EVALUATION OF GPS BLOCK IIR TIME KEEPING SYSTEM FOR INTEGRITY MONITORING

Dr. Andy Wu
The Aerospace Corporation
2350 E El Segundo Blvd. M5/689
El Segundo, CA 90245-4691
E-mail: *c.wu@aero.org*

Abstract

Onboard GPS clock monitoring will be required for GPS III satellites. This paper will discuss some of the key integrity monitoring parameters in the context of the GPS Block IIR TKS. The paper will also show that: (1) the phase meter output, comparing the phase difference of the Rb Atomic Frequency Standard (AFS) and the VCXO in a 1.5-second GPS epoch, behaves like a Gaussian distribution; (2) The TKS probability of false alarm is almost equal to zero due to its rather large detection threshold; (3) The TKS can detect and compensate for "large" VCXO frequency steps with no significant TKS output phase error; (4) The TKS cannot compensate "large" VCXO frequency drift steps and may require a MCS (Master Control Station) contingency upload to remove phase bias; (5) The TKS cannot detect "large" AFS frequency steps or frequency drift steps that cause the TKS output phase error to run away, but steps of that type have not be observed in IIR operation so far.

1. INTRODUCTION

This paper will evaluate how the GPS Block IIR Time Keeping System would operate as an integrity monitoring system. There was no integrity monitoring requirement for the GPS IIR Time Keeping System (TKS), but onboard clock monitoring will be required for GPS III satellites. The paper will include the following topics: review of GPS Block IIR time keeping system (TKS); analysis of the GPS Block IIR TKS phase meter output; over-bounding cumulative probability distribution function (CPDF); evaluation of integrity monitoring parameters for the GPS IIR TKS; GPS Block IIR TKS integrity monitoring considerations; consequences of large detection threshold, and a summary.

2. REVIEW OF GPS BLOCK IIR TIME KEEPING SYSTEM

The primary functions of the GPS Block IIR Time Keeping System (TKS) are to generate the GPS frequency of 10.23 MHz from a Voltage Control Crystal Oscillator (VCXO), using a Rubidium Atomic Frequency Standard (RAFS) as an input reference, and to accommodate aging and the selective availability (SA) dither frequency requirement, as shown in Figure 1 **[1,2]**. The Block IIR TKS also incorporates hardware monitors to detect: (1) RAFS output, (2) VCXO output, (3) whether the RAFS is frequency-locked, (4) the level of RAFS modulating signal (second harmonic level), and other monitors to ensure that a single TKS component failure cannot go undetected **[1]**.

The Block IIR TKS has the capability of adjusting the phase, frequency, and frequency drift of its online RAFS. Residual RAFS frequency offset and frequency drift are estimated by the GPS Master Control Station, and their estimated corrections are provided in the NAV message sent to the user **[3]**.

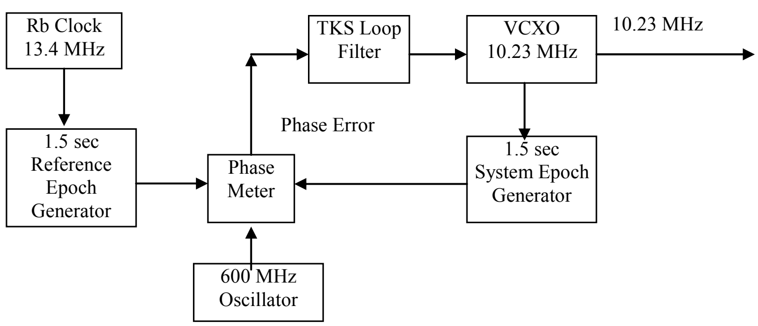

Figure 1. Simplified TKS block diagram.

The specified Hadamard deviations of the three TKS major error sources are shown in Figure 2 **[1]**. The actual measured performances are better than the specifications. The TKS Phase Meter (PM) uses a 600 MHz oscillator to measure phase difference between the reference clock (RAFS) and the system clock (VCXO) and results in a resolution of 1.67 ns ($1/600 \times 10^6 = 1.67 \times 10^{-9}$), which is poor compared with a typical phase meter resolution of better than 1 ps (1×10^{-12} s). Accurate phase difference measurements between AFS and VCXO should be a key capability of future GPS clock integrity monitoring schemes. The IIR TKS loop constants were selected based on trade-offs to attenuate the effect of the phase-meter noise and to take advantage of the excellent short-term stability of the VCXO and long-term stability of the RAFS.

