# On-Board Signal Integrity for GPS *

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**BIOGRAPHY**

Marc Weiss has worked at the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards, NBS) in Boulder Colorado since 1978. He wrote the firmware for the NBS/GPS Time Transfer System for which he received the Applied Research Award of the NBS in 1983, along with the other principals. Dr. Weiss has been active in studying and developing time transfer systems especially using the Global Positioning System, for applications such as the generation of International Atomic Time. He also has led the NIST contract with the GPS program office for support of their clocks and timing systems. In addition Dr. Weiss has specialized in new time scale algorithms and in synchronization in telecommunications systems. He has worked on problems with Relativity as they relate to GPS and to primary frequency standards.

Ron Beard is the Head of the Space Applications Branch and is involved with Precise Time and Time Interval (PTTI) technology for military navigation and communication systems. He is a member of the Executive Steering Committee for the Annual PTTI Systems and Planning Conference and a member of the Board for the Joint Navigation Conference. He has served on a number of committees and panels involved with advanced space technology, time and frequency and GPS. Notably he was the U.S. representative to the NATO Working Group for Precise Time and Frequency Standards; chairman of the DoD Reliance Space Technology GNC subpanel; ad hoc member USAF SAB study on Global Air Navigation Systems; and member of the NRAC summer study into Vulnerability of Naval GPS Systems. He was a key participant in the NAVSEA Common Time Reference System Engineering Team. He is a member of the Precise Time and Frequency committee of the DoD Militarily Critical Technology panel, past chair of the ITU-R Special Rapporteur Group on the future of the UTC Time Scale, and current International Chairman of the ITU-R Working Party 7A, Precise Time and Frequency Broadcast Services. He is a member of Sigma Xi, the Institute of Navigation, American Geophysical Society, and American Institute of Aeronautics and Astronautics.

Pradipta Shome is currently with the Federal Aviation Administration working on Satellite Based Navigation development for Aviation. He has more than 20 years experience in developmental methods for: GPS autonomous navigation methods, GPS time keeping systems, Next generation GPS architectures for enhancing signal integrity, and Precision Orbit Determination Methods. Previously, he worked with Lockheed and ITT on GPS IIR, GPS III, Titan IV, Large Space Structures and Air Traffic Control Systems projects.

**ABSTRACT**

The elements of a space-based integrity approach are to monitor the signals on-board the satellite, such that signal performance can be maintained well within desired integrity limits. These elements include 1) a system for monitoring multiple atomic frequency standards (AFS) or clocks, detecting anomalies, and automatically transferring the signal source to a reliable clock, 2) deriving a clock and ephemeris solution from

a data set independent of the ground control segment, for on-board comparison and verification of the broadcast message 3) hardware methods to ensure valid formation of the broadcast signal. Many of the needed elements are already present in GPS architecture. This combination of design elements is capable of supporting stringent levels of signal integrity.

## INTRODUCTION: SIGNAL INTEGRITY

A key requirement, signal integrity for aviation and other safety critical services, has several components, such as the time-to-alert (TTA), probability of hazardous misleading information (HMI), service availability and continuity. TTA refers to the necessity of providing timely warning to the users when the system is degraded and should not be used. HMI faults could result from the failure to detect a broadcast of misleading information or a failure to broadcast an alarm about misleading information within the TTA. High signal service availability with continuity, along with attributes mentioned above, are required for dependable operation. Having methods for providing signals with rigorous, testable standards is the motivation for this paper.

A space-based navigation system, such as GPS, differs from ground-based navigation aids, because the impact of degraded satellites is not easy to identify and notify the diverse users, as the areas of degraded coverage are not stationary. As a result, the current GPS by itself does not provide adequate levels of integrity, continuity and time-to-alert requirements to permit primary reliance for safety-of-life applications. Augmentation systems are being developed and deployed to address some of these shortcomings [1], but inherent aspects of the current architectures make it difficult to achieve required performance levels, as embodied in the RTCA standards [2, 3]. Since an important objective for future generations of satellite-based navigation is to meet and exceed the service guarantees of presently provided radio navigation aids, such as the instrument landing system (ILS), the VHF omnidirectional radio range (VOR) and Distance measuring equipment (DME) [4], overcoming the limitations of ground-based augmentation systems and providing service quality consistent with FAA standards, is a primary requirement of a next-generation GPS system.

