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INVESTIGATION OF THE GPS BLOCK IIR TIME KEEPING SYSTEM (TKS) ANOMALIES CAUSED BY THE VOLTAGE-CONTROLLED CRYSTAL OSCILLATOR (VCXO)

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Abstract

Since the launch of the first GPS Block IIR (SNV43) on 7/22/97, its TKS performance has been outstanding. SVN43 TKS has the lowest Hadamard deviation of all the GPS constellation satellite clocks. Nevertheless there have been five reported Block IIR TKS anomalies in which non-standard codes were transmitted by the SV to protect GPS users. ITT analyzed the first two events, which occurred on 12/10/97 and 2/9/98, and conjectured with limited data that large frequency jumps in the Rb clock output were the cause of both problems. These two anomalies occurred outside of the normal daily contact windows by the ground control, so no recorded telemetry is available to accurately identify or simulate the cause of these anomalies. To remedy this shortcoming, the satellite software was modified in May 1998 to store key data in several circular buffers in a ± 150-second window around a TKS transient. These buffers in the SV computer memory can be dumped at subsequent SV contact with the ground for analysis. Since the upload of the modified software, three TKS anomalies were reported on 8/16/98. 1/29/99, and 7/22/99. This paper presents the TKS simulations performed to reproduce these three events, and will show that they were most likely caused by VCXO transients. Recorded data indicate VCXO transients are highly correlated with eclipses. The paper will also suggest ways to prevent or curtail anomalies caused by VCXO transients.

INTRODUCTION

The GPS Block IIR TKS generates the 10.23 MHz signal from a VCXO using a rubidium (Rb) clock as an input reference. The TKS is a phase-lock loop using a phase meter to measure the phase difference between the VCXO and the Rb clock. Any transient from either VCXO or Rb clock will result in phase build up at the phase meter output. The SV computer routinely monitors the phase meter output and the SV will transmit non-standard codes to protect GPS users when persistent large phase errors are detected. Since the launch of the first GPS Block IIR SV (SNV43) on 7/22/97, its TKS performance has been outstanding. SVN43 TKS has the lowest Hadamard deviation of all the GPS constellation satellite clocks, as shown in Figure 1. However, there have been five reported Block IIR TKS anomalies in which non-standard codes were transmitted by the SV to protect GPS users. ITT had analyzed the first two-event [1], which occurred on 12/10/97 and 2/9/97. ITT provides the TKS as part of the total navigation payload for the Lockheed-Martin Block IIR GPS satellites. This paper presents the TKS simulations performed to reproduce the last three events that occurred on 8/16/98, 1/29/99, and 7/22/99 and show that they were most likely caused by VCXO transients. Recorded data indicate that VCXO activities are highly correlated with eclipses. The paper will also suggest ways to prevent or curtail the anomaly caused by a VCXO transient.

TKS DESCRIPTION

The GPS Block IIR TKS is described in detail in References [2] and [3] and its performance was analyzed and evaluated fully in Reference [4]. A simplified TKS block diagram is shown in Figure 2. The 10.23 MHz VCXO, which provides the heartbeat for the GPS signals, is phased-locked to a reference Rb clock. Normally, the TKS operates in slow loop mode with a filter time constant of 150 seconds to greatly reduce the phase meter noise, as documented in Reference [4].

When the TKS software detects large phase errors (>16 nanoseconds) between the Rb clock and the VCXO at the phase meter output for two consecutive epochs (1.5 seconds), the SV will transmit non-standard codes to protect GPS users. The TKS will then operate in the fast loop mode with a shorter 15-s filter time constant to reduce phase error quickly. At a later time when the phase errors become small (< 2 nanoseconds) for 60 consecutive epochs, the TKS will revert back to operate in the slow loop mode and the SV can be restored to transmit standard codes by ground command. This interruption will normally last for less than four hours.