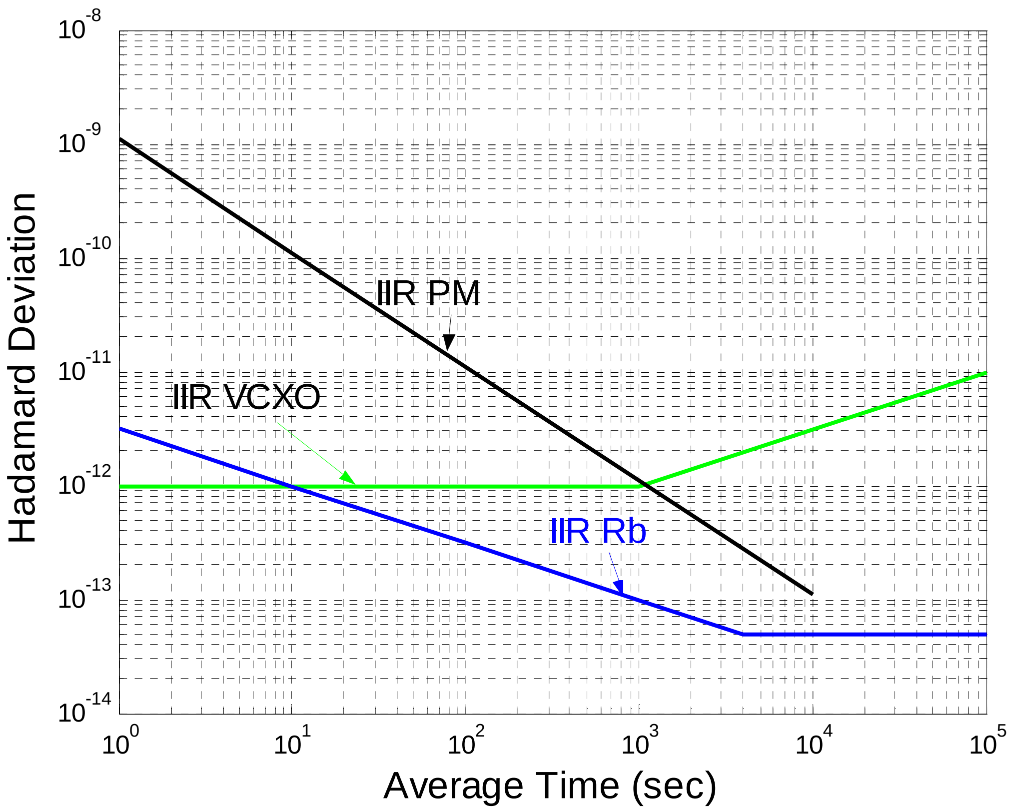

Figure 2. Hadamard deviation of the TKS components.

The TKS loop filter is implemented in software, and it can be modified or tuned. A simplified IIR TKS error model in the S domain is shown in Figure 3, which will help analyze TKS system responses subject to step or ramp inputs. The filter coefficients (a, K1, and K2) determine the filter type and time constant that can be predetermined and stored in a lookup table. The other coefficient, a_w, was added to the control loop software to handle VCXO disturbances during and around eclipse periods that occurred on SVN 43 **[4,5]**. It has a value between 1 and 6 to weight large phase errors and a value between 0.7 and 1 to weight smaller phase errors (< 1 ns) **[5]**. So the TKS becomes an adaptive time constant (ATC) system. However, for a fixed a_w, the TKS is still a linear system, and all the linear system techniques/tools can be used.

There is an integrator, K1/S, shown in blue in Fig. 3 that is used to estimate and compensate for the frequency offset of the VCXO with respect to the RAFS and to compensate for the nominal drift of the VCXO with respect to the RAFS.