One solution to this dilemma is an on-board, satellite-based integrity monitoring system, proposed by some authors [4, 5, 6]**.** The most effective monitor of the satellite signals would be at the source, on-board, where the signals are generated. This proximity allows rapid failure detection and alerting by integrating fault detection and alerting capabilities within the satellite platform, where most of the anomalies arise, as revealed by the Integrity Failure Modes and Effects Analysis (IFMEA) study [7, 8]. The necessary features of such a monitoring service have been described and could be implemented on a space based platform [9].

Such a safety system could be organized in a natural hierarchy, so that faults are contained and mitigated within one layer, without propagating further downstream. Once a failure is detected within the satellite functions, a message is sent to the on-board processor to change the broadcast message and notify the users to the nature and level of degradation, as specified by a user-range accuracy (URA) index. In the event of a serious non-restorable anomaly, the satellite is taken out of active service by disseminating non-standard code (NSC). Augmentation systems that monitor signal performance from the ground, naturally detect errors later than satellite-based monitoring.

The IFMEA study established that clocks are the major source of GPS signal anomalies. Since the satellite clock signal is the basis for all other transmitted signals, detecting and removing clock anomalies eliminates many causes of signal aberration. Precisely monitoring clock signals normally requires a more stable reference signal. A rigorous approach, consistent with exacting integrity criteria, is to evaluate the performance of atomic standards by combining precise phase or time comparison between multiple clocks of similar type, such that the deviation of an individual clock can be measured and evaluated for subsequent restoration actions, thus providing a fail operational mode.

## PERFORMANCE MONITORING AND FAILURE DETECTION

In addition to clock monitoring, it is possible to also monitor the message and transmission elements of the payload (code generators, modulators, power amplifiers, filters and antenna diplexer), with a data demodulation receiver onboard and a portion of the transmitted signal fed back to it, so that the full navigation payload could be independently monitored for short- and long-term delay stability.

Fundamentally, GPS navigation works by providing synchronized signals from known locations in space. Both the signal synchronization and the satellite positions are predictions of clock behavior and true satellite positions (in the form of satellite ephemerides) that are uploaded from the ground. These data sets are currently uploaded nominally once per day, though contingency uploads are accomplished more often. Cross-link data transmissions have been considered as a means of shortening the time between uploads. With this method, the ground control station uploads the data for the entire constellation to one satellite. The cross-link data system then propagates those data throughout the constellation. These predictions are based on pseudo-range measurements made at ground-based monitor stations.

Cross-link ranging, by contrast with cross-link data, provides the basis for a completely independent estimate of satellite prediction parameters. A system developed in GPS block II employs these measurements with a UHF-based cross-link system to support on-board estimation of parameters if the ground link is lost for an extended period. Unfortunately, the UHF band used is not in a reserved band of spectrum, hence unintentional interference is common. A more advanced cross-link data and ranging system is being considered for later parts of GPS III. This could provide a more accurate autonomous system. Measurements among satellites themselves would derive independent sets of clock and ephemeris, which could be compared to uploaded values from the ground. This comparison would provide an additional integrity check of the uploaded data set, which currently has no independent comparison.

Continually comparing two on-board clocks could provide measurements to alert a clock signal failure, but would not determine which clock had failed. A measurement rate significantly faster than a time-to-alert requirement would be necessary for redundancy in this critical system. For example, measuring at a 10 Hz rate would allow repeated measurements to increase certainty within a 6 s TTA window. For isolation of the fault at least three independent sources are required for majority voting. Such redundancy could be achieved, at least in part, by using the constellation clock ensemble average from cross-link ranging, if the ranging and computation noise level were sufficiently low.

This on-board monitoring capability would provide an immediate detection of anomalies in the on-line clock and, possibly even the navigation message and payload elements. The resulting status could be inserted into the navigation message for direct broadcast to the users and to the ground segment monitoring stations, thereby providing a real-time alerting capability to the system. The data associated with the fault indication could also be telemetered to the control segment for diagnostic and remedial actions.

