MCS ZERO AGE OF DATA MEASUREMENT TECHNIQUES

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Abstract

Advances in 1999 provided Boeing GPS navigation support contractors the ability to transfer, archive, and manipulate Master Control Station (MCS) Kalman filter data. Since then, these data have been reported in the System Performance Measurement and Analysis (SPMA) quarterly report, and used to assess GPS performance through a variety of metrics, including Zero Age of Data error. This error, in part a byproduct of the real-time, predictive nature of the MCS Kalman filter, affects many navigation and time transfer users.

This paper describes the methodology by which the MCS Kalman filter states are compared to "truth" sources such as NIMA and IGS to calculate Zero Age of Data error. Results show that typical Zero Age of Data errors vary from spacecraft to spacecraft and over time. Also examined are on-orbit frequency standard, ephemeris, and solar events and their associated impacts on Zero Age of Data error. Future efforts to improve Zero Age of Data error are explored. Conclusions reveal that considerable insight is gained by calculating and observing Zero Age of Data characteristics in the effort to understand and reduce this error source in the future.

I. INTRODUCTION

This paper has two goals: First, to educate the Timing community about the availability of GPS Signal-in-Space Performance reports through a Web-based SPMA reporting system; and second, to examine the quality of GPS MCS estimation through the SPMA Zero Age of Data (ZAOD) User Range Error (URE) metric. The ZAOD URE is important to the timing community because it represents the highest quality ephemeris and timing the GPS Navigation Message can provide to the GPS User.

Beginning in June, 1999, Boeing Navigation Payload Support staff began digitally transferring ERD and several other data types pertinent to GPS Signal-in-Space performance from the OCS into Unclassified navigation performance archives. In the Autumn of 2000, the GPS JPO commissioned Boeing to establish a set of OCS metrics to be collected, archived, and reported, which would serve as a performance baseline against which GPS upgrades could be measured. In response to this task, Boeing hosted a group of GPS Community analysis experts to determine the performance metric list and reporting frequency. The result was the establishment of GPS System Performance Measurement and Analysis (SPMA), which hosts Web-based quarterly reports on the GPS Sustainment Information

Management System (GSIMS). The metrics reported in SPMA come from a variety of sources (OCS, NIMA, NRL, 2SOPS, IGS, 50th Comm Sq, and others). The list of SPMA reported metrics is included in Table 1.

SPMA Metrics List		
Events Summary	System Response Times	URE
Beta Angle	PDOP	Zero Age of Data URE
Outage Summary	NAVSOL	Measurement Residuals
Contacts Summary	URA	Earth Orientation
ERD	GPS Timescale	
Upload Counts	ORD	

Table 1. SPMA Metrics List

The SPMA Reports complement the Reliability, Maintainability, and Availability (RMA) reports in supporting assessment and prognoses for the GPS system. It can be seen from the metrics list that SPMA is concerned predominantly with GPS Signal-in-Space (SIS) Performance. The SPMA parameters give visibility into internal Control Segment/Space Segment performance, as well as insights into how the OCS is performing with regard to external standards (NIMA, IGS, NRL). The data group is intended to give indications of how well the estimation and prediction natures of PVT services are performing. Along with the SPMA data, the GSIMS Web site also contains a thorough SPMA Parameters definitions document, along with copies of the GPS Spacecraft Contractors Quarterly Reports for correlation analyses **[1]**.

An example of the utility of the long-term performance archive is demonstrated in the constellation configuration plot and long-term ERD trend plot shown in Figure 1. This figure shows the constellation makeup and ERD performance trends by GPS generation over the past 9 years, and, given the projected replenishment estimate, it shows the expected ERD performance improvements 6 years into the future. System planners can make good use of these data in evaluating the merits of proposed improvements. Several earlier papers from the Boeing group have analyzed the performance exhibited by the predictive nature of the OCS. This paper looks at the accuracy of the OCS estimation process, as exhibited by Zero Age of Data User Range Error (ZAOD URE).

II. ZERO AGE OF DATA ERROR CALCULATION

Signal-in-Space User Range Error (URE) is a metric that gives insight into how the error in the satellite's broadcast navigation message will contribute to the GPS user's overall error. Thus, URE relates the SV Nav Message to some truth source. Zero Age of Data URE (or ZAOD URE) actually compares the MCS estimation quality to some truth source (we typically use NIMA precise ephemeris and clock as the truth source). The algorithm SPMA uses to construct ZAOD instantaneous URE is described in the SPMA Definitions document and included below **[2]**.

Letting $\vec{\delta}_{Eph}$ be the SV position error vector, δ_{Clock} be the clock error, which points along the Line-Of-Sight unit vector ($\vec{\mathbf{LOS}}$) from any user on the surface of the Earth visible to the SV, the SIS-URE for any such user is given by

$$SIS - URE = \left(\vec{\delta}_{Eph} \bullet \mathbf{L\vec{O}S}\right) - \left(c * \delta_{Clock}\right) \tag{1}$$

where c is the speed of light constant. The squared mean of the SIS-URE is defined by integrating the square of the above equation over all users visible to the SV (i.e., over the visible surface of the Earth).

$$\overline{SIS - URE}^{2} = \frac{1}{S_V} \int_S \left(\vec{\delta}_{Eph} \bullet \mathbf{L\vec{O}S} - c\delta_{Clock}\right)^2 dS \tag{1}$$

where S_V is the visible surface given by

$$S_V = \int_S dS = \int_0^{\beta_m} (R_E \cdot \sin\beta)\, d\beta \cdot \int_0^{2\pi} R_E d\phi \tag{2}$$

which then becomes

$$S_V = 2\pi R_E^2 (1 - \cos\beta_m) \tag{3}$$

where β is the user colatitude with respect to SV nadir, β_m is the maximum colatitude, and R_E is the WGS84 Earth radius. Note that cos β_m is the equal to sin α_m, where α_m is one half the angle subtended by the Earth at the SV (or Earth chord half angle); see Figure 2 for the angles.

