

GPS Block IIR Clocks in Space: Current Performance and Plans for the Future

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Abstract—ITT Industries developed GPS IIR satellite payloads have been on-orbit since July of 1997, providing outstanding signal-in-space performance. Much of the credit for this outstanding performance can be given to the GPS IIR Time Keeping System (TKS). A key component of the TKS system is Perkin Elmer's Rubidium Atomic Frequency Standard (RAFS). We now have over 40 years of on-orbit experience with the GPS IIR TKS and RAFS. In this paper we will present the characteristics of the twelve on-orbit operating frequency standards, eight of which are in family and are the best performers in the GPS constellation, although four of which exhibit detectable features. This paper will provide insight into the unique characteristics of each on-orbit operational RAFS.

I. INTRODUCTION

The GPS IIR Time Keeping System (TKS) contains a 10.23 MHz system oscillator phase locked to a Rubidium Atomic Frequency Standard (RAFS) reference oscillator [1]. The system oscillator provides short-term stability ($\tau < 5$ minutes) while the reference oscillator provides long-term stability ($\tau > 5$ minutes). The system oscillator feeds both the pseudo-random noise code generators and the carrier frequency synthesizers. Therefore, the long-term stability of the GPS IIR navigation signals and navigation performance, is driven by the stability of the RAFS supplied by Perkin Elmer. In particular, the stability of the RAFS at a τ of 1-day is an important performance measure since, typically, each GPS satellite is uploaded once every 24 hours with fresh data for broadcast. The broadcast data contains the predicted satellite time offsets (phase, frequency, and frequency drift) from the GPS Master Clock (GPS Time).

In general, the GPS IIR RAFS has exhibited outstanding stability resulting in superior navigation performance delivered to the user. The addition of GPS IIR satellites has significantly contributed to an improving trend for the average stability of the GPS constellation. In this paper, we examine the stability, common features, and unique features observed in the GPS IIR RAFS. In addition, we describe the adjustments applied to the IIR TKS to steer the satellite time

towards GPS Time. Finally, we look at plans for the GPS IIR RAFS in the coming years.

II. GPS IIR CONTRIBUTION

The “R” in IIR stands for “Replacement”. The GPS IIR is a replacement for the aging constellation of GPS Block II and IIA satellites. This paper records the GPS IIR history as of June 2005. Currently, there are 12 Block IIR satellites in a constellation of 28 as shown in Fig. 1. The figure indicates GPS satellites sorted by orbital plane (A through F) and slot (1 through 6).

There are two numbers associated with each satellite, namely its PRN (Pseudorandom Ranging code Number) and its SVN (Satellite Vehicle Number). Typically, user receiver equipment tracks the satellite by its PRN because the PRN is used to generate the pseudorandom code to select the signal from this satellite and reject the signal from the other satellites in the GPS constellation. When a GPS satellite is retired, its PRN becomes inactive and is put in a pool of available PRN values. When a new GPS satellite is launched, it is assigned a PRN value from this pool. Thus, a PRN value can be associated with more than one satellite. In fact, there are only 30 PRN numbers assigned to the operational GPS satellites. Most PRN values have been associated with more than one satellite. The US Air Force assigns an SVN value to each GPS satellite to serve as a unique identifier for that satellite. The Block IIR GPS satellite SVN values range from 41 to 61. The figures that follow Fig. 1 will reference the IIR satellites by SVN rather than PRN since SVN is the reference used by the US Air Force. There are three RAFS atomic clocks on each GPS IIR satellite, labeled 1, 2 or 3. The SVN and clock number uniquely identify a given GPS IIR clock in the constellation. Table 1 describes each IIR clock by SVN value and by clock number. Each of the GPS IIR satellites has had only one operational clock. Thus, the other references to clocks, in this paper, refer to the clock only by its SVN number and one can use Table 1 to identify the active clock.

	1	2	3	4	5	6
A	39 (09)	25 (25)	38 (08)	27 (27)		
B	56 (16)	30 (30)	44 (28)	35 (05)		
C	36 (06)	33 (03)	59 (19)	37 (07)		
D	61 (02)	46 (11)	45 (21)	34 (04)	15 (15)	24 (24)
E	51 (20)	47 (22)	40 (10)	54 (18)		
F	41 (14)	26 (26)	43 (13)	60 (23)	29 (29)	32 (01)

SVN (PRN)

Figure 1. SV Constellation Sorted By Plane and Slot (IIR Satellites are Highlighted)

Fig. 2 shows the GPS constellation stability trend by quarter over the last 5 years. The GPS IIR additions to the constellation are shown when they occurred as IIR-2 through IIR-13. (IIR-1 was destroyed in a booster failure on 17-Jan-97.) The figure shows that the average stability (Hadamard Deviation or HDEV) of IIR has been outstanding at about 2×10^{-14} (HDEV $\tau = 1$ -day). The figure also shows the improving stability trend of the constellation as IIR satellites replaced the older technology block II and IIA satellites [2].