## CLASSIFICATIONS OF CLOCK ANOMALIES

Achieving integrity and time-to-alert requirements for aviation and space requires the ability to detect true anomalies and false alerts with high probability. Clock systems, such as the atomic standards on GPS, commonly experience anomalies and deviations that can be damaging from an integrity perspective. Deviations seen in timing systems include:

- occasional bad or outlier points,
- phase jumps in the clock system that later return to stable or predictable values,
- phase jumps in the clock system that do not return to predicted values,
- frequency deviations that return to predicted values, and
- true frequency steps that remain in the clock performance.

These anomalous effects may happen singly or in combination, suddenly, or over a period of time. Such serious situations related to satellite clock anomalies can be resolved by detection of these aberrations onboard, where the clock's behavior can be monitored in real-time without additional noise or errors added by communication and measurement from the ground. To this end, redundant frequency standards on-board or using cross-link ranging measurements or both are necessary.

## ON-BOARD SATELLITE CLOCK COMPARISONS

The comparison of the on-board clocks may be accomplished by a system such as the GPS Block IIR satellite subsystem known as the Time Keeping System (TKS) [10, 11], shown in Figure 1. The TKS was designed to provide a common interface for different types of atomic clocks as well as determine the differences between the on-board atomic clocks and the output VCXO (Voltage Controlled Crystal Oscillator). The output from the VCXO actually provides the stable signals for the rest of the satellite and transmitters. This system was configured to provide an interface for three atomic clocks, any one of which when operating, was compared with a redundant VCXO by a phase comparator running at 600 MHz. The VCXO produces the final signal but is adjusted or disciplined to the atomic clock’s output. This inter-comparison produces a measure of signal integrity but is ambiguous as to the cause or degree of variance produced.

In this system the VCXO is not free running but is locked to an atomic standard in a control loop whose time constant is somewhat variable. Only one of the atomic standards is operated at a time. The control loop time constant can be set to control the degree the VCXO performance contributes to the short term performance of the combination. To understand the interaction between the VCXO and the atomic standard a simulation of the control loop, to illustrate the stability performance, was developed by Wu [12, 13], and shown in Figure 2.

