GPS CHANGES BEFORE AND AFTER IMPLEMENTATION OF THE ARCHITECTURE EVOLUTION PLAN*

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Abstract

We characterize the performance of GPS signals before, and after Architecture Evolution Plan (AEP) implementation. We use the period from 20 May through 13 September 2007, MJDs 54240-54356, as the period before AEP. We use the interval from 14 September 2007 through 31 December 2007, MJDs 54357- 5446 as the period after the implementation of AEP. We use a variance analysis to characterize performance, allowing us to characterize periodic behavior in the presence of power-law noise types. Computing the ratio of TDEV of various data after AEP implementation divided by the TDEV before the implementation allows us to see changes in deviation due to both power-law noise and periodic effects.

We analyze two types of data for changes between these time periods: 1) error in broadcast ephemerides and clock corrections as combined for pseudoranges at NIST, Boulder, using National Geospatial-Intelligence Agency's (NGA) postprocessed estimates as the reference, and 2) the error of each satellite's broadcast ephemeris and clock model separately against the NGA estimates. Generally, we find evidence of some worsening in ephemerides from before to after the implementation of AEP. RMS 15-minute stabilities across satellite blocks worsened by 8-30%. Twelve-hour and 24-hour periodic behavior generally worsened. Though results vary by satellite block and ephemeris component, the best was a 13% improvement, and the worst was a worsening of 29%. Results vary significantly by individual satellite. By contrast, broadcast clock correction values generally showed little change from before to after the implementation of AEP.

In the process of this study, we found evidence of an approximate 27-day periodic variation in the difference: broadcast minus NGA radial ephemeris of all satellites studied. The periodic variation is not evident in the difference data themselves, but in the broadcast minus NGA radial velocity and acceleration data. The effect is a periodic variation in the magnitude of the deviation. It can be seen in the 900-s Dynamic TDEV values of the radial differences, the evolution of the TDEV values at 900 s.

ANALYSIS DESIGN

THE ARCHITECTURE EVOLUTION PLAN (AEP)

This report is an excerpt of a full report that gives details on each satellite **[1]**. The Architecture Evolution Plan (AEP) was a phased transition of the 22-year-old Legacy GPS Master Control Station (MCS) to the AEP control segment. The process was a multi-year cooperative effort to achieve a seamless navigation service transition to GPS users. The actual operations start date was 14 September 2007, MJD 54357. To determine any possible changes from before to after this implementation date, we characterized broadcast satellite data before and after this date, and compared them. We compared the broadcast ephemerides and clock correction data to the estimates from the National Geospatial-Intelligence Agency (NGA). We obtained the broadcast data from the IGS archives. We used the NGA antenna-phase centered (APC) data, to ensure consistency with the broadcast data.

We characterize broadcast minus NGA differences over two intervals. The first, segment 'A' is from 20 May through 13 September 2007, a period of 117 days from MJD 54240 through 54356. The second, segment 'B', starts with 14 September and runs through 31 December 2007, 109 days from MJD 54357 inclusively through 54465. We compare these characterizations, looking for changes.

We assume that the NGA estimates are more accurate than the broadcast data; hence, the differences reflect inaccuracies in the broadcast data. We note, however, that it is possible for broadcast clock correction errors and ephemeris errors to cancel. Thus, users might have a more accurate pseudo-range estimate than perhaps indicated by the error estimates against NGA "truth." To look at data the way users actually use them requires picking a specific user location. We have done this for the first part of our analysis, using NIST, Boulder, Colorado as our location. We characterize errors using a variance analysis, as discussed below.

THE TIME DEVIATION (TDEV)

We analyze the performance of data primarily using a variance analysis. This allows us to compare a measure before implementation of AEP with the same type of measure taken after AEP was implemented. We compute the Time Variance and its square root, the Time Deviation or TDEV, of various data from segments A and B, then use the ratio of each segment B TDEV to the respective segment A TDEV as a measure of change from before the implementation of AEP to after. We chose TDEV, since it focuses clearly on white, flicker, and random walk phase modulation, the noise types we expect to dominate in looking at ephemeris and clock corrections.

TDEV gives a measure of variation, but not accuracy *per se*. However, instability here is generally a result of inaccuracy. Hence, TDEV can give us a measure of both the accuracy and the stability of various components of the system. In particular, TDEV can give an indication of a periodic component in the system. It is a particularly useful way of finding periodic deviations when they are mixed with low-frequency noise, such as flicker or random walk phase noise, since these noise types can obscure periodic measures when computing the spectrum directly. TDEV gives the noise level in each segment without the need for the data lengths to be the same. Thus, we use TDEV as the primary tool for characterizing changes in GPS before and after AEP.

One focus here is the change in periodic variations before and after AEP. GPS satellites have an orbital period of one-half of a sidereal day. With the earth rotation under the satellites, the system also has a natural period of 1 sidereal day, the period of repeated ground tracks. Hence, it is not surprising to find periodic effects in the data at one-half and 1 day. Our resolution is not fine enough to distinguish between sidereal and solar days.

We characterize two factors in this analysis: 1) short-term stability of broadcast corrections at 15 minutes, and 2) behavior of periodic effects, particularly at one cycle per orbit, one-half a sidereal day, and at one cycle per sidereal day. The measure we use is the ratio of TDEV after- to before-AEP. Where this ratio is greater than 1.0, performance is worse by that factor. Where the ratio is less than 1.0, we see improvement after AEP, again by the value of the ratio.

In many of the results, we find periodic effects. To better understand these, we present the response of TDEV to a simulated pure sine wave.

The response of TDEV to a pure modulating frequency f_m with peak-to-peak amplitude of x_{pp} is given by equation 1 below **[2]**. Note the maximum will occur when $f_m \tau = ½$. Since the period of modulation, $per = 1/f_m$, we find the maximum when $\tau = per/2$, i.e. at one-half the period of modulation. Note also that the value at the maximum, per equation 1 below, is $x_{pp}/(½ * \sqrt{8\pi})$. Since x_{pp} is twice the amplitude of the periodic behavior, we find that the amplitude of the periodic effect is $(\sqrt{8\pi}/4)*\sigma_x(\tau_{max}) \cong 1.25*\sigma_x(\tau_{max})$, where $\sigma_x(\tau_{max})$ is the value of TDEV at the maximum.

TDEV values from a periodic variation will attenuate according to $1/\tau$.

$$\sigma_x(\tau) = \frac{x_{pp} \sin^2(\pi f_m \tau)}{\sqrt{8\pi} f_m \tau}$$

Equation 1. The response of TDEV to a pure modulating frequency f_m with peak-to-peak amplitude of x_{pp}.

THE DYNAMIC TIME DEVIATION (DTDEV)

The Dynamic Time Deviation **[3]** is computed by computing TDEV over successive overlapping sub-intervals of the analysis period. These sub-intervals in our case are 4 days long, shifted by 1 day for each successive TDEV. These then are plotted as a surface, showing the evolution of TDEV values over the analysis period. In this plot, we can see in one picture the evolution of the stability at all integrations times plotted. By computing TDEV over 4 days, we see the values at ¼ day and ½ day, revealing the evolution of the ½- and 1- day periodic amplitudes. For each DTDEV plot, we also show the cross-section plots: 1) giving the evolution of the short-term stability (15 minutes in this study), and 2) giving the evolution of the amplitude of the ½- and 1-day periodic variations. For the cross section plots of 2), we have used Eq. 1 above to determine the amplitude, x_{pp}, and plotted that, rather than the TDEV values.

