THE 2 SOPS EPHEMERIS ENHANCEMENT ENDEAVOR (EEE)

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Abstract

Historically, one of the main goals of the 2d Space Operations Squadron (2 SOPS) in maintaining the GPS constellation has been to achieve the best possible system accuracy. The Master Control Station (MCS) Kalman filter plays a key role in meeting this goal. Through a process known as tuning, the database values that control the Kalman filter operation are optimized to provide the best possible estimation and prediction. Over the years, a series of in-house efforts have dramatically improved the accuracy, reliability, and integrity of the GPS signal. The latest iteration of these efforts is called the Ephemeris Enhancement Endeavor (EEE).

Air Force and contractor personnel have concentrated on two main areas as part of the EEE: Kalman filter tuning and deterministic models. Results of this effort demonstrate a 20% reduction in ranging errors and a 17% reduction in time transfer errors. The authors will present descriptions of each area investigated, explain how the new tuning parameters were derived, and provide detailed results of their efforts to date.

BACKGROUND

The mission of the 2d Space Operations Squadron (2 SOPS) is to provide highly accurate time transfer and navigation data to properly equipped military and civilian users. In the process of accomplishing this mission, the 2 SOPS has established several goals. Among these goals is to continuously improve operations and to exceed customer expectations. The 2 SOPS actively participates in routine interaction and feedback sessions with all GPS users. One of the most effective forums for this feedback is the Performance Analysis Working Group (PAWG).

The 1996 PAWG, held in August at Peterson Air Force Base, identified unprecedented levels of GPS timing and position accuracy. Several presentations highlighted and lauded the work of the men and women of the 2 SOPS in constellation operations. There were, however, also several presentations that identified periodic errors affecting GPS performance. The identification and resolution of these errors is the topic of this paper. Prior to elaborating on this project, we must first establish some additional background about how the Master Control Station (MCS) Kalman filter operates.

MCS KALMAN FILTER *Q*s AND TUNING

The MCS Kalman filter process is controlled by several database parameters maintained by the 2 SOPS. These parameters collectively serve to optimize or *tune* filter performance. In practice, tuning the Kalman filter is not an easy task. However, it can be safely said that the majority of this task is accomplished through a set of values known as *filter q*s. These values are maintained in a database file, called the *KKS file*, for each satellite.[1]

There are essentially two types of *q*s in the MCS Kalman filter: measurement *q*s, which model noise inherent in the measurement-taking process (such as monitor station receiver noise), and system *q*s, which model the random processes in the actual GPS system. These system *q*s can be further broken down into clock, ephemeris, and solar pressure *q*s.

Until 1994, the *q*s in the Kalman filter had remained mostly unchanged since the inception of GPS. That is, those values that were derived prior to the first Block II/IIA launch were never recalculated from actual on-orbit data once vehicles were launched. In 1994, the 2 SOPS undertook an effort to recalculate these values for the satellite vehicle atomic frequency standards. Using clock stability analysis data from the Naval Research Laboratory (NRL), 2 SOPS showed that empirical performance could be related to optimal choices for clock *q*s. Subsequently new, larger *q*s were calculated. Once implemented, GPS navigation and time transfer efforts improved significantly, a result supported by several outside agencies.[2]

RESULTS OF PAWG-96

One of the first presentations made at PAWG-96 solidified the need for 2 SOPS to revisit the tuning process, this time for ephemeris and solar states. Mr. Steve Malys of the National Imagery and Mapping Agency (NIMA) presented his methods for comparing the broadcast navigation message to the NIMA precise ephemeris. He then represented these differences as a function of User Range Error (URE) and plotted the constellation average, as shown in Figure 1. The results indicated a 12-hour periodic with an amplitude of 2-3 meters.[3]

The Aerospace Corporation and the Naval Surface Warfare Center presented similar results. Mr. Everett Swift identified an excessively long "memory effect" in the MCS Kalman filter, implying that the filter seemed to respond sluggishly to changes in ephemeris or solar states. This conclusion was consistent with MCS experience, and suggested that the ephemeris and solar *q*s were set too low and/or the measurement *q*s were too large.[4]

Yet a third presentation placed a final twist on this issue. Results presented by Lockheed Martin demonstrated that performance errors can in part be related to the minimum Sun-Vehicle-Earth angle (beta angle) of the satellite in question. Figure 2 showed how URE increased with decreasing beta angle. The correlation of these errors to the satellite position in its orbit further suggested solar pressure mismodeling.[5]

Given the definitive results of PAWG-96, 2 SOPS/DOUAN decided it was time to revisit the ephemeris/solar state accuracy topic. Members of 2 SOPS/DOUAN, the United States Naval Observatory (USNO), Boeing North American, NIMA, Lockheed Martin, and Aerospace met in late August 1996 to discuss this issue.