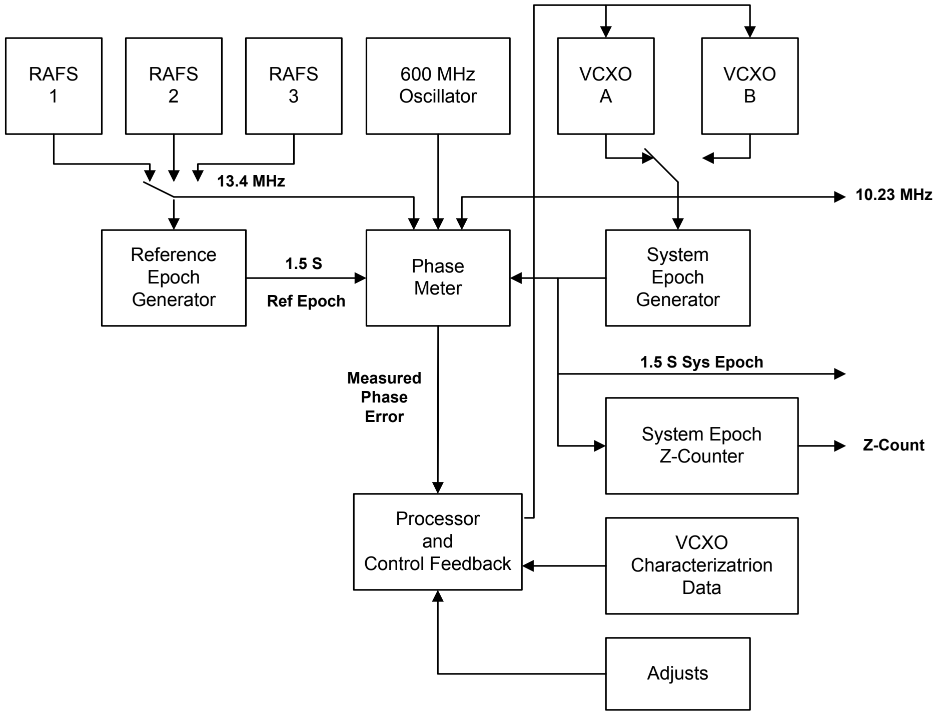


**Figure 1:** Block IIR Time Keeping System Block Diagram

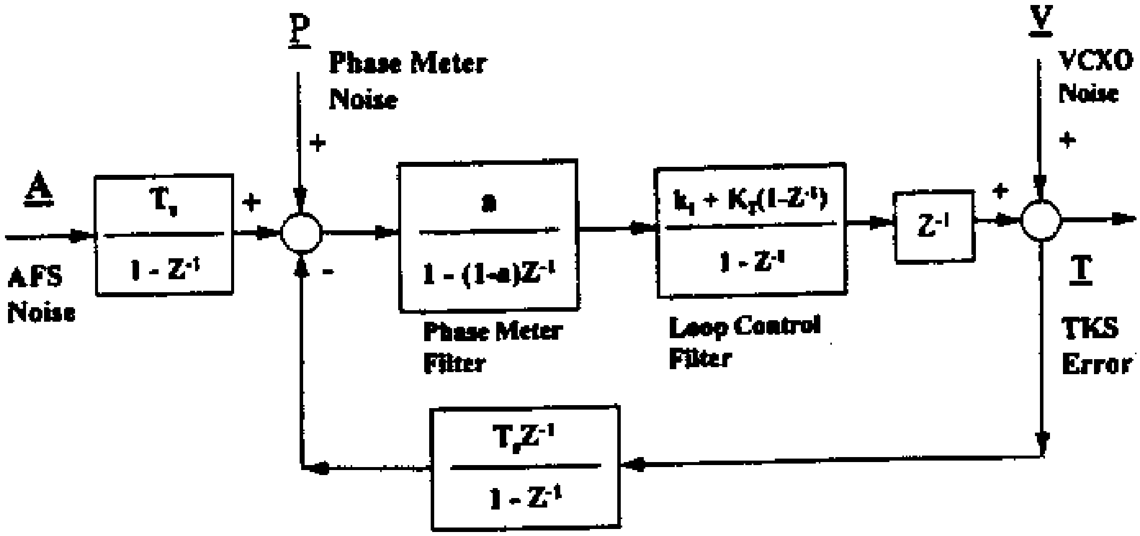


**Figure 2:** TKS Control LOOP model

The simulation was validated against the on-orbit performance of the Block IIR satellites. The results of the simulation using representative values of stability for the VCXO and the atomic standards and different values of the loop time constant is shown in Figure 3. These results clearly show that the resultant performance of a TKS comparison system will be dominated by the VCXO stability to possibly over 1000 seconds. This short term noise will affect the system performance as well as the ability to predict the clock values. GPS users rely on the broadcast clock prediction to correct the actual clock signal for positioning and time outputs. Precise correction is necessary in order to synchronize the multiple satellite signals onto precisely the same time for pseudorange measurements. The predicted corrections are broadcast in the satellite messages. Between updates of these predictions the clock signals will move away from those predictions, as shown in Figure 4.

To mitigate these shortcomings, multiple AFS should be compared to one another. This requires running multiple AFS simultaneously and measuring their differences. At least two AFS should be compared on-board a satellite. However, if cross-link ranging among neighboring satellites is sufficiently fast and accurate it could provide an additional option for verification. When two AFS on-board show a difference from prediction exceeding an integrity threshold, it is impossible to determine which clock has failed and which is reliable. The system must respond with an integrity failure alert. This would provide fail-safe capability. A third or more AFS comparison could provide majority voting logic to determine the failed system. This would provide fail-operational capability, thus increasing availability and continuity. Cross-link ranging could be used to provide additional AFS comparisons beyond, perhaps, two AFS compared on-board. This would place the strongest requirement for failure detection on the satellite, with cross-link ranging supporting failure recovery and continued operation. This makes sense, in that a new cross-link system might have less chance of reliable success than an on-board measurement system.

Moreover, the potential for integrity alerting from a comparison between an atomic frequency standard (AFS) and a VCXO is limited by stability of the latter for time periods longer than about 1 minute. Generally, the on-board VCXO would be locked to the AFS, and not be free-running. Such a system can only detect a failure that occurs over a period significantly shorter than the lock time of the VCXO. An integrity failure due to clock performance can happen in many ways. GPS users rely on the broadcast clock prediction to correct the actual clock signal for GPS time and for universal coordinated time (UTC) as broadcast from GPS. Between uploads of this prediction, the clock signal may move away from its prediction. Generally, a VCXO will depart in a random way much more rapidly than the AFS, after a period of about ~60 seconds. Thus, a comparison between a VCXO and an AFS can detect a failure of either system only if one of the oscillators (the VCXO or AFS) has a phase run-off that exceeds the integrity threshold in a time interval on the order of 1 minute. There are many other failure modes that can cause the AFS to diverge from its prediction more than an integrity threshold would allow over an upload interval. To obviate these shortcomings, atomic frequency standards can be compared on-board.