BROADCAST MINUS NGA POSTPROCESSED CORRECTIONS

We study broadcast satellite clock and ephemerides estimates differenced against the postprocessed, antenna-phase-centered, ephemerides from the NGA. In the process of this study, an approximate 27-day periodic in variance was discovered in the radial error of seemingly all satellites. In the Results section, we first give preliminary results for this effect. Then we return to our study of changes before-to-after AEP. We examine overall system performance first, looking at data the way they are used for pseudorange. Then we study satellite blocks looking at effects over Block IIA satellites with cesium (Cs) clocks, then Block IIA satellites with rubidium (Rb) clocks, then Block IIR satellites, then finally consider the three Block IIR-M satellites that were available in 2007. We show TDEV plots of root-mean-squared (RMS) values. These were computed by taking the RMS of all satellites in a block for each section first, then taking the ratio of these RMS values. The results for individual satellites are listed in tables.

Broadcast versus NGA corrections are useful in breaking apart the performance of clock corrections from ephemeris for each satellite continuously over each segment. However, real-time users must use a combination of clock and ephemeris data for navigation or timing. While the NGA estimates may be more accurate, errors against the NGA estimates in the broadcast ephemeris from a satellite, particularly radial errors, correlate with clock errors. Hence, indication of error or instability in these ephemeris data separate from clock corrections may not give a prediction of results for users.

We begin our study by looking at broadcast data errors as they are used, combining clock corrections errors and ephemeris errors as they are seen from a particular site. Our data here are from the BIPM GGTTS format [4], one point taken every 16 minutes. We use NIST, Boulder, Colorado for this site. We compute GPS time against UTC (NIST) using both broadcast and NGA postprocessed data. The difference of these leaves only the difference of the two estimates. The clocks and measurement noise cancel exactly. In this way, we are able to compare overall system performance before and after AEP.

For most of this study, we looked at the individual components of ephemeris and clock correction. The precise ephemerides are stored as the satellite coordinates for each 15-minute point. We evaluated the broadcast ephemerides at each 15-minute point over the data period matching these. We differenced the vector positions and cast them into radial, on-track, and cross-track directions for each of these times. The difference between the clock corrections, the broadcast minus the NGA, is effectively a double difference between satellite clocks and GPS time. This cancels both the clocks and the GPS time scale, leaving the broadcast clock correction error itself against the NGA estimates.

We obtained the broadcast ephemerides from IGS archives. These data sets occasionally have problems, notably at times of upload transitions. Data that were clearly outside the steady-state performance were compared with historical Notice Advisories to Navstar Users (NANUs). Large events for which there was no NANU indicate processing errors, probably in determining the exact broadcast ephemeris page. In either case, we edited data that were outside of steady-state performance. After differencing broadcast minus NGA data, we confined differences to the tolerances in Table 1 below.

Table 1. Tolerances used for editing data.

	Radial, m	On-Track, m	Cross-Track, m	Clock Correction, ns
Segment A	3.0	9.0	5.0	25.0
Segment B	4.0	13.0	8.0	25.0

RESULTS

GPS satellite vehicles (SVs) are generally referred to by use of two different numbering systems. There is the SV number (SVN), a unique number that is assigned to the satellite on launch. Satellites are also referred to by the pseudo-random code number (PRN) that satellite uses for identification by users. It is possible for a PRN to change, though this has almost never happened. SVNs are generally used by GPS control system personnel. PRNs are often applied by GPS users. We give both numbers in this report.

27-DAY PERIODIC VARIATION

This study revealed a clear periodic variation in broadcast ephemerides against NGA postprocessed of approximately 27 days. Before launching into the AEP study, we take a side-track to present some of these results. The effect first appeared in the DTDEV short-term evolution of TDEV of the radial broadcast error. The periodic effect does not appear in the radial error data themselves. It is overwhelmed by low-frequency variation in those data, such as flicker noise. Taking a first difference over time pre-whitens the flicker noise. The periodic variation is visible on a plot of radial velocity error. However, the periodic effect is in the deviation of the radial velocity, not in the mean values themselves. So the spectrum of the radial velocity error does not show the periodic effect. However, taking the standard deviation of the velocity error over some interval and plotting the evolution does have a variation of one, and in some cases two, cycles every 27 days, approximately. It does not appear to be one cycle every 28 days. The phases of the variations are different for different satellites. We see the period as a "line" in the spectrum of the standard deviation, as well as in the spectrum of the dynamic TDEV data. The periodic variation appears in plots of the 4-day dynamic TDEV, (DTDEV), as it does in the second difference over time of the radial error. This is similar to taking the standard deviation over 4 days of the radial acceleration error. Thus, the DTDEV plots of individual satellites in the full study can be used to view this periodic effect.

We give an example of this periodic effect using SVN/PRN 47/22 from plane E. The "line" for this periodic effect does not appear in the spectrum of the radial residual data, but does appear in the spectrum of the standard deviation and the spectrum of the DTDEV data. Though plots of the first and second differences of the radial residuals give a visual image of the periodic variation, the spectra of neither of those data sets have the spectral line indicating the 27-day period. Again, the effect is in the variation, not in the mean values themselves.

SVN 47/PRN 22, plane E

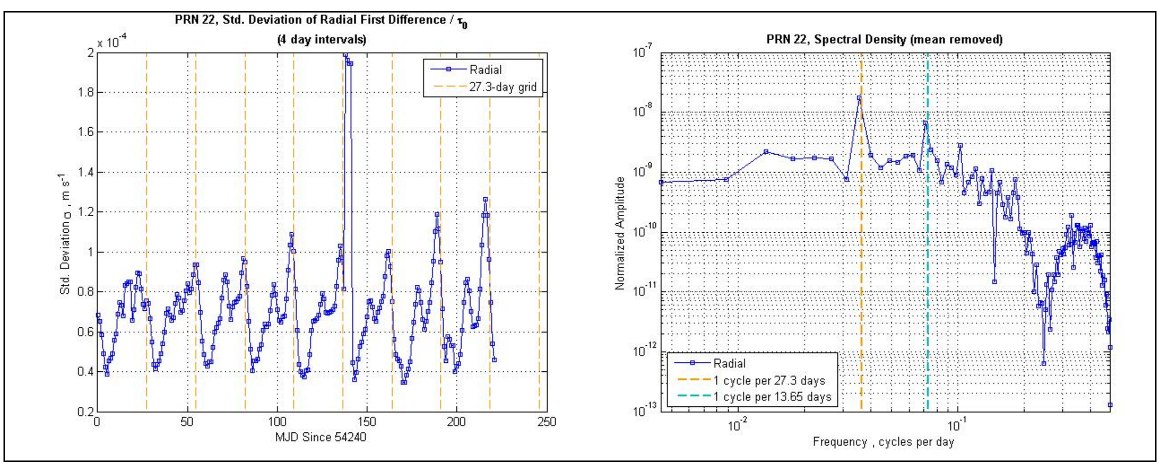

Figure 1. On the left are standard deviations from overlapping 4-day intervals of radial velocity errors. Successive 4-day intervals increase start dates by 1 day. The spectral density of these standard deviations with the mean removed is in the log-log plot on the right. The data are for SVN47/PRN22 from 20 May to 31 December 2007.

As for other SVs shown, eight cycles of the 27-day periodic effect are clear in the successive standard deviations of Fig. 1. There is also evidence of an event around 8-10 October. The spectrum of those data shows strong components at 1 cycle per 27.5 and 1 cycle per 13.7 days. The data set is 220 days long. The points of the computed spectrum closest to a 27.3 period have periods of 31.4, 27.5 and 24.4 days. Those closest to a 13.65-day period are 14.7, 13.7, and 12.9 days.

Figs. 2 and 3 below show the event around 8 to 10 October in the DTDEV data, as in the data of Fig. 1. The periodic effect is clear in the DTDEV values at 900 s. This reinforces that DTDEV plots of individual satellites can be used to view this periodic effect. The form of the periodic variation is different for different satellites. The pattern taken by this satellite is not the same as that in others. DTDEV plots as in Fig. 2 are available for each SV in the full report **[1]**.

