A SUMMARY OF THE GPS CONSTELLATION CLOCK PERFORMANCE

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Abstract

The Naval Research Laboratory (NRL) conducts comprehensive analyses of the Global Positioning System (GPS) atomic frequency standards under the sponsorship of the 2nd Space Operations Squadron (2SOPS) at the Master Control Station (MCS) in Colorado Springs, Colorado. The analysis is based on clock estimates that NRL computes from GPS monitor station carrier-derived pseudo-range measurements and National Geospatial-Intelligence Agency (NGA) computed precise post-fit orbit ephemerides. The purpose of the analyses is to determine the performance of the timing signals originating from the atomic frequency standards onboard the space vehicles. Metrics used in the analyses include frequency, drift, stability profiles, and stability histories based on the Allan and Hadamard variances. The relative performance of the space vehicle clocks is ranked and presented according to the clock types flown in GPS. An overview of the GPS constellation with respect to the lifetimes of space vehicles and space vehicle clocks, both active and deactivated, is also presented.

INTRODUCTION

Performance of the Navstar space vehicle clocks is continuously analyzed and evaluated by NRL using a multi-year database that includes data collected from June 1995 to the present. This work is sponsored by the U.S. Air Force 2nd Space Operations Squadron (2SOPS) and supports operations of the GPS Master Control Station at Schriever AFB in Colorado Springs, CO. The measurements are collected from a network of ground monitor stations operated by the U.S. Air Force and the National Geospatial-Intelligence Agency (NGA). Clock estimates are computed for all Navstar and monitor station clocks and are referenced to the U.S. Naval Observatory (USNO) DOD Master Clock in Washington, D.C. 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 are also reported to the GPS Frequency Standards Working Group (FSWG), archived, and made available to FSWG members on an NRL Web site.

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CONSTELLATION OVERVIEW

The operational Navstar space vehicles in the GPS constellation as of 20 November 2007 are shown in Figure 1. The figure depicts satellite position, satellite type, and the type of clock being operated on each Navstar. The most recent constellation changes are also denoted, which include the new launch of SVN 55, two Navstar clock switches on SVN 37 and SVN 40, the repositioning of SVN 26 to make room for the new launch, and the reactivation of SVN 23 after three and a half years of being deactivated. The current constellation consists of 31 Navstar satellites operating 7 Block IIA Cs clocks, 8 Block IIA Rb clocks, 12 Block IIR Rb clocks, and 4 Block IIR-M Rb clocks. The total operating time or age of each Navstar Block II, IIA, IIR, and IIR-M satellite is shown in Figure 2. Of the 28 Block II and IIA space vehicles, there are 15 Block IIA space vehicles still operating with an average age of 14 years, and all but one of the deactivated Block II and IIA space vehicles met the required mean mission duration of 6 years. The average age of the 16 Block IIR and IIR-M satellites is 4.7 years, with a required mean mission duration of seven and a half years. None of these newer types of satellites have been deactivated. Figure 3 summarizes the number of clocks operated versus the total number of clocks available on each operational Navstar. The Block IIA satellites each carry four clocks, two Cs and two Rb. The Block IIR and IIR-M satellites each carry three Rb clocks. Eleven of the Block IIA satellites are on their last clock and four others still have additional clocks to operate. All but two of the 16 Block IIR and IIR-M have used only one clock. The operating history of clocks is shown for each operational Navstar in Figures 4-9. Each figure contains the space vehicles according to plane. A quick snapshot of the frequency standards operated over the life of each space vehicle can be easily seen as in Figure 8, where the Rb clock of SVN 23 was returned to operation in mid-2007 after it was initially operated for only a short period of time in early 2004 before the spacecraft was deactivated.

In assessing the lifetime of atomic clocks on-orbit, the operating time of each clock can be observed. Figure 10 shows the operating times or age of the current active clocks on-orbit for the seven Block IIA Cs clocks with an average age of 4.1 years, the eight Block IIA Rb with an average age of 3.9 years, and the sixteen Block IIR and IIR-M Rb clocks with an average age of 4.6 years. Figures 11 and 12 show the operating times of deactivated Block II/IIA Cs and Block II/IIA Rb clocks respectively. From these data, an indication of clock lifetime can be inferred, with the Block II/IIA Cs clocks averaging 5.4 years and the Block II/IIA Rb clocks averaging 1.8 years. A look at the distribution of data, however, shows the Block II/IIA Cs clock age to be closely linearly distributed, while the Block II/IIA Rb clock age is more exponentially distributed. Other analysis within the community has shown the short lifetimes of Block II/IIA Rb clocks to be correlated with long storage times on-orbit before activation. A more rigorous statistical analysis of the data distribution may be performed in the future in order to predict a more accurate lifetime of these types of clocks.

ANALYSIS METHODOLOGY

Figure 13 shows the data flow and processes used to derive the clock estimates that are the basis for this analysis. Measurements are made from each Navstar by each of the monitor stations shown in the ground network, which consists of six USAF, eleven NGA, and two IGS monitor stations. These data are processed by NGA to provide post-fit precise GPS satellite ephemerides and corrected smoothed pseudo-range measurements at continuous 15-minute epochs. The offset of each Navstar clock relative to the monitor station clocks are then determined at NRL by computing the theoretical signal path delay and subtracting the smoothed observed pseudo-range measurements. Finally, an optimal linear least-squares solution to the set of network equations is determined to provide Navstar clock phase estimates with respect to the USNO DoD Master Clock at the Washington (WAS) monitor station **[2]**. These phase estimates are used to compute frequency, drift, frequency stability, and frequency stability history of Navstar clocks presented in this analysis.

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 output signal from the atomic frequency standard is fed to the Frequency Standard Distribution Unit (FSDU) for the Block II/IIA space vehicles and to the Time Keeping System (TKS) for the Block IIR/IIR-M space vehicles. The TKS provides the additional capability of adjusting the frequency and drift of the timing signal. Where this capability has been employed, the offset of the frequency from the DoD Master Clock has been adjusted to less than 3 pp10^{12}, and the drift has been adjusted to less than 2 pp10^{14}/day.

