ANALYSIS OF ON-ORBIT BEHAVIOR OF GPS BLOCK II-R TIME KEEPING SYSTEM

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Abstract

This paper presents three phases of the Time Keeping System analysis (TKS) of the first on-orbit GPS IIR Satellite, SVN 43. The first phase is a comparison of the performance of the SVN 43 Rubidium Atomic Frequency Standard (RAFS) to other GPS satellite clocks. The results indicate that the SVN 43 RAFS is performing better than specification and ranks highly when compared to the other clocks in the constellation. The second phase was to analyze all available data to determine the causes of several transients seen in the SVN 43 TKS. This led to a concentration on the RAFS and associated inputs and outputs, as well as the utilization of TKS simulation tools. The third phase was to examine the entire system to determine how to improve our visibility into the TKS operation. This led to an SV software enhancement whose purpose is to buffer TKS related data in SV memory for subsequent dump and analysis. An example will be presented showing the value of this new TKS buffer capability in the investigation of some TKS events that occurred in August 1998.

INTRODUCTION

The first Block II-R satellite (SVN 43) of the Global Positioning System (GPS) Replenishment constellation built by Lockheed Martin Missiles and Space was made available to users on 31 January 1998. ITT ACD built the Navigation Payload for the Block IIR. The Navigation Payload produces the signals for the GPS users. Block IIR provides an order of magnitude enhancement to the GPS system, including accuracy, simplicity, and low on-orbit maintenance. The SVN 43's primary Rubidium Atomic Frequency Standard (RAFS#1) designed by EG&G has been powered since 13 August 1997. The RAFS stabilized quickly, and until 20 December 1997 no unusual phase or frequency jumps were observed.

RAFS STABILITY

Figure 1 and Figure 2 put into perspective the excellent performance that has been seen with the SVN 43 RAFS. These charts were made with the use of the precise clock data available at the National Imagery and Mapping Agency (NIMA) website[1]. The SVN 43 RAFS is performing better than the GPS Block IIR one-day stability requirement of $5x10^{14}$ parts. The chart depicts rubidium clocks with a clear bar and cesium clocks with a solid bar. Note that the rubidium clocks, in general, have the best one-day stability.

NAVIGATION PERFORMANCE

The GPS Master Control Station (MCS) computes an estimated range deviation (ERD) which is an estimate of the range error an authorized user would see using the broadcast ephemeris and clock. The daily peak ERDs for the second quarter of 1998 were averaged and the SVs were ranked in order of this averaged peak ERD,[2] as shown in Figure 3. The ranking in this chart correlates very closely with the ranking by the one-day Hadamard deviation. In other words, as one would expect, the clocks with the higher one-day stability are yielding superior Navigation performance.

TKS DESIGN

A simplified block diagram of the TKS is shown inFigure 4. As can be seen from the diagram, the 10.23 MHz VCXO is kept in phase lock with the RAFS. The 10.23 MHz VCXO provides the heartbeat for the GPS P/Y/CA code ranging signal. Software monitors the difference between the expected phase and actual phase and makes VCXO tuning adjustments to maintain lock of the VCXO to the RAFS.

Transients in either the VCXO or the RAFS will show up as larger than expected phase errors. Capturing these phase error measurements is critical to determining the nature of transient in the TKS. Phase error measurements are collected from telemetry whenever the 2SOPS (Second Space Operations Squadron) is in contact with the SV, which is typically less than 1 hour in any 24-hour period. With limited contact time, it is very unlikely that phase error data will have been captured during a TKS transient. This is why the capability to buffer phase error data on board the SV was recently added.

SUMMARY OF SVN 43 TRANSIENTS

The SVN 43 RAFS has exhibited transient behavior in space for short periods of time. The transients occurred between the fourth and sixth months after AFS turn-on. There were five phase transients identified to date and they are summarized inTable 1. In every case, the phase moved in the same direction.

Table 1. Summary of Transients

When	From AFS On	Size
12/20/97	129 Days	~ +16 μs (non-standard codes)
1/19/98	159 Days	+9.8 ns
1/22/98	162 Days	+12.2 ns
1/22/98	162 Days	+6.8 ns
2/9/98	180 Days	+192 ns (non-standard codes)

The TKS has software logic to autonomously protect GPS users from phase transients larger than 15.84 ns. This logic activated in two of the five events listed above and is identified by the words "non-standard codes." The events large enough to cause non-standard codes are evident to the 2SOPS. In these cases, the 2SOPS took action to correct the phase offset via a new Navigation upload and restored standard codes to get the SV back on line.

The other cases are less noticeable to the 2SOPS since they fall into the normal range of errors that are typically seen with GPS satellites over the course of a day. In these more subtle cases, NIMA data were the first place we noticed the transients. After identifying a transient with NIMA data, we went back to the MCS Kalman reports to verify there was a rise in ERD at the time of day the NIMA data showed a transient.