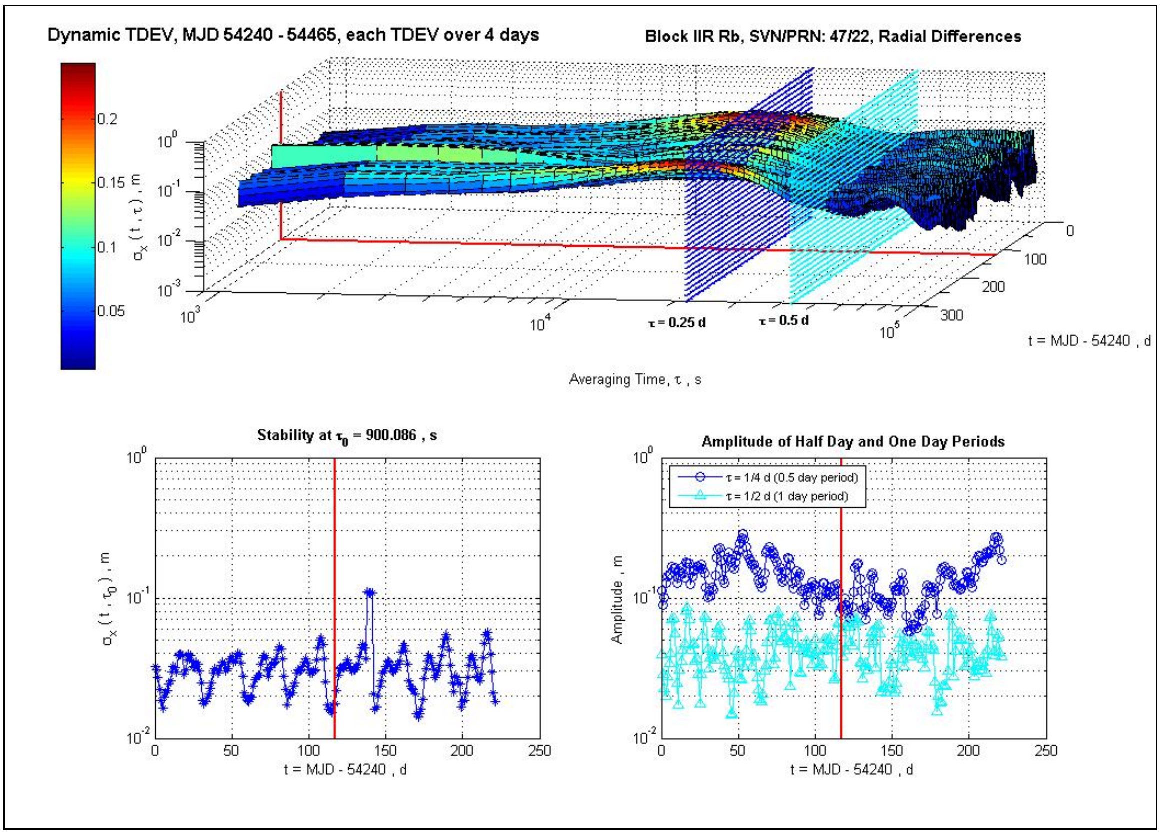

Figure 2. The Dynamic TDEV values of SVN/PRN 47/22 radial ephemeris data. The data are the differences: broadcast minus NGA antenna-phase-centered (APC) data projected in the radial direction. The upper plot is the full DTDEV surface. The lower left is a cross-section of that surface at the minimum spacing, 900 s. The lower right plot shows the evolution of the amplitude of the ½- and 1-day periodic components, computed from TDEV values using Eq. 1.

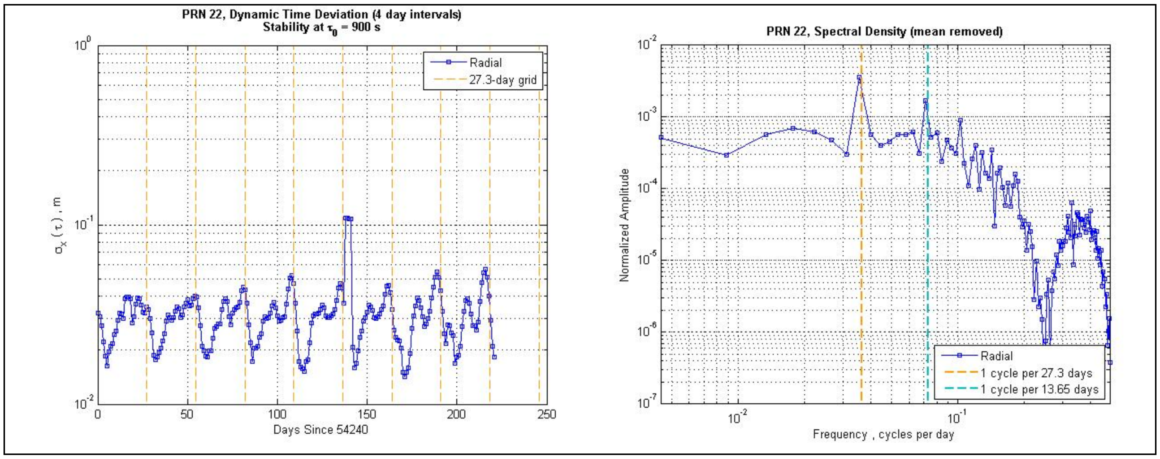

Figure 3. On the left are DTDEV values at the minimum spacing from overlapping 4-day intervals of radial velocity errors, as in Fig. 2. Successive 4-day intervals increase start dates by 1 day. The spectral density of these standard deviations with the mean removed is in the log-log plot on the right. The data are for SVN47/PRN22 from 20 May to 31 December 2007.

GPS TIME AGAINST UTC (NIST)

We start with an overall system characterization of the performance of the broadcast GPS parameters: satellite ephemeris and clock correction terms. Users are required to apply these terms to the measured pseudo-ranges in order to obtain GPS time against their local clock. To characterize these corrections in an overall system way, we take our measures of GPS time against UTC (NIST) using broadcast corrections and subtract the exact same measures, but using the NGA postprocessed terms. Thus, these data are the residuals of the broadcast terms as a user would apply them in Boulder, Colorado, referenced against the NGA postprocessed terms applied in an identical way. If we accept that the NGA data are more accurate, then these data are the errors in broadcast parameters as they affect users. This is a system-wide look, in that the data include all satellites when they are in view from Boulder, Colorado. The data corrections used match the GGTTS data taken at NIST, Boulder **[4]**. All satellites are tracked, and the data are reduced to one point every 16 minutes. Then at each 16 minute time-slot, we average across all satellites, giving us one averaged point every 16 minutes. Thus, we look at an average constellation performance of the broadcast parameters.

We look at these data in Fig. 4 below, from 1 January 2007 through 31 March 2008.