Evaluating equation (2) across the area show in Figure 2 yields

$$\begin{aligned}\overline{SIS - URE}^{2} &= (g(y)\delta_{Radial} - c\delta_{Clock})^2 + \left(f(y) - g(y)^2\right)\delta_{Radial}^2 \\ &+ \frac{1}{2}(\delta_{Along-track}^2 + \delta_{Cross-track}^2)\, h(y)\end{aligned} \tag{4}$$

where δ_{Radial}, $\delta_{\text{Along-track}}$, and $\delta_{\text{Cross-track}}$ are the Radial, Along-track, and Cross-track components of $\vec{\delta}_{Eph}$, δ_{Clock} is the magnitude of $\vec{\delta}_{Clock}$, and

$$f(y) = \frac{(1-y)(1+y)^2}{8y} \ln\left(\frac{1+y}{1-y}\right) + \frac{(1-y)(3+2y)}{4} \tag{5}$$

$$g(y) = \frac{2(1+y)}{3y}\sqrt{1-y^2} - \frac{(1-y)(2+y)}{3y} \tag{6}$$

$$h(y) = -\frac{(1-y)(1+y)^2}{8y} \ln\left(\frac{1+y}{1-y}\right) + \frac{1+y+2y^2}{4} \tag{7}$$

with

$$y = \frac{R_E}{R} = \frac{R_E}{(a^2)} = \cos\beta_m = \sin\alpha_m \tag{8}$$

where R is the nominal distance of the SV to the user (a^2; a is the square root of the mean semi-major axis GPS satellite (5153 $m^{½}$)) and R_E is the WGS-84 Earth radius (6378137 m). Using these values with (9) yields that $\alpha_m \approx 13.9°$ and the SIS-URE in equation (5) can be simplified to:

$$SIS-URE = [c^2\delta^2{}_{Clock} + 0.96*\delta^2{}_{Radial} + 0.02*\delta^2{}_{Horizontal} - 1.96c*\delta_{Radial}*\delta_{Clock}]^{1/2} \tag{9}$$

where δ_{Clock} , δ_{Radial} , and $\delta_{Horizontal}$ are the OCS NAV Message minus the NIMA Precise Ephemeris clock bias and the Radial and Horizontal Ephemeris differences, respectively. The Horizontal Ephemeris is the quadrature addition of $\delta_{\text{Along-track}}$ and $\delta_{\text{Cross-track}}$. Equation (10) projects the ephemeris errors across all visible terrestrial users.

The Instantaneous URE at a time t_k is defined as the projection of the OCS NAV Message versus NIMA Precise Ephemeris differences across all visible terrestrial users over the surface of the Earth. Instantaneous URE is decomposed into ephemeris (with δ_{Clock} equal to zero in (10)), clock (absolute value of δ_{Clock}), and total (all components as shown in (10)).

$$SIS-URE_{Eph} = \left[0.96*\delta^2_{Radial} + 0.02*\delta^2_{Horizontal}\right]^{½} \tag{10}$$

$$SIS-URE_{Clock} = \left|c*\delta_{Clock}\right| \tag{11}$$

III. RESULTS OF DATA ANALYSIS

Because the GPS constellation consists of 28 satellites (as of 2nd Quarter, 2003), the individual satellite outliers do not significantly affect the overall constellation RMS values for each day. Figure 3 shows daily Zero Age of Data values for the entire GPS Constellation.

Note that the daily RMS values usually vary by only a fraction of a nanosecond (ns), while the monthly variation is quite a bit less. April's constellation RMS Zero Age of Data value was 2.0 ns, May's value was 2.2 ns, and June's value was 2.0 ns. These numbers are fairly typical from month to month, with the largest value in the last year being 2.9 ns in December of 2002 (the smallest was 2.0 ns in April 2003). The event that caused the outlier on Day 146 (May 26, 2003) will be addressed in Section IV.

A wider variation in Zero Age of Data is apparent when looking at the constellation satellite by satellite. Figure 4 shows the RMS Zero Age of Data by satellite for the second quarter of 2003.

Two factors predominate in the accumulation of Zero Age of Data: ephemeris perturbations and clock error. In Figure 4, it can be seen that problems estimating one often leads to problems estimating the other. Although the specifics of large Zero Age of Data are left to Section IV, it can be observed that sub-optimal MCS modeling tends to bleed over from ephemeris to clock and vice versa.

SVN 32 uses a cesium frequency standard that is near the bottom of the GPS constellation list in terms of stability (although it is still well within spec). SVN 32 also has no known ephemeris problems (e.g. unusual solar array configuration or occasional small thruster firings). In Figure 4, SVN 32 is shown to have both large clock and ephemeris components of Zero Age of Data. Likewise, SVN 26 has very low clock and ephemeris components of Zero Age of Data, although its ephemeris states are presumably no more unstable than the orbit of SVN 32. This difference is largely due to the fact that SVN 26's rubidium frequency standard is very stable and has one of the best 1-day Hadamard deviation values in the GPS constellation.

Figure 5 shows the ZAOD URE performance on a daily basis, broken down into clock and ephemeris components. It is worth noting that the overall URE is consistently 0.5 − 1 ns less than the clock and ephemeris UREs. This is due to Kalman filter aliasing – the inclusion of clock effects into ephemeris states and vice versa. An extreme instance of Kalman filter aliasing (SVN 36) will be discussed in Section IV.

Figure 6 shows how the Zero Age of Data changes over the course of a day. On this particular day, SVN 26 was performing at a typical level. Notice that the Zero Age of Data varies from a low of 0.1 ns to a high of 2.6 ns. The RMS for this day was 0.9 ns. Although it is tempting to try to correlate Zero Age of Data to the number of monitor stations producing measurements (or in this case, determine an inverse correlation), the correlation for this satellite on this day is a moderate value of –0.20 **[3]**.

IV. ZERO AGE OF DATA OUTLIERS

As Figures 3, 4, and 5 show, there are several significant outliers present in the quarterly reports. There is usually a well-known reason why the actual clock or ephemeris states have larger than normal deviations from the states predicted by the MCS Kalman filter. However, due to limitations caused by the satellite's advanced age or failing components, the poorer performance is often accepted as the price of keeping the satellite operational.

Satellites 13, 15, and 17 are the oldest satellites in the GPS constellation. As Block II satellites, they were the first production satellites to follow the Block I research and development phase. They have proven to be valuable contributors to the GPS constellation, but their advanced age caused them to be operated in a degraded manner during most of the 2nd quarter of 2003. During this time, they were configured to allow for occasional thruster firings. These thruster firings resulted in small changes to their operational orbit. Not only did these ephemeris perturbations degrade the broadcast navigation message, they also prevented accurate modeling and caused an increase in the Zero Age of Data.

