

THE INFUSION OF MCS KALMAN FILTER DATA INTO GPS BLOCK II/IIA FREQUENCY STANDARD ANALYSIS TECHNIQUES

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Abstract

Recent advances have allowed Boeing GPS navigation payload analysts the ability to transfer, archive, and manipulate Master Control Station (MCS) Kalman filter data. Previously, access to these data was cumbersome and restricted to a limited timespan. The new data retrieval process has proven to be useful in many areas of GPS analysis, including frequency standard performance characterization. Both routine and anomalous frequency standard performance analysis techniques are enhanced by considering the characteristics and trends of key MCS filter variables.

This paper describes the methodology by which the MCS Kalman filter data is attained. It also examines situations in which MCS Kalman filter clock state estimates and navigation performance metrics have proven to be useful in analyzing frequency standard performance. Examples include routine examination of frequency standard stability using MCS phase offset estimates, analysis of MCS frequency offset estimates before and after a "clock q-bump," and comparison of MCS clock state estimates versus those of the National Imagery and Mapping Agency (NIMA). Conclusions reveal that new, valuable insight is gained by considering MCS Kalman filter data when performing frequency standard analysis.

MCS KALMAN FILTER DATA TRANSFER METHODOLOGY

Until the summer of 1999, analysis of GPS Kalman filter data was limited to on-line tools. Because of security constraints and the awkwardness of the Jovial-based architecture, the ability to move data off-line and employ COTS analysis tools was labor-intensive and, in practice, rarely done. Instead, most analysis was done on-line and in real-time. The on-line tools are relatively effective in spotting and analyzing anomalies as they occur, but any additional analysis often has to be performed by outside agencies.

Beginning in the summer of 1999, Boeing personnel working at the MCS began retrieving selected MCS data from the on-line system and archiving it off-line. This method of archiving data allowed much greater flexibility for analysis. COTS tools such as Stable32 and MS Excel could be used to analyze and graphically display the data. Also, time spans are limited only by the beginning of this archive. Many on-line tools are restricted to accessing data from the last 48 - 72 hours. Even MCS tapes containing stored data are erased within 6 months.

The data retrieval activity is a three-step process. First, one or more batch scripts are run on the standby mission package. The standby mission package is identical to the active mission package, and is kept in a

state of readiness in case there is a need to switch-over. The batch jobs are run on the standby package to prevent any slow-downs of the various processes required to run the MCS mission package. Once the batch jobs have created the files containing the various GPS performance data, the files are transferred to a classified PC. This is a relatively slow process; 1 day's worth of data takes approximately one hour to transfer. Once the files are on the classified PC, they are transferred to a zip drive by secure means. Finally, the files on the zip disk are moved to an unclassified PC and archived on the Schriever AFB LAN.

This rather tedious, labor-intensive process is performed every weekday to ensure that the archives have the most up-to-date information available. The information is in ASCII format and can be read by most COTS analysis tools.

Clearly, the process would be improved by automation. Boeing personnel, in conjunction with the Air Force and other GPS contractors, are trying to streamline the process. Several issues remain to be addressed. Security is a major issue. Several aspects of the GPS mission package are classified. Any scheme to remove data (even unclassified data) from a classified system requires extensive security reviews. Several means of removing the data from the system have been rejected for security reasons. Our ultimate goal is to have the additional MCS data automatically downloaded to the Integrated Mission Operations Support Center (IMOSC) terminals, where an ensemble of Windows-based analysis tools will reside.

The advanced age and complexity of the MCS Legacy system is another difficult issue. The Air Force is trying to move MCS operations to a newer, more advanced system. This makes it very difficult to commit resources to upgrading the older, Legacy system. Although the new system is not expected to be delivered for several years, few MCS Operational Control System (OCS) resources are devoted to the outgoing Legacy system. Despite these challenges, the authors believe that the data retrieval and archival process can be streamlined and that this valuable effort will continue.

Currently, 18 files are transferred on a daily basis. This list of files contains the following data: Kalman state estimates (including backup and KF maintenance activities); reference trajectory data and coordinate system (ECI-ECEF) transformation data; GPS-UTC steering activity; smoothed measurements and residuals; navigation message upload data; and performance monitoring data (Estimated Range Deviations (ERDs), Observed Range Deviations (ORDs); and navigation solution (NAVSOL) data).

ROUTINE DATA ANALYSIS

Transferred MCS data, along with downloaded NIMA ephemeris and clock data, and published Notice Advisories to NAVSTAR Users (NANUs), are combined to generate 3 groups of periodic reports: weekly, monthly, and quarterly.

The weekly report consists of an upload count plot (see Figure 1), which shows the number of navigation uploads transmitted to each SV over the previous week. A health scan is also done, and only those uploads transmitted while the SV was healthy are counted. This report grew out of a contingency upload list which formerly was manually transcribed from crew Payload Systems Operator (PSO) log records. Reasons for excessive uploads are listed on the chart. Typical reasons for additional uploads include AFS instability, momentum dumps, and eclipse season operations.

Weekly ERD plots (see Figure 2) are used to investigate reasons for extra uploads. These charts are compiled weekly, but not distributed due to their large file size.

Monthly reports include a constellation ERD summary, an upload count summary, an upload aging summary, and a NIMA vs. MCS clock stability comparison chart. The ERD summary chart (Figure 3) lists an average daily RMS value for the constellation (both with and without GPS IIR SVs included), along with a monthly average daily RMS summary by SV. Finally, notes describe the poorest and best performers in the GPS constellation.