TKS ANOMALY ON AUGUST 16, 1998

The following scenario of TKS transitions were recorded by the ground control on 8/16/98:

1. TKS transition to fast loop at 01:46:21.0
2. TKS transmitted non-standard codes at 01:46:22.5
3. TKS Transition to slow loop at 01:48:04.5
4. TKS transition to fast loop at 01:51:00.0
5. TKS transition to slow loop at 01:52:42.0
6. Command by ground to transmit standard codes at 05:35:19.5

The SV computer captured the key data in the circular buffer when this event occurred. The recorded TKS phase error as shown in Figure 3 covers the first three transitions described above. Figure 4 shows the reproduction of the TKS phase error using the Aerospace TKS simulation program. It is evident that the simulated TKS phase error matches the recorded phase error very well in terms of time span and amplitude. The transient was reproduced when VCXO was subject to a ramp frequency change of 9E-10 df/f in about 7.5 minutes, as shown in Figure 5. Figure 6 displays the simulated phase errors of five transitions as described above and it reproduces the 4.5 minutes separation of the two fast loop transitions very well.

TKS ANOMALY ON JANUARY 29, 1999

The SV computer did not save the buffer data for the transient that occurred on 1/29/99, because a subsequent smaller transient overwrote it. However, the ground station at that time was in contacted with the SV, so the phase error data were transmitted by the SV telemetry and are shown in Figure 7. Figure 8 displays the simulated phase error and it matches the recorded data very well. The VCXO frequency drift profile to reproduce the recorded phase error is shown in Figure 9.

TKS ANOMALY ON JULY 22, 1999

The signature of this anomaly is almost identical to that on August 16, 1998, so no additional data are provided.

VERIFICATION OF THE SIMULATED PHASE METER NOISE

The phase meter noise was simulated as white noise with a standard deviation of 0.68 nanoseconds, equal to the square root of $T^2/6$ [6], where T is the period of the 600 MHz clock used by the TKS system. Simulated raw phase, dominated by the phase meter noise, is shown in Figure 10. The TKS raw phase error recorded in the satellite data buffer is displayed in Figure 11 when the TKS is operating in benign condition. Note that these two plots match very well in amplitude fluctuations. The recorded data have a computed mean and standard deviation of 0.74 and 0.17 nanoseconds, respectively. The recorded data are affected by additional noise from the VCXO and other hardware sources that are not included in the TKS simulation program.

PREVENTION OF THE TKS ANOMALIES CAUSED BY VCXO

There are seven TKS time constants that can be selected by the ground control through SV database upload [4]. Analysis and simulation show that these three anomalies caused by VCXO misbehavior can be avoided if a shorter TKS time constant is used. Figures 12 and 13 show the resulting TKS phase errors if a 50-second time constant is used for the two events. It is evident that use of a 50s time constant constrains the phase error within the 16 ns limit and could have prevented the TKS from operating in fast loop mode and transmitting non-standard codes.

The problem associated with using a shorter TKS time constant of 50s is that the TKS would not meet the Block IIR TKS Allan deviation specification in the average time from 20s to 90s as shown in Figure 14. However, this has negligible impact on the one-day average URE (User Range error). Note that the TKS still meets the GPS specification imposed by the government.

CORRELATION OF VCXO TRANSIENTS WITH ECLIPSES

The three reported VCXO transients occurred when the Block IIR SV (SVN43) was exiting from one of many eclipses during each period of 8/2/98 - 8/31/98, 1/25/99 - 2/20/99 and 7/22/99 – 9/6/99. In the TKS software, there is an integrator to estimate and to compensate any VCXO frequency changes. These frequency estimate values are saved and later sent to the ground through S-band telemetry during the next ground contact with the satellite. A plot of the frequency estimate provided by ITT is shown in Figure 15. It is evident that the VCXO frequency started to decrease around the onset of the three eclipses and took about a month to recover. The magnitudes of the first two VCXO frequency changes of 9E-10 and 8E-10 agreed with the simulated VCXO transient inputs as provided in Figures 4 and 9 of Section 4. The TKS software also saves a clipping counter that will increase by one whenever the filtered phase error between the Rb clock and the VCXO crosses the clipping threshold of 3.5 ns. The clipping counter also confirmed the eclipse related VCXO activity. The plot of the clipping counter during eclipses is provided in Figure 16. The figure shows that the clipping counter started to increase around the beginning of each eclipse and stopped increasing when the eclipse ended. Noted that the counter was reset when the SV software was re-initialized at the end of June 1999.