Fig. 3 shows the ranking by stability for HDEV ($\tau = 1$ -day) for the 2nd quarter of 2005. Most of the IIR RAFS have stability better than 2×10^{-14} and appear towards the left in the Fig. 3. However, there are some RAFS that are out-of-family and appear higher in the center of figure. We can also observe in Fig. 3 that the Rubidium clocks are generally more stable than the Cesium clocks in the Block II and IIA

TABLE I. FEATURES OF THE IIR RAFS BY SVN/CLOCK NO.

SVN	Characterization
SVN 41/1	The RAFS is usually in family and very well behaved with the exception of frequency breaks seen as vertical spikes in the plot. There are generally two breaks per year. Large (about one part in 10^{-12}) positive frequency breaks occur toward the end of each year. Smaller (parts in 10^{-13}) negative frequency breaks occur early to midyear.
SVN 43/1	The RAFS is usually in family and very well behaved with the exception of small negative frequency breaks about every 3 years. The breaks in the plot are the negative spikes in years 4 and 7.
SVN 44/2	The RAFS is out of family. It is generally noisier than in family RAFS all the time with no individual breaks predominating.
SVN 45/3	The RAFS was noisier at beginning of life but has improved over time. No individual breaks predominate.
SVN 46/1	The RAFS is very well behaved.
SVN 47/3	The RAFS has been out of family with many breaks in its first year of life. Perhaps this will improve over time as the SVN 45 RAFS did.
SVN 51/1	The RAFS is very well behaved.
SVN 54/1	The RAFS is very well behaved.
SVN 56/3	The RAFS is very well behaved.
SVN 59/3	The RAFS is very well behaved.
SVN 60/2	The RAFS is very well behaved.
SVN 61/3	Initial Data is promising.

The migration of the II/IIA clocks from Cesium to Rubidium has also contributed to an improving trend in the overall constellation stability. This migration to Rubidium clocks in the Block II/IIA has occurred as Rubidium clocks replaced the failed Cesium clocks.

III. STEERING GPS IIR SATELLITE TIME

There is a requirement to keep the phase of the satellite clock within $\pm 976.562 \mu\text{s}$ of GPS Time. The number of bits available in the navigation message to broadcast the phase offset dictates this requirement. There are controls in the IIR TKS that allow the ground crew (2nd Space Operations Squadron) to set phase, frequency, and frequency drift. We established a process for IIR initialization to set phase about $-100 \mu\text{s}$ and frequency about $+15 \times 10^{-12}$ [3]. There is no correction applied to frequency drift initially so the natural negative frequency drift of the RAFS integrates into frequency over time pulling it down from its initial positive value. When frequency comes close to zero we begin the process of occasional frequency drift adjustments about once every two years to four years, on the average, for the rest of the life of the RAFS. The frequency drift adjustments are used to keep frequency bounded by $\pm 4 \times 10^{-12}$. Frequency drift adjustments can be made while the SV is healthy without impact to users. Keeping frequency offset low (always within $\pm 4 \times 10^{-12}$) ensures that phase offset will stay within the $\pm 976.562 \mu\text{s}$ of GPS Time requirement.