Figure 7 shows the effects of a pair of thruster firings that precipitate a run-off in the Zero Age of Data for SVN 17. After the small impulse, the MCS ephemeris state estimates begin to diverge from the actual orbit states. About 5 hours after the thruster event, the 2SOPS operator actively intervened in the state estimation process. Only after the MCS Kalman Filter was directed to reprocess the data did the Zero Age of Data return to a more normal value. It should be noted here that the run-off in Zero Age of Data was *not* due to negligence. Per 2SOPS operational strategy, the operators choose to allow the state estimate to drift off and perform corrections after the fact. To perform filter manipulation in real time could prevent the operator from gaining insight into current performance and might constitute an unacceptable integrity risk.

A poorly performing frequency standard can also have a detrimental effect on the Zero Age of Data. Unlike the example used above, the troubles associated with an unstable frequency standard can rarely be traced to a single discrete change in the Kalman filter states. A period of increased instability can continue for an uncertain period of time. A given episode of instability may end after a short time, or can signal the end of the useful life of the clock.

Figure 8 shows how a malfunctioning frequency standard can create large errors in the Zero Age of Data URE. On May 26, 2003, SVN 27 experienced some erratic frequency movement. Because the MCS Kalman filter did not adapt quickly to these changes, the ZAOD URE quickly ran off to approximately 200 nanoseconds. Although the output frequency returned to its nominal value for two short periods, the MCS operators chose not to intervene until they were fairly certain the episode had stopped (the satellite navigation message was set Unhealthy early in this episode). After some Kalman filter manipulation, the ZAOD URE returned to a near-zero value.

SVN 36 has a fairly large periodic in the output of its cesium frequency standard (see Figure 9). Although this periodic has been evident for years, the method by which the GPS Kalman filter models this periodic to provide a usable, accurate timing signal may be less well known.

The MCS Kalman filter models satellite frequency standard systematics using a polynomial (1st order for cesium frequency standards, 2nd order polynomial for rubidium frequency standards). As Figure 9 shows, this linear fit (SVN 36 uses a cesium frequency standard) does not allow for the relatively large variation that occurs with a near-12 hour periodic. Since the same ranging measurements are used by the MCS Kalman filter to derive both clock and ephemeris state estimates, effects of the near-12 hour periodic shows up in the ephemeris estimate. This ephemeris-clock Kalman filter aliasing works to provide ranging signals more accurate than what would be possible from a linear clock estimate and an ephemeris model which more strictly resembled "truth."

Figure 10 demonstrates the results of the clock-ephemeris Kalman filter aliasing for SVN 36. The Total ZAOD URE is consistently lower than either the clock or the ephemeris component. In this case, the periodic nature of the clock is modeled (although not perfectly) by the ephemeris component of the MCS Kalman filter. Other frequency standards also show periodic behavior, but none is as pronounced as the one on SVN 36.

V. IMPROVING ZERO AGE OF DATA

Current Operational Environment

As seen in Section IV, ZAOD URE varies from spacecraft to spacecraft and is impacted by several different factors. Monitor station visibility is a key factor in Kalman filter estimation. More Monitor Station-to-spacecraft visibility yields more measurements for the Kalman filter, which usually produces more accurate clock and ephemeris state estimates. Monitor station visibility varies from spacecraft to spacecraft and depends on the vehicle orbit. Better estimation results are realized when all monitor stations are available for operational use. Cases where a monitor station is out for maintenance or down due to any reason can negatively affect ZAOD URE.

From a spacecraft perspective, ZAOD URE is best when the spacecraft bus is functioning optimally and a stable frequency standard is operational. Spacecraft suffering from the need to perform momentum dumping through thruster firing or SVs having solar arrays in a non-standard configuration may at times experience sub-optimal ZAOD URE. A satellite whose frequency standard's stability is less than desired also increases ZAOD URE.

Future Enhancements

Looking to the future, there are GPS system enhancements on the horizon that will improve ZAOD URE. Most obviously, improved spacecraft performance will have a positive effect on ZAOD URE. As more of the older Block II/IIA spacecraft are replaced with IIR and eventually IIF spacecraft, an improvement will be realized in on-orbit frequency standard stability, which will have a positive impact on ZAOD URE. In addition to improved frequency standard performance, the launch of Block IIR and Block IIF satellite will allow the disposal of older satellites with spacecraft bus problems. The current Air Force schedule calls for the first Block IIF spacecraft to be launched in April 2006. Figure 1 shows the changing GPS constellation composition by spacecraft block.

The transition from the currently operating Legacy Control Segment to the AEP Control Segment architecture will provide an improvement to ZAOD URE. This improvement will result largely from the addition of NIMA Monitor Station measurements to the MCS Kalman filter. Not only will the additional Monitor Stations provide a tremendous system integrity improvement, but also the additional measurement and the expanded measurement geometry will benefit Kalman filter estimation processing and improve ZAOD URE. In addition, the ability of the AEP Kalman filter to perform its estimation task with reduced partitioning simplification can translate into possible future ZAOD URE improvement **[4]**.

OCS modeling improvements, such as an improved JPL solar pressure model, will allow for more accurate ephemeris modeling and bring about ZAOD URE improvement. Earth model and earth rotation model improvements will also allow for more accurate ephemeris modeling. As Figure 4 demonstrates, improving the accuracy of either clock or ephemeris modeling tends to improve the modeling of the other **[5]**.

VI. CONCLUSION

The SPMA report, available to the GPS community through the JPO, is providing insight into Zero Age of Data performance, as well as other useful system performance metrics. Typical ZAOD URE performance is in the 2.0 – 2.5 ns range, but this varies from spacecraft to spacecraft and day to day. Although efforts are made to minimize the occurrence and effects of anomalous behavior, outliers can reach the hundreds of nanoseconds. These are caused by unpredictable ephemeris perturbations as well as frequency standard abnormalities. ZAOD URE performance will improve as older spacecraft are replaced with newer, better performing satellites with more stable frequency standards and bus configurations. Control Segment enhancements such as the addition of NIMA monitor stations will also improve Zero Age of Data performance. The SPMA team will continue to monitor and report ZAOD URE in the system-wide effort to increase the knowledge and understanding of GPS performance.

VII. ACKNOWLEDGMENTS

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Dr. Art Dorsey, Lockheed Martin
SPMA Contributors: NIMA, NRL, 2SOPS, Lockheed Martin, IGS
The Boeing GPS Operations Team at Schriever AFB, CO
The Men and Women of 2 SOPS

VIII. REFERENCES

[1] SPMA Working Group Technical Interchange Meeting Presentation, 17 May 2001.