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 typically 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 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 of the dominance of measurement noise at the shorter sample times, the estimates of stability for these sample times are characteristic more of the noise than of the timing signal. Since 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 **[3]**. 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 specified sample time, window width, and time span. The sample times of interest are usually 6 hours and 1 day, and the window width is chosen to insure sufficient averaging to achieve confidence in the estimates. The time spans may be over months or years, depending on the type of analysis being performed. In all cases, discontinuities in the data for which the cause is unknown are left uncorrected.

FREQUENCY STABILITY PROFILE

Frequency stability profiles were computed for sample times of 15 minutes to 18 days for the 6 months ending 1 October 2007. In Figures 14 and 15, the frequency stability profiles shown are the Allan and Hadamard deviations respectively for all clocks in the constellation that were active as of 1 October 2007 and color coded according to clock type. In the Allan deviation of Figure 14, the estimates of stability for a sample time of 18 days can be seen to fall into two groups. Because of the dominance of the drift in the timing signals originating with the Block II/IIA rubidium clocks, the stability estimates of these timing signals for a sample time of 18 days all fall above 4 pp10^{13}. By contrast, the stability estimates for the timing signals originating with the Block II/IIA cesium clocks and the Block IIR rubidium clocks all fall below 2 pp10^{13}. With the removal of the drift inherent in the computation of the Hadamard deviation shown in Figure 15, the stability estimates at a sample time of 18 days for all timing signals showed improvement. The improvement was the greatest for the timing signals originating with the Block II/IIA rubidium clocks. The most stable timing signals can be seen to be those originating with the Block IIR rubidium clocks. Behavior of the different clock types is more easily seen in Figures 16-18, which show the Hadamard deviation from 15 minutes to 18 days according to clock type, Block IIA Cs, Block IIA Rb, and Block IIR/IIR-M respectively. Stability profiles in Figure 16 of the Block IIA Cs clocks are tightly grouped, exhibiting Hadamard variances of 8 pp10^{14} at a sample time of 1 day except for that of SVN 32, which has a Hadamard variance of 1-2 pp10^{13} at a sample time of 1 day. In Figure 17, the better performing block IIA Rb clocks show Hadamard variances of 2-3 pp10^{14} at a sample time of 1 day, except for those of SVN 37 and SVN 40, which are newly activated clocks that are exhibiting transient turn-on behavior. The best are the block IIR/IIR-M Rb clocks in Figure 18, with most showing Hadamard variances of 1-2 pp10^{14} at a sample time of 1 day and the four lesser performing clocks having Hadamard variances of 3-8 pp10^{14} at a sample time of 1 day. Figure 19 presents Hadamard variances of all active clocks using data for the month of September 2007 at sample times of 6 hours and 1 day and ordered according to the 1-day Hadamard variance. The 6-hour Hadamard variances show effects in clock behavior that are not seen in the 1-day sample times because of aliasing in the data.

RELATIVE FREQUENCY PERFORMANCE

Linear residuals of the 1-day averaged frequency offset are shown in Figures 20-25 for all active Navstar clocks, and each figure is according to the satellite plane for a period of 6 months of data. These figures are presented with the consistent scale of 1 pp10^{12} frequency offset and provide a quick look at relative frequency performance among the clocks. The magnitude of frequency noise is larger in the Block IIA Cs clocks, which also exhibit a constant frequency characteristic over the 6-month period. A significant drift component can be seen in the frequency characteristics in the Block IIA Rb clocks of SVN 25, SVN 35, and SVN 36. The transient turn-on behavior is evident in the newly activated Block IIA Rb clocks of SVN 37 and SVN 40. A higher magnitude of frequency noise can be seen in data of the SVN 44 clock and frequency jumps can be seen in that of the SVN 47 clock. These are both the lesser performing of the Block IIR Rb clocks. All of the best clocks exhibit a low frequency noise component and show a constant frequency for the period of data. These consist of most of the Block IIR/IIR-M Rb clocks in the constellation.

FREQUENCY STABILITY HISTORY

Allan and Hadamard variances are computed with a sample time of 1 day, averaged over a sliding 10-day period, and presented for the entire operating lifetime of the Navstar clocks. These frequency stability histories allow for the examination of nonstationary behavior in the clocks. The eclipse seasons of the space vehicles are also shown as shaded area, which have sometimes correlated with clock anomalistic behavior. Some examples are given in Figures 26-33. Data of the oldest active clock in the constellation, the Block IIA Cs of SVN 32, are shown in Figure 26. The averaged 1-day Allan variance has been consistently better than the specification of 2 pp10^{13} for more than 10 years. As shown in Figure 27, the Block IIR Rb clock of SVN 41 exhibited Hadamard variances that were worse than the specification of 6 pp10^{14} on several occasions from 2001 to 2003 and, since then, has performed consistently better than the specification. Figure 28 shows the consistently worse than specification of the Hadamard variance in the Block IIR Rb on SVN 44. The Block IIA Rb on SVN 45 is seen to be out of specification in Figure 29 for a short period of time early after activation and then improves and shows a consistent Hadamard deviation of 1-2 pp10^{14} over the last 2 years of operation. One of the best clocks, the Block IIR Rb on SVN 51, is shown to have a well-behaved Hadamard variance of 1-2 pp10^{14} for the entire 7 years of operation. Three of the most recently activated Block IIR-M clocks on SVN 52, SVN 53, and SVN 58 have Hadamard deviations within specification, as shown in Figures 31-33 with that of SVN 58 close to 1 pp10^{14} after a short period of transient turn-on behavior. Finally, Figures 34 and 35 summarize the Allan and Hadamard deviation performance of all the Navstar clocks in the constellation for the 6-month period of April through October 2007, where all of the respective clock types are shown to be within specification, with exception of the clock on SVN 44.

CONCLUSIONS

The lifetimes of all the Navstar clocks are meeting the required mean mission duration specification for the space vehicles. On the Block II/IIA Navstar space vehicles, 52 of the 60 clocks in space have been operated, and the average space vehicle age is 14 years. For the Block IIR/IIR-M space vehicles, 18 of 48 clocks in space have been operated, and the average space vehicle age is 4.7 years. All of the Block IIR/IIR-M space vehicles remain in operation with 14 out of 16 still operating the first of three onboard clocks. None of the Block II/IIA space vehicles has been removed from service because of a clock failure. The average age of the deactivated clocks is 5.4 years and 1.8 years for the Block II/IIA Cs and Block II/IIA Rb clocks respectively. Finally, all but the Block IIR Rb clock on Navstar 44, which falls marginally below the specification, meet or exceed the Hadamard variance stability specification of 6 pp10^{14} at a sample time of 1 day.

