PERFORMANCE OF GPS ON-ORBIT NAVSTAR FREQUENCY STANDARDS AND MONITOR STATION TIME REFERENCES

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Abstract

The U.S. Naval Research Laboratory (NRL) conducts comprehensive analyses of the Global Positioning System (GPS) atomic frequency standards under the sponsorship of the GPS Joint Program Office (JPO) and in cooperation with the 2nd Space Operations Squadron (2SOPS) at the Master Control Station (MCS) in Colorado Springs, Colorado. Included in the analysis are the on-orbit Navstar space vehicle clocks and the ground reference clocks at each of the five Air Force and seven National Imagery and Mapping Agency (NIMA) GPS monitor stations. A presentation will be made of the performance of the Navstar clocks currently operating in the constellation, which are characterized through the use of phase, frequency, drift and stability histories in addition to frequency stability profiles based on the Allan and Hadamard variances. Clock performance is analyzed using a multi-year database comprised of pseudorange measurements collected by each of the 12 GPS monitor stations. Results of these analyses are routinely used by the MCS in optimizing the q's in the Kalman filter.

Continuous 15-minute measurements of the phase offset of each monitor station time reference from the DoD Master Clock are obtained from Linked Common-View Time Transfer from DoD Master Clock, which is the reference clock at the NIMA Washington, D.C. monitor station. The method is extended to obtain continuous 15-minute measurements of the phase offset of each active Navstar space vehicle clock from the DoD Master Clock. Hence, the performance of all space and control segment clocks is referenced to the DoD Master Clock.

Discontinuities in the phase and frequency of the clocks are removed to yield the unperturbed performance of the clocks. The corrections, together with the probable cause of the discontinuity, are summarized. Examples of the frequency history and the exhaustive calculation, for every multiple of the sample period of 15 minutes from 15 minutes to 18 days, of the frequency stability profile for several Navstar space vehicle clocks and for the time reference at two of the GPS monitor stations will be presented. Analysis of the performance of the first on-orbit Block IIR operational rubidium clock will also be presented.

INTRODUCTION

The pseudorange measurements upon which this analysis is based were collected at the five Air Force and the seven National Imagery and Mapping Agency (NIMA) monitor stations using dual-frequency GPS receivers. *Figure 1* presents the information flow from a single Navstar space vehicle to each of the GPS monitor stations. The use of dual frequencies enabled ionospheric corrections to be based on the measured ionosphere. The pseudorange measurements were collected every six seconds synchronized to GPS time and smoothed to one point every 15 minutes. Clock offsets were computed using the NIMA post-processed ephemerides and observations that were collected at the 12 GPS monitor stations. All monitor station clock performance was computed using Linked Common-View Time Transfer from the NIMA Washington, D.C. site.

A key feature in the NRL Clock Analysis Software System (CLASS) is the capability to detect phase and frequency discontinuities, to solve for the discontinuity, and to correct the clock data. Correction of the data makes possible the analysis of long-term clock, system, and environmental effects[1]. The results of the analysis are included in NRL Quarterly Reports to the GPS Joint Program Office (JPO) and to the Master Control Station (MCS), as well as to other interested members of the scientific community.

Other measures of performance are determined, such as the total operating time for each operational Navstar space vehicle and the operating time for each Navstar clock. Included are histories of the phase, the frequency, and the frequency stability.

CONSTELLATION

The constellation as of 30 September 1998 is shown in *Figure 2*. This table shows by plane and by position in the plane each of the Block II/IIA/IIR Navstar space vehicles in the constellation and the type of clock that was operating. Of the active cesium clocks, Frequency & Time Systems, Inc. manufactured all but the Navstar 30 cesium clock. Kernco, Inc. manufactured the Navstar 30 cesium clock. All Block II/IIA rubidium clocks were manufactured by Rockwell, Inc. The Block IIR rubidium clock on Navstar 43 was manufactured by EG&G. Seven of the 27 clocks operating were rubidium, while twenty were cesium atomic frequency standards. Three of the six planes have four Navstars, while the other three planes contain five Navstar space vehicles (SV) each, although the SVs are not evenly spaced in the planes.