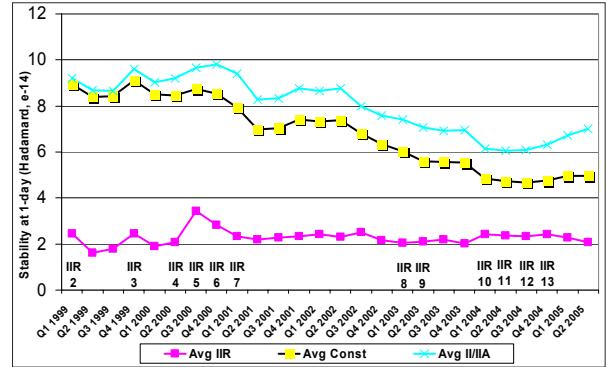


Figure 2. GPS Stability Trend

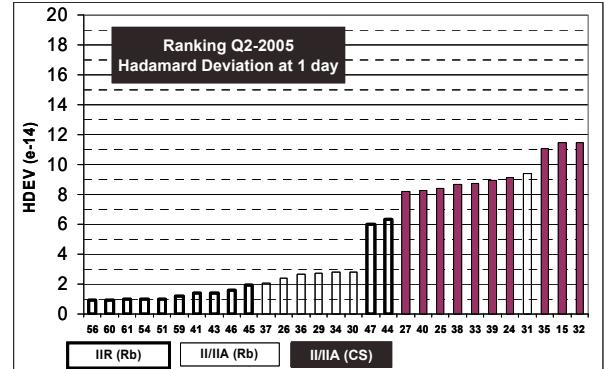


Figure 3. Stability Ranking

Fig. 4 shows a frequency offset plot of all IIR SVs. We can see in the figure that frequency is initialized to a high positive value ($+15 \times 10^{-12}$). The natural negative frequency drift value of the RAFS integrates into frequency and pulls it down into the $\pm 4 \times 10^{-12}$ range usually within the first year. When frequency falls into this range, we start the frequency drift correction process, described above. The frequency drift adjustments are a relatively simple matter that piggybacks onto the normal daily upload. In addition, the SV can remain healthy during the process so there is no user impact.

Fig. 5 shows the results of keeping frequency offset low ($\pm 4 \times 10^{-12}$ range). The figure shows a phase offset plot for all IIR SVs. The figure indicates that phase offset is well within the bounds of $\pm 976.562 \mu\text{s}$.

Fig. 6 shows the effects of canceling the inherent RAFS drift. We took a snapshot of the RAFS drift and the net drift after frequency drift correction at the four-year mark for the 6 RAFS that have reached this age. We see that these RAFS have a drift in units of $10^{-14}/\text{day}$ that ranges from -3.3 to -1.9 with a mean drift of -2.85 and a standard deviation of 0.51 . The net drift has a range from -0.4 to $+1.3$ with a mean 0.21 and rms of 0.57 . This shows that the frequency drift correction, in this case, reduced the mean of a negative value in the range of -2 to $-4 \times 10^{-14}/\text{day}$ to a value much closer to zero while not significantly reducing the rms variation around the mean. This is typical of what we expect to be the effects of frequency drift correction.