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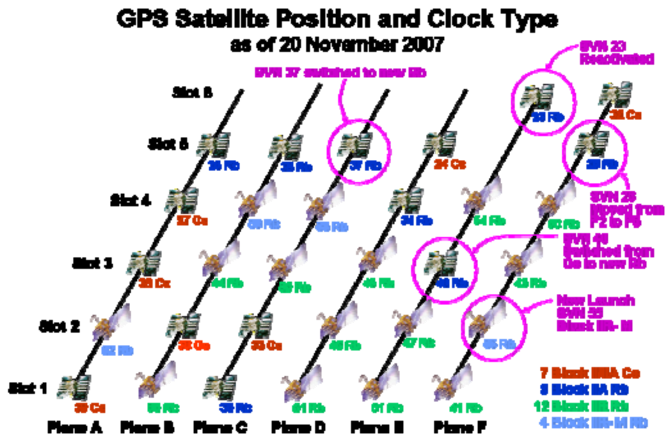

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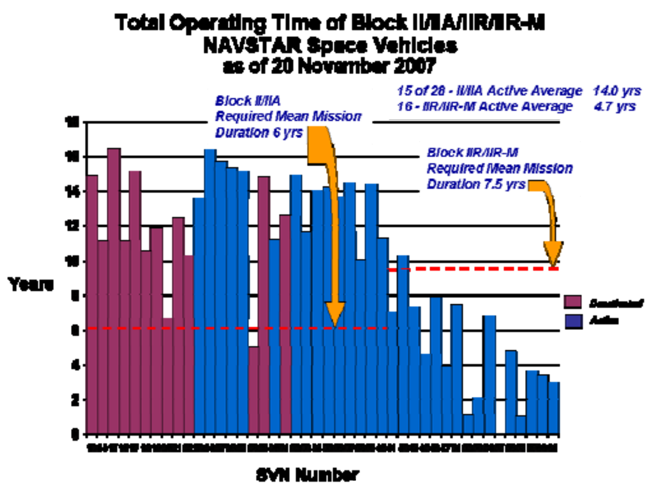

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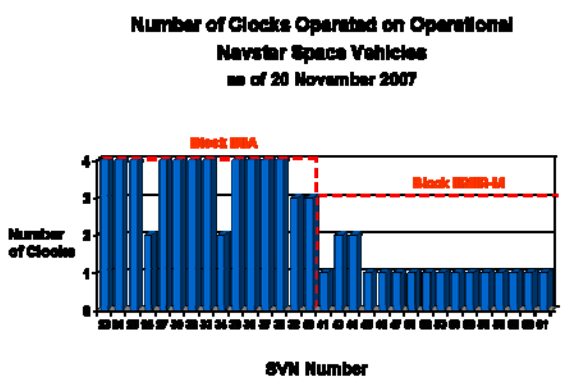

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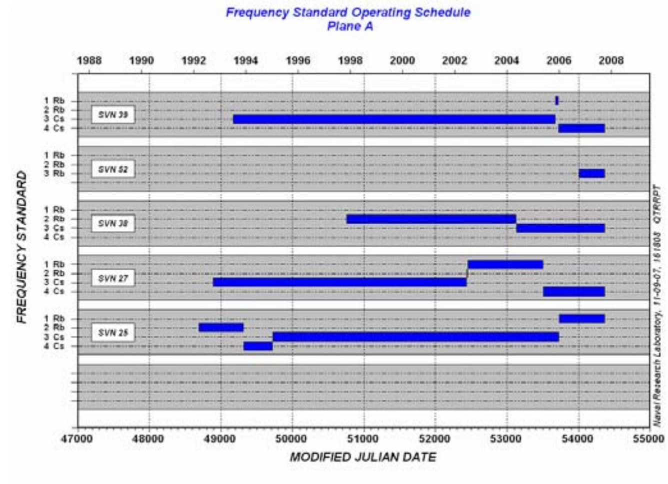

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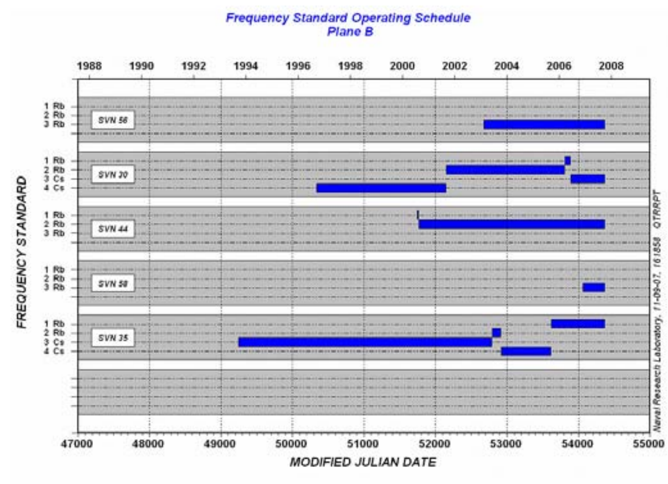

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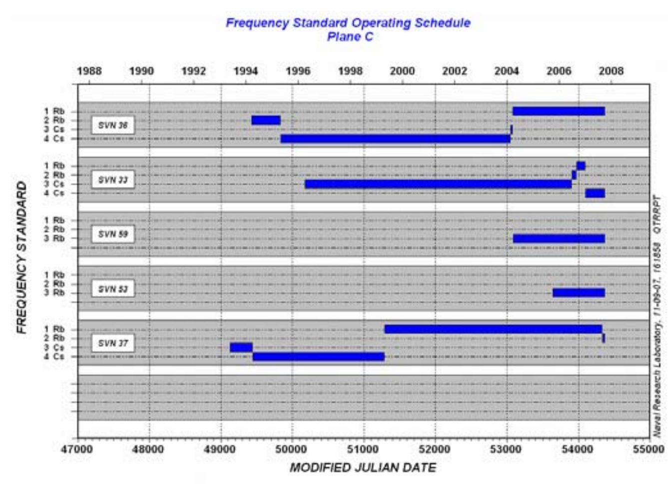