EEE AREAS OF INVESTIGATION

The EEE team concentrated its initial investigation in two areas: deterministic errors and MCS Kalman filter tuning. Several elements of the MCS deterministic modeling process contain known or suspected deficiencies. They include:

1. Solar Pressure States. A 1995 study revealed that some deficiencies exist within the solar state model used by the MCS Satellite Vehicle Positioning (SVPOS) software.[6] This deterministic model, used to generate the solar component of the satellite reference trajectory, does not account for solar transients observed early in the life of each satellite. Further work by Mr. Henry Fliegel of the Aerospace Corporation showed several shortcomings in the solar model—namely the omission of vehicle plume shield and thermal radiation effects—that combine to cause a 7% to 10% error in solar force calculation.[7] Still other studies identify similar shortcomings in other deterministic models such as the Earth Albedo model and the solar panel alignment model.

2. Solar Array Slewing/Misalignments. These errors result from the inability of SVPOS to model effects of array pointing during eclipse season.

3. Thruster Firings. Five GPS satellites currently use thrusters to manage reaction wheel momentum. Over time, these thruster firings can perturb the MCS model of the satellite vehicle orbit.

4. The SVPOS Integrator. Evidence from four extended stationkeeping maneuvers (over 20 minutes) suggested that the SVPOS integrator may lack fidelity. Specifically, when comparisons are made between other models and SVPOS models for extended maneuvers, large offsets on the order of tens of kilometers typically result.

5. Relativistic Effects. Many presentations have been made debating the MCS Kalman filter model of relativity. Some argue the MCS does not properly compensate for these effects, while others argue the math is handled correctly. Recent work has shown that this error source is negligible or non-existent, and poses no immediate concern for future tuning work.[8]

Several *q*s affect the MCS Kalman filter processing of routine ephemeris and solar state behavior. They include:

1. Gravitational Velocity Process Noise Variance. This process noise compensates for random velocity changes resulting from irregularities in the Earth's gravitational field. They are broken into radial, along-track, and cross-track (RAC) components.

2. Solar Pressure Process Noise Variance. This process noise compensates for solar radiation acceleration on the satellite. It is broken into the familiar solar K_1 and K_2 components.

The EEE team decided that filter tuning would be the easiest and most logical place to start with these improvements; the entire process could be performed in-house at no additional cost to the government. The next section details how the new ephemeris and solar *q*s were derived.

THE NEW FILTER EPHEMERIS AND SOLAR *Q*s

The EEE team used the previously accomplished clock tuning as the guide for this tuning analysis.[2] In the clock world, the task of estimating a clock's polynomial coefficients is made challenging by natural disturbances called *noise*. Besides measurement noise, precision oscillators exhibit what the MCS calls *process noise*. In particular, clock states have a tendency to somewhat randomly wander off as a function of time. The clock "random walks" that the MCS accounts for are *random walk PM* (or white FM), *random walk FM*, and *random run FM*.

In the Kalman filter, the MCS accounts for these effects by increasing the clock state covariances during each time update. The MCS qs should ideally depend on the magnitude of the respective random walk effects. Clock qs relate as follows: [9]

***Q* Value:**	**Accounts for random walk in:**	**Noise type:**
q_1	phase (BIAS)	random walk PM (White FM)
q_2	frequency (DRIFT)	random walk FM
q_3	frequency drift (DRIFT RATE)	random run FM

Work done in 1995 showed that not only does the MCS model help to account for most of the observable atomic frequency standard noise, but that an equation exists to easily relate empirical performance towards optimal choices for clock qs.[9]

For orbital states, the challenge becomes complicated. One could safely argue that GPS satellite orbits exhibit largely random walk behaviors in most of the classical orbital elements, such as eccentricity, inclination, and right ascension of the ascending node. However, the MCS does not explicitly treat these as random walk processes. Rather, the MCS uses three q values, for radial, along-track, and cross-track velocities. Though, over time, the "random" behavior of RAC values between 15-minute updates will propagate into changes in the classical orbital elements, RAC deviations themselves behave more as 12-hour periodics rather than as random walks. The problem further complicates with the addition (and coupling) of solar states, whose values (and changes) propagate into ephemeris states.

RAC *Q*s

The approach to the first challenge was to examine the RAC component that behaves closest to a random walk process -- the along-track component. Though, over 12 hours, orbit perturbations will show a periodic in along-track, over 2-3 days, the effect will appear more like a random walk. And, for longer periods, the deviation will behave more as a random run, meaning not only is the position randomly walking off, but the rate or slope (velocity) at which the along-track is deviating also appears to randomly walk.

MCS along-track deviation plots were examined for all GPS satellites operational at the time (August 96), and it was possible to pinpoint Tau (time interval since the previous reference trajectory update) values that appeared to show a random walk in velocity (a random run in position).

For clock states, random walks in frequency translate into phase variance by the following equation:

$$\text{Variance}_{\text{phase}} = \frac{q_2 \tau^3}{3} \tag{1}$$

Applying this equation to the analogy for along-track error:

$$\text{Error}^2_{\text{ATRK}} = \frac{q_{\text{va}} \tau^3}{3} \tag{2}$$

where q_{va} is the MCS's along-track velocity q.