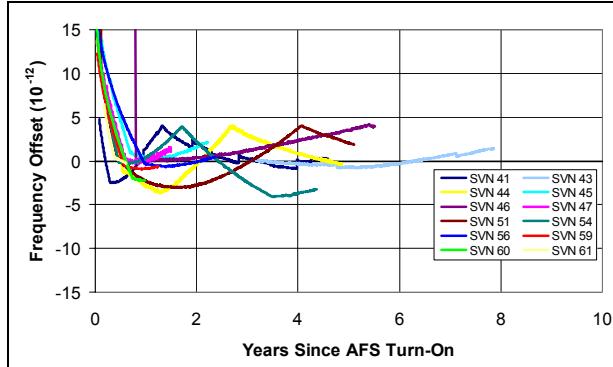


Figure 4. IIR Frequency Offset

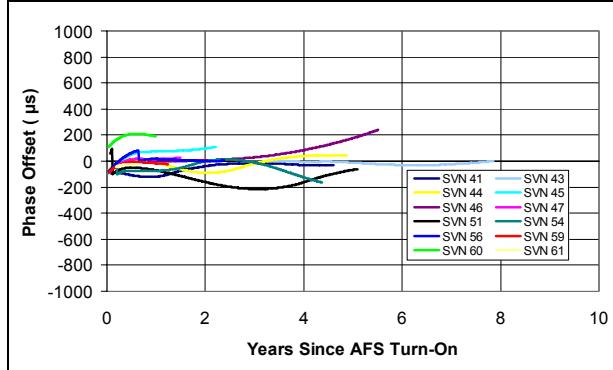


Figure 5. IIR Phase Offset

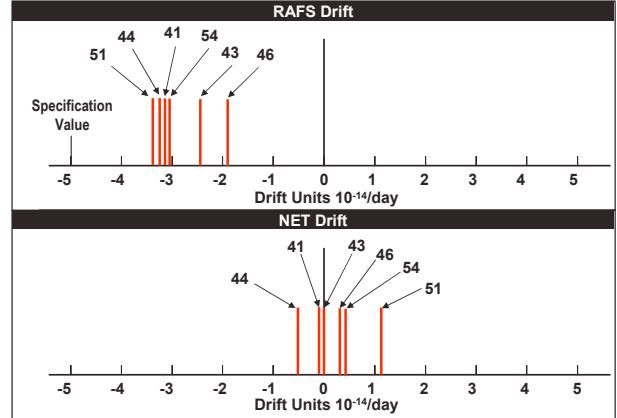


Figure 6. Distribution of RAFS Drift and NET Drift

Fig. 4 and Fig. 5 also show the operational life of each IIR RAFS. The oldest is SVN 43 at over 7.5 years. All 12 of the GPS IIR are on their first operational RAFS. We have had no on-orbit RAFS failures, which leave 2 viable backup RAFS units on each satellite. We estimate that many of the initial operational RAFS will serve the majority of the life of its SV and we may never have to decommission a IIR SV for lack of a clock. This suggests that a viable strategy for order-of-RAFS-use in the IIR is to select a better RAFS early in the SV lifetime

IV. RAFS FREQUENCY DRIFT CHARACTERISTIC

The long term frequency drift characteristic of all the IIR RAFS follows a common pattern as shown in Fig. 7. In general, the frequency drift typically starts at a large negative value but decays, asymptotically, to an average value roughly between $-1.0 \times 10^{-14}/\text{day}$ and $-4.0 \times 10^{-14}/\text{day}$. We use this knowledge of the underlying RAFS frequency drift decay in choosing the frequency drift adjustment values. For example, if we are in the early high drift phase of the RAFS, we may not null out quite as much of the frequency drift as in the later phases when frequency drift rate of change is low. The frequency drift is not a direct observable but is formed by a first derivative of the frequency or a second derivative of the phase. All numerical derivatives use a low pass filter to prevent the high frequency noise from overwhelming the drift characteristic we want to examine.

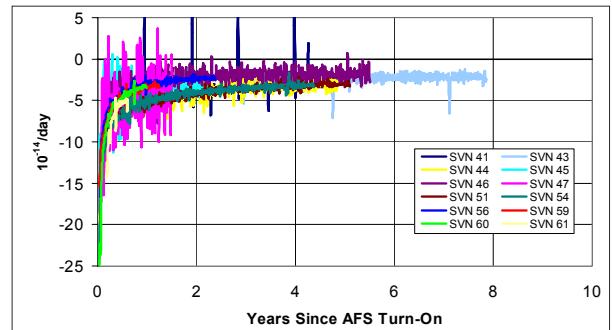


Figure 7. RAFS Frequency Drift

The drift curves in this paper were generated by a second difference of the phase with a 14-day span. This means that one can see long term drifts well but features less than a week in duration are distorted and attenuated by the drift calculation process

V. RAFS DIRFT AND STABILITY FEATURES

Most of the behavior of the RAFS follows the standard clock model, which describes a clock in terms of white noise PM and FM, flicker noise FM, random walk FM and frequency drift. However, the behavior of certain RAFS also contains some special features such as large frequency steps. To be sure, there is a wide range of such steps, varying from very large steps to medium or small steps. In the following, we limit ourselves to a discussion of large steps because the smaller steps have little effect on clock performance. Also, as they get smaller and smaller, it becomes more difficult to separate a step from normal clock noise.

A few of the features detectable in the plots are due to various events in the lives of the satellites and to clock control commands sent to the satellites. To obtain a true assessment of clock behavior, it is important to determine where these events have occurred and cancel their effects. Clearly, the frequency drift corrections are examples of a change in clock behavior due to a ground control command to the SVN. References [3] and [4] address these issues and [5] describes how changes in the satellite orbit for station keeping or other reasons cause frequency steps as a result of relativistic effects. The Naval Research Laboratory, (NRL) has the responsibility of monitoring the behavior of the GPS clocks, determining which effects are related to processes outside of the clocks, and investigating the various anomalies associated with the clocks. Fig. 8 highlights some features of various RAFS units. In particular, the sharp spikes are generally due to fast frequency steps. In cases of interest, we can diagnose these features better by careful examination of the phase and frequency plots of the clocks.