The monthly upload summary (Figure 4) shows the average number of uploads per day (while SVs are healthy) for the entire constellation for the past 6 months. Also included in this report are the daily upload statistics for each SV for the current and previous months. A table at the bottom lists SV outages.

Monthly upload aging plots (Figure 5) are compiled each month for each SV over a two-week and 60-day duration for the period 2 months prior to the current month. In these reports, every upload built for each SV for the month is reconstructed and compared to NIMA precise ephemeris and clock data. Mean uploads for each SV are plotted. Over 6,000,000 data points are processed each month to generate the upload aging report. [1]

The NIMA vs. MCS comparison report is also accomplished on a monthly basis. This report compares the stability (Hadamard deviation) of the MCS Kalman clock phase estimates with the phase estimates derived through NIMA post-processing. This check is accomplished on a Windows-PC platform using Stable32 developed Hamilton Technical Services. Three examples are discussed in more detail in the next section.

In addition to weekly and monthly reports, the quarterly reports contain a 90-day ERD summary for each SV (average and RMS daily statistics), and an overall ERD summary (see Figures 6 & 7).

RESULTS OF DATA ANALYSIS

NIMA Vs. Kalman Comparison

Figure 8 is an example of a "good" stability comparison between NIMA and MCS Kalman data. In this case, the Hadamard deviation plots line up on top of each other for $\tau > 2000$ s. For $\tau < 2000$ s, there is some divergence, but as this occurs for every satellite in the GPS constellation, it is assumed that this is due to processing differences between the MCS and NIMA.

Figure 9 is an example of a "poor" comparison between NIMA and MCS Kalman data. In this case, the phase data supplied by the MCS Kalman filter indicates a more stable clock than NIMA's phase data. This is due to the process noise values (Q's) that are specific to that particular clock. As a clock's characteristics change over time, the process noise values are periodically updated. Since new process noise values are derived approximately once per quarter, it is possible that a frequency standard's current performance characteristics can be different than the performance characteristics as measured several months ago.

Figure 10 is an example of intentional clock-ephemeris "cross corruption" of MCS Kalman filter states. In this case, the frequency standard has known, time-dependent, periodic behavior. Since the MCS Kalman filter can not model periodic behavior in the clock states, the process noise values (Q's) are set artificially tight. In this manner, periodic behavior in the clock states is transferred to the ephemeris states. Although this results in the separate ephemeris and clock states being modeled improperly, the combination results in a more accurate navigation solution.

SVN 19 Frequency Step Analysis

On May 25, 2000, SVN 19's Cesium Frequency Standard #3 experienced a frequency offset shift of approximately 2E-12 s/s. Frequency jumps, although not common, are on-orbit anomalies that 2 SOPS operators expect from time to time. Although there is nothing that 2 SOPS can do from a hardware perspective to minimize the effect of such perturbations, proper MCS Kalman filter maintenance can ensure a minimal impact on navigation signal accuracy, as well as on the MCS crew workload.

Each satellite's process noise values (Q's) are optimized for day-to-day operations, and do not take anomalous behavior such as frequency steps into consideration. In the case just described, it is the job of 2 SOPS analysts to adjust the filter to allow for the frequency step. This is accomplished by re-initializing the clock process noise to a database value. This procedure is known as a clock "Q-bump."

The transferred Kalman data, along with a set of "truth" data (in this case post-processed NIMA data), provides valuable insight into this anomaly, its effects, and the 2 SOPS corrective action taken. Figure 11 shows a plot of the phase-derived NIMA frequency offset estimates for SVN 19 during the timeframe of the frequency step. As seen in the figure, the frequency offset shifted at approximately 18:00 Z on 5/25/00. Also seen in this figure is the MCS Kalman filter frequency offset estimate before any filter maintenance was performed (Pre-Q-Bump). It is seen that the MCS filter frequency offset estimate did not react instantaneously to the frequency step (as discussed, the filter is designed for prediction purposes, and nominally does not expect a sudden shift in frequency). Once MCS operators observed the problem, a clock state Q-bump was performed. The figure shows how the filter adjusted its frequency offset estimate to fall in line with what actually occurred on the spacecraft.

Figure 12 shows not only the NIMA (non-phase-derived, in this case) and MCS frequency offset estimates, but also how the MCS mismodeling affected the navigation signal. It is clearly seen that SVN 19's navigation signal accuracy was degraded during the period of misestimation, and the MCS crews were kept busy re-uploading the navigation message. (New uploads appear as downward spikes in ERD data.) However, it is also seen that once the clock Q-bump was performed and the spacecraft was uploaded with an adjusted navigation message, the ERD runoff was much less severe, and eventually performance returned to normal. This careful post-anomaly analysis allows us to refine operational recommendations and procedures to minimize navigation signal accuracy and GPS crew impacts.

SVN 22 C-Field Tune Analysis

The current operational method of changing a GPS frequency standard's output frequency is to tune its C-field. After a C-field tune is commanded, the previous MCS Kalman filter estimate of the clock frequency is incorrect, and a ranging error runoff will occur. To correct this error, 2 SOPS operators use navigation signal data collected at the MCS monitor stations to calculate the new clock frequency and update the Kalman filter's state estimates.

Figure 13 shows data from a C-field tune which occurred on SVN 22's Rubidium Frequency Standard #1 on 6/15/00. As is typical in the case of a C-field tune, the spacecraft was set unhealthy to users (this timeframe can be seen as the shaded area in the figure). In this case, one can observe from comparing NIMA frequency offset estimates to MCS Kalman filter estimates that the MCS estimate was not optimal at the conclusion of the C-field tune and associated filter maintenance. Although the MCS estimate was close enough that the spacecraft could be set healthy, several additional navigation message updates were necessary during the first couple days following the event. ERD levels did not stay consistently low until the MCS estimate caught up with the actual frequency offset.