The total operating time for each of the Navstar space vehicles since the space vehicle was inserted into the constellation is presented in *Figure 3*. Thirteen of the space vehicles have been in operation for six years or more, which exceeds the mean mission duration specification.

The number of clocks that have been placed in operation on each space vehicle is presented in *Figure 4*. Eight of the space vehicles are operating the first clock, thirteen are operating the second clock, four are operating the third clock, and two are operating the last clock. Navstar 43 is operating its second clock, but one of the clocks was activated as a test and could be used again when needed.

NAVSTAR CLOCKS

The operating time or length of service, of the clocks that were operating as of 30 September 1998 is presented in *Figure 5*. The shaded bars correspond to the cesium clocks and the unshaded bars to the rubidium clocks. Nine clocks, all cesium frequency standards, have exceeded five years of continuous operation. Two clocks, both cesium frequency standards, have exceeded eight years of continuous operation. Two of the rubidium clocks have attained three years of continuous operation.

The operating times of Block II cesium and rubidium clocks respectively both active and deactivated clocks are presented in *Figures 6* and *7*. The data are presented in order of activation. The shaded bars correspond to the active clocks, while the open bars correspond to the deactivated clocks. The comparison shows that the Block II cesium clocks have an average operating time on-orbit of 3.7 years, while the rubidium clocks have an average operating time on-orbit of 1.3 years.

The one-day frequency offset history for the clocks in plane B of the GPS constellation as of 30 September 1998 is presented in *Figure 8*. NRL analyzes each clock in each plane in the constellation, but only plane B is presented for brevity. The history of the clocks in all planes is included in the NRL quarterly reports.

The two-day frequency drift for each of the clocks in the constellation, presented by *Figure 9*, shows that the rubidium clocks exhibit typically large drift rates, which are characteristic of rubidium frequency standards--the largest being Navstar 38 with a drift of $-5.0\ pp10^{13}$ per day. Six rubidium clocks exhibit negative drift, excluding the rubidium in Navstar 34, which was activated on September 14,1998 and did not have sufficient data to be included. *Figure 10* is a plot on an expanded scale of the two-day average drift of the cesium clocks. Ten of the cesium clocks exhibit a negative drift, while the other ten exhibit a positive drift. All but one of the cesium clocks exhibit a drift with a magnitude below $5\ pp10^{15}$ per day, which is two orders of magnitude less than the largest drift rate reported for the Block II rubidium clocks.

Figures 11 through *14* are examples of the frequency stability profile for four of the 27 Navstar clocks. *Figure 11* shows the stability of the Navstar 19 rubidium clock, which is typical of the performance of the rubidium clocks manufactured by Rockwell Corporation. *Figure 12* shows the effects of a 10-15 nanosecond oscillation at the orbital period in the phase offset of the Navstar 36 cesium clock manufactured by Frequency and Time Systems. The cause of these oscillations which affected a number of clocks has not been identified. *Figure 13* shows the performance of the best cesium clock in the constellation, the Navstar 30 alternate-source cesium clock manufactured by Kernco. The stability of this clock for a sample time of one day was estimated to be $7\ pp10^{14}$. *Figure 14* shows the performance of the best rubidium clock in the constellation, the Navstar 43 Block IIR clock manufactured by EG&G. The stability of this clock at one day was estimated to be near the noise threshold of the receiver at $2.4\ pp10^{14}$.

The frequency stability profile, made using the precise ephemerides, for the 27 clocks in the constellation that were operational on 30 September 1998 is presented in *Figure 15*. All but seven of the clocks are evenly distributed between $7\ pp10^{14}$ and $1.4\ pp10^{13}$ at one day. *Figures 16* and *17* show the ranking of the estimates of the frequency stability for a sample time of one day using the Allan and Hadamard deviations respectively. In *Figure 16*, three of the six rubidium clocks for which the stability was estimated rank last because of the large drift typical of rubidium clocks. In *Figure 17*, based on the Hadamard deviation which adaptively corrects for the drift [2], all six of the rubidium clocks rank before the cesium clocks with values of stability measured in $pp10^{14}$.