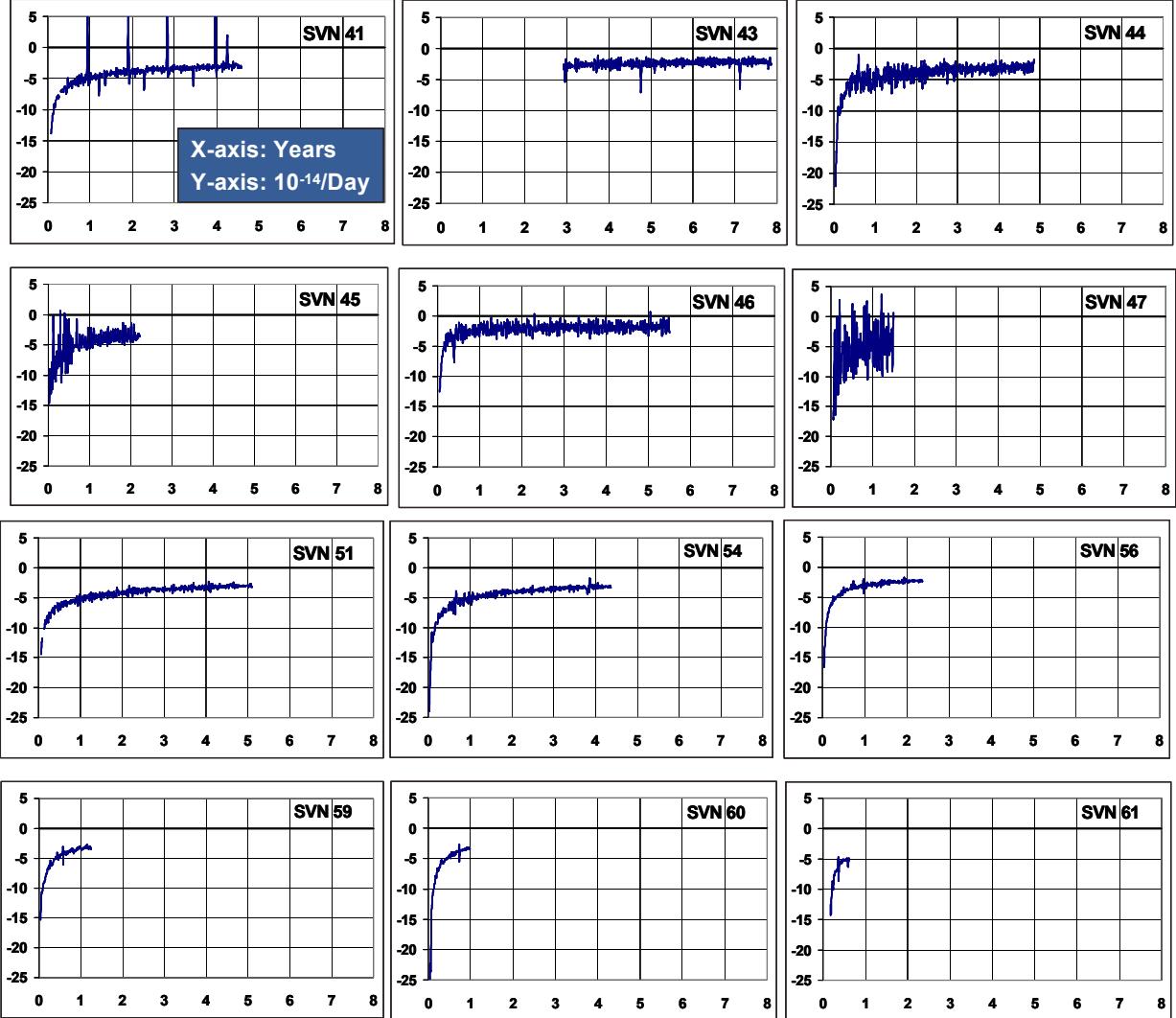


Figure 8. Per SV RAFS Frequency Drift

More details of these features can be found in the NRL reports [4].

Table I characterizes the RAFS from observations of the features visible in the frequency drift plots in Fig. 8.

Fig. 9 shows the average stability of IIR RAFS over the last year to date. The stability measure used is HDEV ($\tau = 1$ -day) using a 10 day moving window. We can see from the plot, the IIR RAFS have been performing well with an average stability of around 2×10^{-14} . The requirement, levied on the RAFS at acceptance testing is 6×10^{-14} , is shown in the plot.