CONCLUSION

The ability to transfer Kalman filter data from the MCS to an offline system has proven to be extremely valuable to Boeing navigation payload analysts. This capability has provided insight into many aspects of GPS navigation payload analysis, including frequency standard trending and anomaly resolution. Although the transfer process is currently fairly cumbersome, plans for the future include an emphasis on ease of use and automation. It is hoped that the continued utilization and refinement of this data transfer process will assist Boeing in not only improving frequency standard analysis techniques, but in continuing to provide 2 SOPS and the user community the best overall GPS support possible.

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REFERENCES

- [1] G. E. Hatten, and J. V. Taylor "Navigation Upload Performance," Proceedings of ION GPS-00, September 2000.

Weekly Upload Count for Week 40, 2000

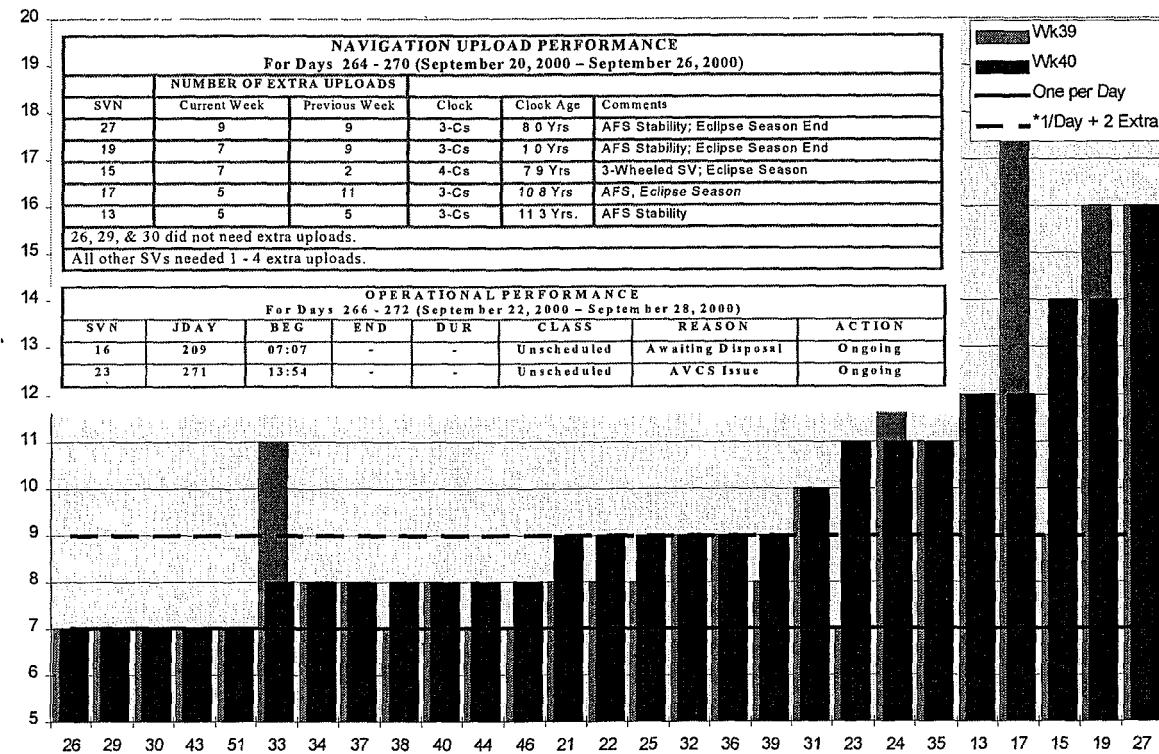


Figure 1. Weekly Upload Count Chart.

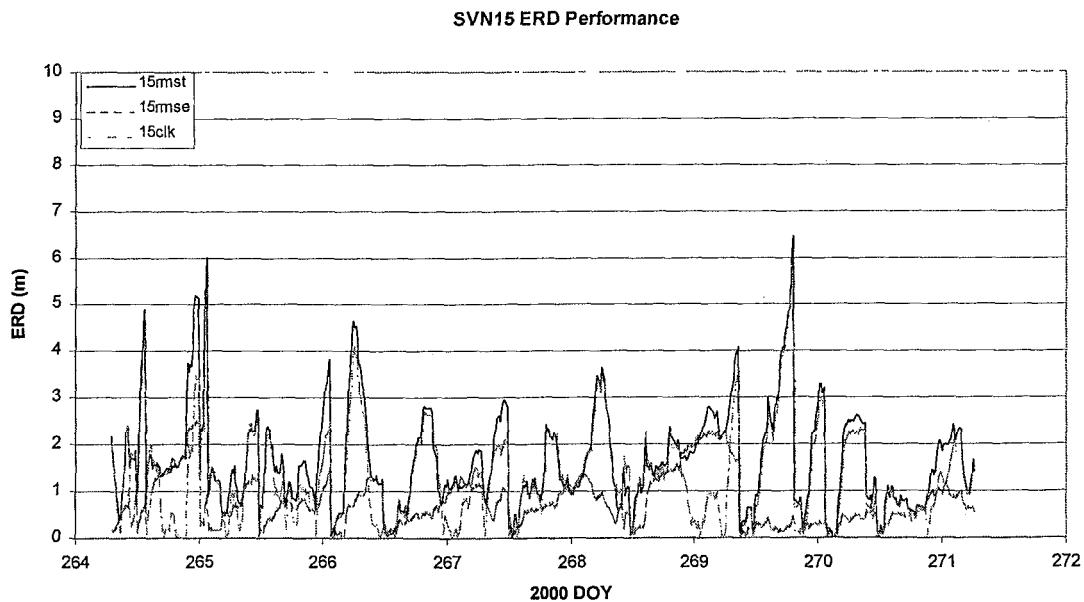


Figure 2. Weekly ERD Performance Chart (SVN15).