The frequency stability estimates for each of the Navstar clocks for a sample time of one day using the post-fit ephemeris are presented in *Figure 18*. Estimates of the frequency stability were made using the Allan deviation without any correction for aging. Superimposed on *Figure 18* are dashed lines corresponding to the GPS system specifications of 2 $pp10^{13}$ and 5 $pp10^{13}$ for the one-day stability of the cesium and rubidium clocks respectively. The frequency stability of all Block II space vehicle clocks can be seen to meet the specifications. Eleven of the Block II clocks--nine cesium frequency standards and two rubidium standards--show stability at or below 1 $pp10^{13}$.

TIME TRANSFER

Linked Common-View Time Transfer is a special case of GPS time transfer [3], which uses simultaneous measurements by two users of a Navstar space vehicle clock when the space vehicle is in view of both users. Each of the two users computes his clock offset with respect to the Navstar clock at the same epoch. Then, the difference between their respective clock offsets with respect to the Navstar clock yields the offset between the two user clocks. This procedure results in a measurement which is independent of the Navstar clock, but which retains the difference in the measurement errors.

The precision of a single common-view time transfer measurement was first demonstrated using common-view time transfer measurements taken over a 20-day time span with a single space vehicle. Recently, the precision of the common-view time transfer measurement was definitively determined through the use of multiple common-view measurements taken at the same epoch [4]. This process was made possible with the full constellation of GPS space vehicles. The estimated precision of a single 15-minute interval has been determined to be between 1.4 and 2.7 nanoseconds. Using the measurements from all Navstar space vehicles in common-view during the 15-minute interval, typically 3-7 space vehicles, improves the estimate of the precision of the time transfer measurement to between 0.65 and 1.13 nanoseconds. This level of measurement precision results in the capability to determine the frequency stability of a remote clock (with respect to the DoD Master Clock) anywhere on Earth to within 2 $pp10^{12}$ for a 15-minute sample time and 2 $pp10^{14}$ for a one-day sample time.

A Linked Common-View Time Transfer measurement results by linking two or more remote sites that are in common-view with either the same or another Navstar space vehicle. The precision of the Linked Common-View measurements can be estimated by considering the special case of the sum of stationary random variables with mean zero and standard deviation equal to the precision of a single common-view time transfer measurement. It is expected that the precision of the Linked Common-View Time Transfer will grow as the square root of the number of links multiplied by the precision of a single common-view measurement. However, in the analysis of the stability of a remote clock, it is possible that other factors such as the quality of the receiver and short-term environmental effects could have a greater influence on the precision of the measurements than the effect of multiple links.

MONITOR STATION CLOCKS

Figures 19 and 20 show the one-day average frequency offset six-month history of the ground reference clocks from the DoD Master Clock for the Air Force and NIMA GPS ground tracking stations respectively. These results were obtained using Linked Common-View Time Transfer[4]. The performance of the ground reference clock at the Colorado Springs Monitor Station is superior. It is the Alternate Master Clock #1 which is a hydrogen maser steered to UTC (USNO) by two-way satellite time transfer [5]. The performance of the ground reference clocks at the remaining four Air Force stations, which are equipped with HP5061 cesium beam tubes, has more noise than that of the ground reference clocks at the NIMA MS, which are equipped with HP5071 high performance cesium-beam tubes. The superior performance of the Colorado Springs monitor station time reference can be seen in the frequency stability profile in *Figure 21*, where its performance is dominated by white phase noise as far out as the profile was estimated, i.e. 18 days. On the other hand, the best NIMA time reference was at the Quito, Ecuador monitor station (Figure *22*), which shows a flicker floor of 1 $pp10^{14}$ being achieved at about five days. This station had the lowest short-term noise of all the monitor stations, whereas the Colorado Springs monitor station had the highest. In addition, the time reference for the Colorado Springs monitor station showed a cyclic component at the fourth harmonic of the orbital period (2.99 hours). The cause of this cyclic component has not been determined. The performance of the time reference at each of the ten monitor stations is compared in *Figure 23*, which presents the frequency stability profile for sample times of one to 18 days. The Colorado Springs monitor station is clearly superior, followed by the five NIMA monitor stations, and finally by the remaining four Air Force monitor stations.