12/20/97 EVENT ANALYSIS

Telemetry indicated on 12/20/97 07:22:30.0, the TKS went to "fast loop/non-standard codes" in response to unexpected large phase errors of greater than 15.84 ns. Six seconds later, the TKS went to "open loop" in response to the RAFS internal frequency-locked loop going out of lock. 2SOPS first made contact with the SV at 08:10 and telemetry from that contact shows the RAFS internal frequency-locked loop in lock and all the RAFS telemetry to be nominal except for a one LSB change of the RAFS VCXO voltage. The phase error from this contact was extrapolated back to the time of the event (07:22:30.0) to determine that a total phase transient of +16μs was present. This phase transient suggests that the RAFS increased frequency over some interval enough to integrate into +16 μs of phase.

An SV memory dump performed during this contact revealed several more clues that helped in the investigation. In particular, the last three phase error measurements were saved, and the fourth prior phase error could be inferred. Also, since this 4th previous phase error caused the TKS to go to "fast loop" mode, we determined that the fifth previous phase error must have exceeded 15.84 ns.

In addition, monitor station measurements collected just prior to non-standard codes imply the occurrence of a RAFS transient rather than a VCXO transient. Those measurements reveal a single measurement with a discontinuity of -114.9 ns just prior to non-standard codes. This is exactly what would be expected with the VCXO tuned to its maximum value. A VCXO transient would have caused several measurement outliers, rather than a single outlier, given the characteristics of the control loop design.

In summary, having examined all available data for the 12/20/97 event, it is clear that the RAFS frequency standard changed frequency within a 3-second window to a very large relative frequency offset of about 1.92e-6. The TKS went to fast loop, and 6-seconds later saw that the "lock" bit from the RAFS was off, and then went to open loop. It appears that the RAFS spontaneously re-locked within 10 seconds of the frequency jump, resulting in a phase error of 16 μs. The RAFS frequency returned to the pre-event level, as there were no frequency discontinuities present in the NIMA clock data.

Prior to this event, SVN 43's status had been set "unhealthy" for testing purposes. If users had been using SVN 43, their receivers would have measured a pseudorange error of 40m for one epoch before SVN 43 recognized the error and effectively ceased transmission.

2/9/98 EVENT ANALYSIS

From the NIMA clock data, we derived the +192 ns permanent phase change. These data also showed that there was no permanent frequency change. A frequency change to the VCXO could have caused only a temporary phase change. The permanent phase change is not a multiple of the 74.6 ns RAFS cycle period of the reference timing change, ruling out the digital timing chain components.

Again, there was no S-Band contact during the event and thus no phase error telemetry captured. However, significantly, a one LSB change in the RAFS VCXO control voltage was observed across the event.

Telemetry indicates on 2/9/98 22:33:13.5, the TKS went to "fast loop/non-standard codes" in response to unexpected large phase errors of greater than 15.84 ns. Later at 22:36:18.0, the TKS went to "slow loop," indicating the event had run its course and the phase error measurements had stabilized.

Monitor station measurements just before non-standard codes do reveal outliers and from those outliers, inferences can be made about the characteristics of the underlying transient in the RAFS. For example, a 5.74 ns outlier is visible in the last monitor station measurement just prior to non-standard codes. This implies that the measured phase error was 35.2 ns. $\pm$ 1.67 ns and that the TKS must have been in "fast loop."

The phase error vs. time curve for the RAFS for the 2/9/98 event is not as easy to nail down as for the 12/20/97 event. To be correct, a RAFS frequency error vs. time curve must meet the following three conditions:

1. Integrated over time, it sums to 192 ns.

2. The first four phase errors (derived from monitor station measurement data) induced in the TKS loop are in the following ranges: < 3.5 ns, 3.5-15 ns., 15-25 ns., 35.2 ± 1.67 ns.
3. The TKS takes about 123 epochs (1 epoch = 1.5 sec) to return to slow loop.

Given the three constraints listed above, Figure 5 shows a possible scenario in which the RAFS frequency error peaks at 8e-9 and then is gradually corrected (epochs 0-75) until it is finally back to its nominal frequency. The integrated frequency error vs. time is exactly 192 ns.

In summary, the 2/9/98 event looks like a less severe version of the 12/20/97 event. Since the maximum frequency offset of the RAFS was ~ 1e-8, the RAFS internal frequency-locked loop stayed locked, or if it ever became unlocked, the unlock condition was not detected by the SV. The TKS protected users from ~ 60m URE errors by generating non-standard codes when the phase error was < 2m (5.74 ns).

SVN 43 DATA CAPTURE ADDITIONS

Capturing phase error data is critical to help characterize the profile of a transient. As an example of the usefulness of phase error data in characterizing a transient, the Control Segment inserted a four-nanosecond phase step in SVN 43 in September 1997 while phase error telemetry data was being recorded. Figure 6 is a plot of the phase error telemetry data overlaid by simulation data for a four-nanosecond phase step. The simulation was used to verify that we have a valid model of the effects of a phase jump in the TKS of SVN 43.