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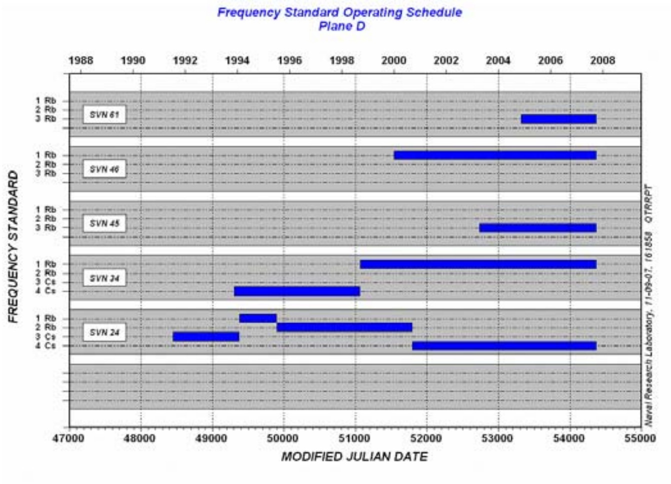

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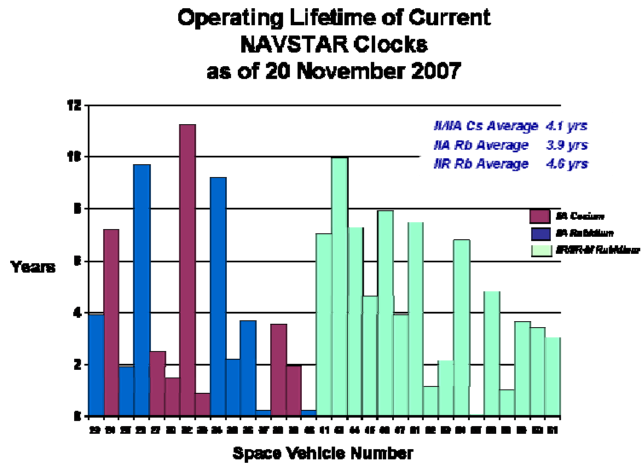

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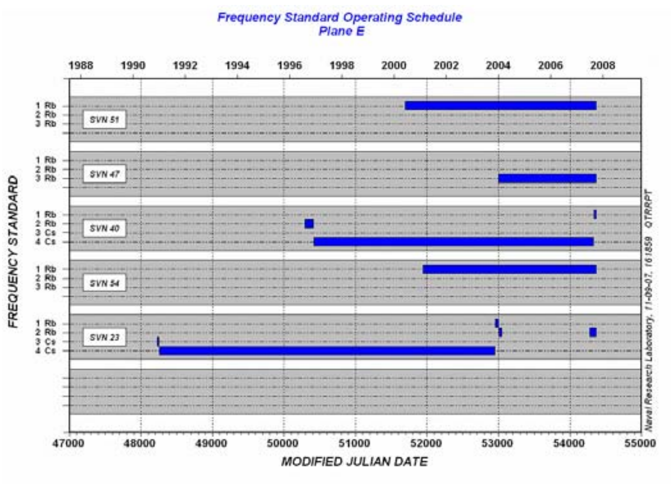

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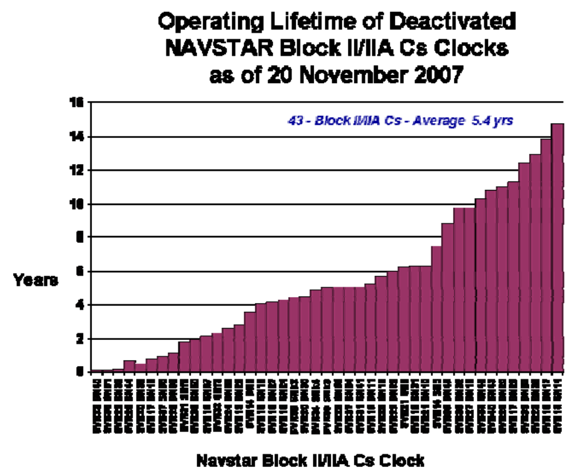

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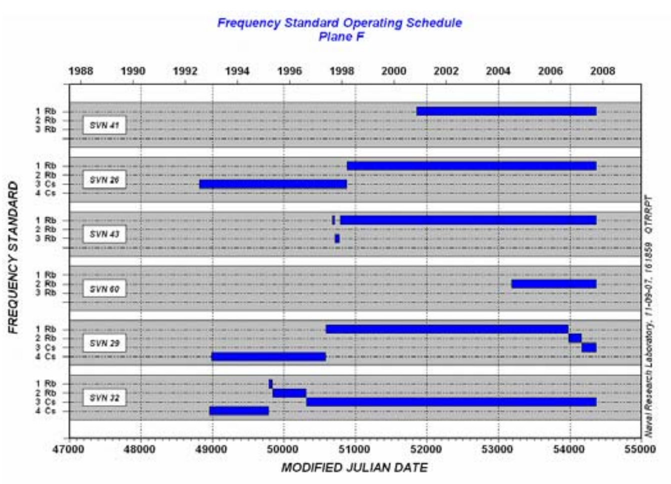

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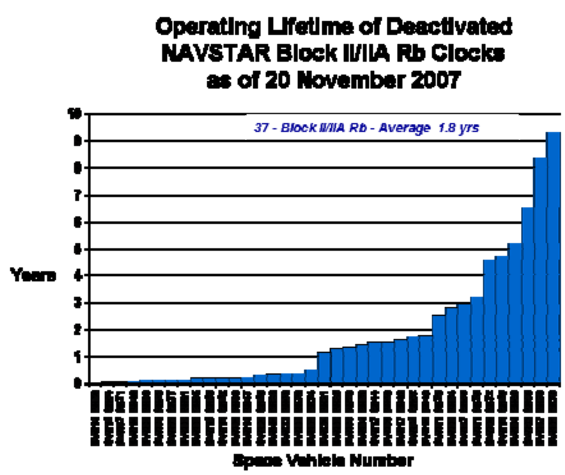