CONCLUSIONS

Thirteen of the Block II space vehicles have been in operation for six years or more and have exceeded the expected mean mission duration. An average of two Block II Navstar clocks per space vehicle has been activated. Twenty-one of the space vehicles have at least two spare clocks available to complete the design lifetime. Fourteen Navstar clocks--more than one-half of the operational constellation--are performing with an estimated one-day frequency stability of 1 $pp10^{13}$ using the precise ephemerides and based on the Hadamard deviation. The time reference at each of the GPS monitor stations exhibited a frequency stability for a sample time of one day of between 3 $pp10^{14}$ to 4.2 $pp10^{14}$.

REFERENCES

[1] McCaskill, T. B., Reid, W.G., Oaks, O.J., Beard, R.L., U.S. Naval Research Laboratory, and Buisson, J. A. and Warren, H. E., SFA, ``Performance of Global Positioning System (GPS) On-orbit Navstar Clocks," 1995 IEEE International Frequency Control Symposium}, 31 May--2 June 1995, pp133--139.

[2] Hutsell, Steven H., ``Relating The Hadamard Variance to MCS Kalman Filter Clock Estimation" Proceedings of the 27th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting}, 29 November—1 December 1995, pp291--301.

[3] Buisson, J. A., McCaskill, T. B., Smith, H., Morgan, P., and Woodger, J., ``Precise Worldwide Station Synchronization via the Navstar GPS Navigation Technology Satellite (NTS-1)", Proc. 8th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, November 30 -- December 2, 1976, Washington, D.C., pp.55--84.

[4] Reid, W.G., McCaskill, T. B., and Oaks, O.J., U.S. Naval Research Laboratory, and Buisson, J. A. and Warren, H.E., Sachs Freeman Associates Incorporated, ``Common View Time Transfer Using Worldwide GPS and DMA Monitor Stations", Proceedings of the 27th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, November 29---1 December 1995, pp145--158.

[5] Breakiron, Lee A., ``Frequency Steering of Hydrogen Masers", Proceedings of the 50th Frequency Control Symposium, 5 June 1996.

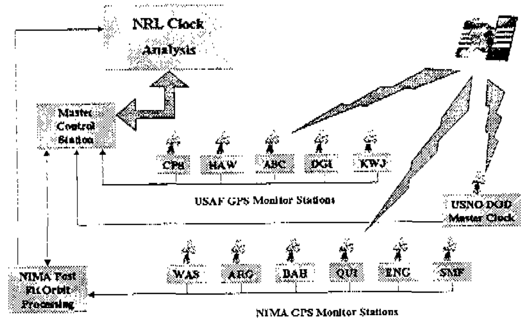

Figure 1. Clock Analysis Data Flow

Plane	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5
A	39	25	27	19	38
B	22	30	13	35	
C	36	33	31	37	
D	24	15	17	34	
E	14	21	16	23	40
F	32	26	18	29	43

Cesium Clock

Rubidium Clock

Figure 2. GPS Constellation Space Vehicle Location and Clock Type
30 September 1998