GPS Navigation Performance (As exhibited by Estimated Range Deviation) August 2000 - 1 Year Performance

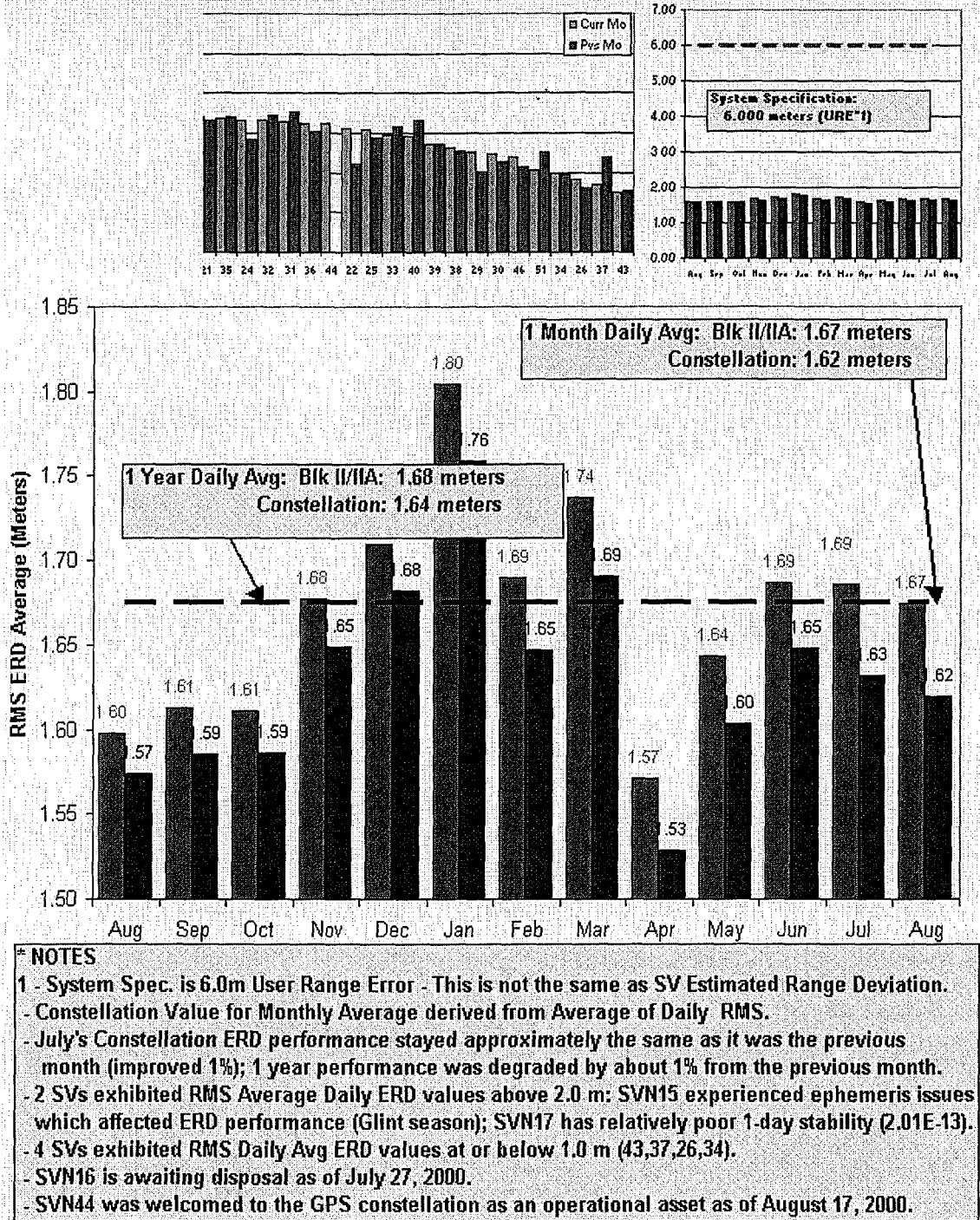


Figure 3. Monthly Navigation Performance Chart.