During the eclipses, it was observed that the recorded SVN43 panel temperature change in the VCXO vicinity was about 6 degrees C in 5 hours. Since the specified VCXO temperature coefficient is 4E-11 df/f/degree C, the expected VCXO frequency accumulated over the five hours will be +2.4E-10. This does not agree with the simulated VCXO frequency changes of +9E-10 in 8 minutes and +8E-10 in 20 minutes, as shown in Figures 4 and 9 respectively.

Aerospace also examined the radiation environment around the time of the three anomalies [6] and found that space radiation environment is not a causative agent.

CONCLUSION

Block IIR SVN43 has the best clock performance of all the GPS satellite clocks. Simulations were used to reproduce the three VCXO anomalies. The TKS raw phase errors and frequency estimates from simulations match very well with that from satellite recorded data in either the computer memory buffer or the SV real time telemetry. Simulations identified VCXO sudden frequency changes as the likely cause of these incidents. The VCXO activities were correlated to the eclipses periods based on the recorded frequency estimates and TKS clipping counts from the TKS computer memory. However, the temperature coefficient of the VCXO and the recorded temperature changes in the VCXO vicinity during eclipses could not support the observed VCXO frequency misbehavior. Change of TKS loop time constant is a possible way to prevent those TKS anomalies caused by VCXO transients.

REFERENCES

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[5] J. Han, "Performance Analysis of Clock Stability for GPS IIR satellites," ATM-93 (3470-01)-5, The Aerospace Corporation, September 27, 1993.

[6] J. Blake, " GPS Anomaly and Space Radiation Environment" an Aerospace Interoffice Correspondence to H. Wishner dated August 12, 1999.