[2] SPMA Definitions Document, 5 August 2003.

[3] SPMA Quarterly Report, 2003 Quarter 2.

[4] C. H. Yinger, W. A. Feess, V. Nuth, and R. N. Haddad, 2003, *"GPS Accuracy Versus Number of NIMA Stations,"* in Proceedings of ION GPS/GNSS-2003 Conference, 9-12 September 2003, Portland, Oregon, USA (Institute of Navigation, Alexandria, Virginia), pp. 1526-1533.

[5] Legacy Accelerated Accuracy Improvement Initiative (A-AII) Technical Kickoff Presentation, Boeing/Lockheed Martin, 21 October 2003.

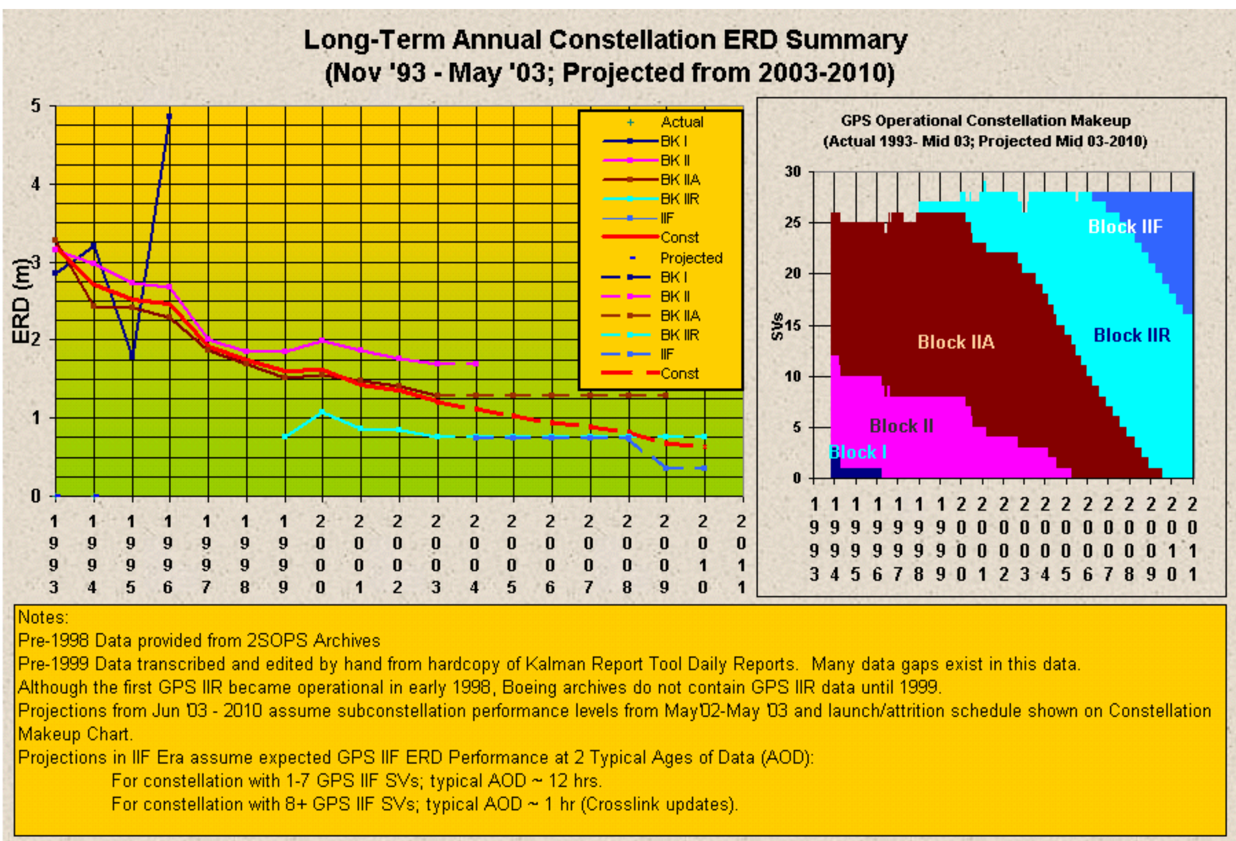

Figure 1. Long-term MCS ERD summary & constellation configuration 1994-2011.

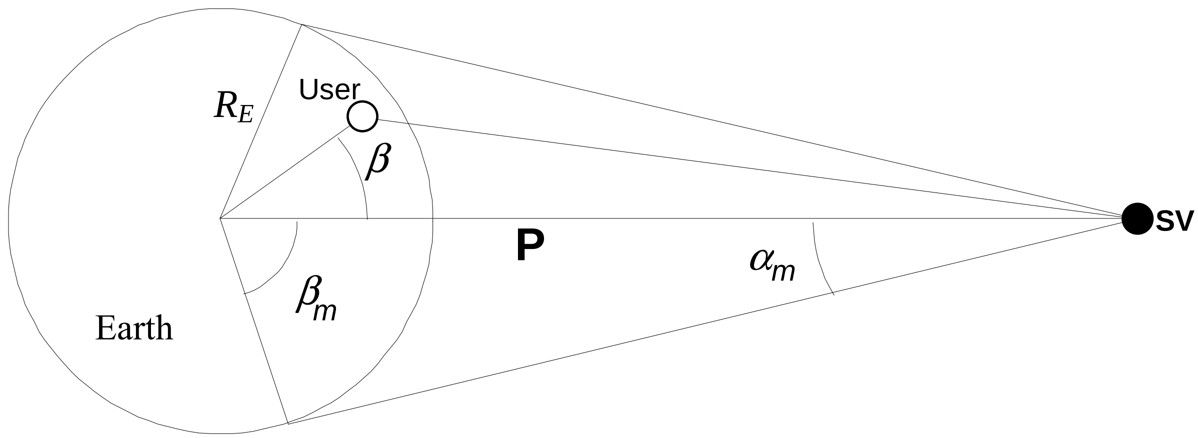

Figure 2. User-SV Geometry where β is colatitude with respect to a spherical coordinate system having its pole P at the sub-satellite point.