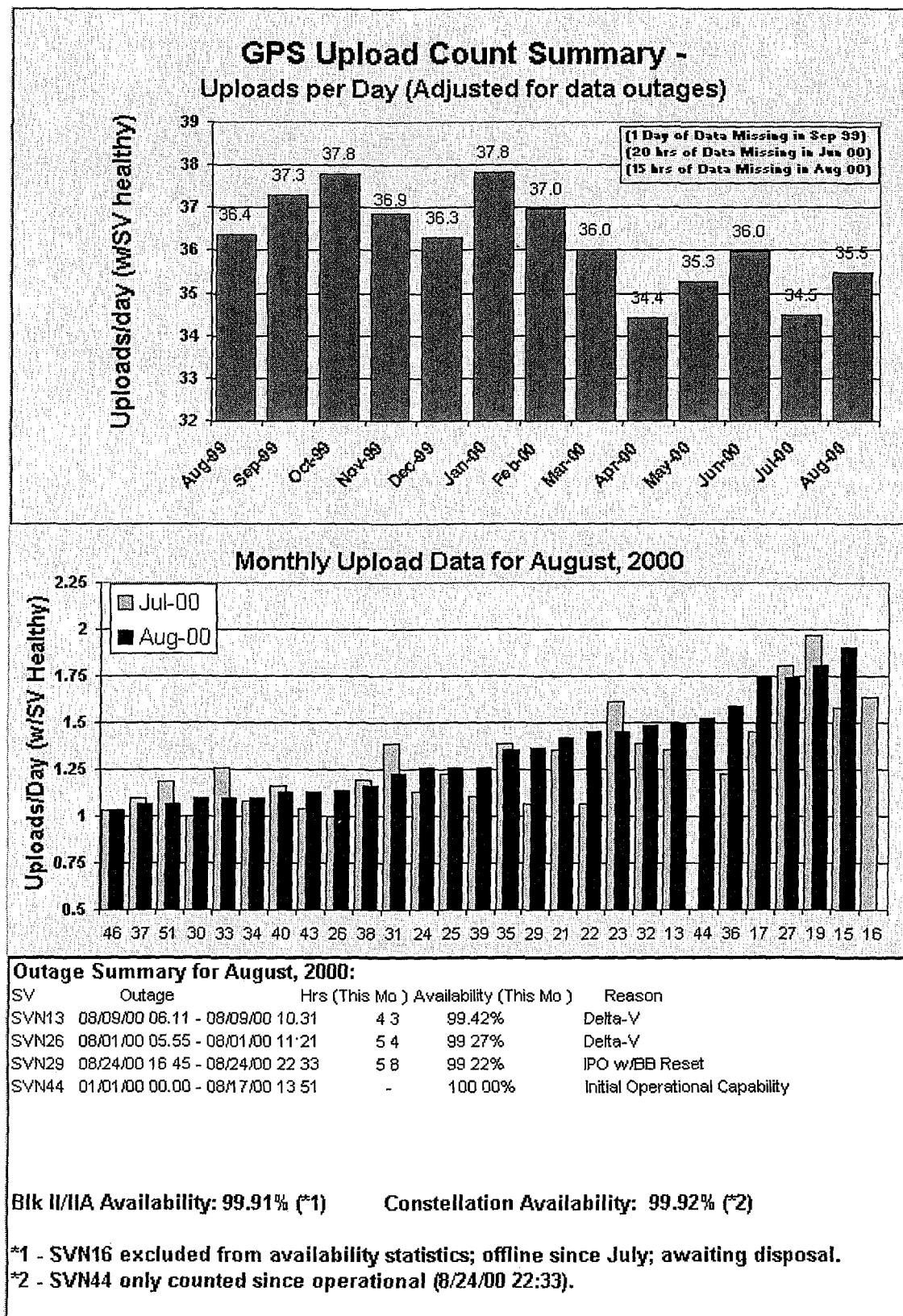
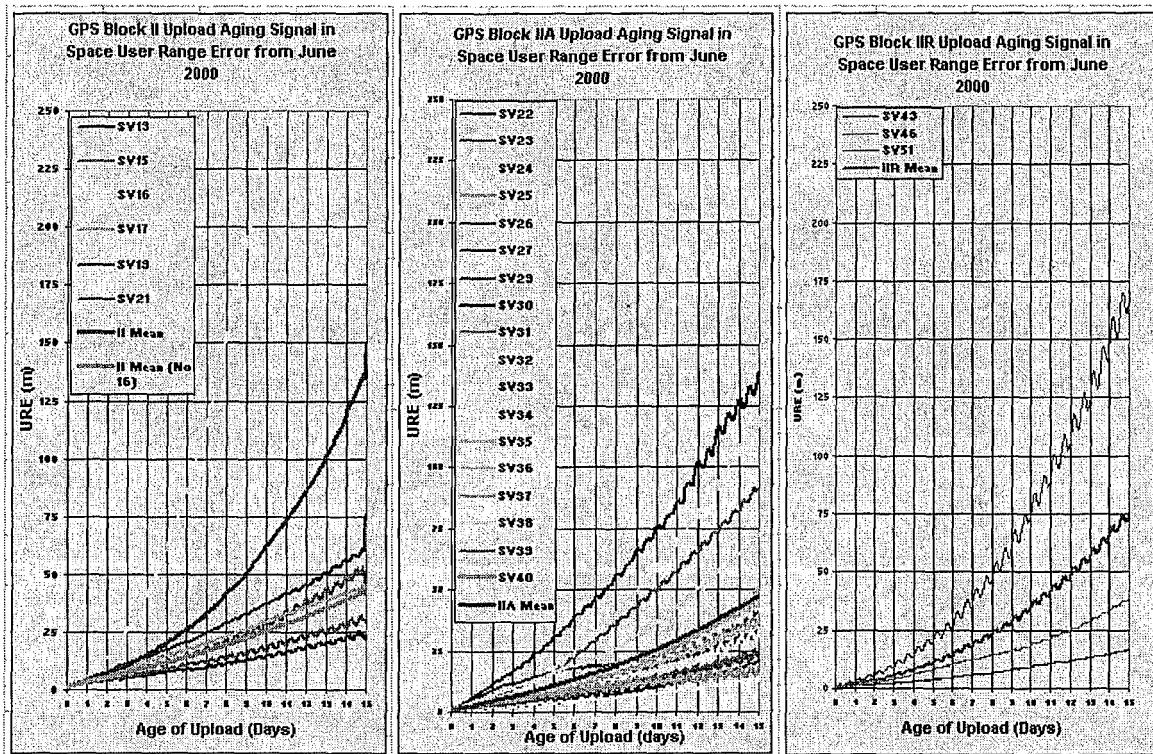


Figure 4. Monthly Upload Count Chart.