Using this equation, various observed Tau values and their corresponding along-track errors were tried, to backwards-derive satellite-specific q_{va} values. The EEE team concluded that the differences between satellites were more likely due to the limited sampling, as opposed to satellite- or orbit-specific uniqueness, therefore one q_{va} value was chosen that seemed to conservatively best represent the constellation as a whole.

The chosen value was: $q_{\text{va}} = 6.12$ E-15 m^2/s^3 (Old value: 2.7 E-16 m^2/s^3)

Orbit perturbations over short intervals (such as 15 minutes) are arguably omnidirectional. Although the net effect results most apparently in along-track, the root cause of along-track error is usually a combination of both along-track and/or radial perturbations. For that reason, an equal q value for radial was chosen:

$q_{\text{vr}} = 6.12$ E-15 m^2/s^3 (Old value: 2.7 E-16 m^2/s^3)

For cross-track, Mr. Ken Brown of IBM-published work discussing the fact that the cross-track q value has historically been kept higher. Simply, cross-track perturbations do not geometrically correlate into radial or along-track errors, and, for that matter, do not orbitally propagate into radial or along-track errors significantly.[10]

Additionally, cross-track errors do not directly translate into ranging errors, due to the orthogonality of cross-track with respect to the locational direction of GPS users. Because of this, 2 SOPS has been able to afford to keep the cross-track q high, since large uncertainty in cross-track estimates do not directly translate into large ranging uncertainties. For this reason, we use:

$q_{\text{vc}} = 4.6$ E-13 m^2/s^3 (No change from old value)

Largely because of the relatively lesser effect of q_{vc}, the EEE team decided to keep it unchanged.

Solar *Q*s

Note that the RAC q derivations have essentially ignored the short-term effects of solar acceleration. Since acceleration is a higher order effect, random walks in acceleration should theoretically show up for Tau values higher than those for random walks in velocity. By assuming this Tau-separation, solar state q derivation would assume a simple approach. In a same-state random walk process, such as clock frequency drift, the state variance relates to the state q as follows:

$$\text{Frequency Drift Variance} = q_3 \times \text{Tau} \quad (3)$$

In the clock example, the square of the frequency drift error, due to random walk in frequency drift, is time proportional to the q_3 value. By examining MCS solar state estimates, and looking for Tau values exhibiting the appearance of a random walk, one can analogously apply the clock frequency drift equation to K_1 and K_2:

$$\text{Error}_{K1}^2 = q_{K1}\tau \quad (4)$$

$$\text{Error}_{K2}^2 = q_{K2}\tau \quad (5)$$

Again, by examining all operational satellites, and choosing values conservatively representative of the constellation as a whole, the EEE team derived the following values:

q_{K1} = 1.15 E-11 1/s (Old value: 3.0 E-12 1/s)
q_{K2} = 3.3 E-27 m^2/s^5 (Old value: 3.3 E-29 m^2/s^5)

For SVN23, since the arrays are manually slewed, an alternate set of solar qs was selected:

q_{K1} = 2.3 E-11 1/s (Old value: 3.0 E-12 1/s)
q_{K2} = 3.3 E-27 m^2/s^5 (Old value: 3.3 E-29 m^2/s^5)

The above values, though derived using empirical data, seemed representative of the general experiences 2 SOPS had with ephemeris/solar state estimation. The periodic effect that several outside agencies identified was likely due to filter time constants that were too lengthy. This in turn implied the old qs were too tight. Though the proposed qs were increases of 1-2 orders of magnitude, the net effect on the degree of freedom in the Filter is a function of, roughly, the quartic (fourth) root of the change in qs. Meaning, a q increase by a factor of 16 should result in a two-fold increase in Filter freedom.

VALIDATION

The EEE team conducted several off-line tests of the new tuning numbers before implementing them in the mission environment. The first of these tests used the Experimental Navigation software package at the MCS. Seven days of mission L-band data were used in a "before and after" comparison; the first run used the old tuning numbers and the second run used the new tuning numbers. The EEE team concluded the new values did not adversely impact GPS performance, and in fact, reduced ranging errors toward the end of the test. With only 7 days of data, however, it was difficult to assess the degree of improvement the new numbers would achieve.

Lockheed Martin Federal Systems (LMFS) in Gaithersburg, MD provided an independent assessment of the qs. Mr. Bill Mathon performed a similar Experimental Navigation simulation using a different 7-day L-band data set. His results supported the 2 SOPS' conclusion and helped pave the way for operational implementation.

IMPLEMENTATION

The 2 SOPS chose to update the satellite-specific files incrementally over a period of several weeks to mitigate the remaining risk of altering these database parameters. The EEE team concluded the safest approach was to choose a single satellite for the first update. SVN30 (PRN30) was chosen based on two main characteristics: it was set unhealthy to the Auxiliary User and it did not contribute to the composite GPS time scale. Given this configuration, the 2 SOPS minimized exposure of the changes to users and allowed the EEE team to safely perform a final verification of the changes.