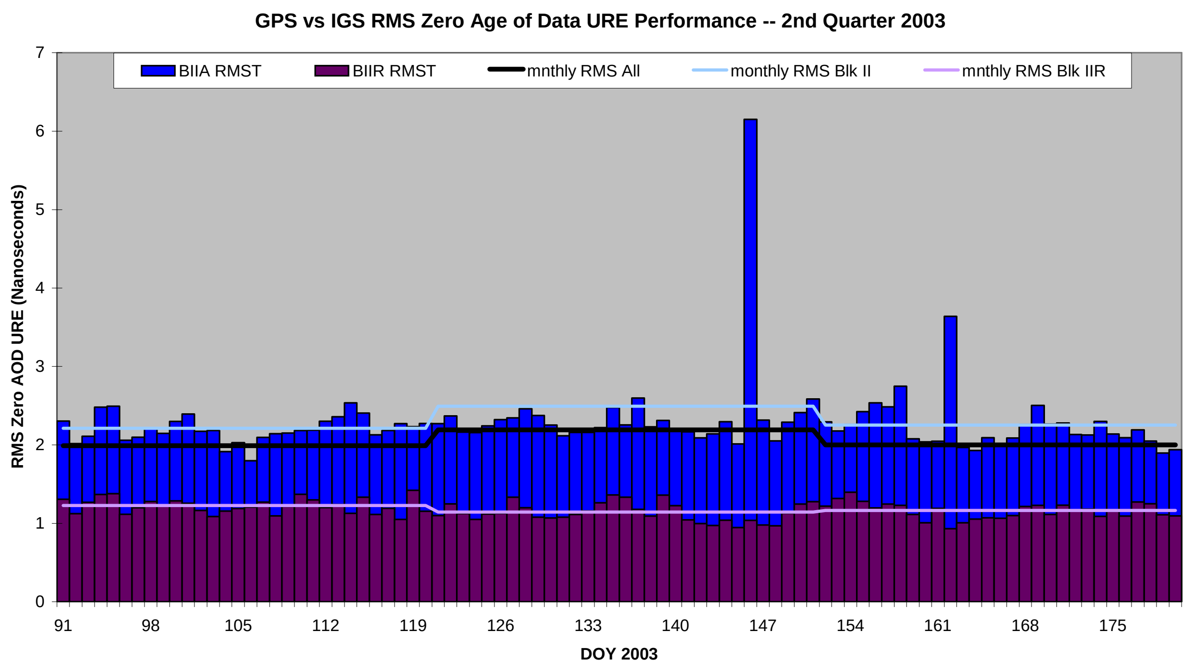

Figure 3. Zero Age of Data daily performance, 2nd quarter 2003.

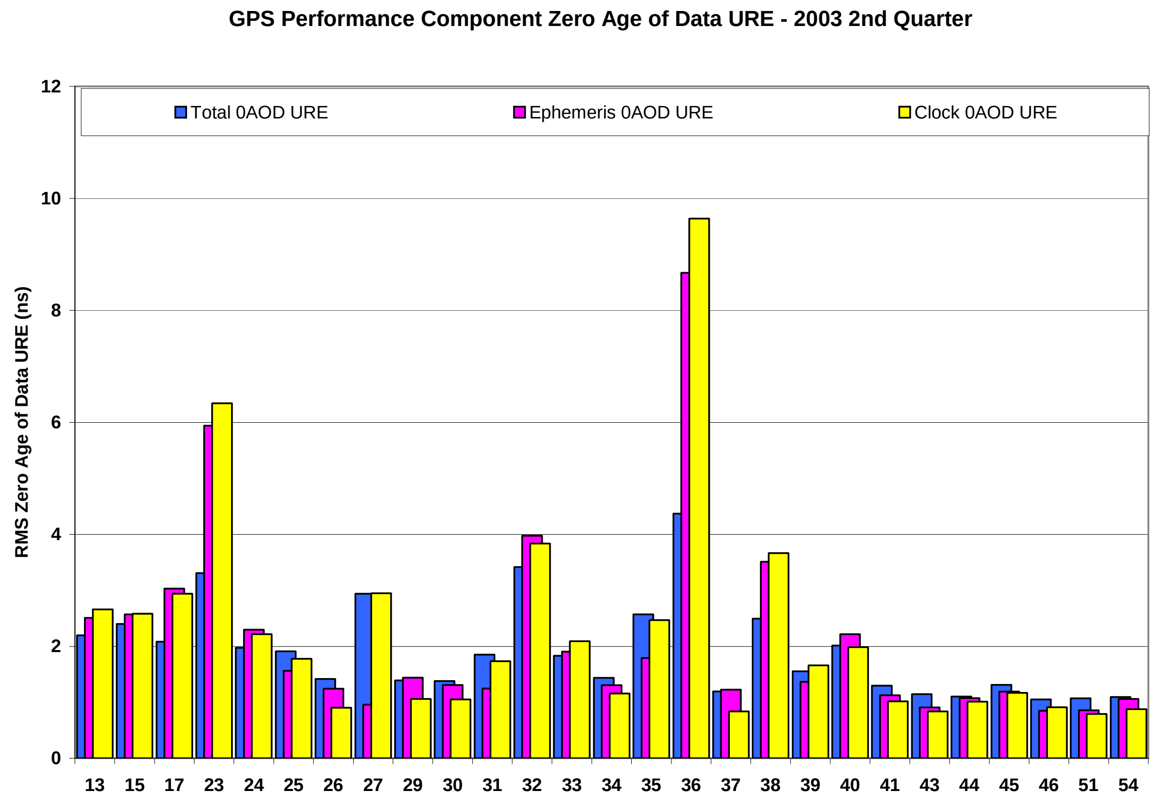

Figure 4. Zero Age of Data individual satellite performance, 2nd quarter 2003.