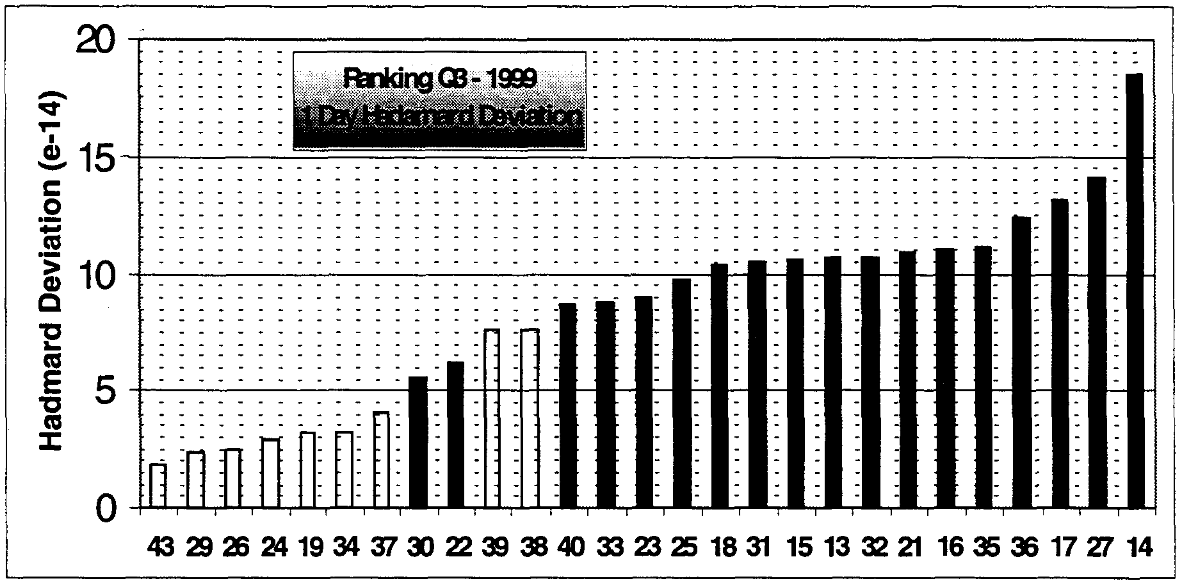

Figure 1 One-Day Hadamard Deviation Ranking for GPS Satellite Clocks

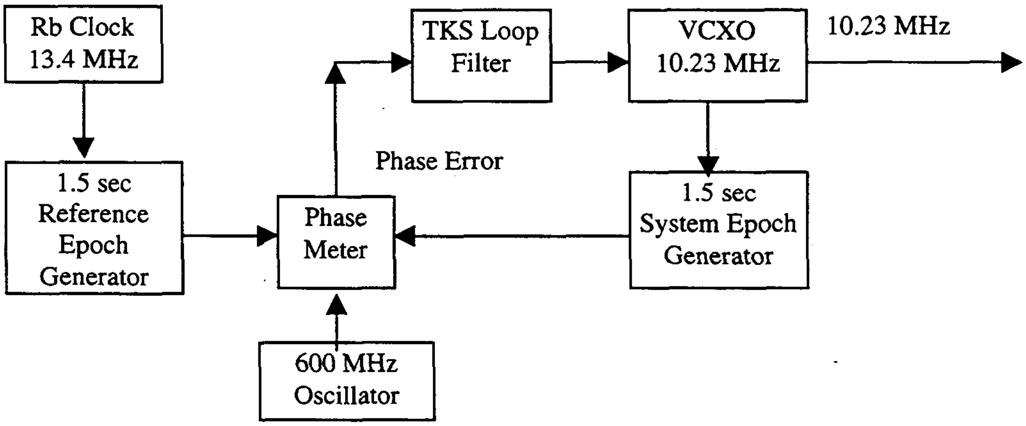

Figure 2. Simplified TKS Block Diagram

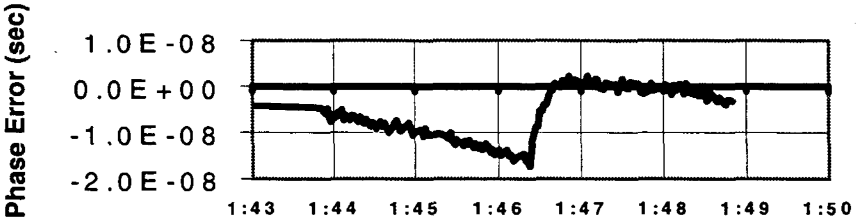

Figure 3. Recorded TKS Raw Phase Error on 8/16/98

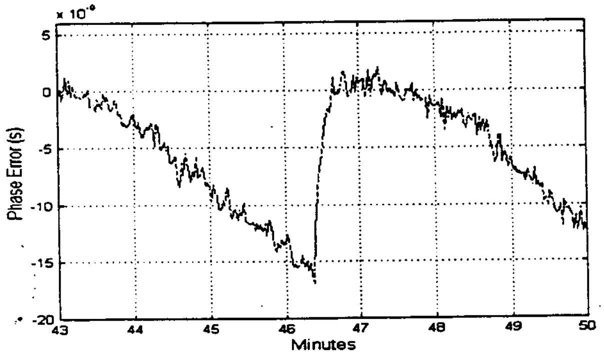

Figure 4. Simulated TKS Raw Phase Error

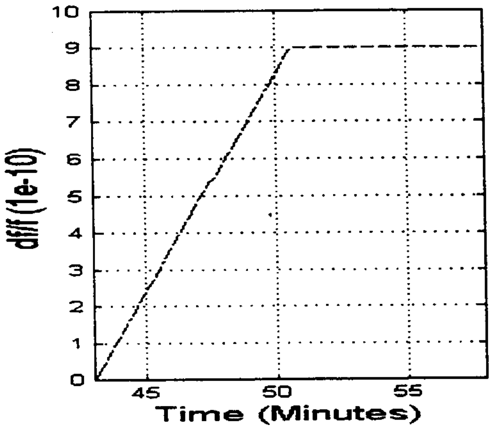

Figure 5. Simulated VCXO Frequency Jumps