On January 30, 1997, the 2 SOPS updated the KKS file for SVN30. Over the course of the next four days, 2 SOPS, USNO, and NIMA closely observed the ranging error and timing performance of SVN30. The results were immediately encouraging. All available metrics indicated improved performance. Based on the positive feedback from NIMA and USNO, the EEE team proceeded to update the KKS files for all other satellites throughout the month of February, completing the process on February 28, 1997.

METRIC SELECTION

The 2 SOPS uses a variety of in-house metrics to validate GPS mission performance. Since these metrics were used in the assessment of EEE, they are briefly summarized here:

- **Estimated Range Deviation (ERD)** – Difference between the range determined from the current Kalman filter state estimates and the range determined from the navigation upload page valid for the same time. Measured in meters and calculated every 15 minutes for all satellites.

- **Observed Range Deviation (ORD)** – Difference between the ionospherically corrected smoothed pseudorange observed at a monitor station and the pseudorange constructed from the navigation upload page for the same time. Measured in meters and calculated every 15 minutes for every satellite-monitor station pair.

- **Zero Age of Data** – Ranging error due to steady state Kalman filter error. Measured in meters and calculated every 24 hours for all satellites.

- **Time Transfer RMS** – RMS of all the UTC(GPS) – UTC(USNO) time difference errors for the previous day. Measured in nanoseconds and calculated every 24 hours for the constellation.

RESULTS

Since the completion of the re-tuning, 2 SOPS and other outside agencies have documented improvements in all facets of GPS mission performance. This section will present data that show significant reduction in the periodic error, time transfer RMS error, and Zero Age of Data error. The results also document an improvement in the daily upload prediction quality and the extended navigation performance.

Figure 3 shows before and after results of GPS ranging errors with increasing age of data.[11] The post-tuning change line illustrates the significant reduction to the periodic error initially identified at PAWG-96.[3] One of the main goals of the EEE project was to remove this periodic error, and Figure 3 shows this goal was met. Further data provided by NIMA indicate a 20% reduction in broadcast ranging errors.[12]

Figure 4 shows the monthly Time Transfer RMS comparisons from 1996 to 1997. Without exception, every month since the tuning changes has had better time transfer performance than the previous year. To date, we have documented a 17.95% improvement from 1996 to 1997. Since 1 Mar 97, the daily time transfer RMS has exceeded 10 ns on only eight days, none since 5 Jun 97.

2 SOPS uses the ERD metric to assess the quality of the broadcast navigation message. As ERDs reach an operations-defined threshold, 2 SOPS chooses to perform an out-of-cycle update to the navigation and timing data on-board the satellite. The navigation uploads are called ERD contingency uploads, and do not count as one of the daily navigation message updates. Prior to the implementation of EEE, 2 SOPS operations crews were performing, on average, more than 5 ERD contingencies per day.

Figure 5 shows the average number of ERD contingencies per day for 1996 and 1997. Note that upon the completion of the re-tuning, the average number of extra uploads dropped to just over 1.2, an improvement of approximately 75%. This significant drop signaled an improvement in the quality of the navigation message prediction; the ranging errors remained below the established threshold for a longer period of time. Given this dramatic drop, 2 SOPS chose to lower the ERD contingency threshold even further on 29 May 97. The more stringent threshold resulted in about 3.2 ERD contingency navigation uploads per day, still well below the pre-tuning update level. Thus, at no extra cost to the operations crews, the 2 SOPS was able to provide even better navigation message accuracy to the user.

The 2 SOPS uses the Smooth Measurement Residual (SMRES) Tool to assess GPS Zero Age of Data performance. Two runs of this program are made every 24 hours. The first run is based on ranging data from NIMA monitor stations only. The second run is based on data from both NIMA and Air Force monitor stations. The tool tests the data against two limits: a 4.2-meter tolerance for individual satellites, and a 3.2-meter tolerance for the constellation RMS. Historically, GPS has performed well within these limits, but the EEE changes resulted in a noticeable improvement to the Zero Age of Data performance.

Figure 6 plots the SMRES data from 1 Jan 97 to 30 Sep 97 for both runs. Each shows an obvious improvement upon completion of the database updates. To date, we have documented a 30% reduction in the Zero Age of Data errors.

The EEE team was presented with a unique opportunity to validate extended navigation operations with the new tuning values. SVN28 (PRN28), an unhealthy but usable asset at the time, was used for this extended navigation test. On 19 Mar 97, 2 SOPS placed a navigation upload into SVN28 and then did not re-upload for approximately 21 days. GPS has a requirement for no more than 200 meters of single-satellite ranging error at 14 days age of data. Our results showed only 49.2 meters of error at 14 days. Although not an exhaustive test, these results indicate that no sacrifice was made to the extended navigation mission in order to achieve the results presented above.