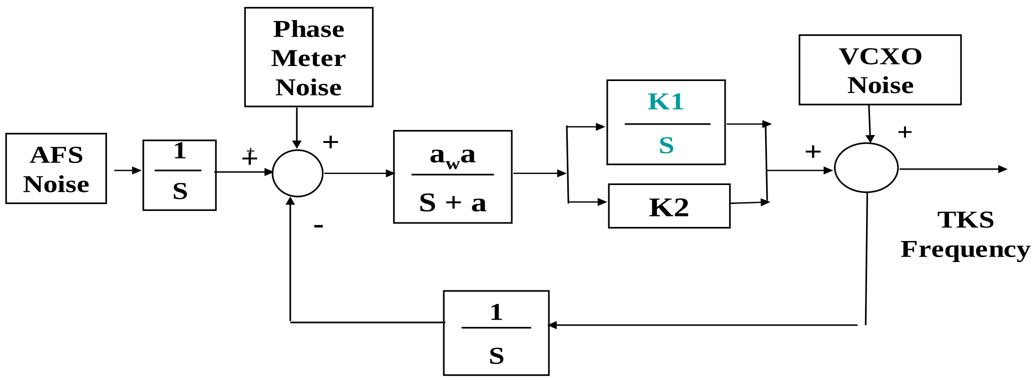

Figure 3 Simplified TKS Error Model in S Domain

3. ANALYSIS OF THE GPS BLOCK IIR TIME KEEPING SYSTEM (TKS) PHASE METER MONITOR OUTPUT

The TKS is a phase-locked loop using a phase meter to measure the phase difference between the VCXO and the RAFS. Any transient or anomaly from either the VCXO or RAFS will result in phase build-up at the phase meter output. If necessary, the TKS can protect users from using the degraded GPS signals by quickly switching to nonstandard codes within seconds of detected failure.

The TKS raw phase meter error data can be recorded every 1.5 seconds (GPS Epoch) in the satellite data buffer and dumped to the ground station during satellite contact by the GPS Master Control Station in Colorado Springs, CO. This is normally done once or twice per day, and each time takes 10 to 15 minutes. ITT at the Master Control Station provided recorded GPS SVN 51 TKS raw phase meter error for the month of December 2005 with a total of 34412 points (14.34 hours of data). Since there were no clock anomalies during that period, the TKS can be assumed to be operating in a benign condition. The recorded data from SVN 51 are shown in Figure 4.

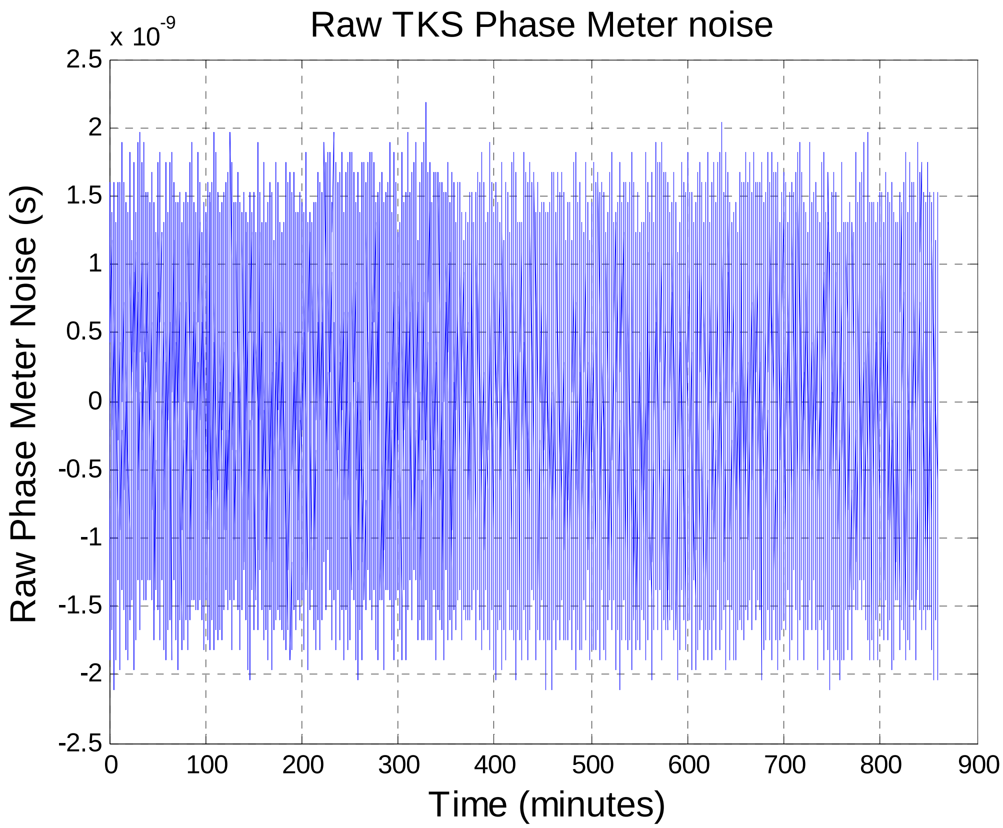

Figure 4. Raw TKS phase meter noise.