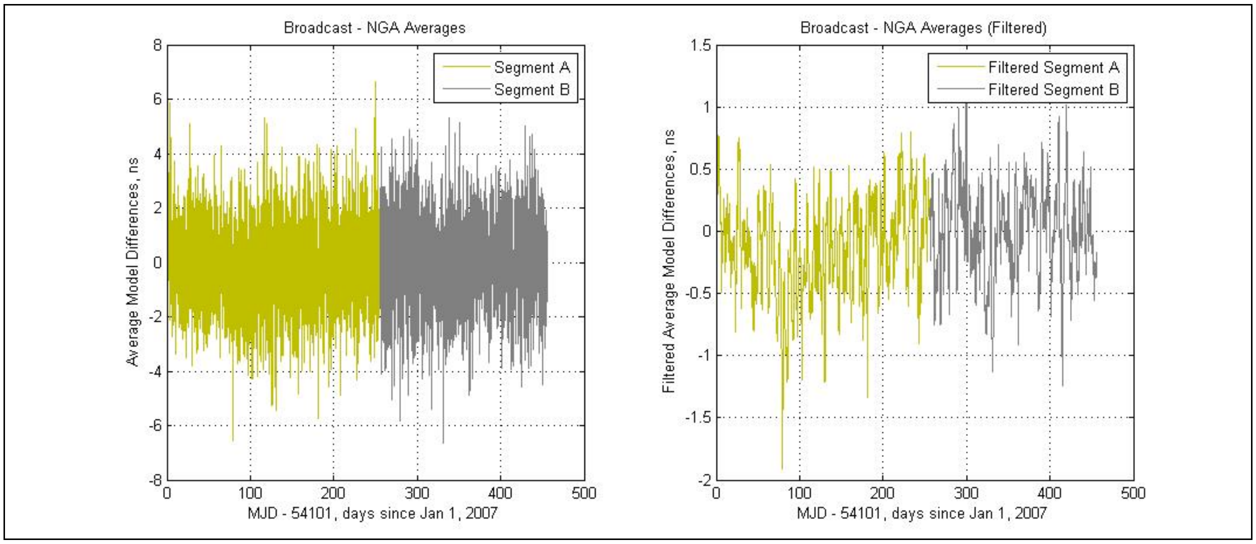

Figure 4. Broadcast minus NGA combined clock and ephemeris corrections as used at NIST, Boulder. Each 16-minute point is averaged over all satellites in view. Segment A is before AEP. Segment B is after. The left plot are the data, in the right plot we have low-pass filtered them to show the slower changes.

As discussed above, the data in Fig. 4 above show how average system errors in broadcast parameters contribute to users' pseudo-range errors. The plot on the right shows how the overall mean error moved from 1 January 2007 through 31 March 2008. This gives a visual display of the short-term behavior of this error.

TDEV analysis in Fig. 5 below gives the steady-state root-mean squared (RMS) variations in various forms: short-term, periodic variations, dominant noise types, over intervals before and after AEP. DTDEV gives the evolution of TDEV values in 10-day segments over this 1.25-year interval. The only significant change is in the amplitude of the 1-day period. This has increased in RMS by 12.5% from before AEP with a value of 0.64 ns, to after AEP with a value of 0.72 ns. A question that arises is whether this increase is a result of a short effect or truly an overall increase. The dynamic TDEV (DTDEV) for the entire data set below in Fig. 6 shows no significant outlier events.

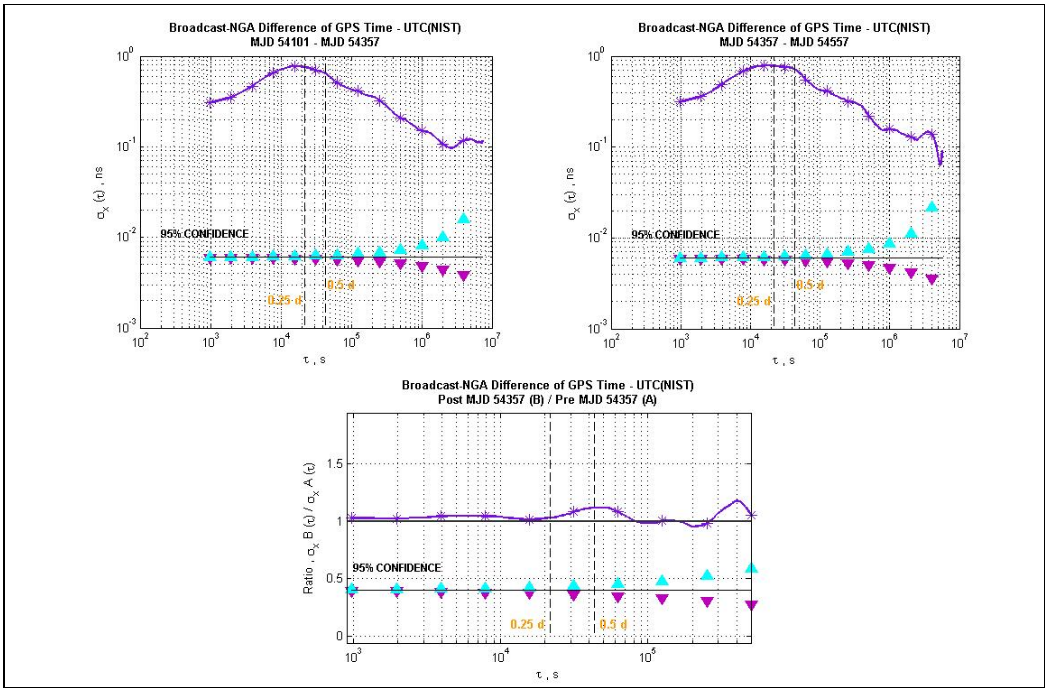

Figure 5. TDEV of the broadcast minus NGA combined clock and ephemeris corrections as used at NIST, Boulder. Each 16-minute point is averaged over all satellites in view. The upper left plot is before AEP, MJD 54537. The upper right plot is after. In the bottom plot, we have the ratio of TDEV values after AEP, divided by TDEV values from before.

There appears to be a worsening of all of the short-term effects right after AEP, MJD 54537. However, the ratio of TDEVs in Fig. 5 above shows that the RMS over the before and after segments only worsens in the 1-day periodic. We conclude that this is probably not due to the worsening period after AEP. If it is due to a short worsening period, a comparison to the next quarter, January through March 2008, should show a reduction of the 1-day period amplitude again.

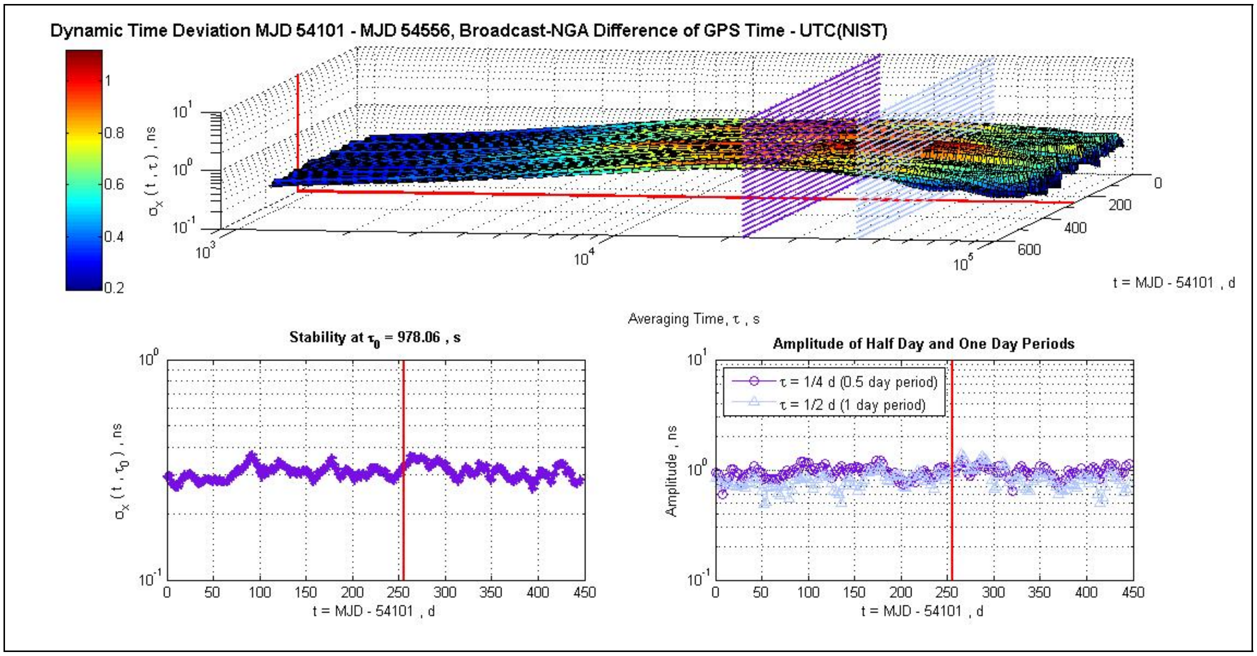

Figure 6. Dynamic TDEV (DTDEV) of the full data set in Fig. 4, the broadcast minus NGA combined clock and ephemeris corrections as used at NIST, Boulder. The bottom left plot shows the evolution of the short-term TDEV. The bottom right plot shows the amplitude of 0.5-day and 1-day periodic effects. The red line indicates the date of AEP.

