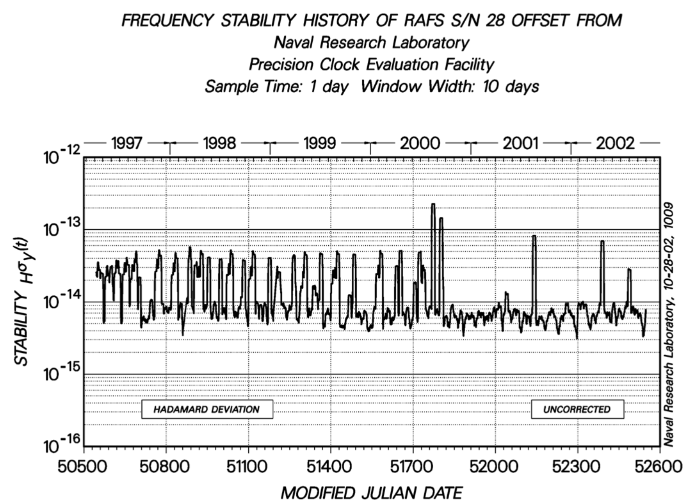


Figure 16.

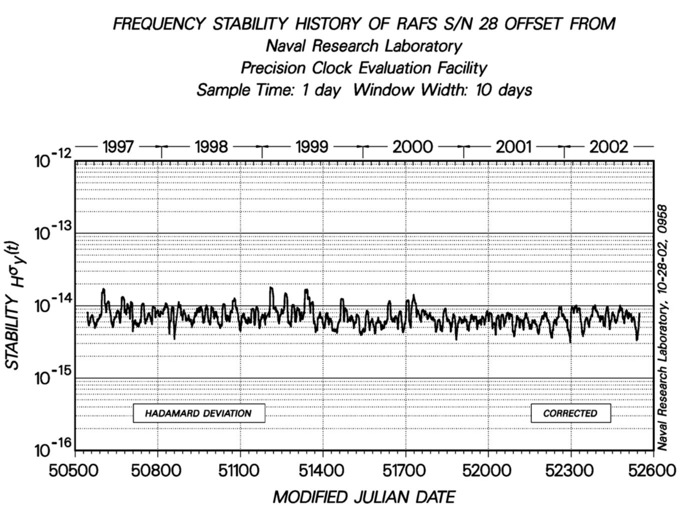


Figure 17.

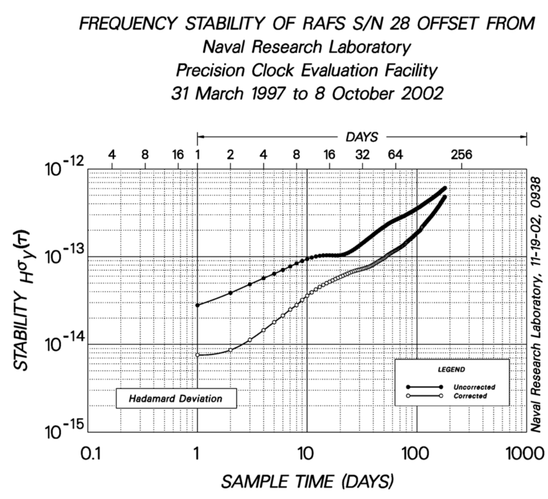


Figure 18.

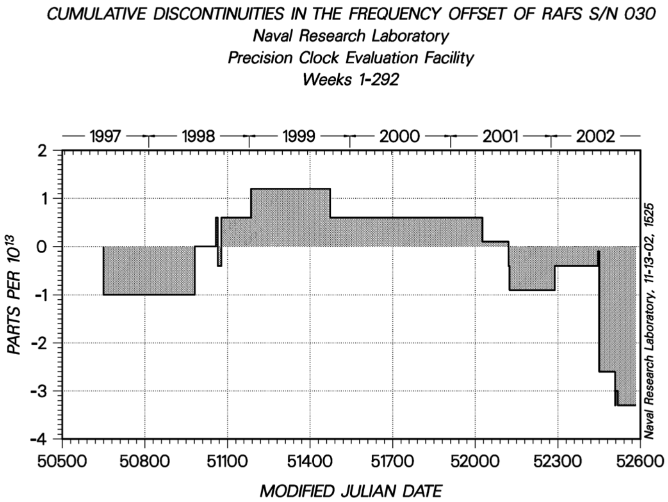


Figure 19.