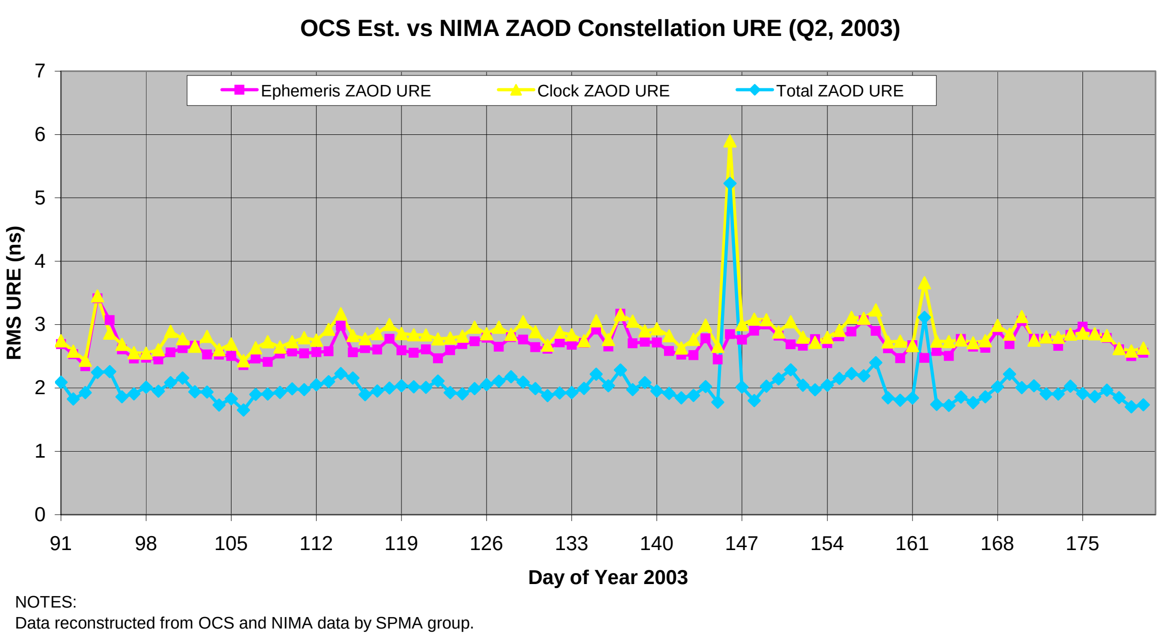

Figure 5. Zero Age of Data daily performance, 2nd quarter 2003.

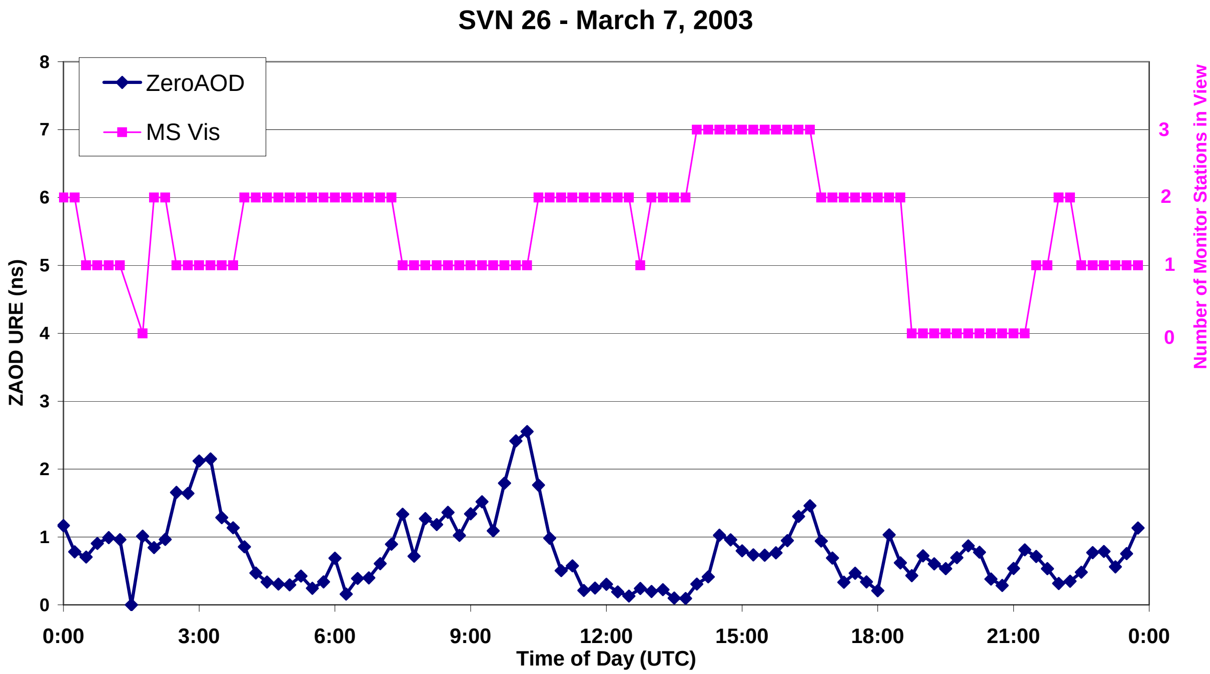

Figure 6. SVN 26 Zero Age of Data and monitor station visibility.

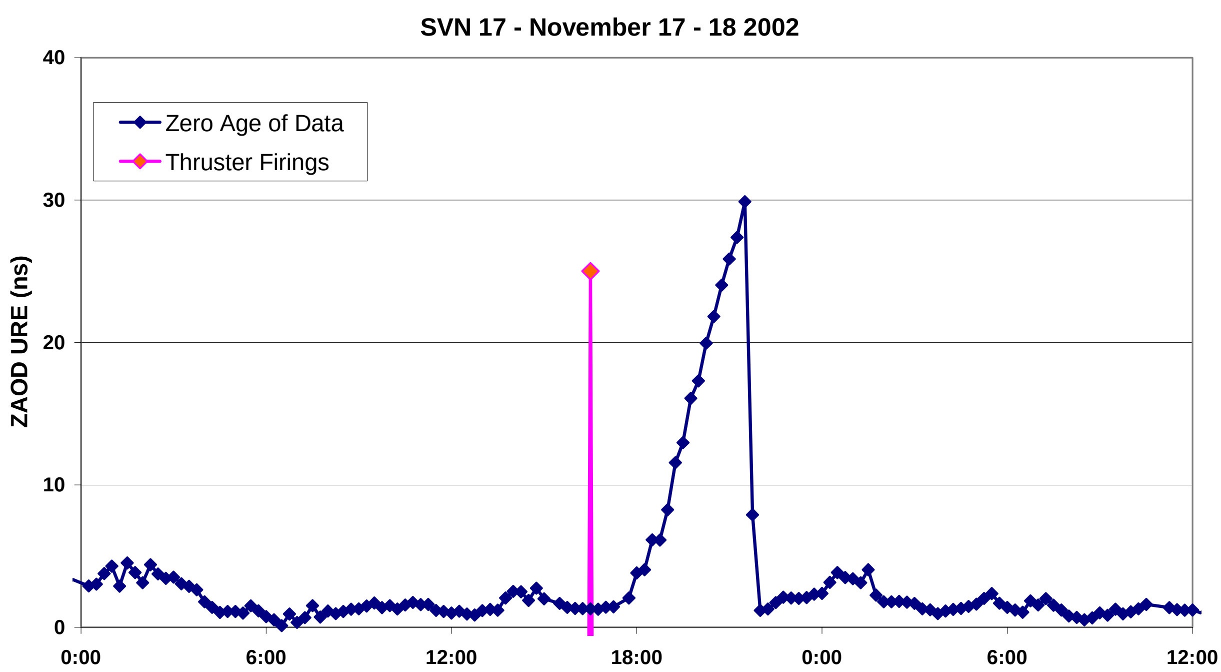

Figure 7. SVN 17 Zero Age of Data following thruster firing.