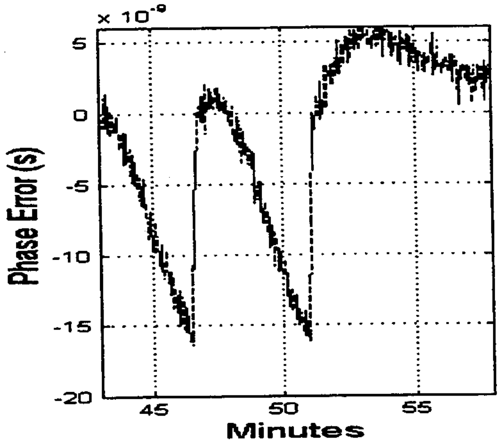

Figure 6. Simulated TKS Phase Errors

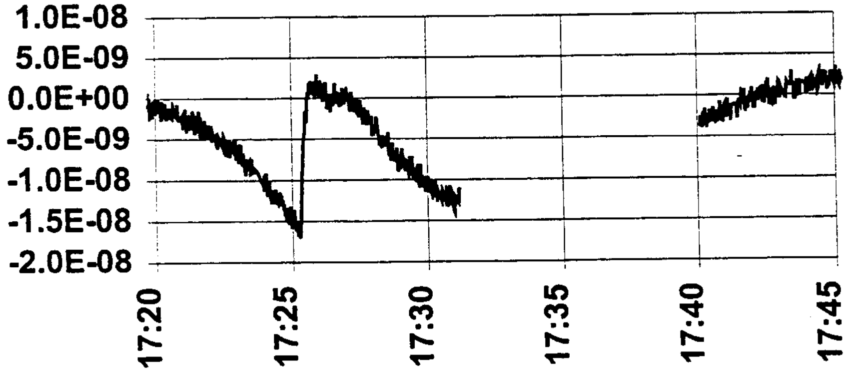

Figure 7. Recorded TKS Phase Error on 1/29/99

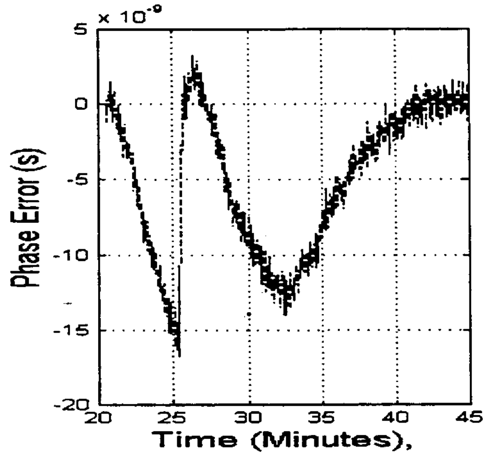

Figure 8. Simulated TKS Phase Error on 1/29/99 Event

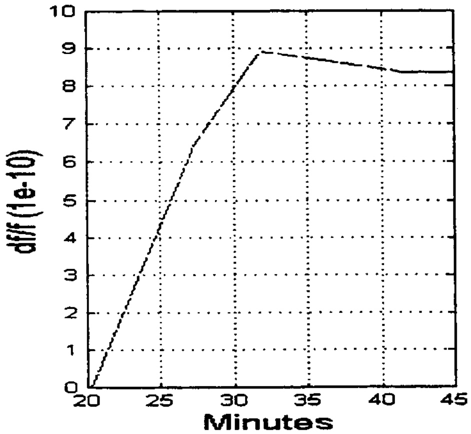

Figure 9. Simulated VCXO Frequency Profile on 1/29/99 Event

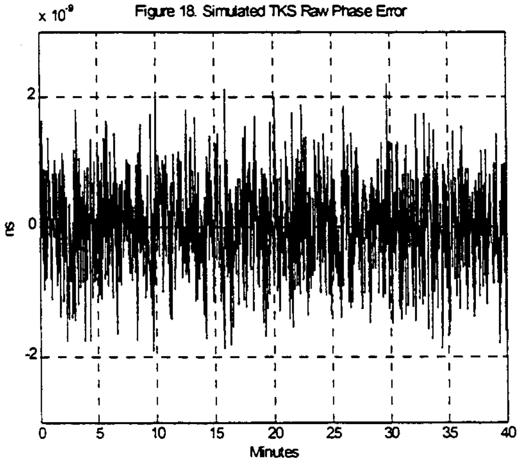