The December 2005 data set has a mean PM noise of -4.2714×10^{-11} seconds, with standard deviation (σ) of 7.2740×10^{-10} seconds. Plots of the cumulative probability distribution function (CPDF) of this data set and a MATLAB-generated Normal distribution data set with the same mean and sigma (σ) are provided in Figure 5. The figure shows that the TKS record set (red line) appears to have a Normal distribution. The TKS CPDF shows many steps because the TKS output data only contain three significant bits, so there are multiple points recorded for the same data value. For example, there are 10 measurements of the same value of 6.27×10^{-10} seconds.

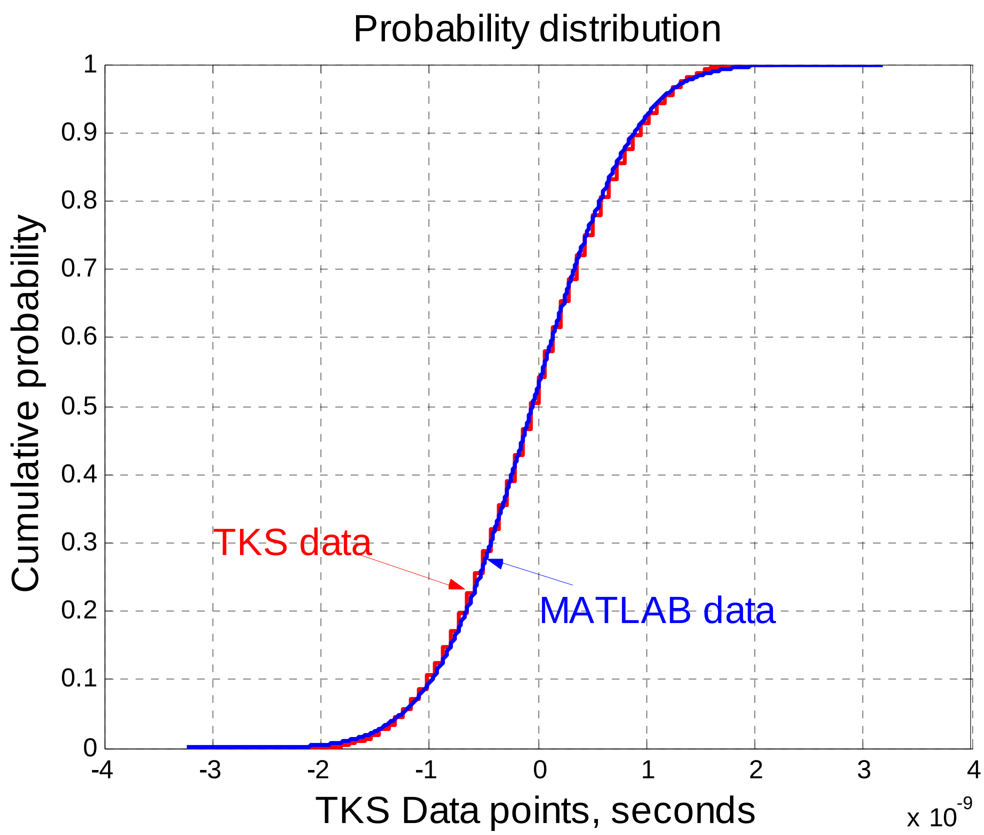

Figure 5. Cumulative probability functions.

4. OVER-BOUNDING CUMULATIVE PROBABILITY DISTRIBUTION FUNCTION (CPDF)

ITT also provided two more sets of TKS raw phase meter error data from SVN 54 and SVN 44. The cumulative probability distribution functions from SVN 51 (black), SVN 54 (red line), and SVN 44 (green line) are shown in Figure 6. They all have the same standard deviation of 0.73 ns, but their means are slightly different. This family of CPDFs can be over-bounded by a Normal distribution with a standard deviation of 0.88 ns and a zero mean, as shown in Figure 6. The over-bounding CPDF **[6]** technique, which is used by the analysts on the FAA WAAS and LAAS programs, can be used to conservatively estimate the CPDF of the IIR TKS phase meter output noise distribution. It is a conservative representation of the data distribution that defines the worst possible case in the absence of a hardware fault. The Normal distribution is recommended for over-bounding because of its well-known probability distribution characteristics.