Fig. 10 contains the stability plots of each SVN prior to the cutoff date. The stability measure used is HDEV ($\tau = 1$ -day) using a 10 day moving window. Table II characterizes the RAFS from observations of the stability plots in Fig. 10. In addition to the stability plot of each SVN, we also provide the average of the stability plots of all the RAFS for comparison. Features of the individual RAFS, such as the large frequency steps of SVN 41, shows as large local peaks in the stability plot of the affected SVN. This illustrates the potential impact of the clock features on performance.

TABLE II. COMMENTS ON STABILITY PLOTS (RAFS BY SVN)

	Characterization
SVN 41	The RAFS is usually in family and very stable, usually better than 2×10^{-14} . There are stability issues caused by frequency breaks in early May 2004, early November 2004, and mid February 2005.
SVN 43	The RAFS is usually in family and very stable, usually better than 2×10^{-14} . There was one stability issue caused by frequency breaks in late September 2004.
SVN 44	The RAFS is out of family. It is generally noisier than in family RAFS all the time with no individual outliers standing out.
SVN 45	The RAFS has stability near the IIR constellation average. The stability plot suggests small frequency/frequency drift discontinuities on regular intervals.
SVN 46	The RAFS is in family and very stable, usually better than 2×10^{-14} .
SVN 47	The RAFS has been out of family with worse than average stability.
SVN 51	The RAFS is in family and very stable, usually better than 2×10^{-14} .
SVN 54	The RAFS is in family and very stable, usually better than 2×10^{-14} .
SVN 56	The RAFS is in family and very stable, usually better than 2×10^{-14} .
SVN 59	The RAFS is in family and very stable, usually better than 2×10^{-14} .
SVN 60	The RAFS is in family and very stable, usually better than 2×10^{-14} .
SVN 61	The early data shows the RAFS is in family.

VI. PLANS FOR FUTURE OF THE RAFS

The previous GPS generations, Blocks I, II and IIA, used the best available space clocks. Block IIR chose the RAFS design, which provided superior performance over the previous clocks. This is not surprising given the fact that there was about 10 years difference between the design of the previous Rubidium atomic standard and the RAFS design. All the IIR satellite family uses the same RAFS design. Of satellites SVN 41 to SVN 61, one is a launch failure, 12 are in orbit and the remaining eight satellites are expected to be launched into orbit in the next few years. These eight satellites are designated IIR-M because they have an improved modernized transmitter and code generator with more output power and an improved signal. However, the clock design is the original RAFS design. The future blocks of GPS will not use this RAFS design. The next GPS generation, the Block IIF, plans to use an improved Rubidium atomic clock standard called Rb Time Standard (RTS) from Perkin Elmer, with better performance than the IIR RAFS. The Block IIF also plans to fly a new Cesium Time Standard (CTS) in addition to the RTS. At this time it is not known which clock technology will be powered initially. Thus, the RAFS will be flown only on the Block IIR/IIRM satellites.

As of now, there is significant information on the on-orbit behavior of the RAFS early life but limited data from two clocks after 4 years and no data on life after 8 years. In the coming years we will collect data on the RAFS performance and life expectancy in its later life. We plan to provide reports for the RAFS performance over the years. When the final Block IIR/IIRM satellite is retired, we should have over 200 years of data, as there are 20 satellites with an expected life of over 10 years each. Rb technologies are planned to be a key clock component for the next generations of GPS SVs. At that time, we will be able to assess not only the performance of the IIR RAFS but also the observed performance improvement of these new clocks.