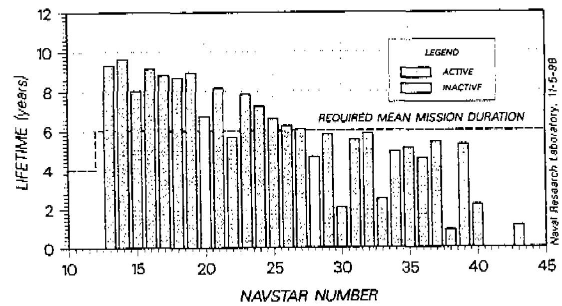

Figure 3. Total Operating Time of Current Navstar Satellites
30 September 1998

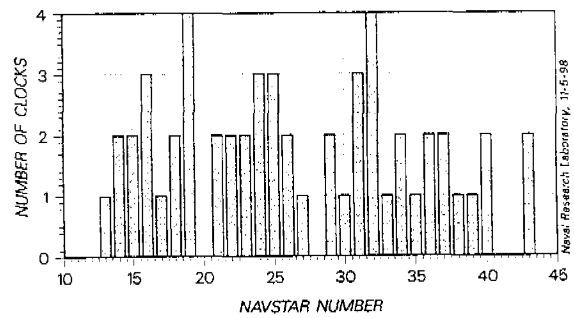

Figure 4. Number of Clocks Operated Since Insertion
30 September 1998

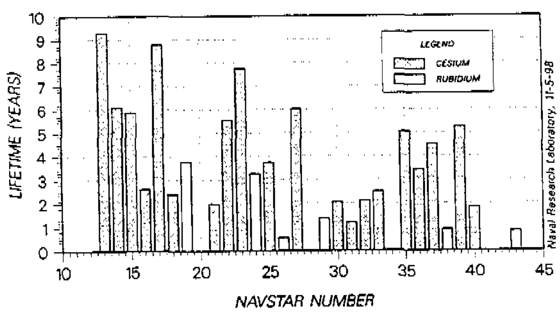

Figure 5. Operating Lifetime of Current Clocks
30 September 1998

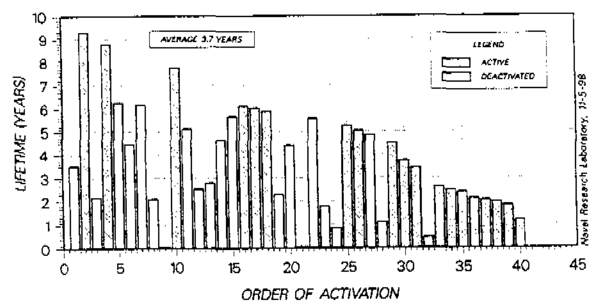

Figure 6. Lifetime of Block II and IIA Cesium Clocks in Order of Activation
30 September 1998

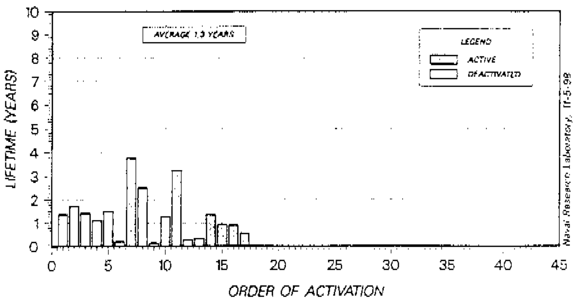

Figure 7. Lifetime of Block II, IIA, and IIR Rubidium Clocks in Order of Activation
30 September 1998

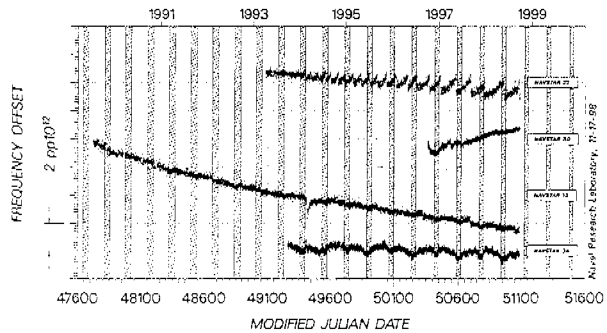

Figure 8. One-Day Frequency Offset History of Navstar Clocks from DoD Master Clock
Plane B

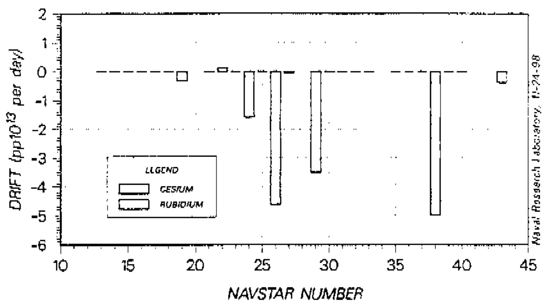

Figure 9. Two-Day Average Frequency Drift of Current Clocks
1 June 1998 to 30 September 1998