STUDIES OVER BLOCKS

We group data into measures against Block IIA Cs, Block IIA Rb, Block IIR, and Block IIR-M satellites. TDEV values are computed for individual satellites over segments A and B separately. Individual satellite results are reported in tables here, and in more detail in the full report **[1]**. For the RMS values, we compute an RMS across individual SV TDEV values for each segment and for each satellite block. We do this for radial, on-track, and cross-track ephemeris components, and for clock corrections. We then compute the ratio of the RMS for segment B divided by the RMS for segment A. Values less than 1.0 show improvement from before to after AEP implementation, for that averaging period, τ. Values greater than 1.0 show a worsening of TDEV performance at the particular τ.

Block IIA Satellites with Cs Clocks

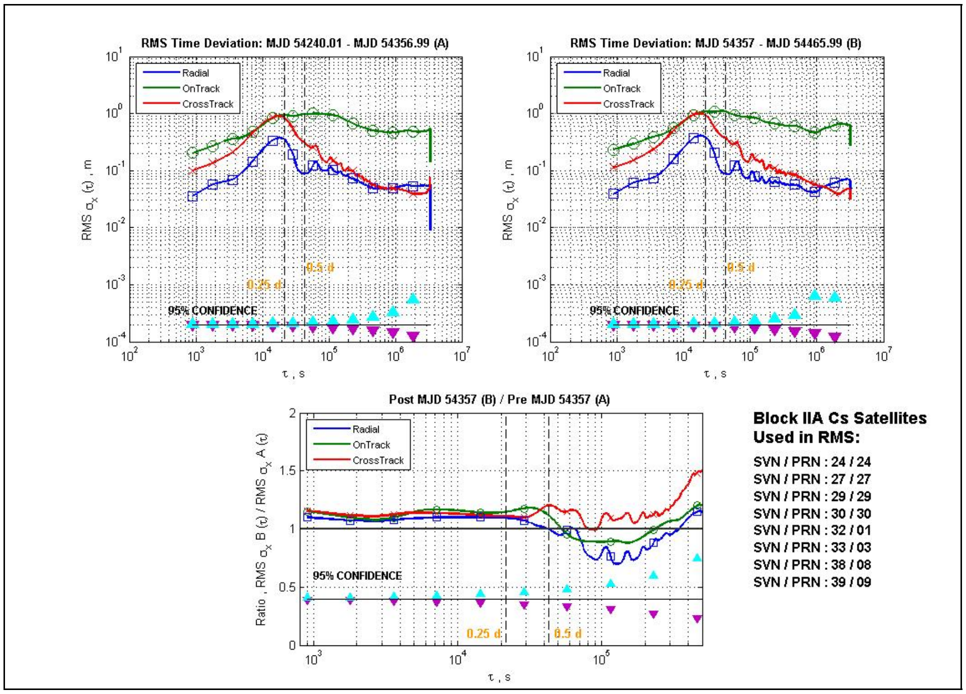

Figure 7. RMS TDEV ephemerides values taken over Block IIA satellites with Cs clocks. The upper left plot is before AEP, MJD 54537. The upper right plot is after. In the bottom plot, we have the ratio of TDEV values after AEP, divided by TDEV values from before.

Looking at the ratio of TDEV values in Fig. 7, we see about a 10 to 16% worsening of ephemerides for these Block IIA Cs satellites, for integration periods from 15 minutes out to 0.25 day. When we look at individual satellites **[1]**, we find there seem to be no specific large events that might cause this. We summarize these changes below in Table 2 for the RMS values taken over the individual SVs, as well as for the individual Block IIA Cs satellites themselves.

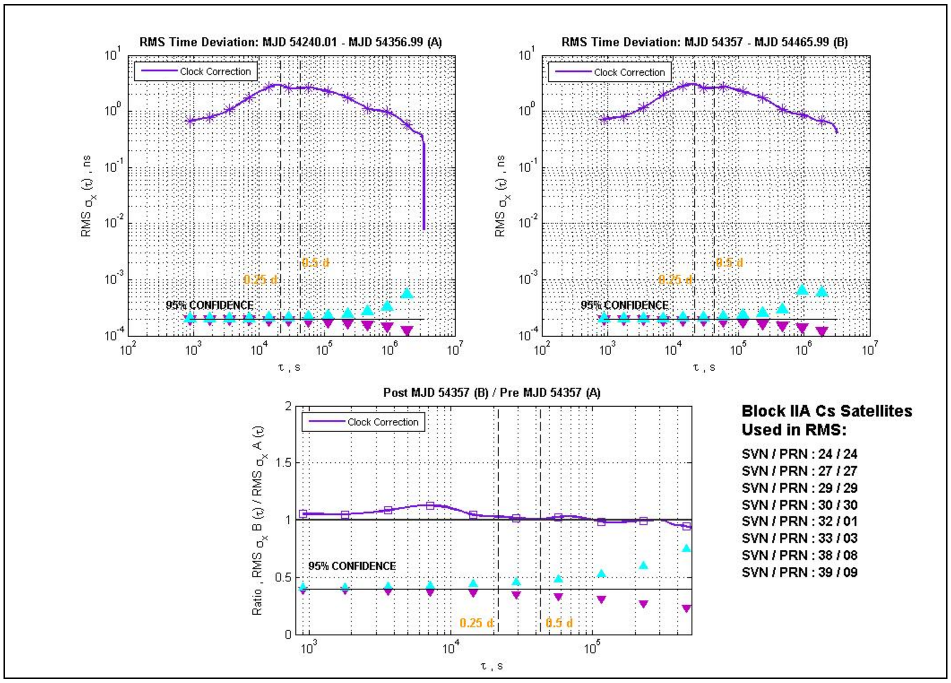

Figure 8. RMS TDEV clock correction values taken over Block IIA satellites with Cs clocks. The upper left plot is before AEP, MJD 54537. The upper right plot is after. In the bottom plot, we have the ratio of TDEV values after AEP, divided by TDEV values from before.

The TDEV ratios in Fig. 8 show little change in the clock correction deviations from before to after AEP for these Block IIA satellites. However, there is a worsening of 13% at an integration period of 2 hours.

We summarize the results for Block IIA Cs satellites in Table 2 below. We give the values after AEP divided by those before for short term at 900 s; for the value at ¼ day, which gives changes to any ½ day periodic effect; and for the value at ½ day, which gives changes to any 1-day periodic effect. Recall that the value 1.0 reflects no change. A value greater than 1.0 implies worsening by that proportion. A value less than 1.0 implies improvement by that proportion.

Table 2. Block IIA Satellites with cesium clocks. TDEV values after AEP divided by respective values before AEP.