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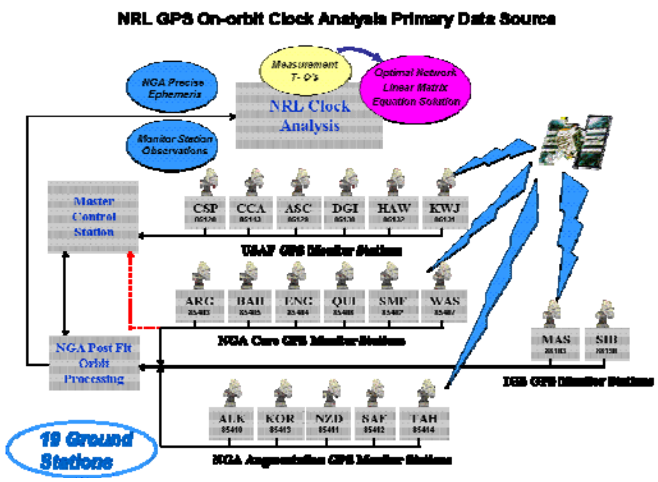

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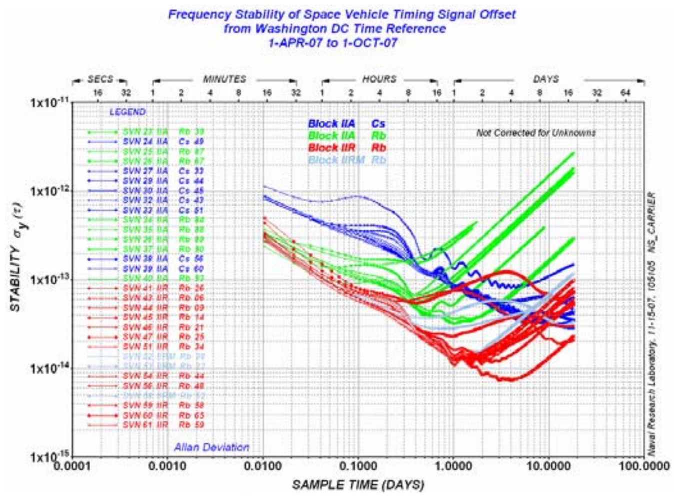

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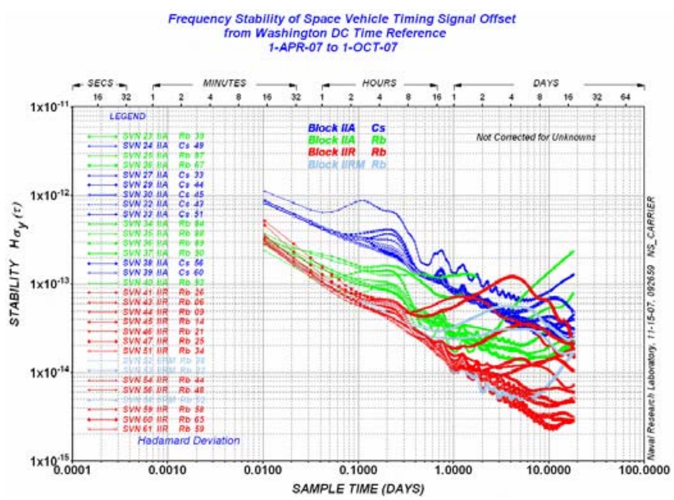

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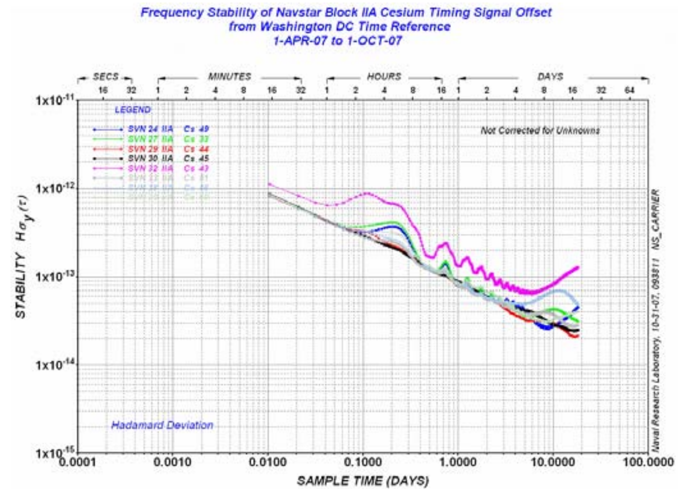

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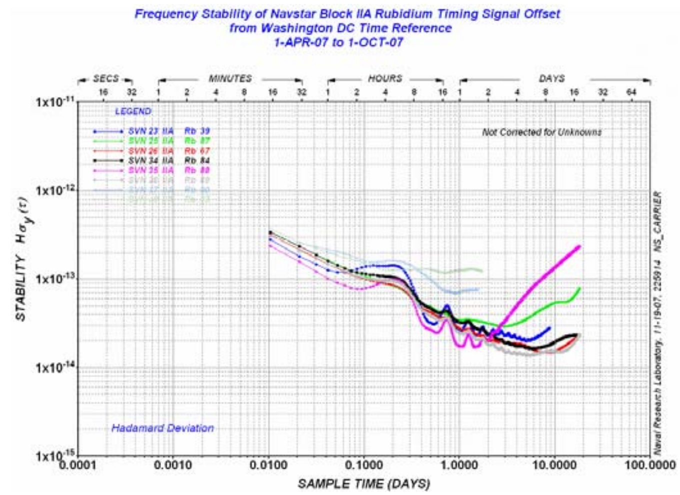

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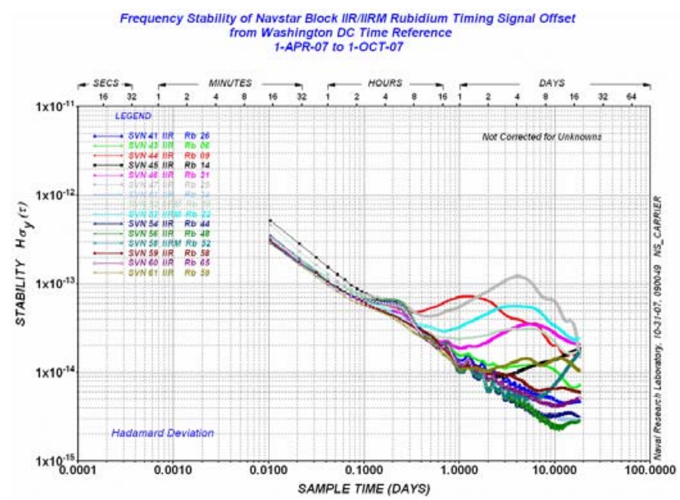