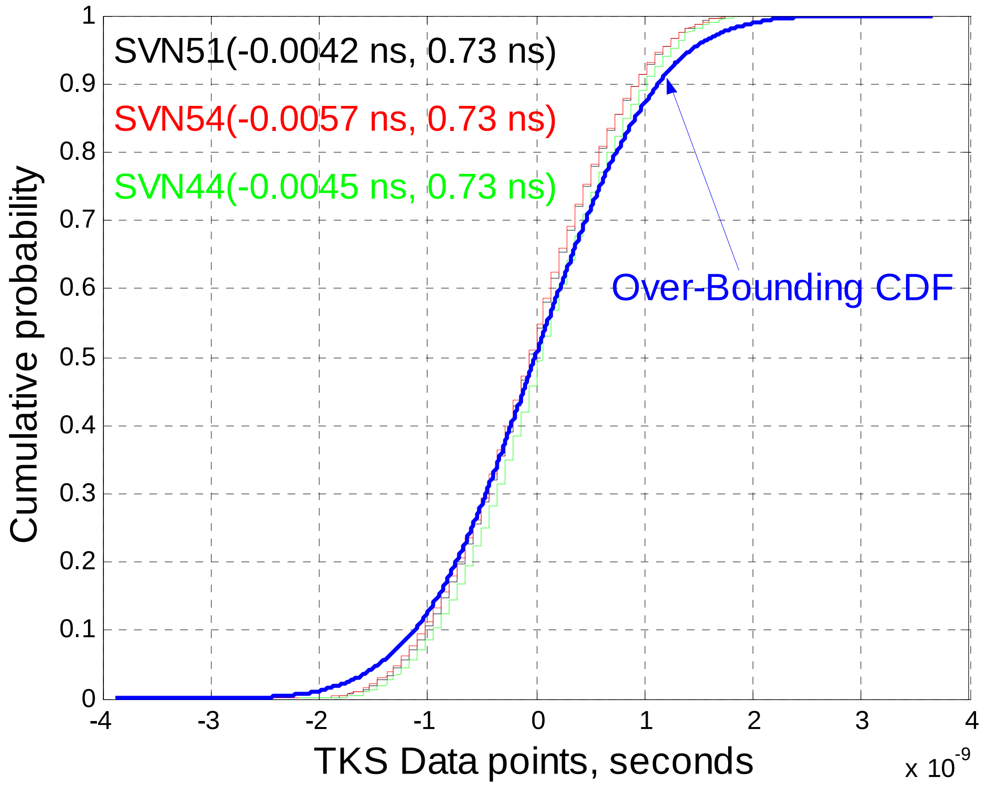

Figure 6. Over-bounding cumulative probability distribution function.

5. INTEGRITY MONITORING PARAMETERS TO EVALUATE IIR TKS

The key integrity monitoring parameters **[7]** that will be used to evaluate the GPS Block IIR TKS are shown in Figure 7. It is more convenient to work with probability density functions than cumulative probability distribution functions for this type of analysis. The probability density function with no bias represents a normal TKS phase meter output with no failure. The probability density function with a bias represents a TKS failure condition. These two probability density functions could be slightly different because of the use of an adaptive time constant. The weighting, a_w, has a value between 1 and 6 to weight large phase errors and a value between 0.7 and 1 to weight smaller phase errors (< 1 ns). When failure occurs, a_w is normally set to 6 to correct for large phase errors more quickly.

The other key integrity parameters are defined below:

- **Probability of false alarm (Pfa)** – the probability of issuing an alarm when there is no failure.
- **Detection threshold (TD)** – if the magnitude of phase-meter output is greater than or equal to this value for a specified time, then an alarm will be issued to indicate that the TKS [TKS or AFS?] is not working properly.

- **Probability of missed detection (Pd)** – the probability that the failure magnitude is greater than or equal to the alert limit and an alarm is not issued.
- **Probability of detection** = 1 – probability of missed detection.
- **Protection Level** – The protection level is the magnitude of a failure that can be determined with given probability of detection and failure probability distribution function. When the magnitude of the failure is greater than the protection level, its probability of detection will be greater than the specified probability of detection.
- **Alert Limit** – Alert Limit is the threshold or objective for the protection level.