SVN/PRN	Radial Ephemeris			On-track Ephemeris			Cross-track Ephemeris			Clock Correction		
	900 s short term	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**	**900 s short term**	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**	**900 s short term**	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**	**900 s short term**	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**
24/24	1.09	1.28	1.08	1.34	1.42	1.39	1.55	1.25	1.04	1.05	1.12	0.98
27/27	1.28	1.03	1.28	1.01	1.17	1.26	1.23	0.90	0.98	1.09	1.16	1.10
29/29	1.10	1.38	0.88	1.26	1.11	0.92	1.14	1.17	1.37	0.99	0.96	0.86
30/30	0.94	0.82	0.79	0.69	0.76	0.73	0.72	0.63	1.15	1.01	0.99	1.02
32/01	1.13	1.02	1.55	1.53	1.18	1.54	1.70	1.21	1.38	1.14	0.98	1.09
33/03	1.19	1.07	1.14	1.30	1.37	1.45	1.43	1.21	1.13	1.02	1.04	0.98
38/08	1.14	0.99	1.07	1.11	1.16	1.23	0.98	1.19	1.20	1.05	1.02	1.04
39/09	0.90	1.10	0.80	0.99	0.99	1.06	0.96	1.38	1.26	0.94	0.98	1.02
RMS	**1.10**	**1.09**	**0.99**	**1.15**	**1.15**	**1.10**	**1.16**	**1.11**	**1.20**	**1.05**	**1.03**	**1.01**

Fig. 9 shows a general worsening of ephemerides deviations after AEP in the Block IIA satellites with Rb clocks. The TDEV ratios in Fig. 10 show little change in the clock correction deviations from before to after AEP for these Block IIA satellites.

Block IIA Satellites with Rb Clocks

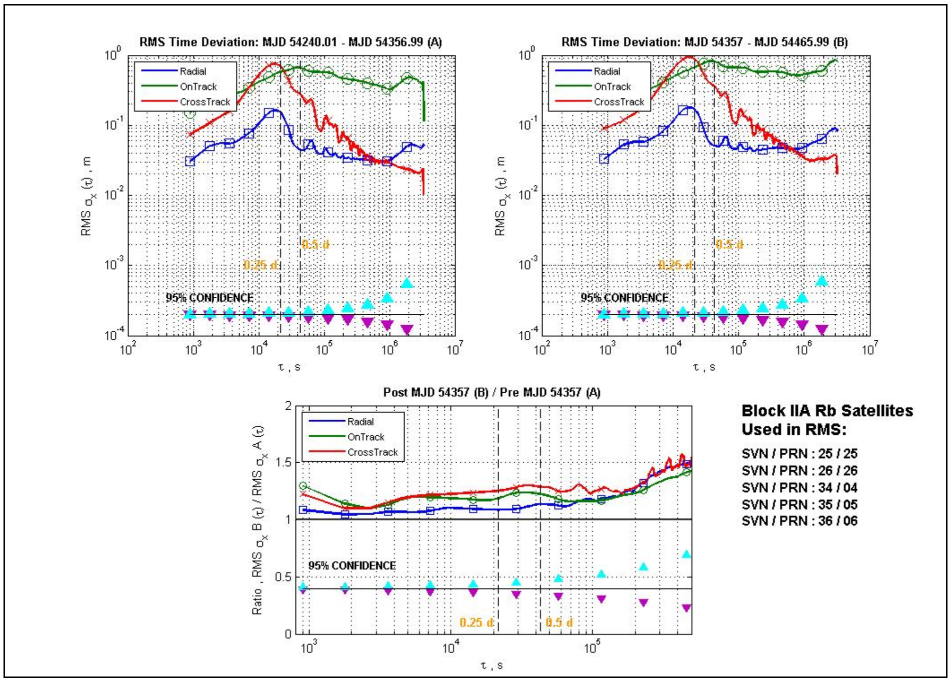

Figure 9. RMS TDEV ephemerides values taken over Block IIA satellites with Rb clocks. The upper left plot is before AEP, MJD 54537. The upper right plot is after. In the bottom plot, we have the ratio of TDEV values after AEP, divided by TDEV values from before.

We summarize the results for Block IIA Rb satellites in Table 3 below. We give the values after AEP divided by those before for short term at 900 s; for the value at ¼ day, which gives changes to any ½ day periodic effect; and for the value at ½ day, which gives changes to any 1 day periodic effect. Recall that the value 1.0 reflects no change. A value greater than 1.0 implies worsening by that proportion. A value less than 1.0 implies improvement by that proportion.

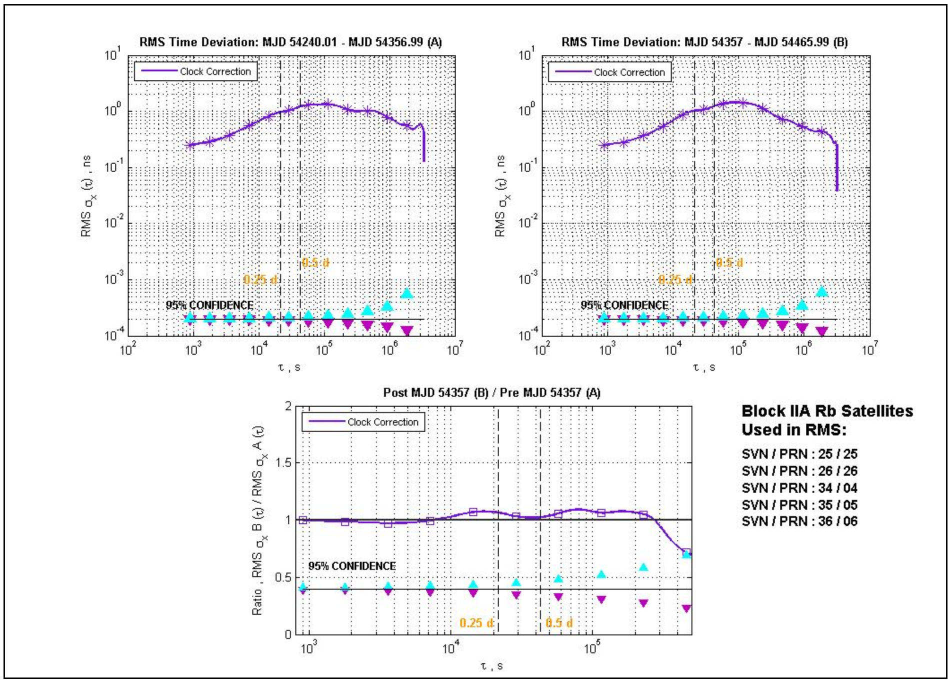

Figure 10. RMS TDEV clock correction values taken over Block IIA satellites with Rb clocks. The upper left plot is before AEP, MJD 54537. The upper right plot is after. In the bottom plot we have the ratio of TDEV values after AEP, divided by TDEV values from before.

Table 3. Block IIA satellites with rubidium clocks. TDEV values after AEP divided by respective values before AEP.

SVN/PRN	Radial Ephemeris			On-track Ephemeris			Cross-track Ephemeris			Clock Correction		
	900 s short term	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**	**900 s short term**	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**	**900 s short term**	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**	**900 s short term**	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**
25/25	1.04	1.02	0.96	1.08	1.02	1.01	0.99	1.12	1.26	1.21	1.26	1.13
26/26	1.10	1.48	1.65	1.53	1.70	1.58	1.46	1.90	1.49	1.02	1.07	0.95
34/04	1.24	1.16	1.21	1.63	1.34	1.39	1.75	1.65	1.39	1.05	1.24	1.09
35/05	0.74	0.49	0.68	0.71	0.62	0.80	0.63	0.62	0.99	0.60	0.64	0.71
36/06	1.46	1.60	1.41	1.54	1.63	1.52	1.52	1.12	1.34	1.00	1.00	1.05
RMS	**1.08**	**1.09**	**1.14**	**1.30**	**1.19**	**1.22**	**1.23**	**1.25**	**1.29**	**1.00**	**1.06**	**1.02**