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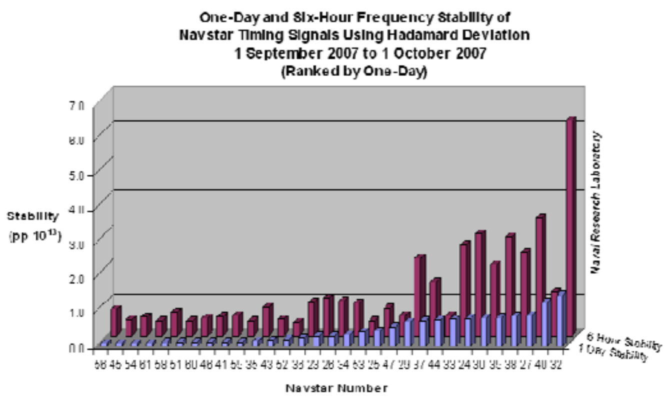

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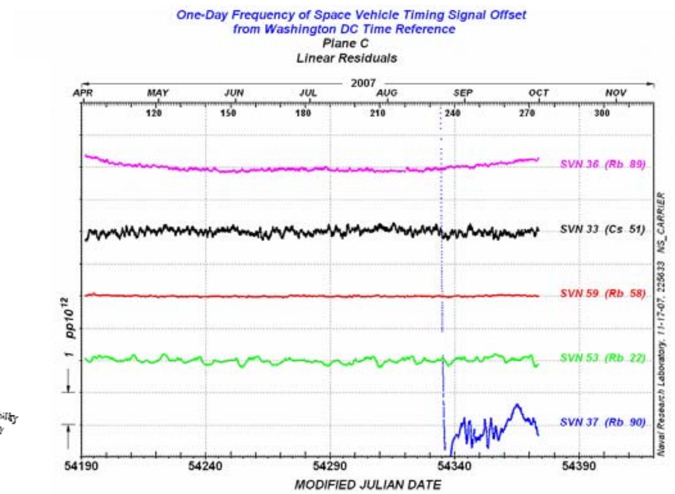

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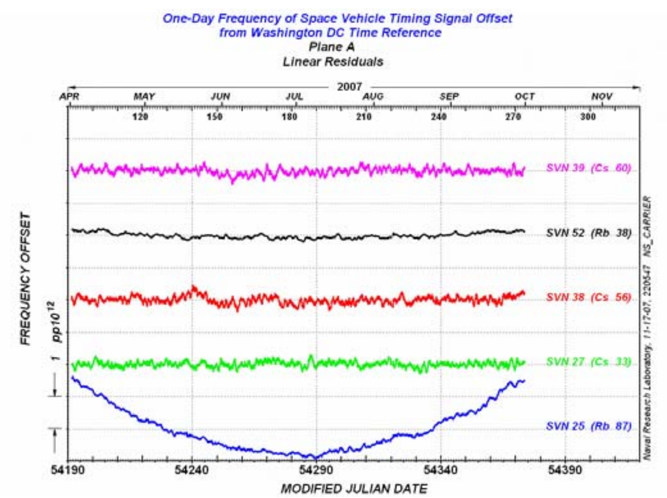

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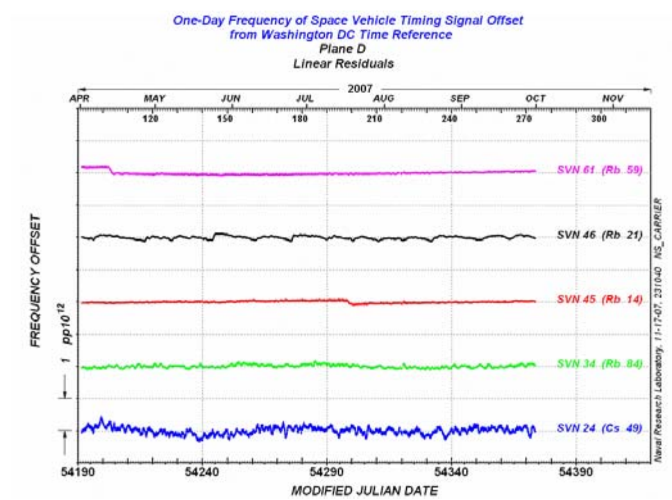

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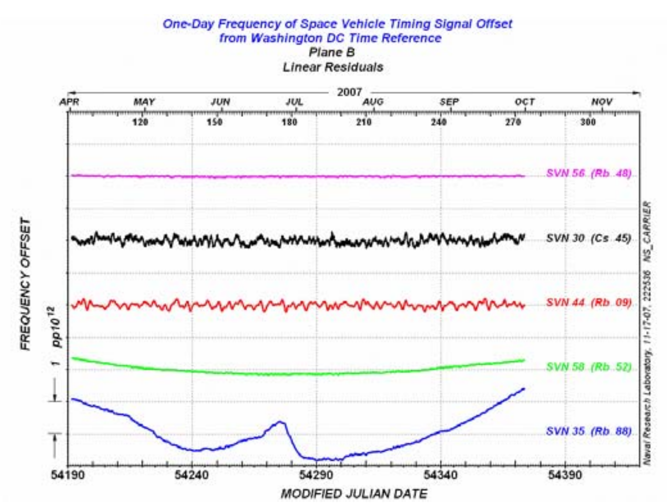