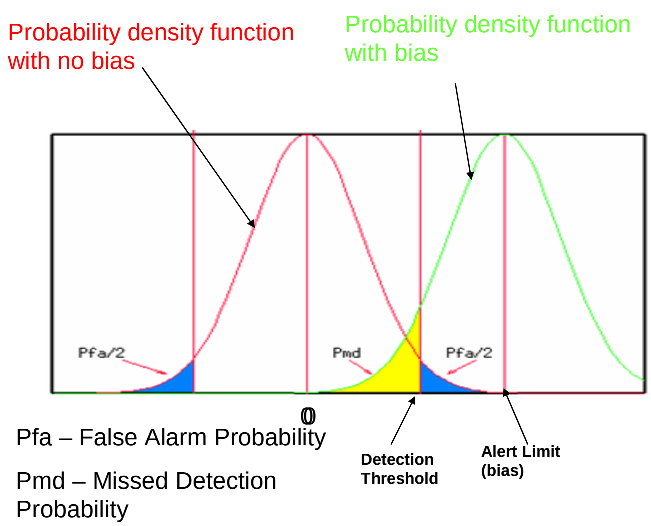

Figure 7. Integrity monitoring parameters.

6. GPS BLOCK IIR TKS INTEGRITY MONITORING CONSIDERATION

There is no integrity monitoring requirement for the Block IIR TKS. However, the IIR TKS has software logic to switch to nonstandard code when the absolute value of the phase-meter output is larger 15.84 ns **[8]**. This value of 15.84 ns can be considered to be the detection threshold of the IIR TKS system. The over-bounding probability distribution function of the IIR TKS phase meter has a Gaussian distribution with zero mean and a standard deviation of 0.88 ns (1σ), as shown in Section 3. Since 15.84 ns is greater than 17 σ (14.96 ns), the probability of false alarm for the IIR TKS is zero.

Even though the Alert Limit and probability of missed detection are not specified for the IIR TKS, their effective paired values can be determined. For example, assuming the over-bounding probability distribution of the IIR TKS with failure is the same as that with no failure, then it remains a Normal distribution, N (0.0 ns, 0. 88 ns), and the Alert Limit is selected as:

Alert Limit = 15.84 ns + 6 σ = 21.12 ns

Since the probability of Normally distributed noise exceeding six sigma (σ) is less than 1×10^{-8}, the corresponding probability of missed detection $< 1 \times 10^{-8}$. In other words, the probability of detecting an IIR TKS absolute phase-meter output error of more than 21.12 ns is greater than $1 - 1 \times 10^{-8}$.

7. CONSEQUENCES OF LARGE DETECTION THRESHOLD

The detection threshold of the IIR TKS is greater than 17σ, and that is rather large. The consequences of this rather large detection threshold are that some of the large frequency jumps and frequency drift jumps from either the VCXO or the RAFS would go undetected. The following results were obtained using a MATLAB GPS Block IIR TKS simulation program.

The IIR TKS will set NSC if the frequency jumps and frequency drift jumps of VCXO or RAFS exceed the following limits:

a. VCXO frequency jump $> 1.2 \times 10^{-9}$
b. VCXO frequency drift jump $> 7.1 \times 10^{-12}$/s
c. RAFS frequency jump $> 1.2 \times 10^{-9}$
d. RAFS frequency drift Jump $> 7.1 \times 10^{-12}$/s

However, after a VCXO frequency jump of 1.1×10^{-9}, the TKS will not set nonstandard code (NSC). The result is depicted in Figure 8. There is a transient response in the phase-meter output and TKS output (less than 14.8 ns or 4.44 m) and it settles to zero mean after 20 minutes.