NOTES:

SVN16 Upload June 2000 UREs varied at 15 days from below 75 meters to over 1500 meters.

SVN18 was decommissioned during June 2000.

Bad upload data from SVN32 was edited out.

Figure 5. Upload Aging Chart (15 Days).

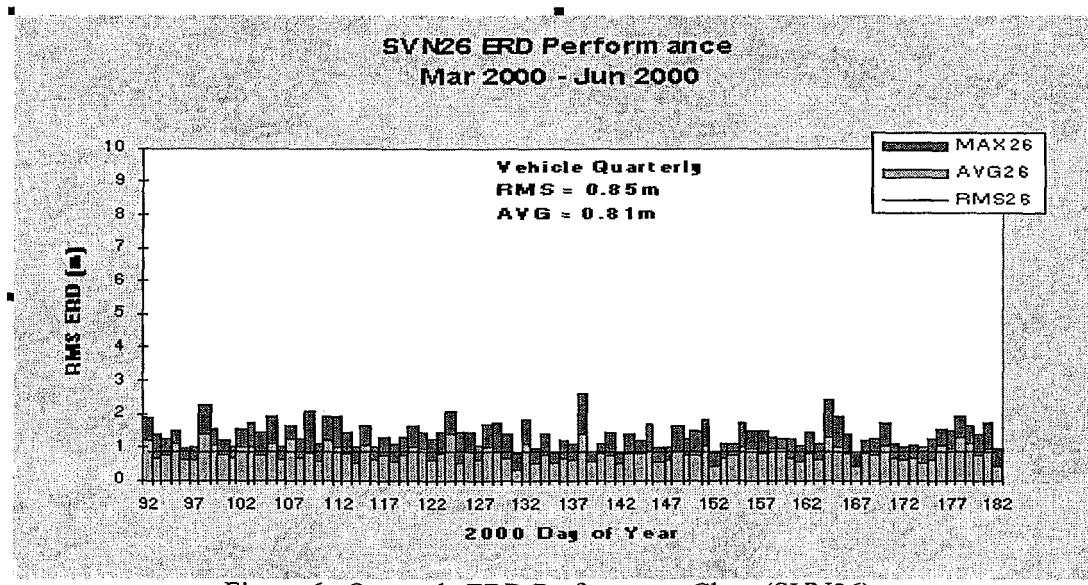


Figure 6. Quarterly ERD Performance Chart (SVN26).

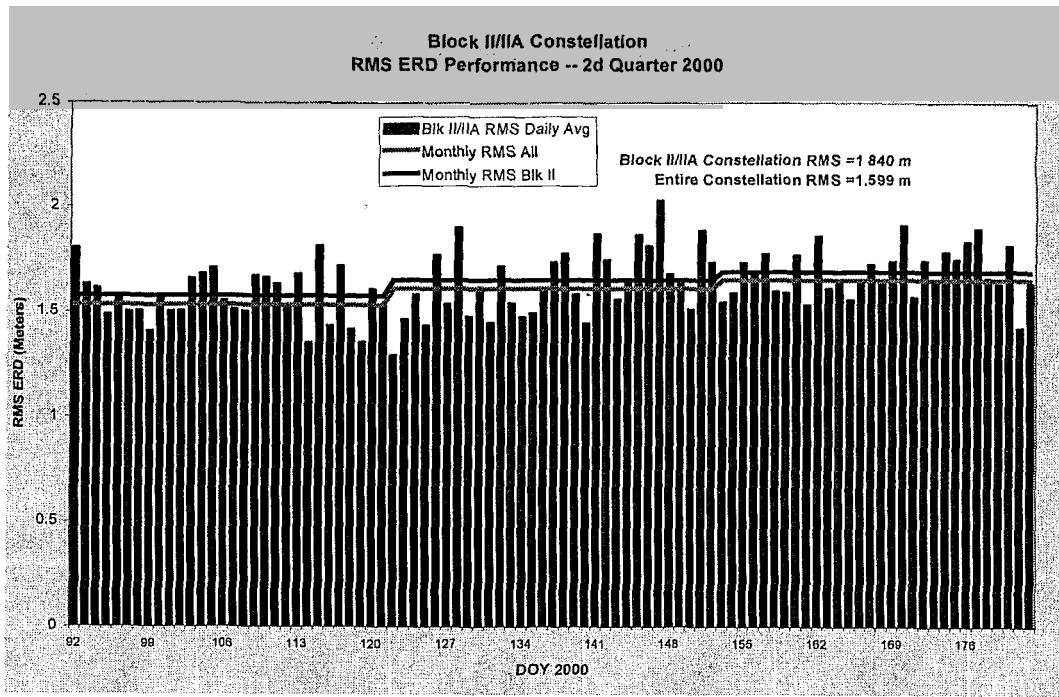


Figure 7. Quarterly ERD Constellation Performance Chart.