Since the noise and the transients are similar, we are sure that we have a valid model of the effects of the phase jump on the TKS system.

The next step was to examine the difference between a phase step and a frequency step. A frequency step was introduced into the ASIC Test Bed (ATB) during formal qualification testing (FQT) of the software. Figure 7 contains a plot of the phase error data during the ATB frequency step transient. A simulated frequency step was overlaid to show that the TKS simulation provides an accurate representation of a frequency step. Figure 7 also shows a window that represents the new phase error buffering capability described in the next paragraph. A simulated phase jump was added to Figure 7 to show how data in the window will show the difference in the phase error output between a frequency and a phase step.

A modification to the SVN 43 software was made to add three buffers to capture phase error telemetry in a plus/minus 150-second window around a TKS transient. These data will be buffered in SV memory for later dump to the ground for analysis. These buffers will be utilized to characterize the profile of a transient. We will be able to distinguish between a frequency vs. a phase transient, the size of the transient step, and random wander variation. The size of a phase step is obtained directly, while the initial slope of the phase error plot determines the size of the frequency step. Figure 7 shows the window of phase error telemetry that we can expect to capture around a transient.

ON BOARD TKS DATA BUFFERING CAPABILITY

On 16-August-1998, the new trace buffer capability paid off by capturing detailed information about some TKS events. This section will show details of the investigation of the events, which include examples of how we used the new capability, as well as other data to aid in the investigation.

DATA CAPTURED IN TKS BUFFERS

There were a few TKS events that occurred during eclipse season in August. Analyses of these events implicate the 10.23 MHz VCXO and not the RAFS. The new TKS Trace Buffer capability worked very well at capturing valuable evidence to help troubleshoot the events.

The first collection of events consisted of two fast to slow loop transitions on 16-August-1998. Telemetry indicated that the TKS entered the first Fast Loop at 01:46:21.0 GPS followed by entry into non-standard codes at 01:46:22.5 GPS. Standard codes were restored by ground command at 05:35:19.5 GPS, which put the SV back on-line for the users. The ERDs remained low through this event and no upload was required prior to bringing the SV back on-line.

The second collection of events occurred toward the end of eclipse from about 23 August 1998 through 31 August 1998. These events were not visible in the ERDs, but were noticed in the NIMA data as uncharacteristic noise in plots of frequency and first difference of phase. Further examination of phase error telemetry uncovered some outliers that indicated noise in the TKS that was likely caused by noise in the 10.23 MHz VCXO frequency.

TKS EVENT EVIDENCE

The following significant telemetry occurred with the 16 August event:

1) Transition to fast loop at 01:46:21.0
2) Transition to non-standard codes at 01:46:22.5
3) Transition to slow loop at 01:48:04.5
4) Transition to fast loop at 01:51:00.0
5) Transition to slow loop at 01:52:42.0
6) Ground command to standard codes at 05:35:19.5.

The TKS trace buffer showed a runoff of phase error that started around 01:30 and peaked at 01:46:21.0, where fast loop was entered when the TKS exceeded the 15.84 ns failure threshold. A plot of the TKS trace buffers with buffer 0 and buffer 1 combined is shown inFigure 8. Fast loop was able to track out the phase error and a transition to slow loop occurred at 01:48:04.5, but whatever was happening with what we believe was VCXO frequency was still present. Fast loop again was entered at 01:51:00.0, followed by a transition to slow loop at 01:52:42. The TKS remained in slow loop after the last transition.

2SOPS made the first contact with the SV at 02:11. Phase error telemetry from that contact starts with a positive bias of about 4 ns. This is shown in Figure 9.

The most telling evidence of what may have happened is found in the samples of the frequency estimate variable from the TKS trace buffer and TKS dumps. This plot is shown Figure 10. The plot shows that the 10.23 MHz VCXO may have taken a rapid frequency change of -1e-9 parts on 16 August. It appears that the VCXO frequency took a month to return to its original value. The rapid step change in VCXO frequency on 16 August was faster than the slow loop time constant could keep up with and, thus, the transition to fast loop. Once the VCXO frequency stabilized, the TKS slow loop was able to compensate for it and keep it locked to the RAFS.

Another indication of noise in the TKS can be seen in the plot of the clipping count (Figure 11), which is stored in the TKS trace buffer. The clipping count shows the number of times the phase error crossed the 3.548 ns clipping threshold. As can be seen from the plot, the counter began incrementing, beginning with the 16 August event, and didn't stop incrementing until 1 September. For reference, eclipse season ended on 31 August. During this whole period, the noise in the TKS wasn't passed appreciably into the L-band as ERDs remained low and stable and non-standard codes protected the user from the rapid change on 16 August.