Figure 10. Simulated TKS Raw Phase Error

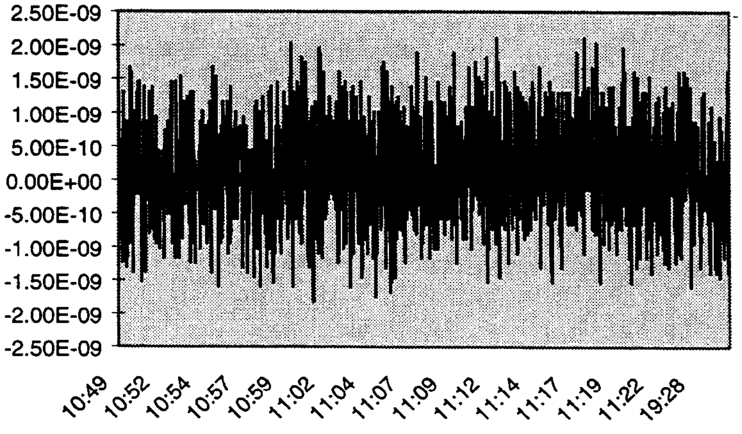

Figure 11. Recorded TKS Raw Phase Meter Error in Benign Condition

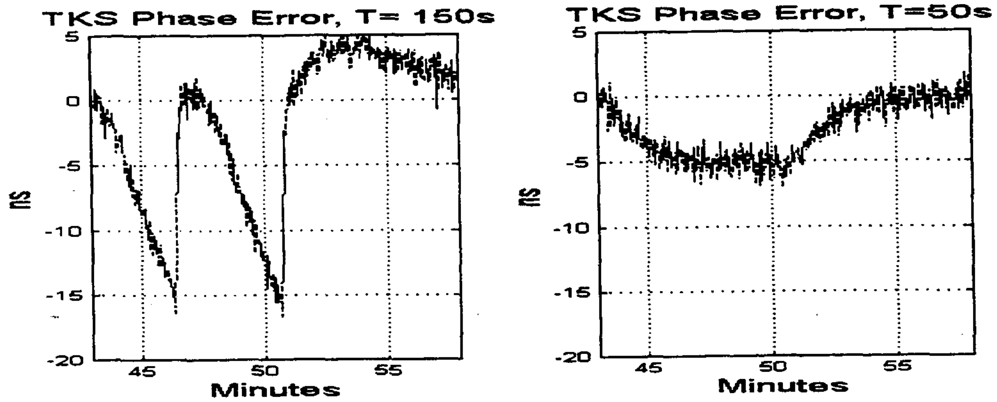

Figure 12. Simulated TKS Phase Errors on 8/16/98 with two time constants

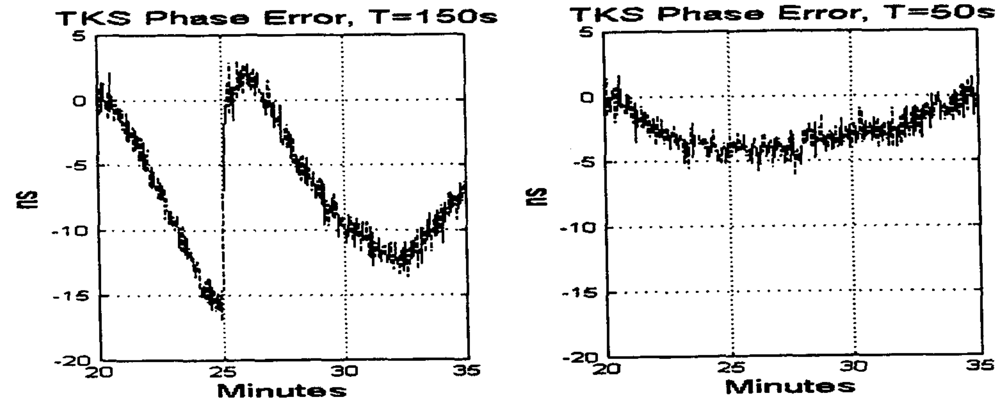

Figure 13. Simulated TKS Phase Errors on 1/29/99 with two time constants

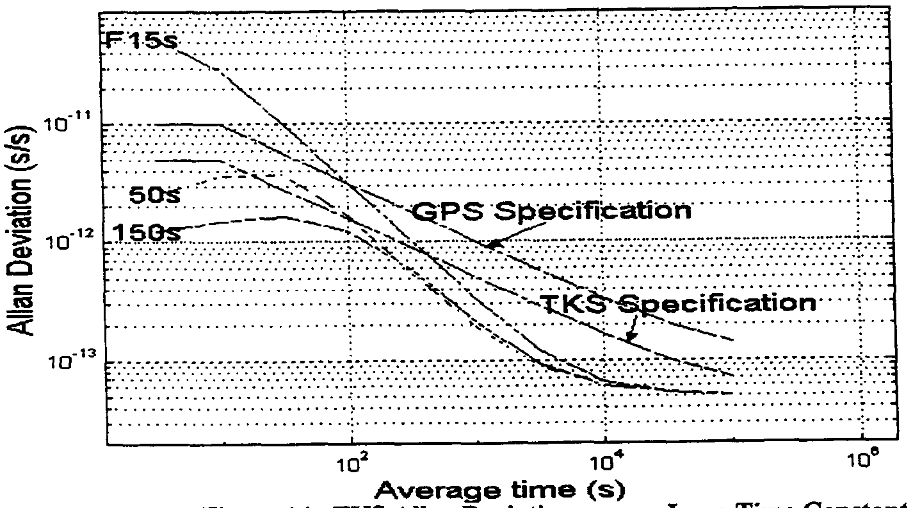