Block IIR Satellites

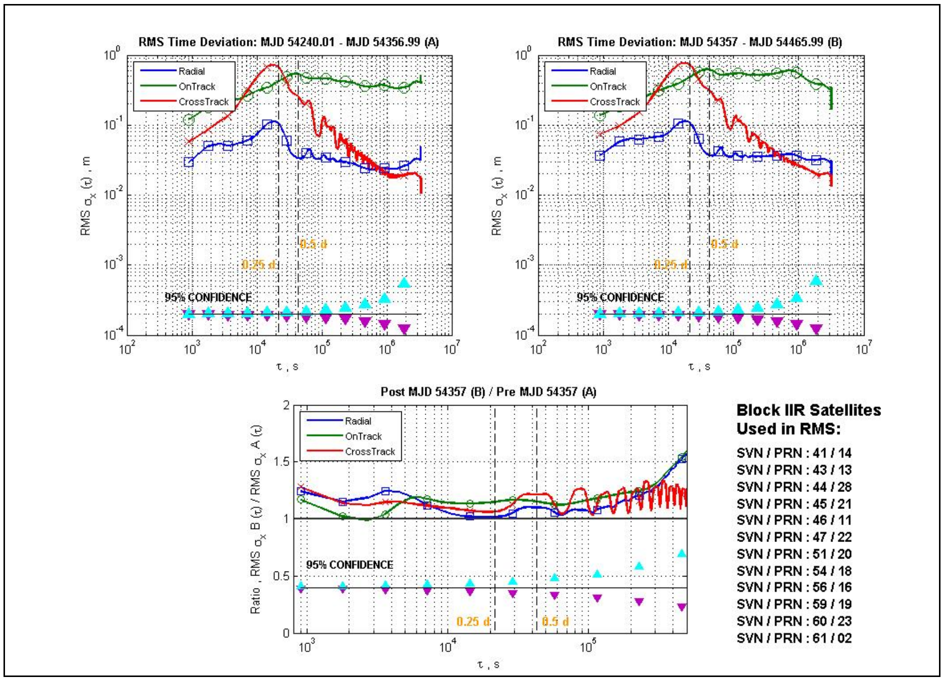

Figure 11. RMS TDEV ephemerides values taken over Block IIR satellites. The upper left plot is before AEP, MJD 54537. The upper right plot is after. In the bottom plot, we have the ratio of TDEV values after AEP, divided by TDEV values from before.

Fig. 11 shows a general slight worsening of ephemerides deviations after AEP in the Block IIR satellites. There was an event around 8-10 October 2008, during which most ephemerides for IIR satellites got significantly worse. An example of this can be seen in Fig. 2. We investigated the extent to which this short event affected the TDEV values in Fig. 11, and found little effect. There is indeed a clear anomalous event in many of the components around 9 October 2007, shortly after AEP implementation. However, after comparing TDEV values with and without that period, we saw little difference. This is because the data length after AEP is long enough, and we have edited the data to remove larger effects.

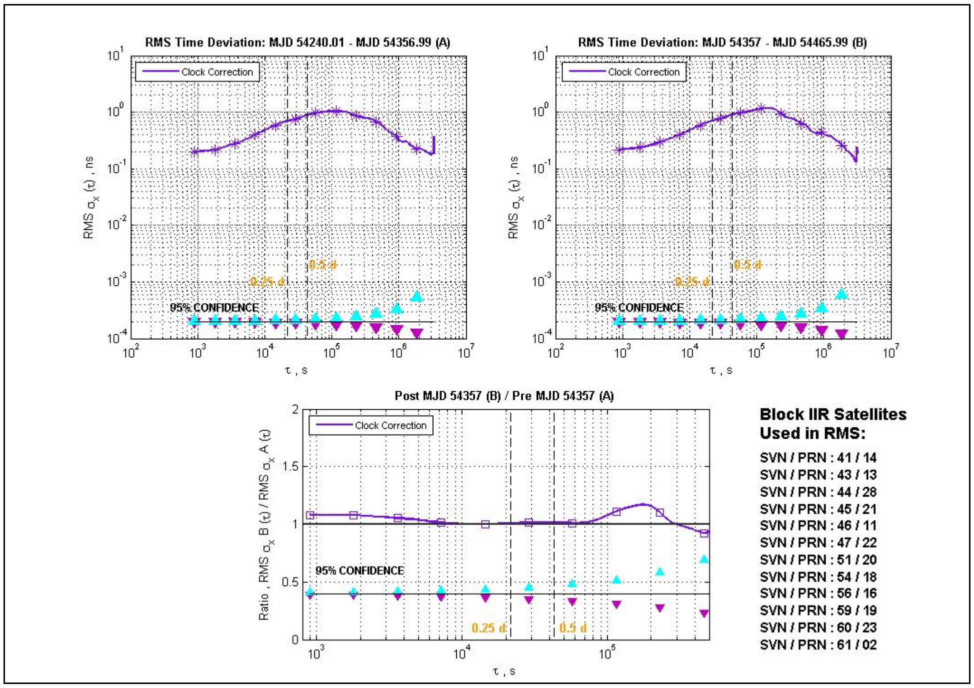

Figure 12. RMS TDEV clock correction values taken over Block IIR satellites. The upper left plot is before AEP, MJD 54537. The upper right plot is after. In the bottom plot, we have the ratio of TDEV values after AEP, divided by TDEV values from before.

The TDEV ratios in Fig. 12 show an increase of 8% in the short-term (900 s) clock correction deviations from before to after AEP, for these Block IIR satellites. The values at 0.25 and 0.5 days, corresponding to the periodic effects at 0.5 and 1.0 day, show little change.

We summarize the results for Block IIR satellites in Table 4 below. We give the values after AEP divided by those before for short term at 900 s; for the value at ¼ day, which gives changes to any ½ day periodic effect; and for the value at ½ day, which gives changes to any 1 day periodic effect. Recall that the value 1.0 reflects no change. A value greater than 1.0 implies worsening by that proportion. A value less than 1.0 implies improvement by that proportion.

Table 4. Block IIR Satellites. TDEV values after AEP divided by respective values before AEP.

SVN/PRN	Radial Ephemeris			On-track Ephemeris			Cross-track Ephemeris			Clock Correction		
	900 s short term	0.25 d value 1/2 day period	0.5 d value 1 day period	900 s short term	0.25 d value 1/2 day period	0.5 d value 1 day period	900 s short term	0.25 d value 1/2 day period	0.5 d value 1 day period	900 s short term	0.25 d value 1/2 day period	0.5 d value 1 day period
41/14	1.11	1.00	1.12	0.98	1.15	1.22	0.98	0.82	1.12	1.04	0.98	1.08
43/13	1.26	0.88	0.97	1.03	1.00	1.02	1.37	1.07	1.15	1.40	1.08	1.26
44/28	1.47	0.91	1.08	1.19	1.27	1.32	1.29	1.45	1.22	1.09	1.02	1.01
45/21	0.95	0.91	1.05	1.14	1.12	1.19	1.52	1.26	1.40	0.90	0.85	0.85
46/11	1.52	1.17	1.17	1.29	1.21	1.21	1.32	0.98	1.29	1.06	1.04	0.98
47/22	1.21	0.86	0.98	0.98	1.07	1.08	1.07	1.19	1.10	1.06	1.00	0.99
51/20	1.36	0.91	0.91	0.98	1.07	1.04	1.23	1.07	1.12	1.02	0.94	1.02
54/18	1.15	0.77	1.06	1.36	1.13	1.16	1.25	0.96	1.25	0.99	0.96	0.80
56/16	1.25	0.70	0.88	1.03	0.99	1.03	1.22	1.12	1.23	1.03	0.91	0.96
59/19	1.50	1.37	1.58	1.64	1.47	1.40	1.37	1.06	1.13	1.15	1.08	1.08
60/23	1.15	1.63	1.31	1.29	1.38	1.34	1.60	1.17	1.24	1.07	1.10	1.25
61/02	1.18	1.55	1.01	1.01	1.11	0.99	1.16	0.88	1.33	1.12	1.18	1.01
RMS	**1.24**	**1.02**	**1.10**	**1.17**	**1.15**	**1.15**	**1.28**	**1.07**	**1.21**	**1.08**	**1.01**	**1.02**