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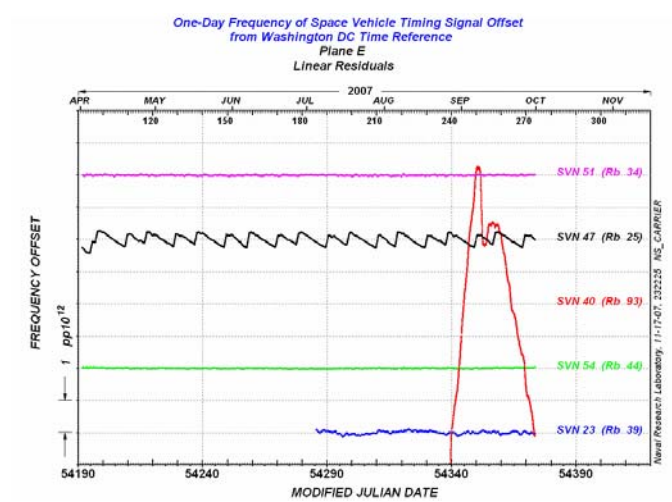

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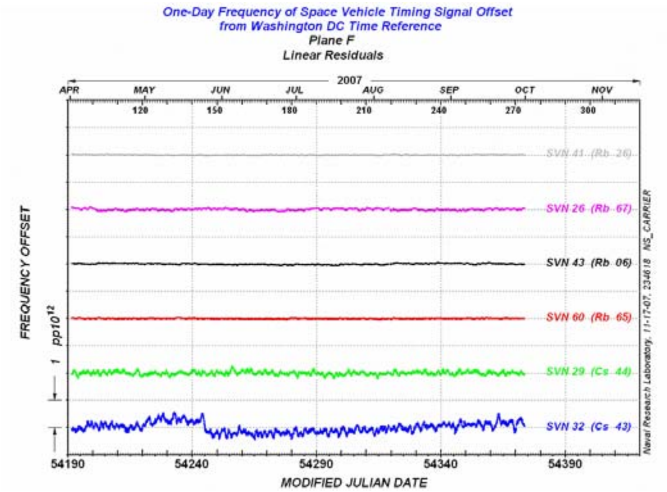

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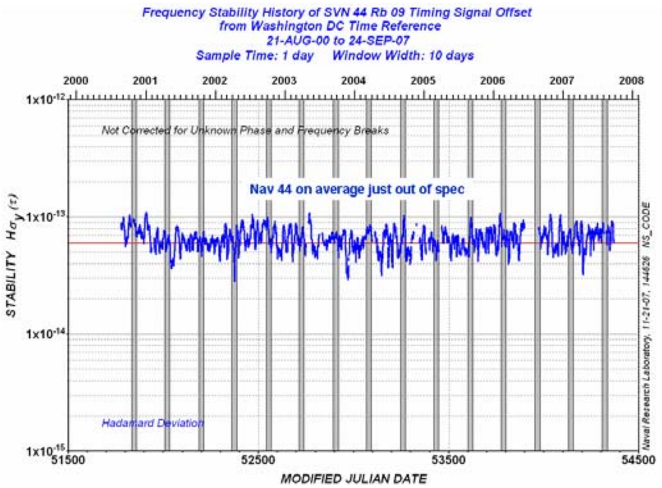

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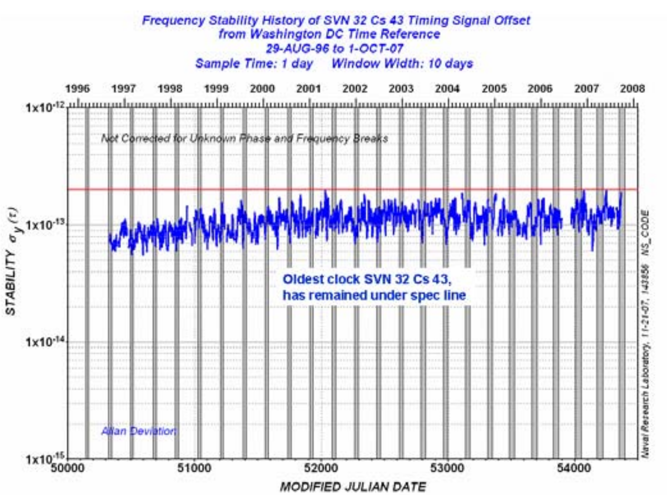

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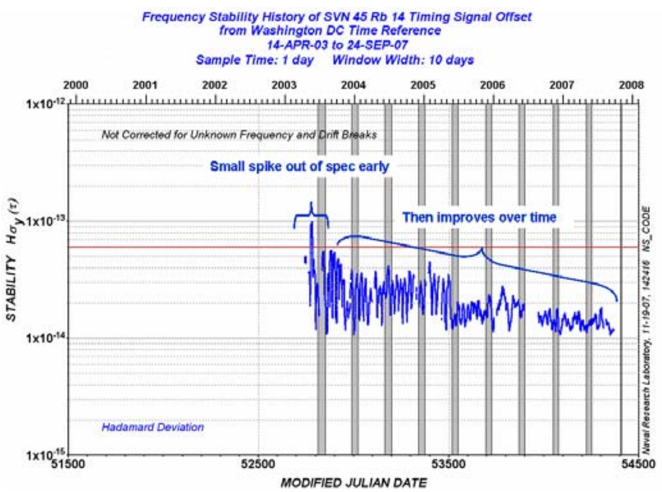

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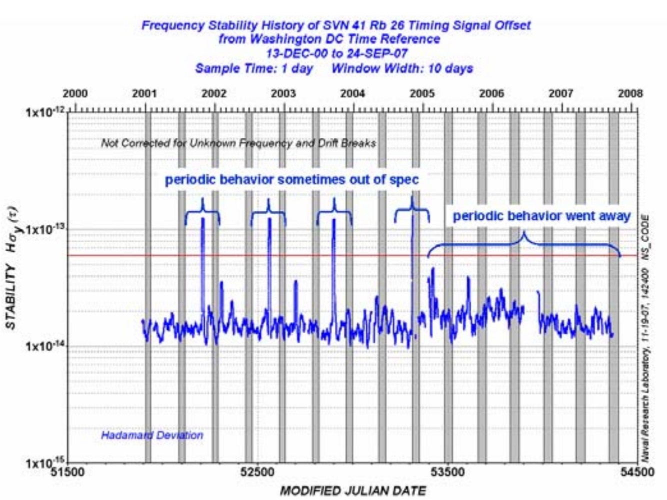