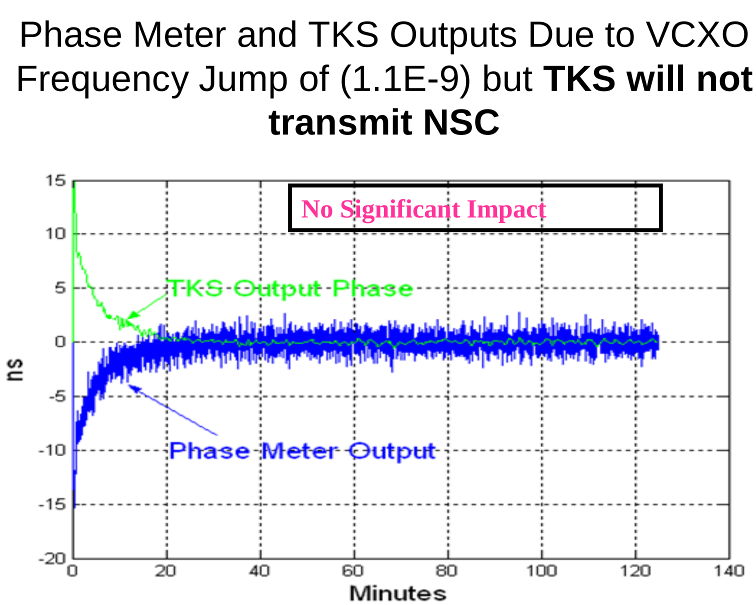

Figure 8. TKS phase transients due to a VCXO frequency jump.

After a VCXO frequency drift jump of 6.9×10^{-12} /s, the TKS will not set NSC. The result is shown in Figure 9. As a result, there will be a 4.5 m bias that will be observed by the master control station (MCS) at Colorado Springs and will require MCS contingency upload to reduce this large bias error.

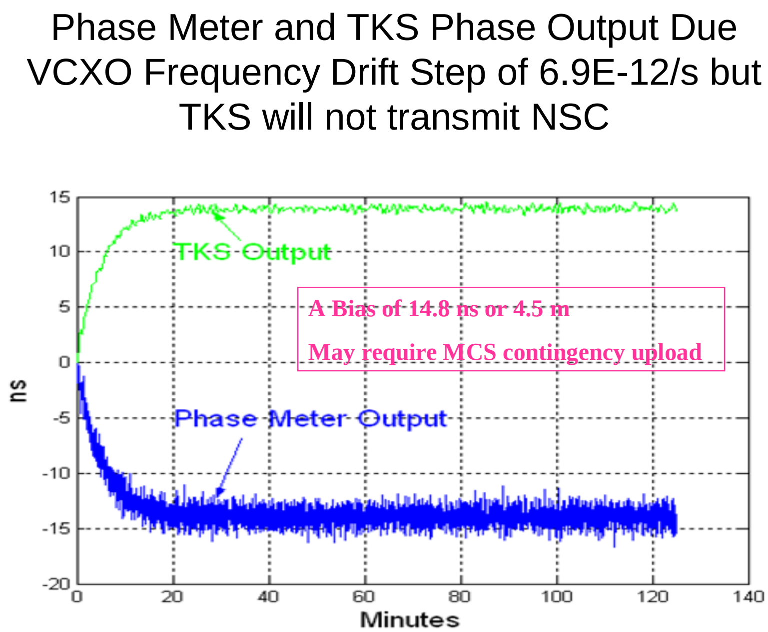

Figure 9. TKS phase transients due to a VCXO frequency drift jump.

After a RAFS frequency jump of 1.1×10^{-9} or frequency drift Jump of 6.9×10^{-12} /s, the TKS will not set NSC. The result is shown in Figure 10. The TKS output phase is running away, and the MCS cannot reduce the magnitude of this error in time by a contingency upload or a system zap to take the satellite off the air. If at least six satellites are in view, this type of error could be detected and excluded by the Receiver Autonomous Integrity Monitoring (RAIM), in which case this GPS signal would not be used.

8. SUMMARY

The results of evaluation of the GPS Block IIR TKS for integrity monitoring can be summarized as:

The IIR TKS phase meter output noise distribution behaves like a Gaussian distribution

a. The IIR TKS phase-meter output noise can be over-bounded by a Gaussian distribution.

b. The IIR TKS detection threshold (failure threshold) is effectively set at 17.9 σ (too large).