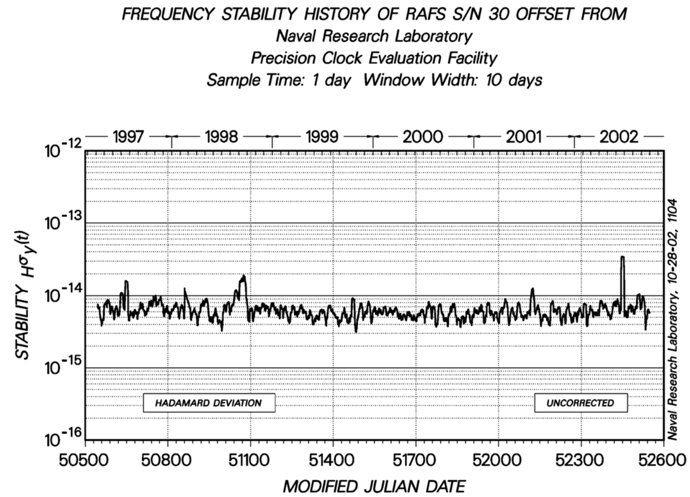


Figure 20.

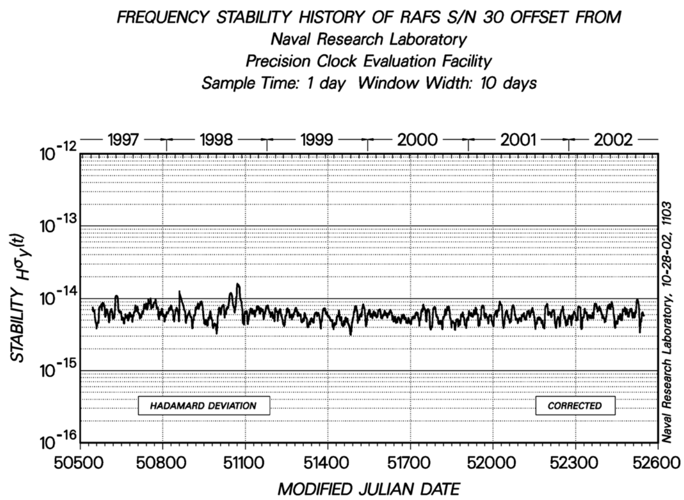


Figure 21.

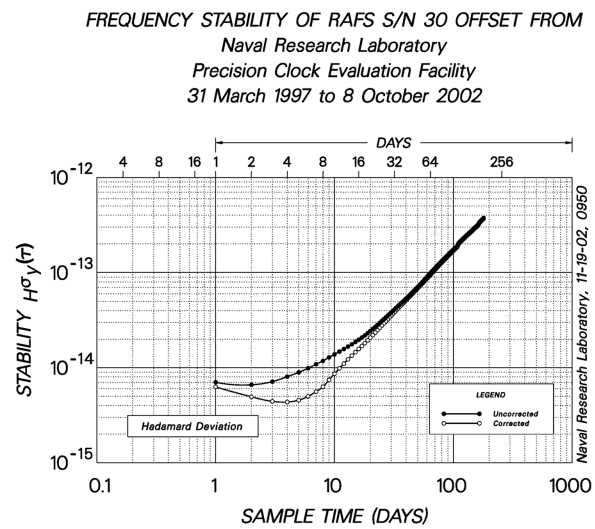


Figure 22.

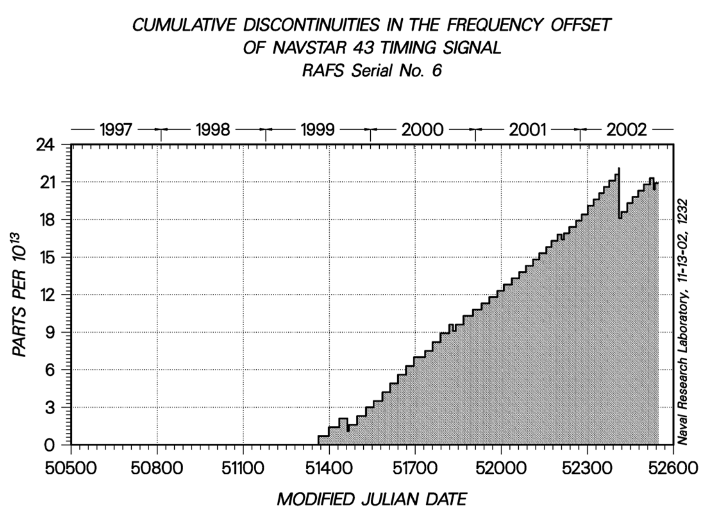


Figure 23.