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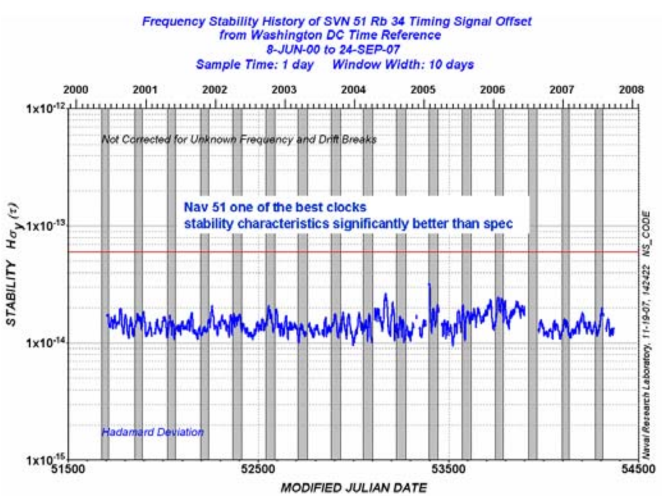

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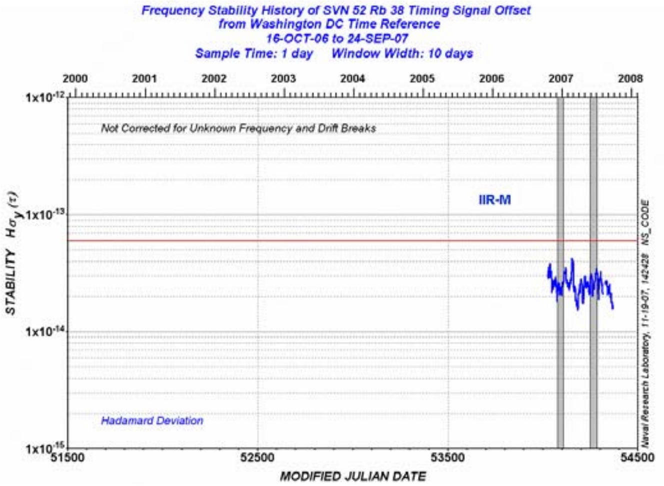

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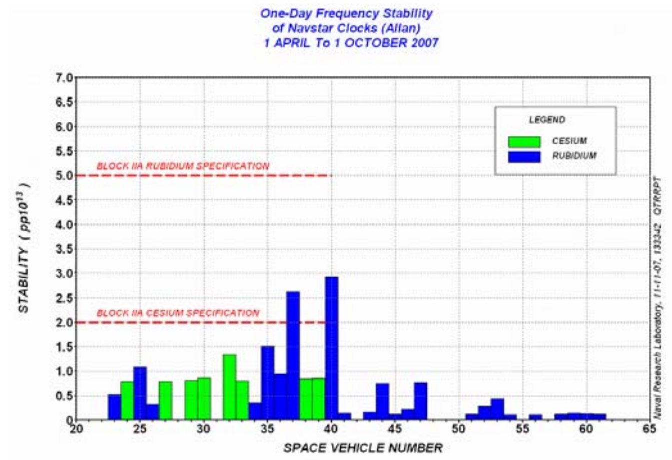

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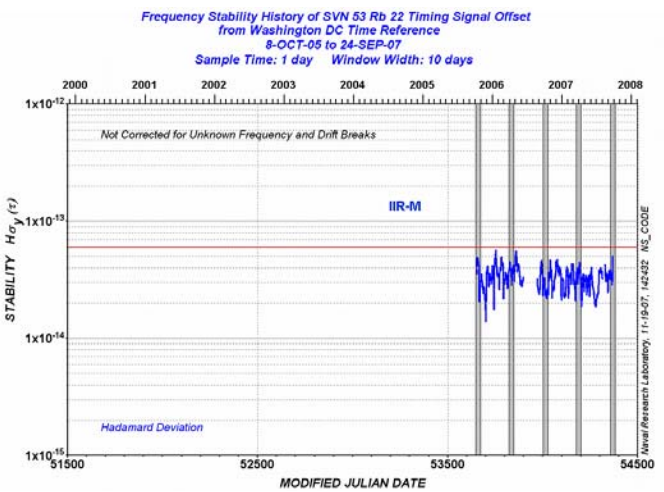

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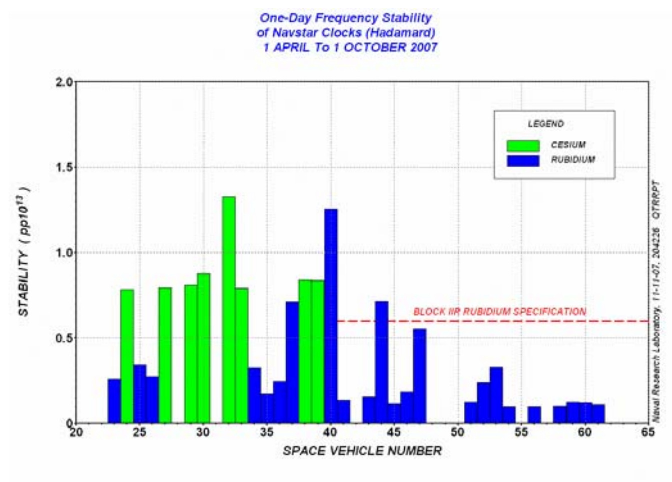

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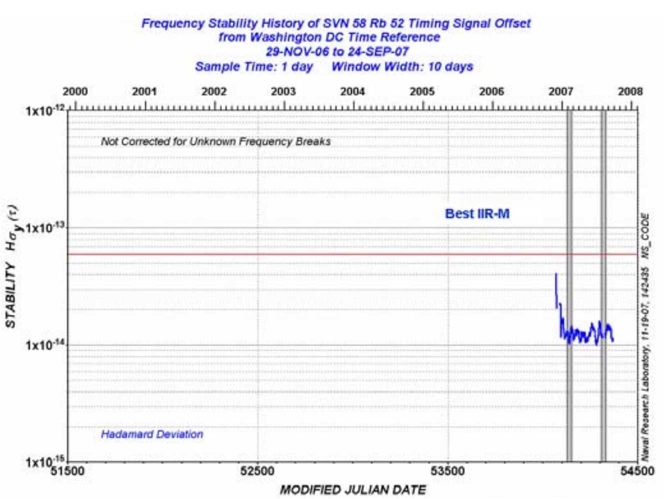

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