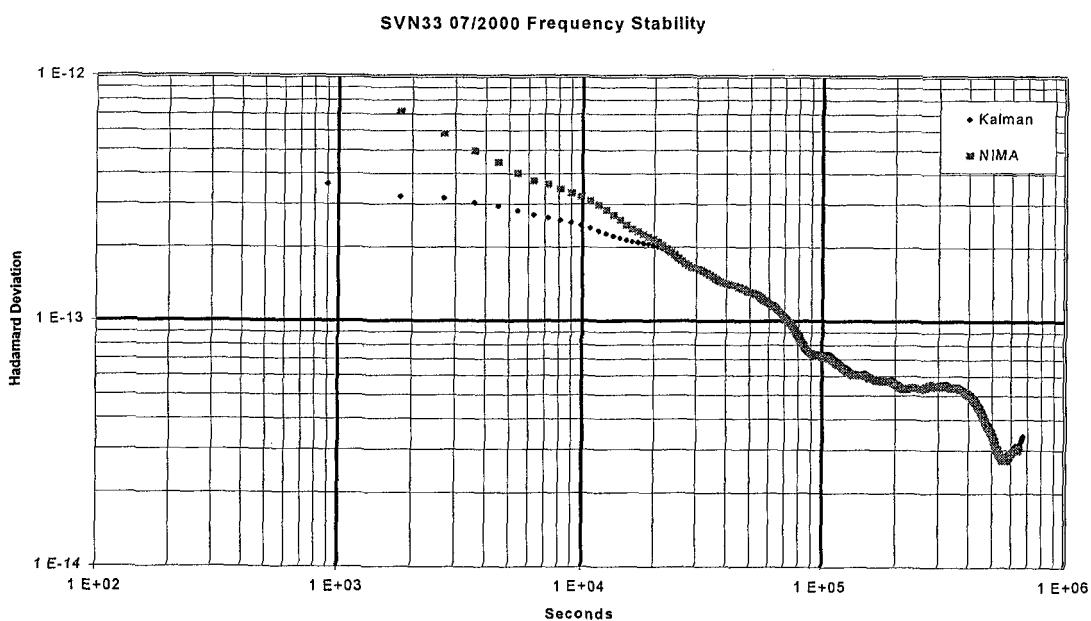


Figure 8. Example of “good” NIMA vs. MCS stability comparison.

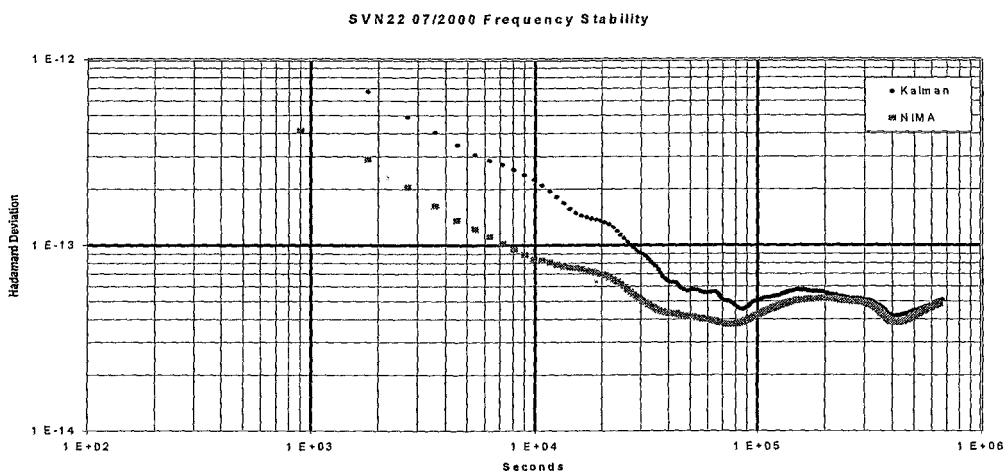


Figure 9. Example of “poor” NIMA vs. MCS stability comparison.

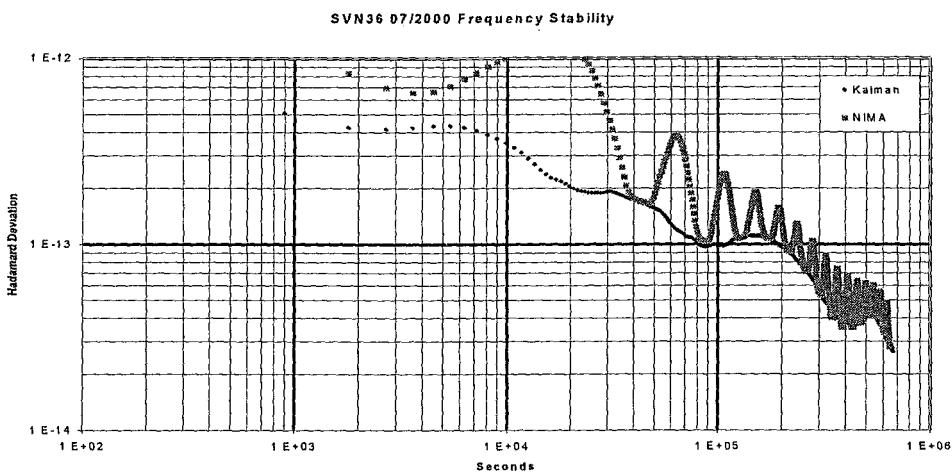


Figure 10. Example of MCS “cross-corruption”.