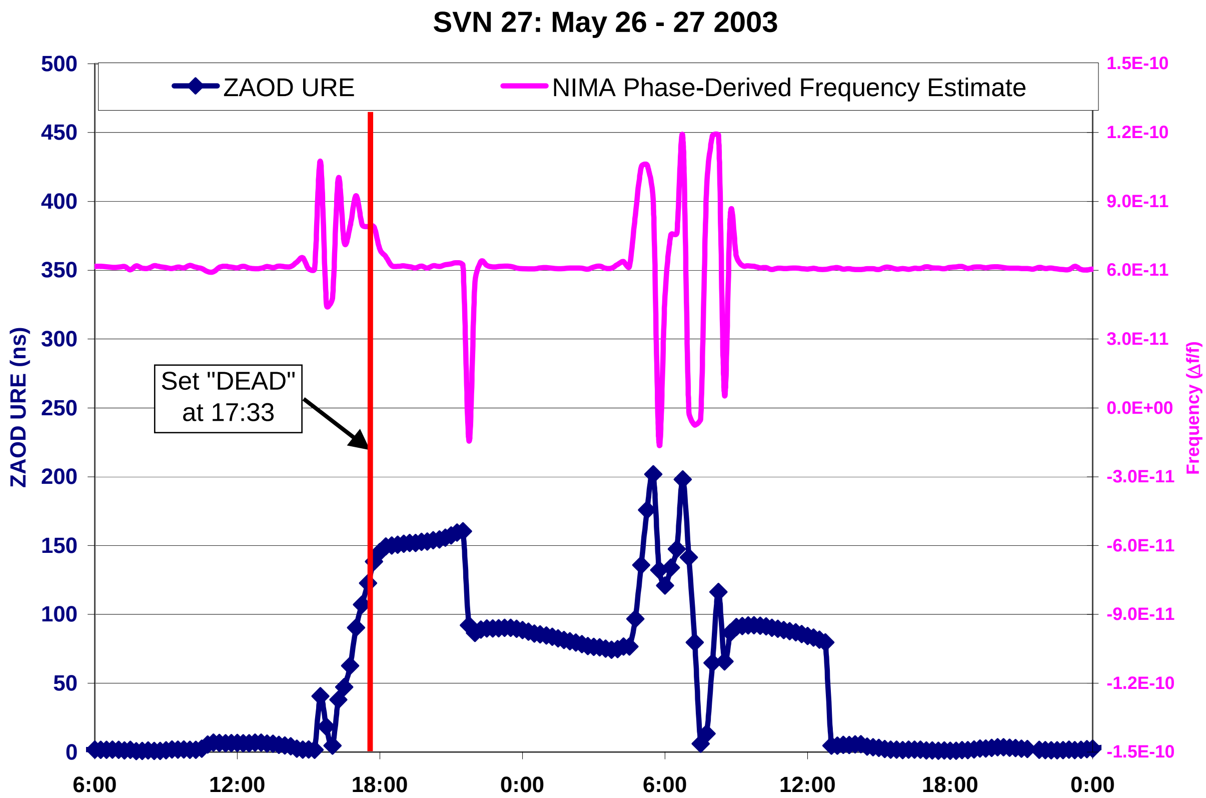

Figure 8. SVN 27 Zero Age of Data during frequency standard anomaly.

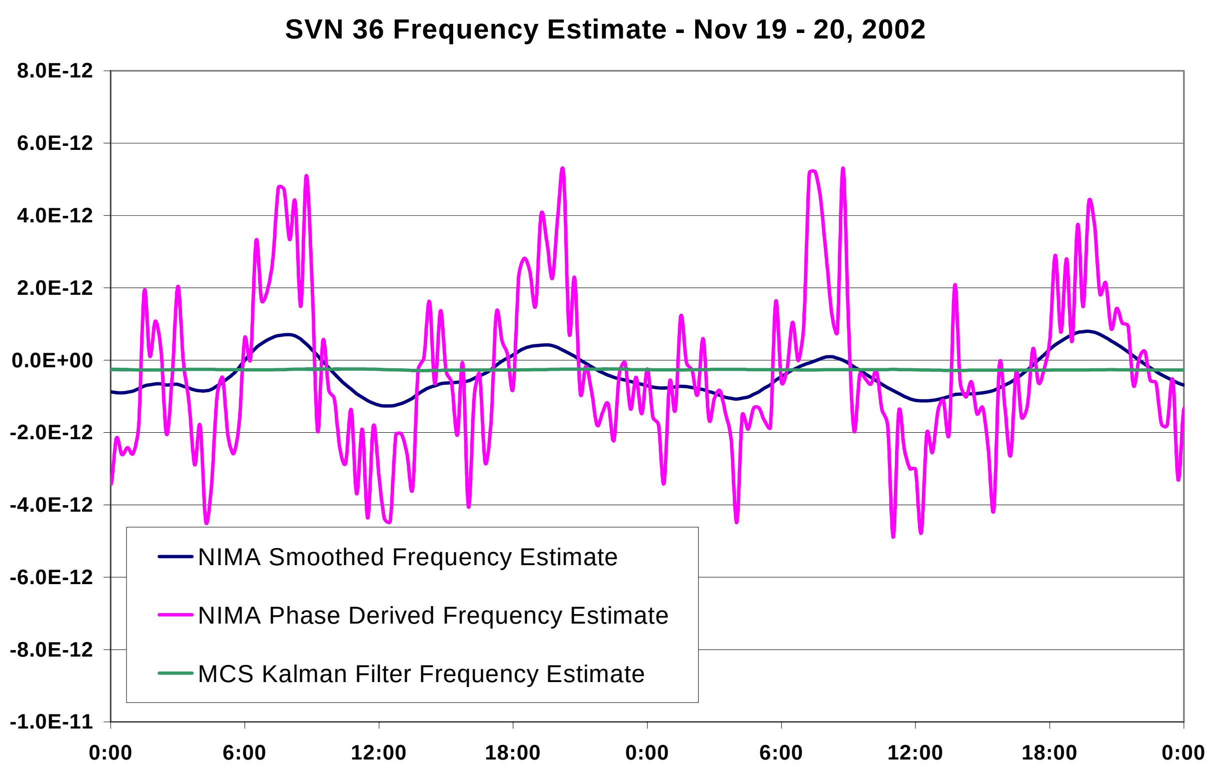

Figure 9. SVN 36 frequency standard periodicity.