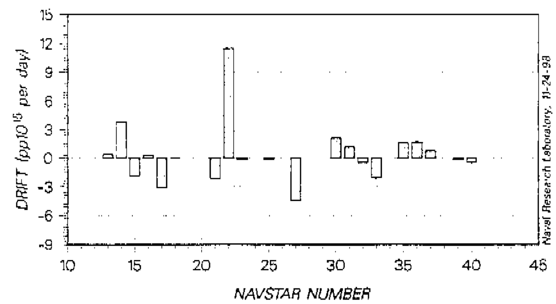

Figure 10. Two-Day Average Frequency Drift of Cesium Clocks
1 June 1998 to 30 September 1998

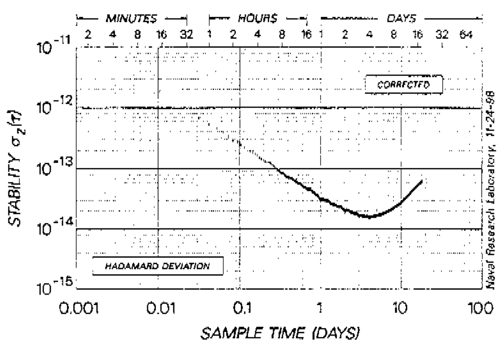

Figure 11. Frequency Stability of Navstar 19 Rubidium Oscillator (No. 53)
1 April 1998 to 1 October 1998

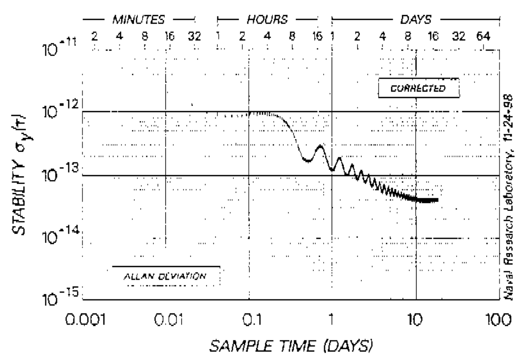

Figure 12. Frequency Stability of Navstar 36 Cesium Oscillator (No. 46)
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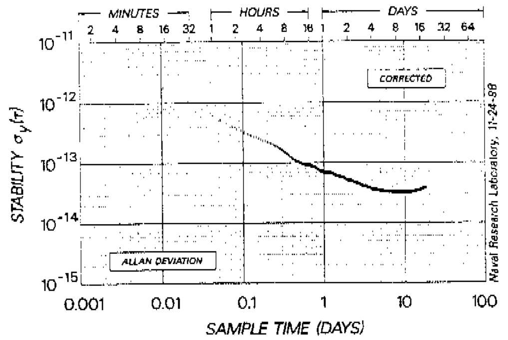

Figure 13. Frequency Stability of Navstar 30 Cesium Oscillator (No. K3)
1 April 1998 to 1 October 1998