FURTHER TUNING CHANGES

Based upon the early results of this effort, the EEE team began to explore updating other database parameters. The next most logical adjustment was the measurement noise increment. This value, also called q_0, is used to account for the white/flicker noise in pseudorange (PR) measurements. This parameter was modified from 1.0 m^2 to 0.74 m^2 for all monitor stations in 1994 following satellite clock tuning.[2] The EEE team investigated the impacts of further lowering this value.

The methodology for the derivation of a new q_0 was similar to that used for the ephemeris and solar qs. The EEE team examined an RMS of the PR residuals at each monitor station over a period of several days. The four non-CONUS sites were all near 0.59 m (0.35 m^2), and COSPM was near 0.72 m (0.52 m^2). The reasons for noisier measurements at COSPM are not clear, but several theories have been presented elsewhere and will not be discussed here.

Again, the EEE team used a 7-day set of L-band data on the Experimental Navigation software package to test these new values. Unfortunately, there was no significant improvement in the Zero Age of Data, and even a minor degradation in ERD performance. LMFS performed a second test in Gaithersburg and reached the same conclusion. As a result, the EEE team decided to leave the q_0 term unchanged at 0.74 m^2 for all monitor stations.

WHAT'S NEXT?

The results of the tuning changes have been overwhelmingly positive. The EEE team met—and exceeded—all of the initial goals with this project. There is, however, still some room for improvement. Some of the other areas we are currently investigating include: refinement of the current tuning numbers, orbit-season specific or satellite-specific qs, and deterministic modeling errors.

Each of these areas requires additional on-orbit data before any conclusions can be made. The initial data indicates that all satellites experienced varying degrees of improvement. In a few rare cases, the "after" errors are slightly larger than the "before" errors. Without exception, however, these satellites had the smallest initial errors to begin with. It is the goal of the EEE team to choose tuning values to optimize the performance of all satellites. This project is an on-going effort, and will continue to evolve as the constellation changes. The 2 SOPS and its contractor support team are committed to providing the best possible navigation and timing signal to the GPS user community.

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REFERENCES

1. Scardera, Michael P.; Smetek, Ronald T. Jr; and Crum, Jeffrey D., *MCS Kalman Filter Mission Support Study Guide*, 3rd edition, 2 SOPS Internal Training Document, pp. 21-136, March 8, 1996.

2. Hutsell, Steven T., *Fine Tuning GPS Clock Estimation in the MCS*, Proceedings of the 26th annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 6-8 December 1994, Reston, VA, USA (NASA CP-3302), pp. 63-74.

3. Malys, Steve, *Comparison of URE Characterization Methods*, Proceedings of PAWG-96, 21-22 August 1996, Peterson AFB, CO, USA.

4. Swift, Everett and Merrigan, Mike, *Expected Improvement in OCS Kalman Filter Estimates and Predictions Due to Adding DMA Stations and Using a Single Partition*, Proceedings of PAWG-96, 21-22 August 1996, Peterson AFB, CO, USA.

5. Frey, Chuck; McReynolds, Steve; Metzger, Tom; Moore, Jerry, *GPS MCS Filter Performance*, Proceedings of PAWG-96, 21-22 August 1996, Peterson AFB, CO, USA.

6. Smetek, Ronald T. Jr and Taylor IV, John V., *Between Sun and Earth: Solar Pressure State Estimation in the GPS Master Control Station*, Proceedings of ION-GPS-94, 20-23 September 1994, Salt Lake City, UT, USA, pp. 275-284.

7. Fliegel, Henry, *A Place in the Sun: Direct and Indirect Solar Effects on GPS Satellites*, The Aerospace Corporation, 8 April 1993.

8. Weiss, Marc and Ashby, Neil, *Comments on GPS and Relativity: An Engineering Overview*, National Institute of Standards and Technology Memo, 13 March 1997.

9. Hutsell, Steven T., *Relating the Hadamard Variance to MCS Kalman Filter Clock Estimation*, Proceedings of the 27th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 29 November – 1 December 1995, San Diego, CA, USA, (NASA CP-3334), pp. 291-299.

10. Brown, Ken, *Characterizations of OCS Kalman Filter Errors*, Proceedings of ION-GPS-91, 11-13 September 1991, Albuquerque, NM, USA.

11. Lockheed Martin Federal Systems and Overlook Systems Technology, *GPS Performance Data Package*, 29 August 1997.

12. McCormick, Lisa, *Analysis of the 2 SOPS Ephemeris Enhancement Endeavor*, Proceedings of PAWG-97, 20-21 August 1997, Peterson AFB, CO, USA.

Figure 1. Total constellation composite showing the offset between broadcast navigation message and NIMA precise ephemeris. Originally presented by Stephen Malys.