Figure 14. TKS Allan Deviations verses Loop Time Constants

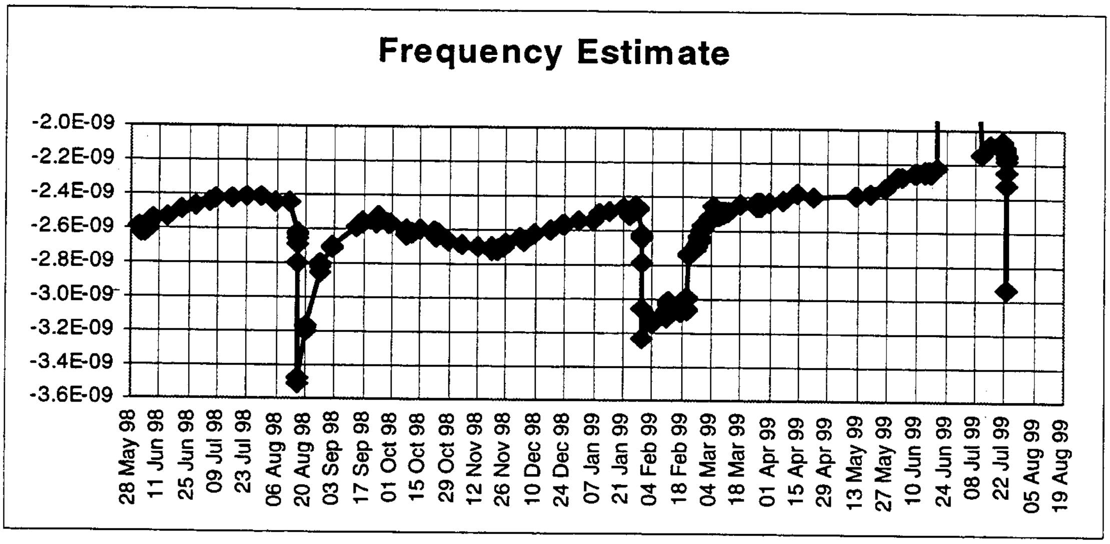

Figure 15. VCXO Frequency Estimates during Eclipses

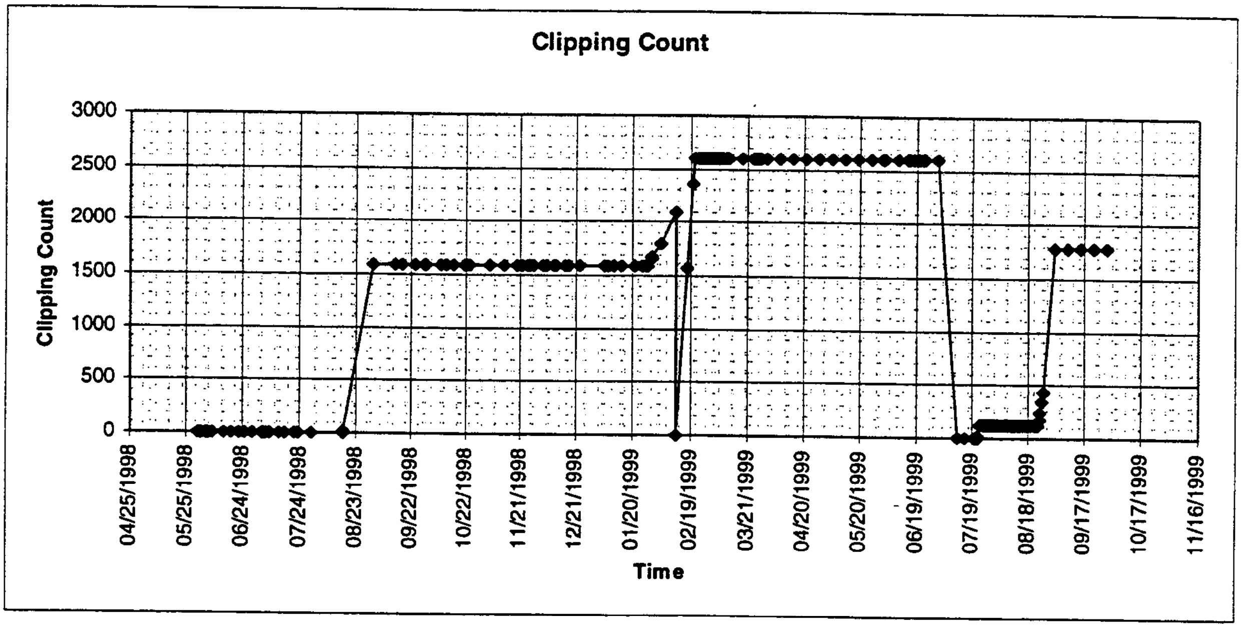

Figure 16. TKS Clipping Counts during Eclipses

Questions and Answers

MARTIN BLOCH (FEIC): I have never known a clock to be able to recognize an eclipse. However, I have known many DC-to-DC converters that are very susceptible to that type of phenomenon. And I would suggest that we take a look at the DC-to-DC driving the VCX on the rubidium, because during an eclipse you have a significant change in bus voltage and some DC-to-DC converters have been known to behave like this.

ANDY WU (Aerospace): Yes, we do look at the voltage input. We are told this is normal; there aren't many changes. We actually simulate the voltage drop, though not on this one. We will talk to you.