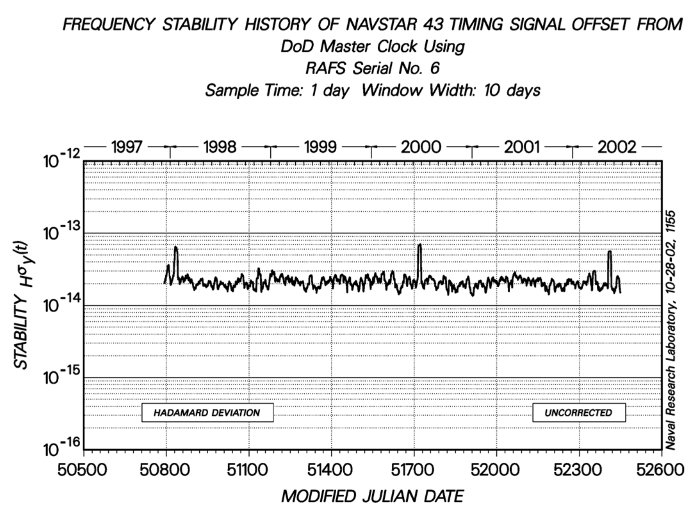


Figure 24.

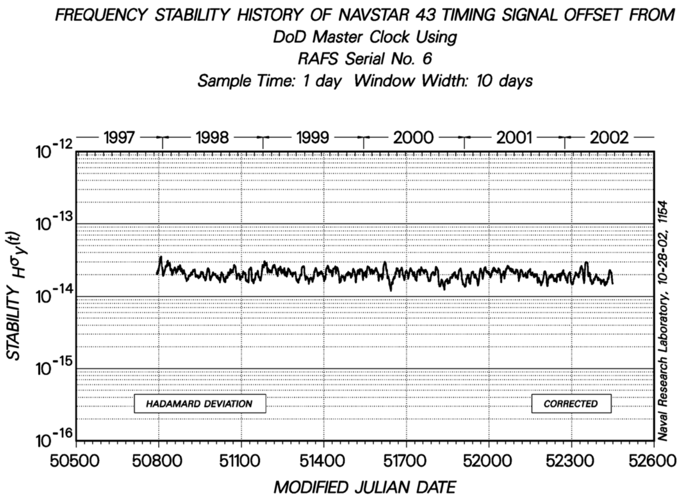


Figure 25.

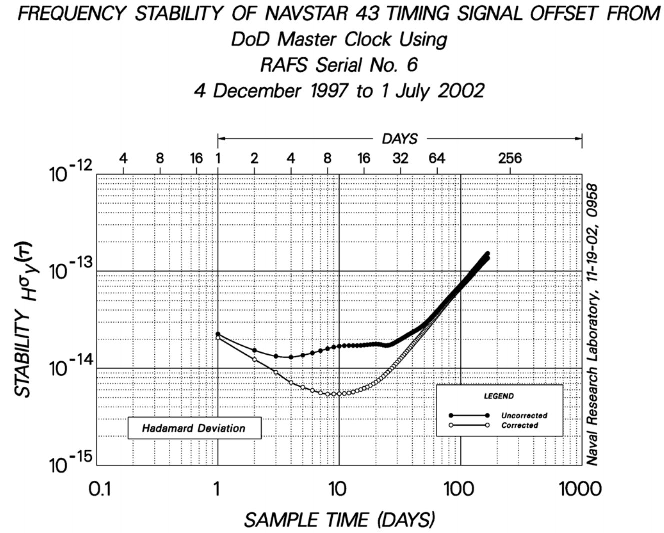


Figure 26.

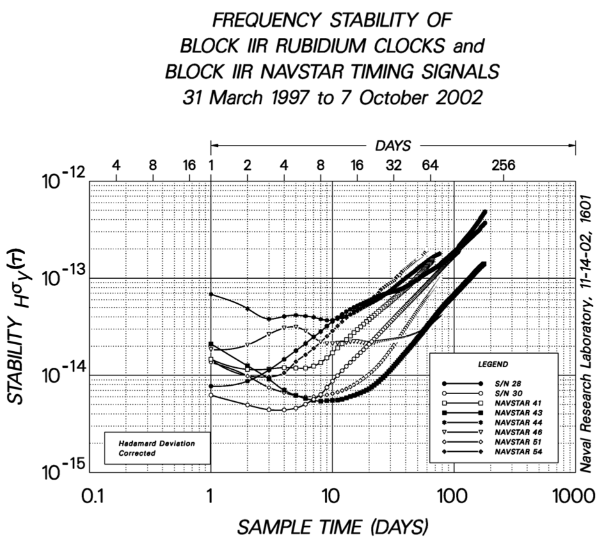


Figure 27.

QUESTIONS AND ANSWERS

JIM CAMPARO (The Aerospace Corporation): I know you said that, regarding those frequency breaks, you did not have any clear origin for them. Do you have any kind of best guess as to what might be going on?

JAY OAKS: No, we keep asking the clock guys, and we correlate the data with other information that we can get. At times, we found cesiums that correlate with temperature or the eclipse seasons, which correlates with temperature changes. With these, I do not think that there is any correlation, and we are just tracking the changes, hoping that somebody might come up with a solution.