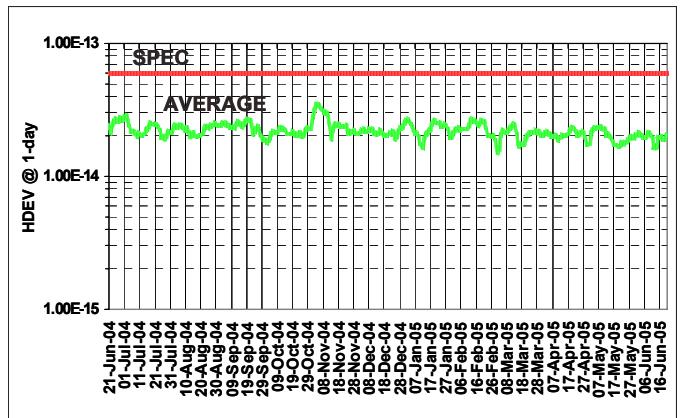


Figure 9: Average IIR RAFS Stability

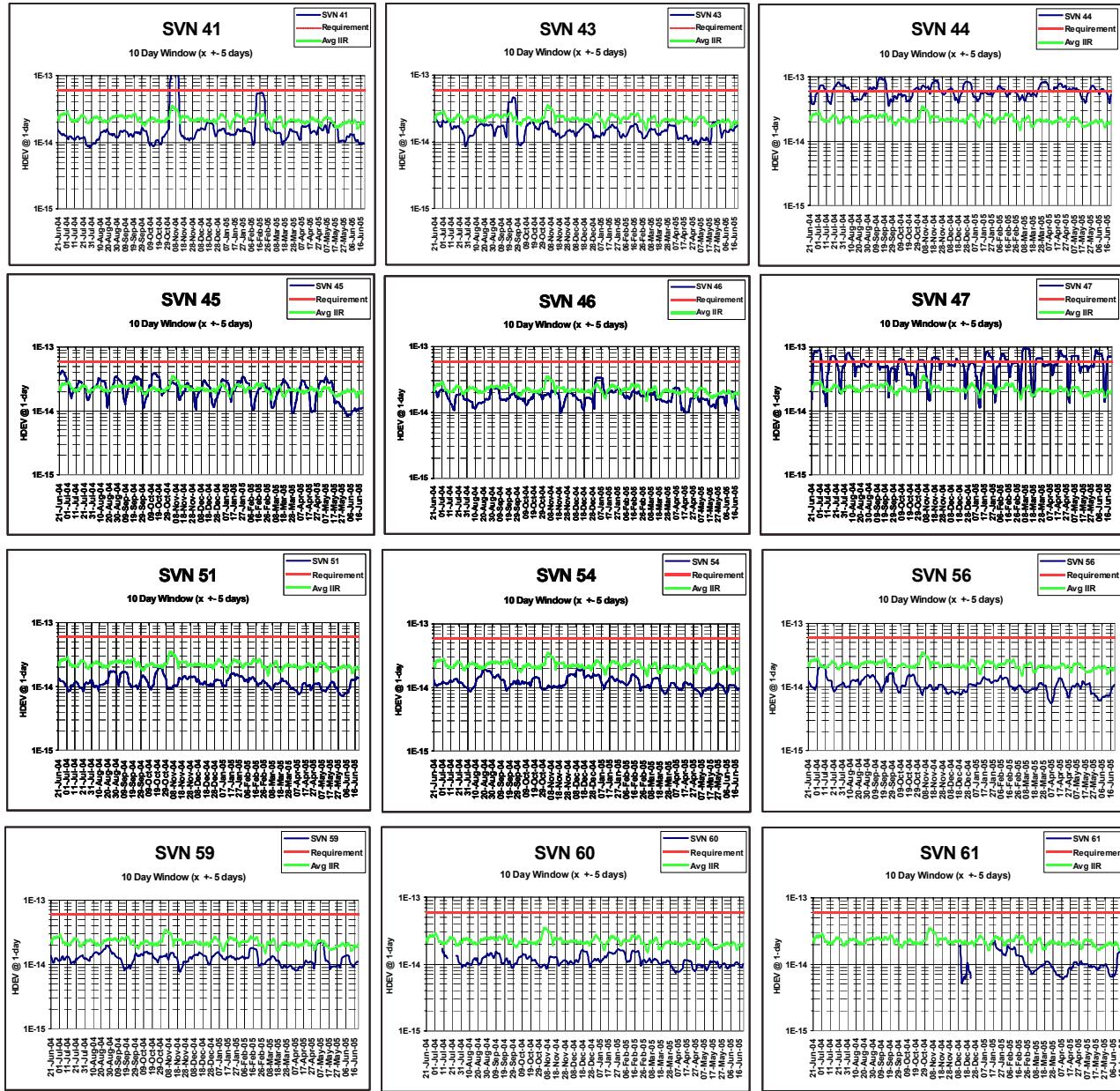


Figure 10. Per SV RAFS Stability

CONCLUSION

The GPS IIR TKS employs convenient controls for ground operators to keep the satellite timing within specification without impact to users. The GPS IIR TKS has significantly contributed to the improving trend of the stability of the GPS constellation. This has translated into improved performance delivered to worldwide users of GPS. This trend is expected

to continue for the remaining Block IIR, Block IIF, and future generations of GPS Satellites.

ACKNOWLEDGMENTS

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