The NIMA phase data did indicate some noise in the TKS that prompted us to look closer into the phase error telemetry. In particular, the first difference of NIMA phase plot (Figure 12) shows some noise in the period between 23 August and 31 August.

There were several outliers noted in the phase error telemetry during this period of noise seen in the NIMA data. One plot shown in Figure 13 indicates the phase error grew to about 10 ns within a ½ hour interval.

THE INVESTIGATION PROGRESS

The investigation into the cause is still ongoing. At this point the RAFS has been ruled out, since there was no permanent phase offset present that was present in the other RAFS-related events. This means that the RAFS has been event free since February 9, 1998. The likely source of this activity falls with the 10.23 MHz VCXO and that has been the focus of current investigation effort.

CONCLUSIONS

The GPS Block II-R Rubidium Atomic Frequency Standard in SVN 43 is the best in the constellation based on the one-and ten-day Hadamard deviations and the second quarter ERDs.

RAFS has exhibited transients. It is still unclear whether these are only beginning of life phenomenon.

The TKS data capture capability now available provides an internal analysis capability that complements the external analysis capability provided by NIMA data and Naval Research Lab GPS clock reports.

The combination of the accuracy of SVN 43 and the analysis capabilities of the data sources insure a more accurate GPS constellation in the future. It also provides a foundation for future satellite designs that provides a better a path to extended GPS constellation availability, integrity, and accuracy.