Block IIR-M Satellites

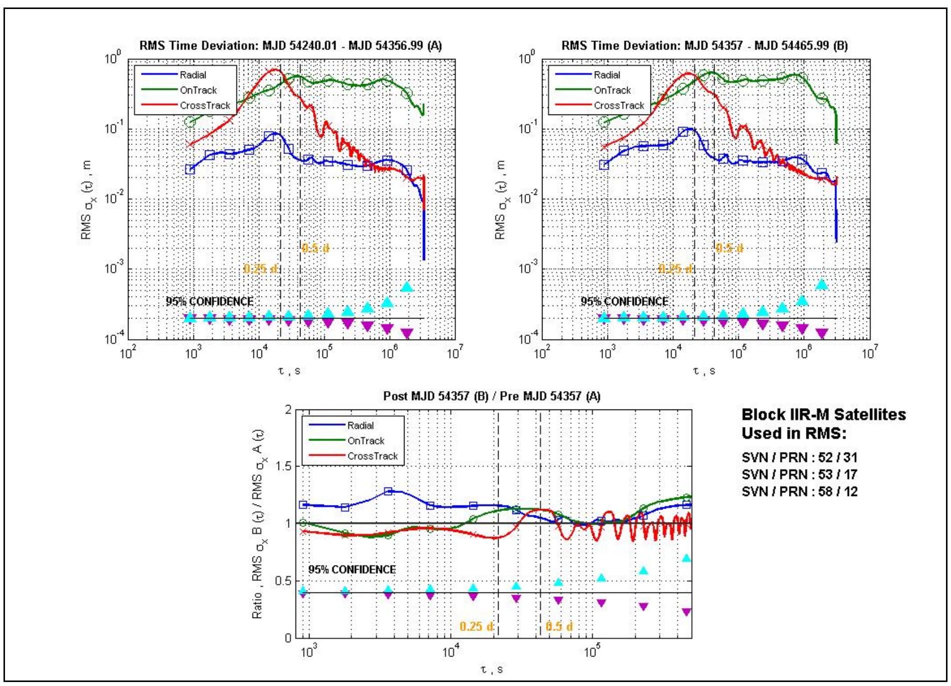

Figure 13. RMS TDEV ephemerides values taken over Block IIR-M satellites. The upper left plot is before AEP, MJD 54537. The upper right plot is after. In the bottom plot, we have the ratio of TDEV values after AEP, divided by TDEV values from before.

We see mixed results in Fig. 13. There is some improvement and some worsening of ephemerides deviations after AEP in the RMS over the three Block IIR-M satellites available for study from MJD 54240 (20 May 2007). We summarize the numerical results in Table 5 below.

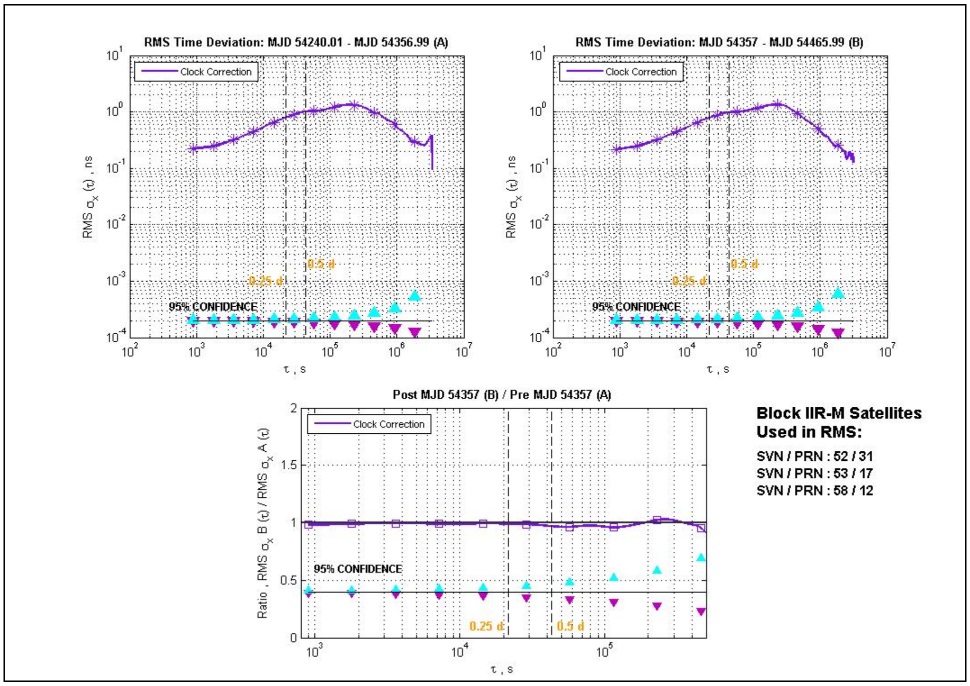

Figure 14. RMS TDEV clock correction values taken over Block IIR satellites. The upper left plot is before AEP, MJD 54537. The upper right plot is after. In the bottom plot, we have the ratio of TDEV values after AEP, divided by TDEV values from before.

The TDEV ratios in Fig. 14 show little change in the clock correction deviations from before to after AEP, three Block IIR-M satellites available for study from MJD 54240 (20 May 2007).

We summarize the results for Block IIR-M satellites in Table 5 below. We give the values after AEP divided by those before for short term at 900 s; for the value at ¼ day, which gives changes to any ½ day periodic effect; and for the value at ½ day, which gives changes to any 1 day periodic effect. Recall that the value 1.0 reflects no change. A value greater than 1.0 implies worsening by that proportion. A value less than 1.0 implies improvement by that proportion.

Table 5. Block IIR-M Satellites. TDEV values after AEP divided by respective values before AEP.

SVN/PRN	Radial Ephemeris			On-track Ephemeris			Cross-track Ephemeris			Clock Correction		
	900 s short term	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**	**900 s short term**	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**	**900 s short term**	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**	**900 s short term**	**0.25 d value 1/2 day period**	**0.5 d value 1 day period**
52/31	1.26	0.99	0.99	1.00	1.21	1.22	0.93	1.10	1.20	0.95	0.98	0.97
53/17	1.01	1.47	1.54	1.09	1.33	1.32	0.98	1.02	1.11	1.01	1.01	1.00
58/12	1.19	1.18	0.84	0.97	0.92	0.92	0.91	0.66	1.06	0.93	0.94	0.76
RMS	**1.16**	**1.16**	**1.05**	**1.01**	**1.11**	**1.12**	**0.93**	**0.87**	**1.12**	**0.98**	**0.99**	**0.97**

CONCLUSIONS

Generally, we find evidence of some worsening in ephemerides from before to after AEP. RMS 15-minute stabilities across satellite blocks worsened by 8% to 30%. Twelve-hour and 24-hour periodic behavior generally worsened. Though results vary by satellite block and ephemeris component, the best was an improvement of 13%, and the worst was a worsening of 29%. Results vary significantly by individual satellite. By contrast, broadcast clock correction values generally showed little change from before to after AEP.

In the process of this study, we found evidence of an approximate 27-day periodic variation in the difference: broadcast minus NGA radial ephemeris of all satellites studied. The periodic variation is not evident in the difference data themselves, but in the broadcast minus NGA radial velocity and acceleration data. The effect is a periodic variation in the magnitude of the deviation. It can be seen in the 900-s Dynamic TDEV values of the radial differences, the evolution of the TDEV values at 900 s.

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