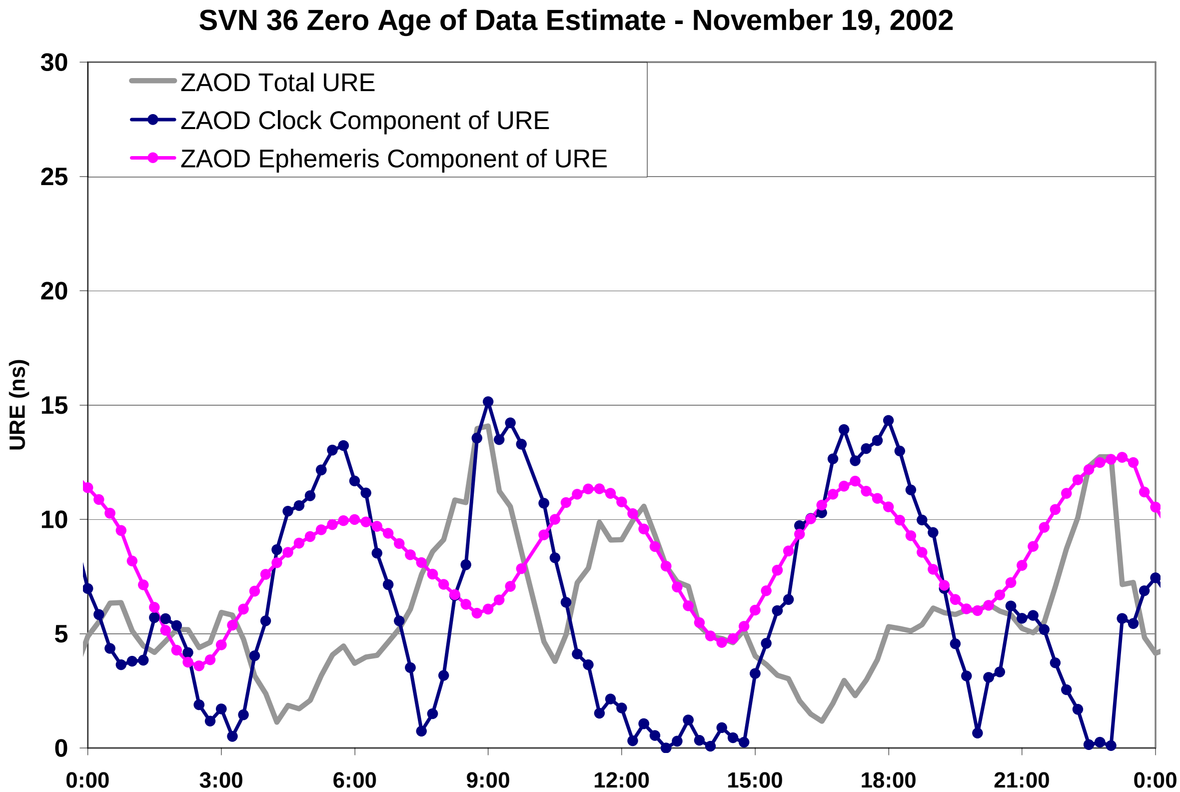

Figure 10. SVN 36 frequency standard periodicity and Zero Age of Data.

QUESTIONS AND ANSWERS

JOHN PETZINGER (ITT): Is there any thought given to adding some clocks' states to the Kalman filter to model the diurnal variation, as opposed to foresee it on to the ephemeris. Especially for users, say, closer to the Equator. Wherever the diurnal clock doesn't model too well as an ephemeris state?

JACK TAYLOR: No, it is not currently envisioned in the control segment improvements.

DENNIS McCARTHY (U.S. Naval Observatory): You mentioned the sun/earth/moon ephemeris improvement and the earth/tide/solarist-type earth model. Which models are being used?

TAYLOR: Actually, offhand, I might have trouble spitting out the sun/moon/ephemeris; I think they are currently using the DE 200 – is there a DE 401?

McCARTHY: DE 405.

TAYLOR: I don't think they are coming all the way up with 405. Is there a 401 model? The answer is they are not using the very latest one, which is the 405. But there was a version between the 200 and the 405 that they are looking at using. They are trying to be consistent with NSWC and NIMA, and I think Everett Swift at NSWC is coming up to 405. But we are trying to come up as far as we can and still validate.

With regard to the solid tide models, I am not familiar enough with the specifics to address it. But under the Accuracy Improvement Initiative, there is a publication out, at least the minutes to the kick-off meeting, where it goes into the details of that. Actually, those algorithmic improvements are being done by Lockheed-Martin Gaithersburg, Art Dorsey. If you know Art, just get a hold of him and he will give you the specifics.

JAY OAKS (U.S. Naval Research Laboratory): Jack, in regard to SVN-23 and those periodics, we have recently switched clocks and we have been looking at the new data. In fact, Jim Buisson thinks maybe those fluctuations went away with the new clock. It is going to be interesting. He is thinking that there might be a report coming out in the near future that you guys will take a look at. But the reasoning about the solar panel mechanical background for it, I don't know. Unless it is something that only affects the cesiums and maybe not a rubidium, because I think the new clock is rubidium.

TAYLOR: That is correct. And actually we thought we might experience some complications because of this. We have seen in performance data in some satellites a direct correlation from the A-2, which is the drift rate state, and K-2, which is the solar pressure along the boom state. We thought that might get complicated when we turned on a rubidium clock. But from what we are hearing, I think we are not seeing anything bad coming out of that.

So, I guess, stayed tuned. We will be looking at it as we get data and if you can provide some, feel free to send it out our way.