REFERENCES

[1] http://164.214.2.59/geospatial/products/GandG/sathtml/

[2] ERD data compiled by Dave Koster of Lockheed Martin Missiles and Space

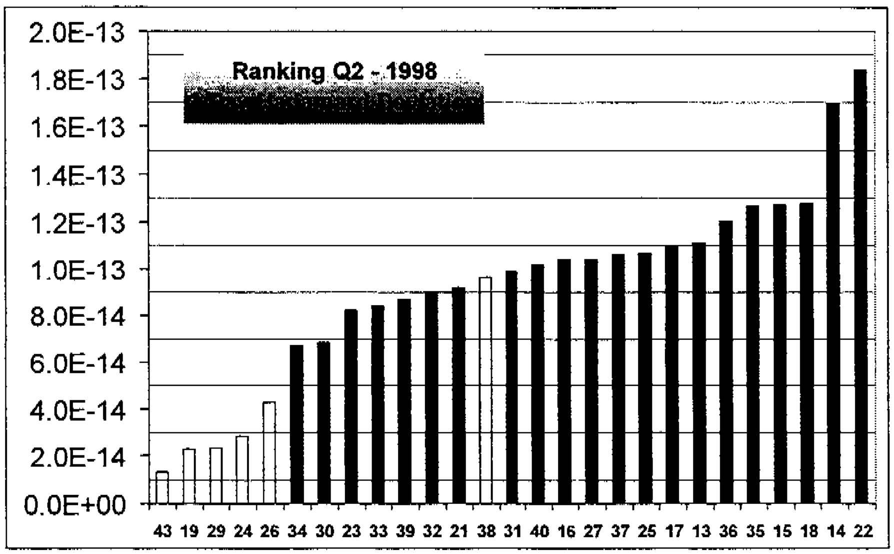

Figure 1. Ranking by 1-Day Hadamard Deviation

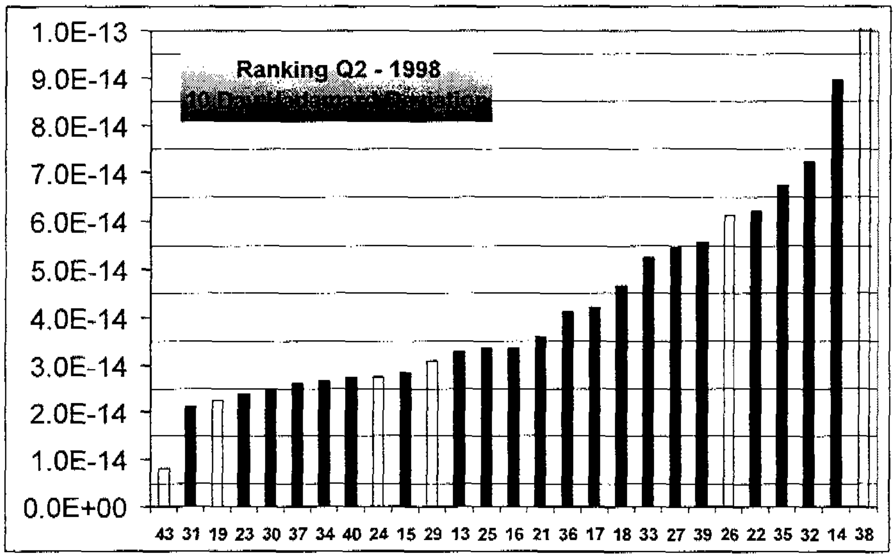

Figure 2. Ranking by 10-Day Hadamard Deviation

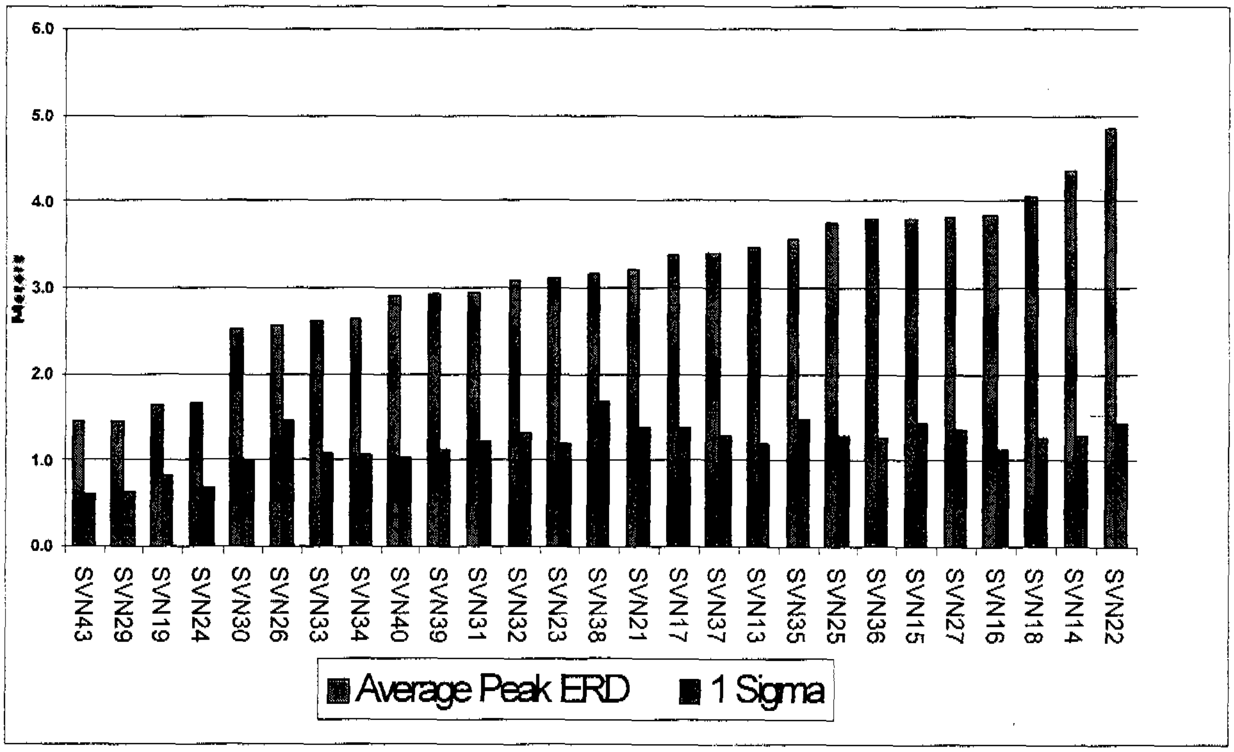

Figure 3. Ranking by ERD

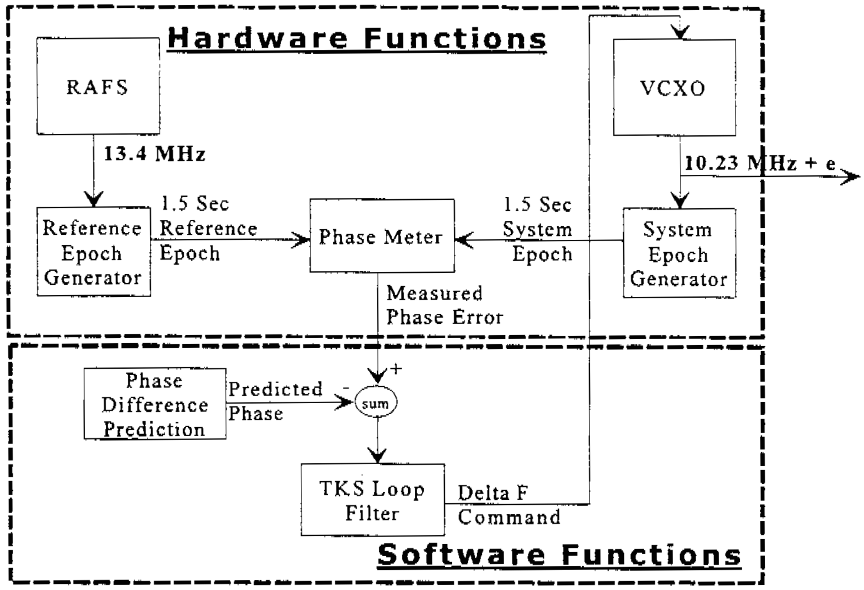

Figure 4. TKS Block Diagram

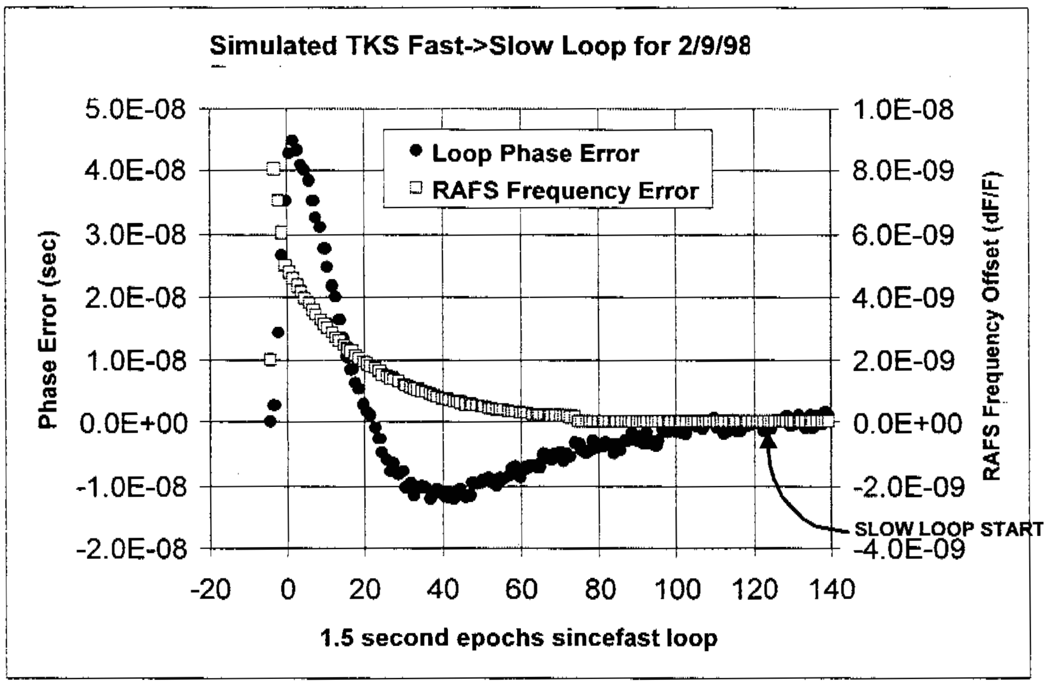

Figure 5. Feb. 9 Event Simulated Transient Profile

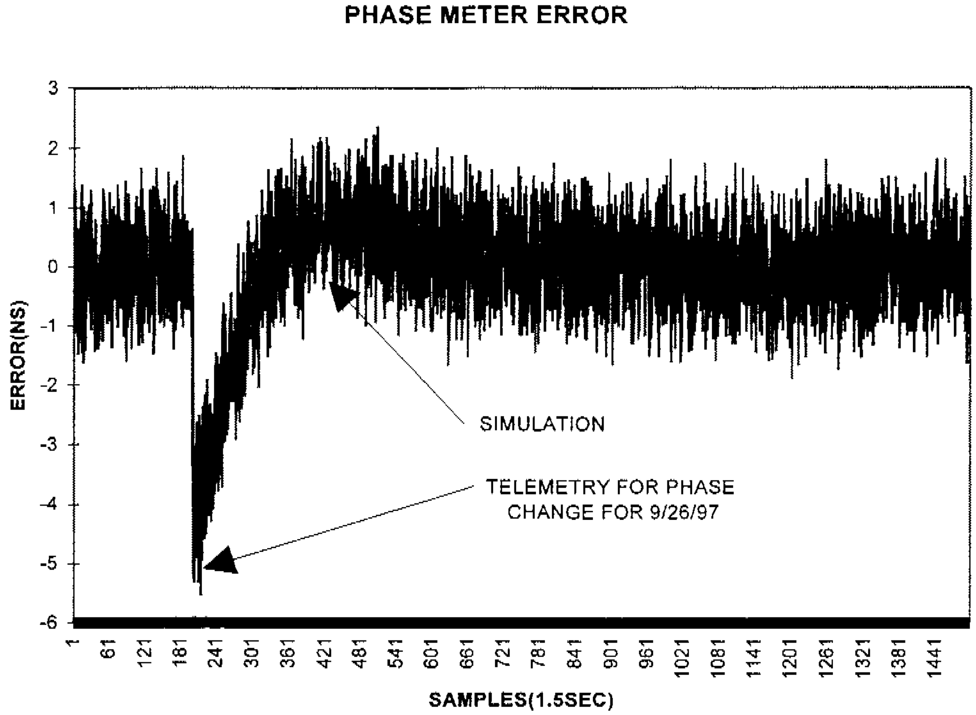