   a. The IIR TKS false alarm probability ≈ 0.0 /sample ≈ 0.0 /hour

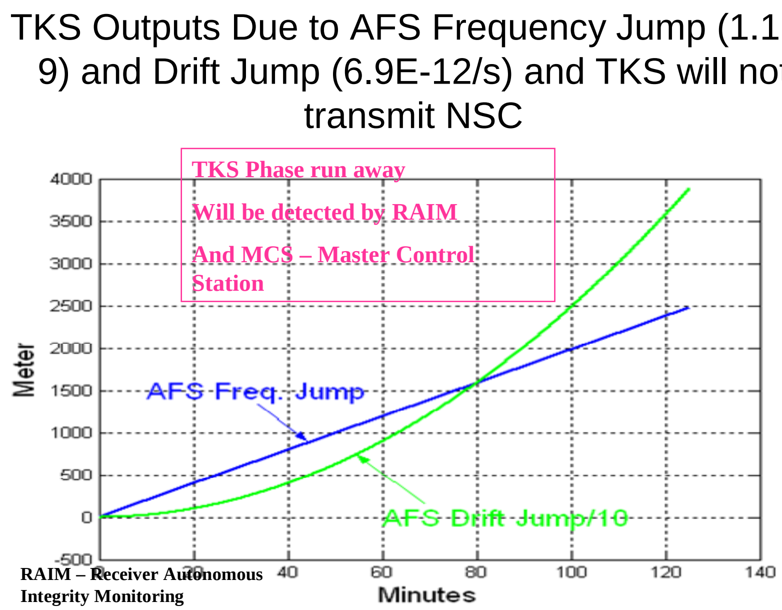

Figure 10. TKS phase runaway due to a RAFS frequency jump and frequency drift jump.

c. The IIR TKS alert limit and missed detection probability are not specified, but can be computed when the failure probability distribution is known and the probability of missed detection is specified.

d. The IIR TKS phase-meter output noise distribution behaves like a Gaussian distribution.

e. The IIR TKS phase-meter output noise can be over-bounded by a Gaussian distribution.

f. The IIR TKS detection threshold (failure threshold) is effectively set at 17.9 σ (too large).

   a. The IIR TKS false alarm probability ≈ 0.0 /sample ≈ 0.0 /hour

g. The IIR TKS alert limit and missed detection probability are not specified, but can be computed when the failure probability distribution is known and the probability of missed detection is specified.

h. The IIR TKS can detect and compensate large VCXO frequency jumps with no significant TKS phase error.

i. Large VCXO frequency drift jumps may not trigger NSC, and may require MCS contingency upload to remove phase bias.

j. Large RAFS frequency jumps and frequency drift jumps may not trigger NSC and will cause the TKS phase to run away. However, but these large jump anomalies have never be observed in real IIR RAFS operation so far.

   – will be detected by RAIM

   – Will be detected by MCS but not in time to warn user.

REFERENCES

[1] A. Baker, 1990, "*GPS Block IIR Time Standard Assembly Architecture,*" in Proceedings of the 22nd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 4-6 December 1990, Vienna, Virginia, USA (NASA Conference Publication 3116), pp. 317-324.

[2] H. Rawicz, M. Epstein, and J. Rajan, 1992, "*The Time Keeping System for GPS Block IIR,*" in Proceedings of the 24th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 1-3 December 1992, McLean, Virginia, USA (NASA Conference Publication 3218), pp. 5-16.

[3] M. Epstein and T. Dass, 2001, *"Management of Phase and Frequency for GPS IIR Satellites,"* in Proceedings of the 33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 November 2001, Long Beach, California, USA, (U.S. Naval Observatory, Washington, D.C.), pp. 481-492.

[4] A. Wu, 1999, *"Investigation of the GPS Block IIR Time Keeping System (TKS) Anomalies Caused by the Voltage-Controlled Crystal Oscillator (VCXO),"* in Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Dana Point, California, USA (US. Naval Observatory, Washington, D.C.), pp. 55-63.

[5] J. Petzinger, R. Reith, and T. Dass, 2002, **"***Enhancements to the GPS Block IIR Timekeeping system,"* in Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 3-5 December 2002, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 89-106.

[6] B. DeCleene, 2000, *"Defining Pseudorange Integrity – Overbounding,"* in Proceedings of the IAIN World Congress in Association with the 56th Annual ION Meeting, 26-28 June 2000, San Diego, California, USA (Institute of Navigation, Alexandria, Virginia), pp 1916-1924.

[7] R. G. Brown and G. Y. Chin, 1998, *"GPS RAIM: Calculation of Threshold and Protection Radius Using Chi-Square Methods – A Geometric Approach,"* **GPS Papers Published in NAVIGATION (Red Book), Vol. 5,** pp. 155 – 178 = RTCA Paper No. 491-94/SC159-584 (RTCA, Inc., Washington, D.C.), November 1994.

[8] T. Doss, J. Petzinger, J. Rajan, and H. Rawicz, 1999, *"Analysis of On Orbit Behavior of Block II-R Time Keeping System,"* in Proceedings of the 30th Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-3 December 1998, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 173-186.