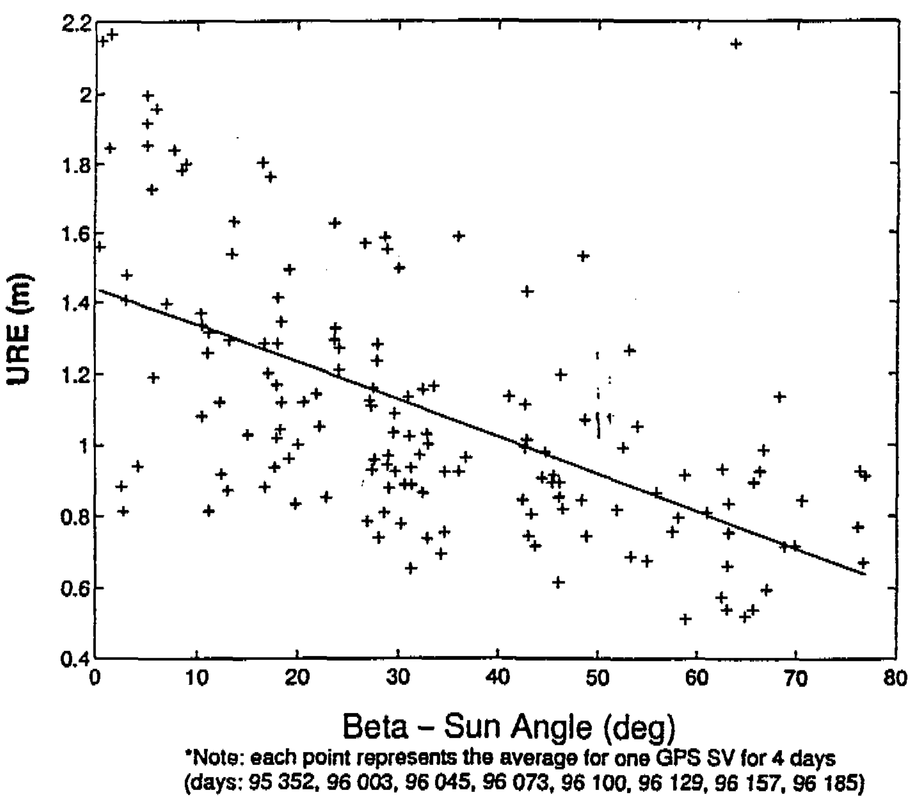

Figure 2. URE vs. Beta Angle. Originally presented by Tom Metzger.

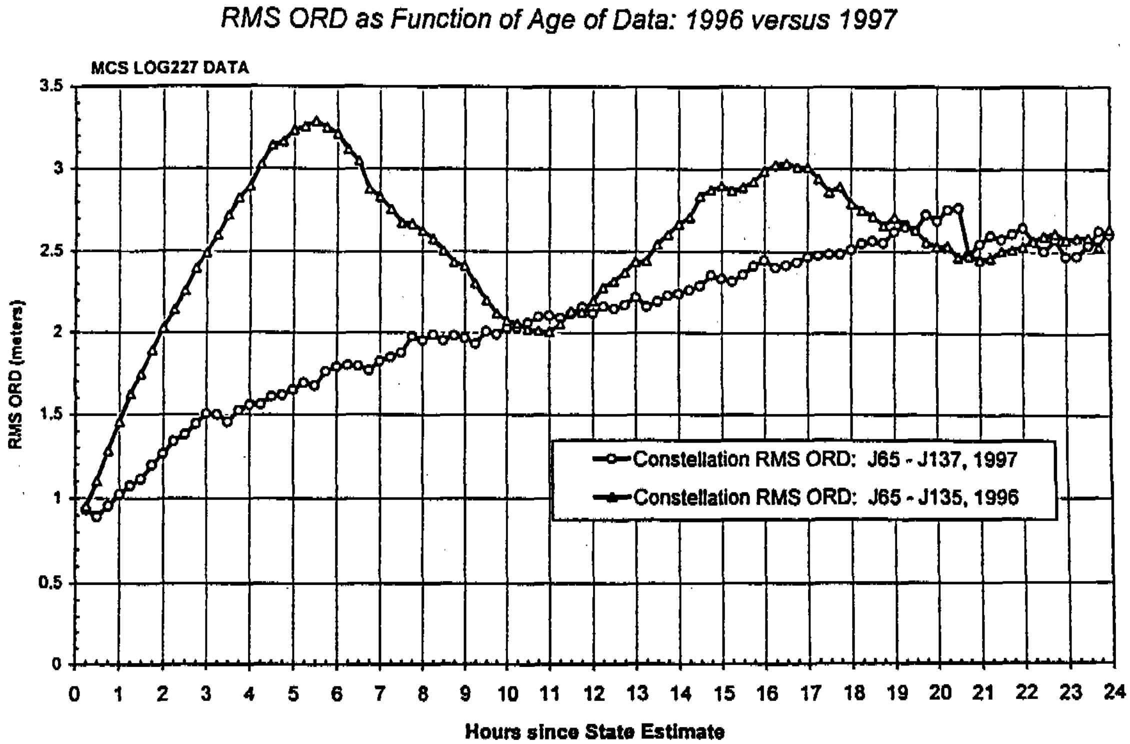

Figure 3. RMS ORD with Increasing Age of Data. Originally presented by LMFS and Overlook.