Figure 6. Phase Error Profile for Phase Transient

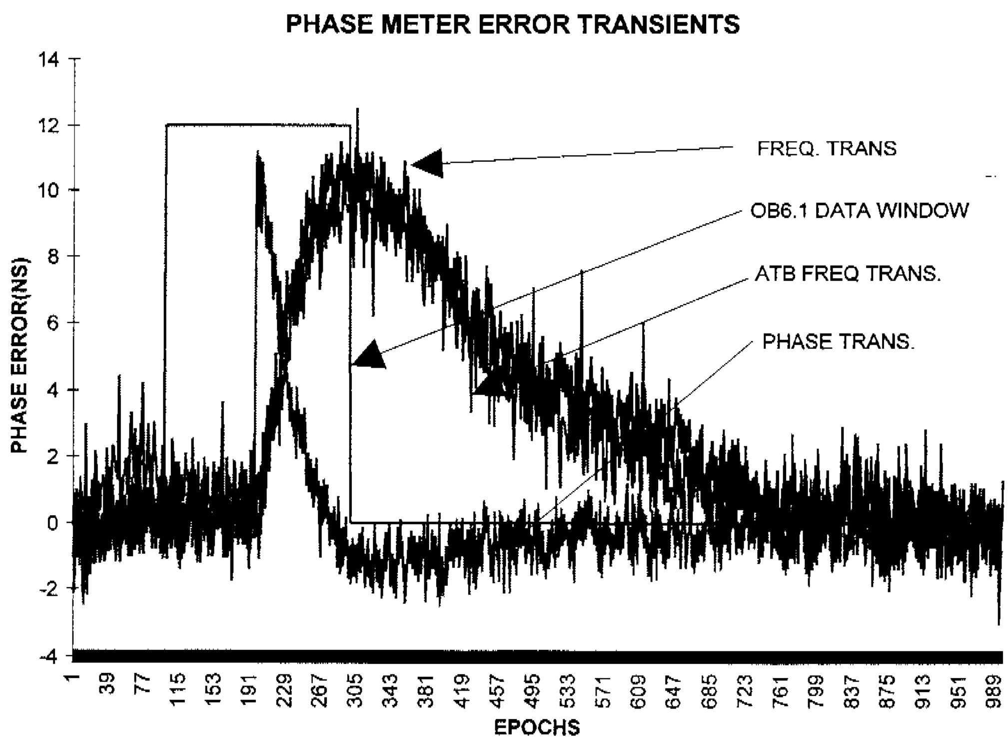

Figure 7. Phase Error Profile for Phase and Frequency Transients

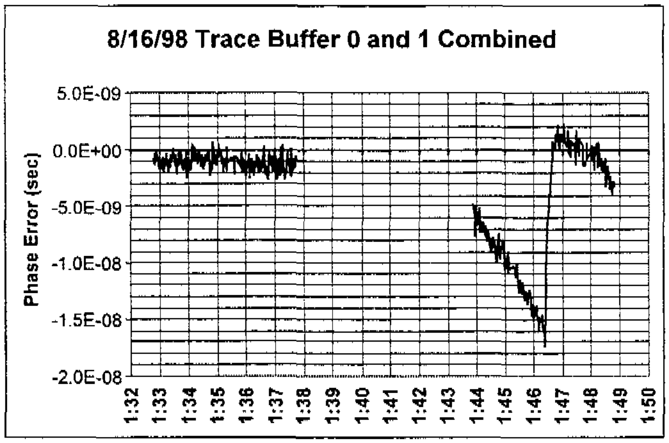

Figure 8. TKS Trace Buffer Plot

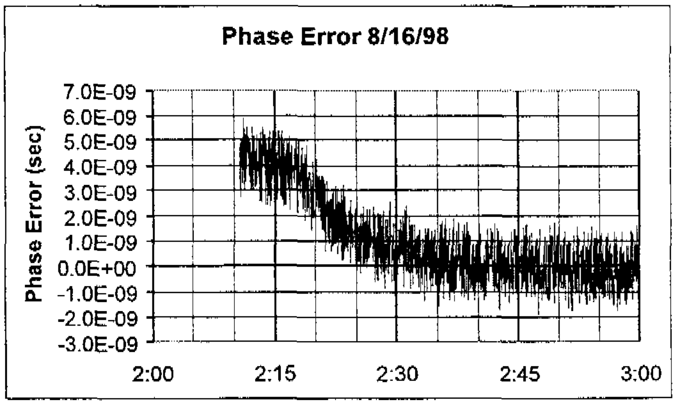

Figure 9. Phase Error Telemetry

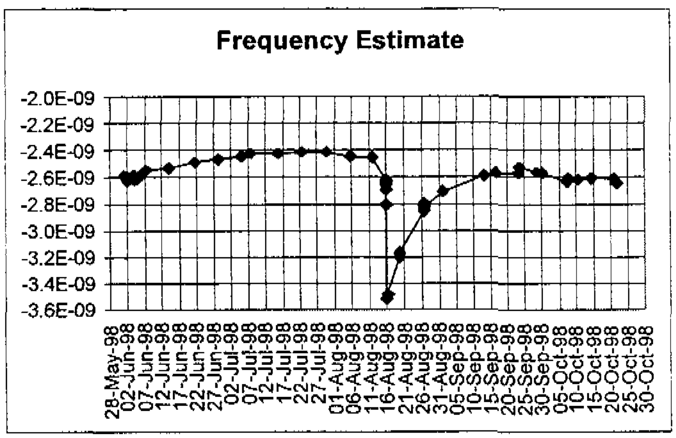

Figure 10. Frequency Estimate Plot

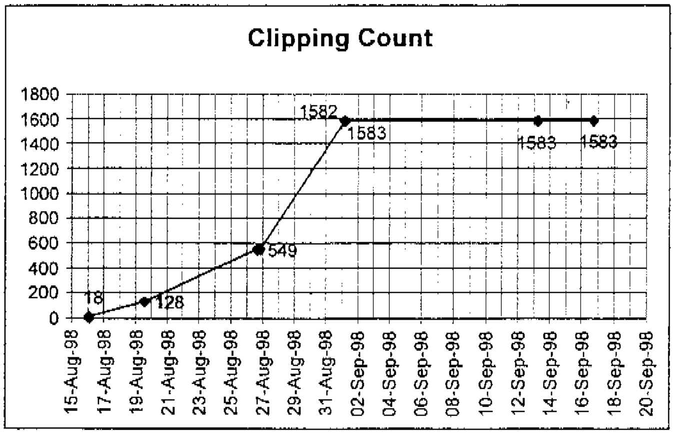

Figure 11. Plot of Clipping Count

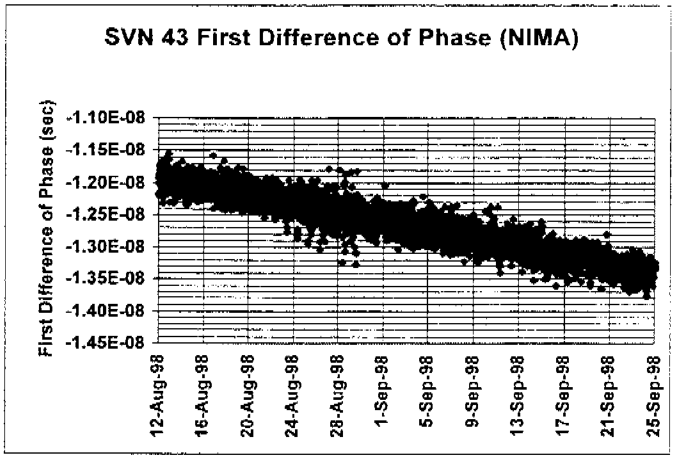

Figure 12. NIMA First Difference of Phase

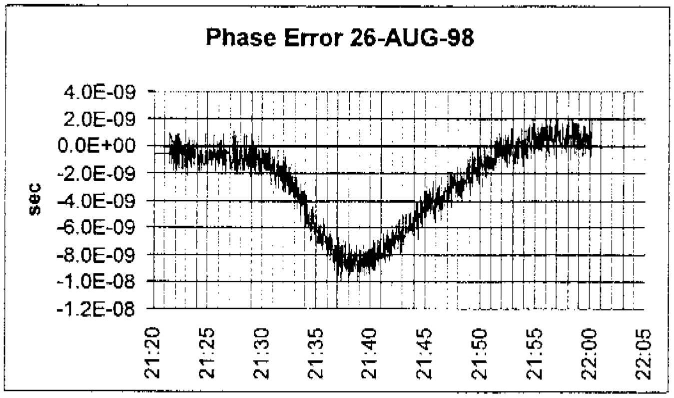

Figure 13. Phase Error Telemetry August 26

Questions and Answers

HUGO FRUEHAUF (Odetics Telecom): Have you considered taking a lot of VCXOs that you have, and checking them in the lab for phase pops to see what their condition is as a possible clue?

THEODORE DASS (ITT): A lot of testing is done on these clocks prior to delivery, and none of the clocks have exhibited any of these phenomena at the EG&G factory or during the RAFs' life test. There was a paper earlier that showed some frequency discontinuities in the RAFs. There has been a lot of testing and more of the RAFs have exhibited this phenomena.

HUGO FRUEHAUF: Yes, but EG&G would only be testing the frequency standard, it would not be testing the external VCXO, right?

THEODORE DASS: In these particular events, we do believe it is not the VCXO, but that it is the RAF. So, we do not suspect the VCXO. Now, we did have another event on August 16th that we do suspect was a VCXO. As my presentation was long, I did not get to it. None of the test data on the VCXOs has shown any of what we saw on August 16th. It should have shown up in the testing if it had exhibited the same thing we saw on-orbit.