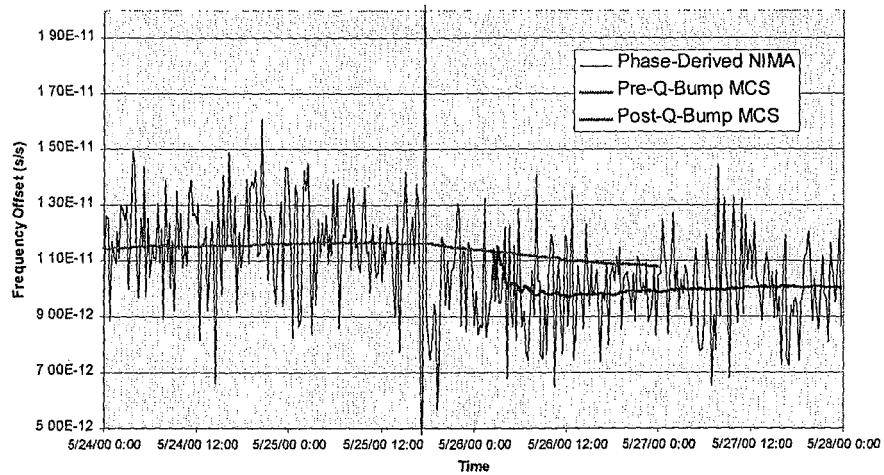


Figure 11. NIMA & MCS SVN 19 Frequency Offset Estimates.

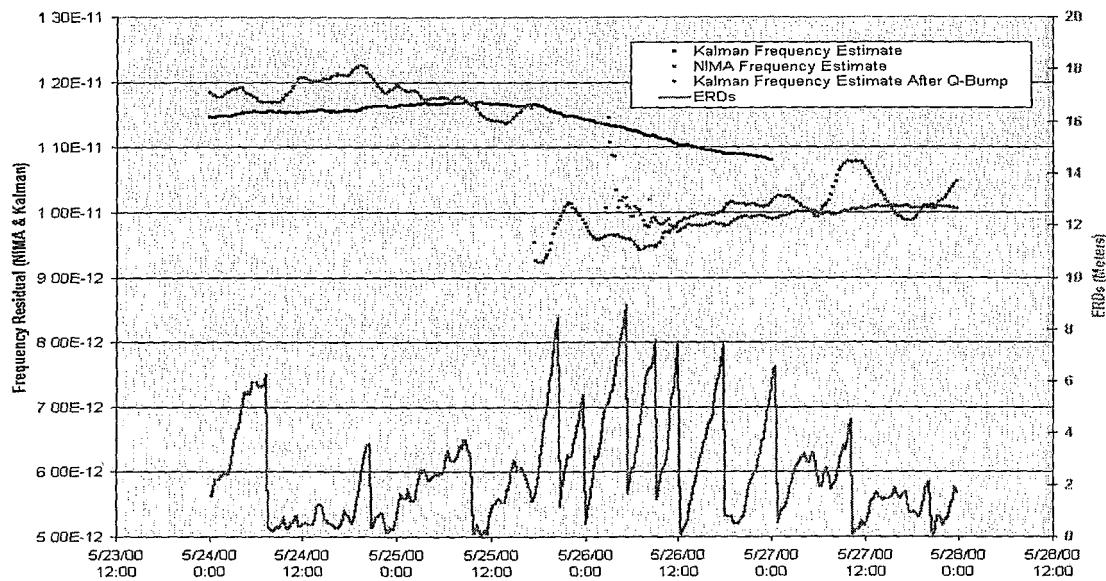


Figure 12. SVN 19 Frequency Step Impacts.

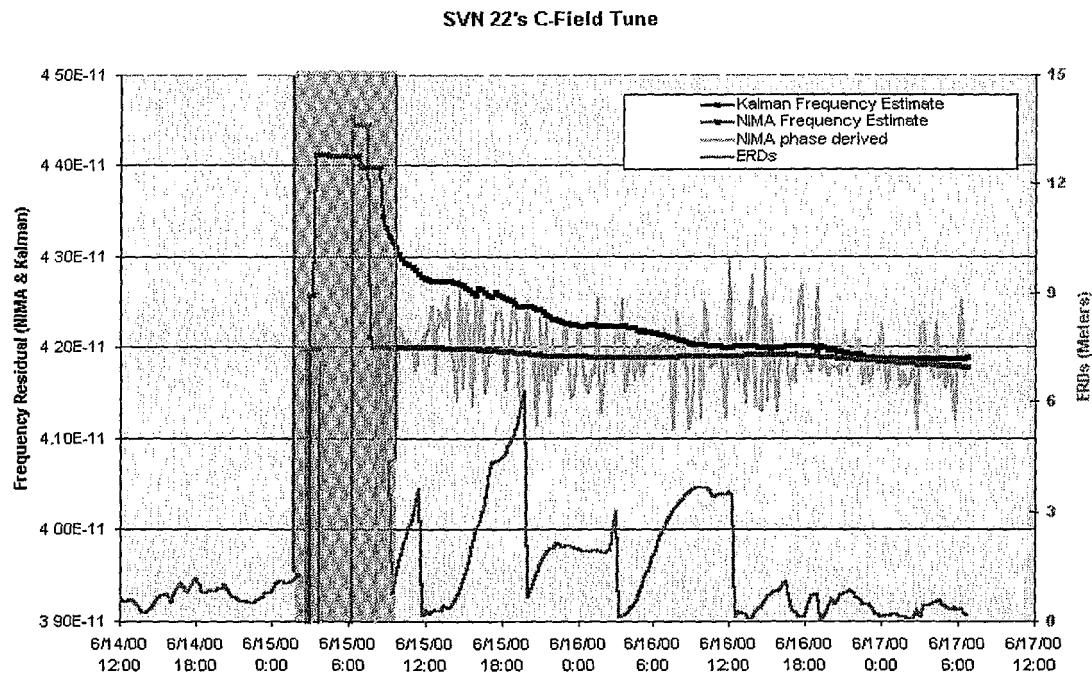


Figure 13. SVN 22 C-Field Tune Impacts.