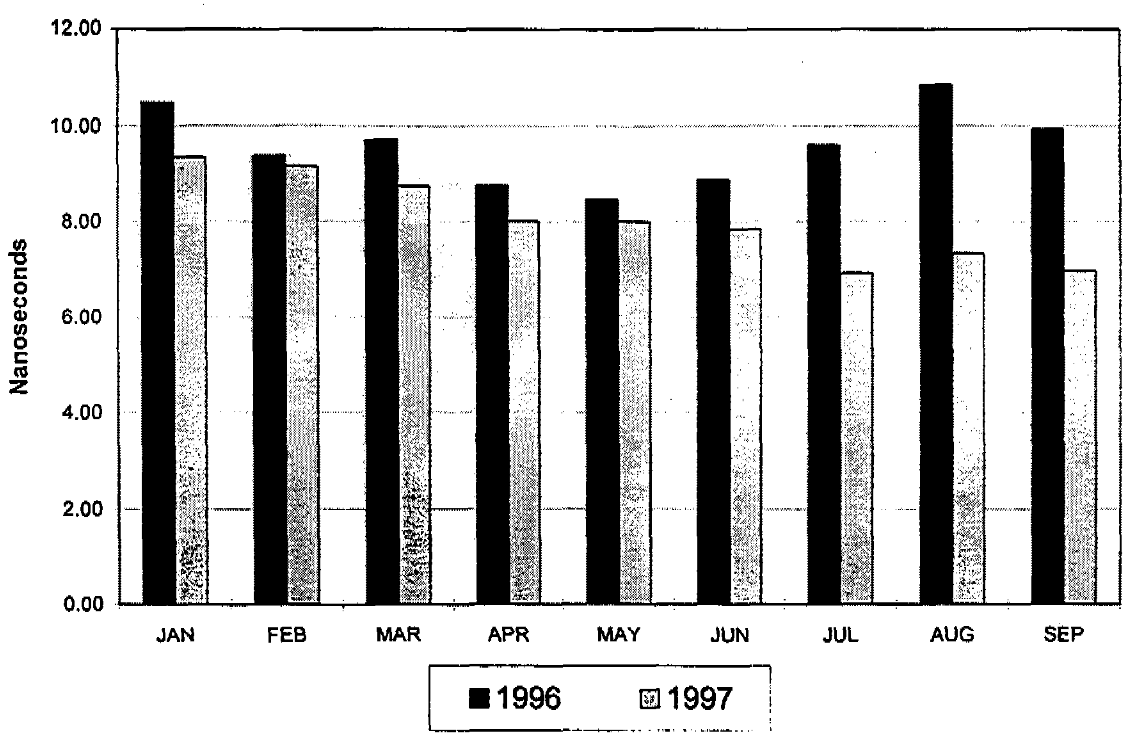

Figure 4. Time Transfer RMS Comparison.

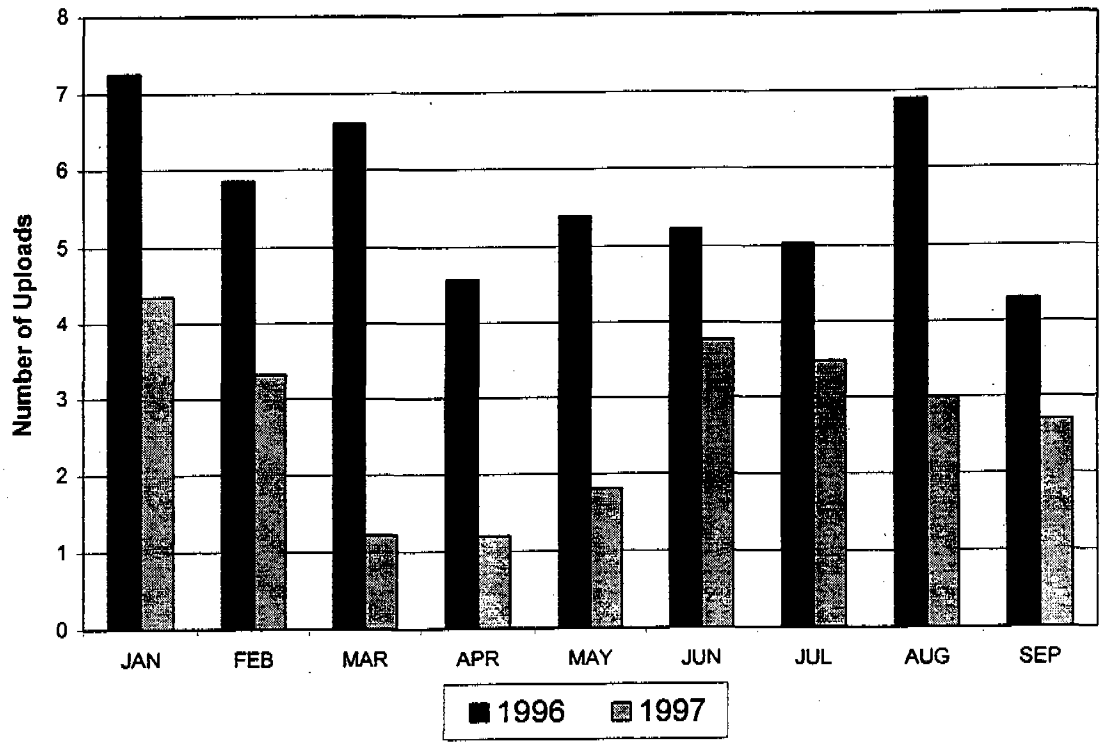

Figure 5. Average Number of Estimated Range Deviation (ERD) Contingency Navigation Uploads per Day.