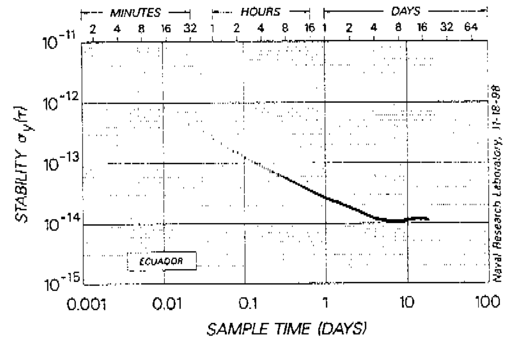

Figure 14. Frequency Stability of Navstar 43 Rubidium Oscillator (No. 06)
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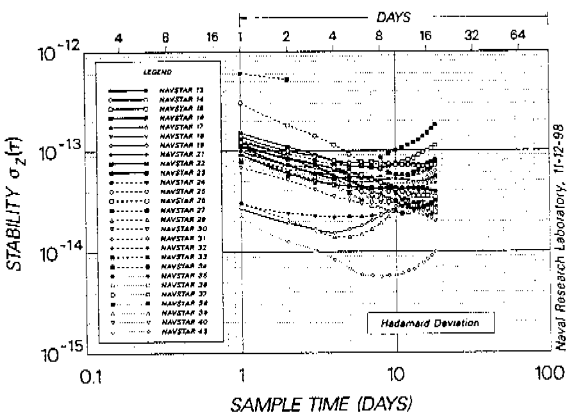

Figure 15. Frequency Stability of Navstar Clocks
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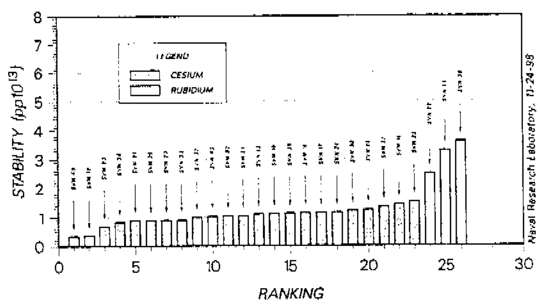

Figure 16. Ranking of One-Day Frequency Stability Estimates of Navstar Space Vehicle Clocks Using Allan Deviation
1 June 1998 to 30 September 1998

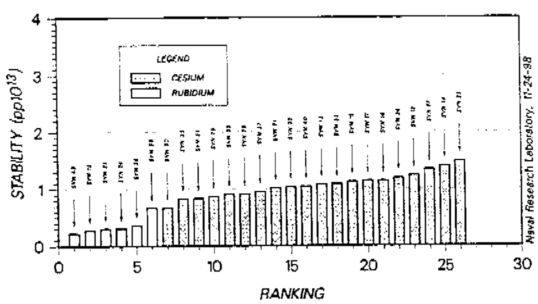

Figure 17. Ranking of One-Day Frequency Stability Estimates of Navstar Space Vehicle Clocks Using Hadamard Deviation
1 June 1998 to 30 September 1998

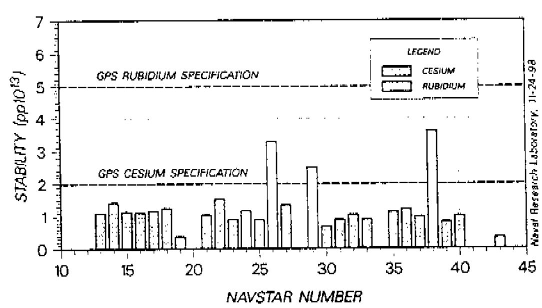

Figure 18. One-Day Frequency Stability Estimates of Navstar Space Vehicle Clocks Using Allan Deviation
1 June 1998 to 30 September 1998

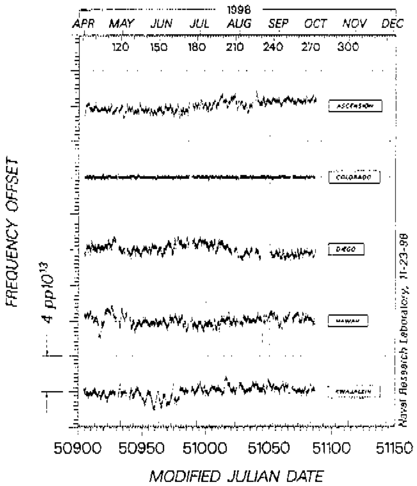

Figure 19. Frequency Offset of Air Force Monitor Station Time Reference from DoD Master Clock