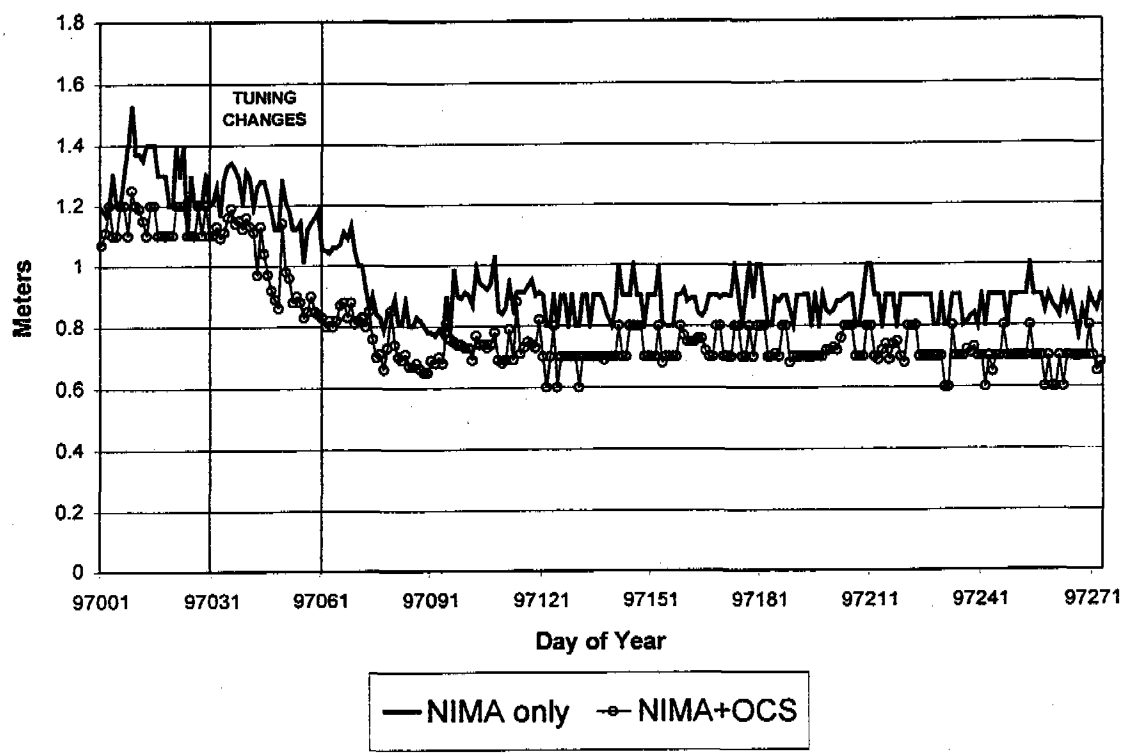

Figure 6. Smooth Measurement Residual (SMRES) Tool Results for 1997.

Questions and Answers

PHIL TALLEY (SFA/NRL): I remember in times past we used to have a parameter that was separated between clock and ephemeris errors. In the effort you are putting in now, does that still leave the clock errors approximately where they were and improve the ephemeris errors?

CAPTAIN JEFF CRUM (FALCON AFB): Are you speaking in addition to the tuning efforts that we are doing quarterly now or are you talking about another parameter?

PHIL TALLEY: I am unfortunately speaking from several years ago when we used to have the estimate of the precision divided between clock and ephemeris errors. Maybe you do not even do that anymore, and maybe I am the only one in the room that is concerned. But I just wondered if it did indicate that improvement was strictly on the ephemeris or if did improve the appearance of the clock performance.

CAPTAIN JEFF CRUM: Yes, there was some leakage of ephemeris error into the clock states because the covariances were too tight for ephemeris and solar. The filter, in trying to do the best that it could was leaking some into the clock states. To some extent, at zero age of data, some of that error actually canceled out. For users that received Kalman filter estimates in near real time, it was not as big a problem; but for users that received the navigation message, that basically do not get updates much more often than once every 24 hours, it was causing a problem. Because, a lot of the times the clock states would be formulated at one of the peaks of the 12-hour or 24-hour humps, if you will; and when the prediction is based off of that, the prediction will be pretty much a straight line if it is a cesium. The frequency estimate will be a straight line over that 24-hour prediction. When it is corrupted like that, due to the periodic, it can and did cause a little bit of error, which this reduced.