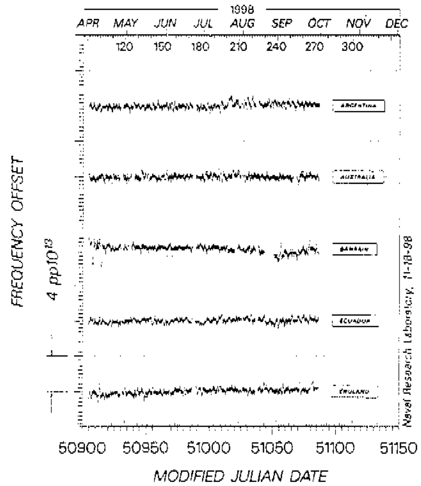

Figure 20. Frequency Offset of NIMA Monitor Station Time Reference from DoD Master Clock

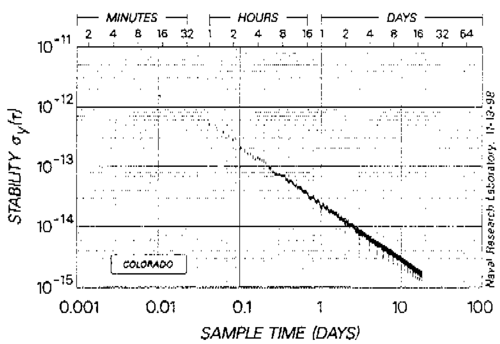

Figure 21. Frequency Stability of Monitor Station Time Reference with Respect to DoD Master Clock via Common-View Time Transfer
1 April 1998 to 1 October 1998

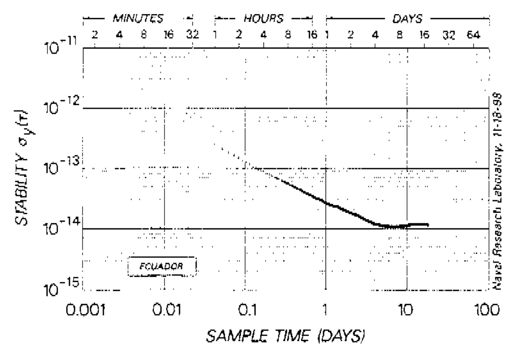

Figure 22. Frequency Stability of Monitor Station Time Reference with Respect to DoD Master Clock via Linked Common-View Time Transfer
1 April 1998 to 1 October 1998

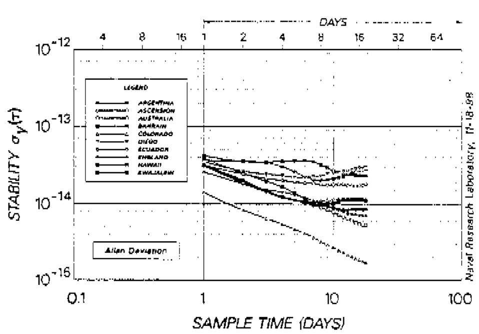

Figure 23. Frequency Stability Profile Comparison of Time References with Respect to DoD Master Clock via Linked Common-View Time Transfer
1 April 1998 to 1 October 1998

Questions and Answers

DENNIS McCARTHY (USNO): To what extent does the quality of the orbits that you are using affect the analysis of the satellite clocks?

JAY OAKS (NRL): This sounds like a loaded question? Obviously, it plays an important part. That is why we use the NIMA precise orbit, which is reported to be accurate within centimeters. What we see here is mostly dominated by the clock, but there are some anomalies that we investigate, like the orbit where it might be showing up.

SIGFRIDO LESCHIUTTA (IEN): Could you please show us one of the last vugraphs concerning the behavior of the USNO clock monitor station frequency stability profile?

JAY OAKS: Was it the monitor station clock frequency?

SIGFRIDO LESCHIUTTA: Yes.

JAY OAKS: This one? We have one like this for the monitor station frequency stability profile, one for monitor station clocks, and one for the space vehicle clocks.

SIGFRIDO LESCHIUTTA: The one concerning your two-way link.

JAY OAKS: That was this. What I had said is that the Colorado Alternate Master Clock, which is shown here, is a hydrogen maser steered using measurements made once an hour using two-way satellite time transfer measurements between the Naval Observatory and the Colorado Station. That is Steven Hutsell's algorithm and if you have some questions about that, he would probably be happy to answer them. Is that what you were asking?

SIGFRIDO LESCHIUTTA: Yes.