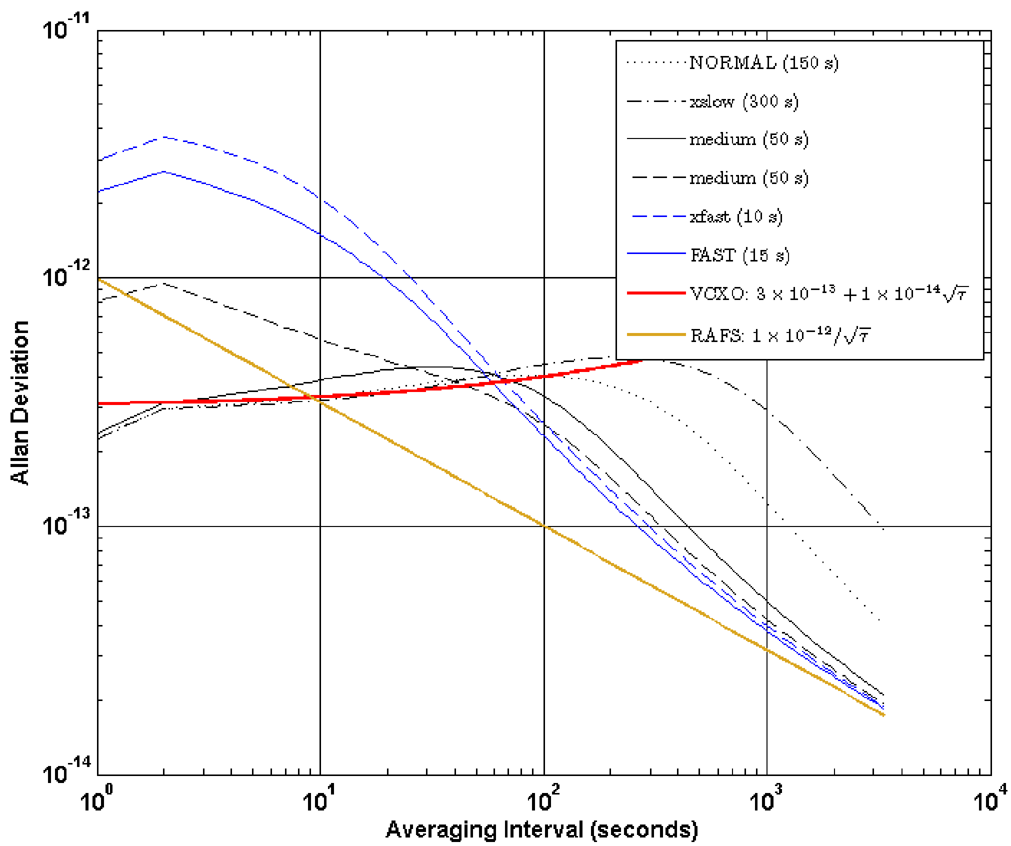


**Figure 3:** TKS short term stability versus loop time constant with a phase resolution value of 30 ps.

Regardless of how clocks are monitored in space, clock stability between ground updates must be good enough to accurately evaluate the transmitted signals and provide automatic integrity monitoring with virtually no false alerts. The frequency standards must be stable enough for performance well below the required peak error threshold between uploads. The time between uploads is currently nominally one day. Studies into decreasing the interval between updates have been conducted by the GPS III teams particularly by using cross-link data transfer.

Shortening the update interval for integrity considerations is dependent upon cross-link data and system operating with reliability compatible with integrity requirements. For example for category I precision approach (CAT-I), the probability of a navigation message data anomaly should be < $10^{-7}$. The capability of the system to maintain integrity monitoring will depend to a degree upon the update interval that can be supported by clock stability. For larger intervals such as approaching a day a more stable clock, which could maintain the integrity threshold time offset error from prediction at a day, is required for GPS III. Such clocks would also need a suitable on-board measurement system for comparison as discussed below.

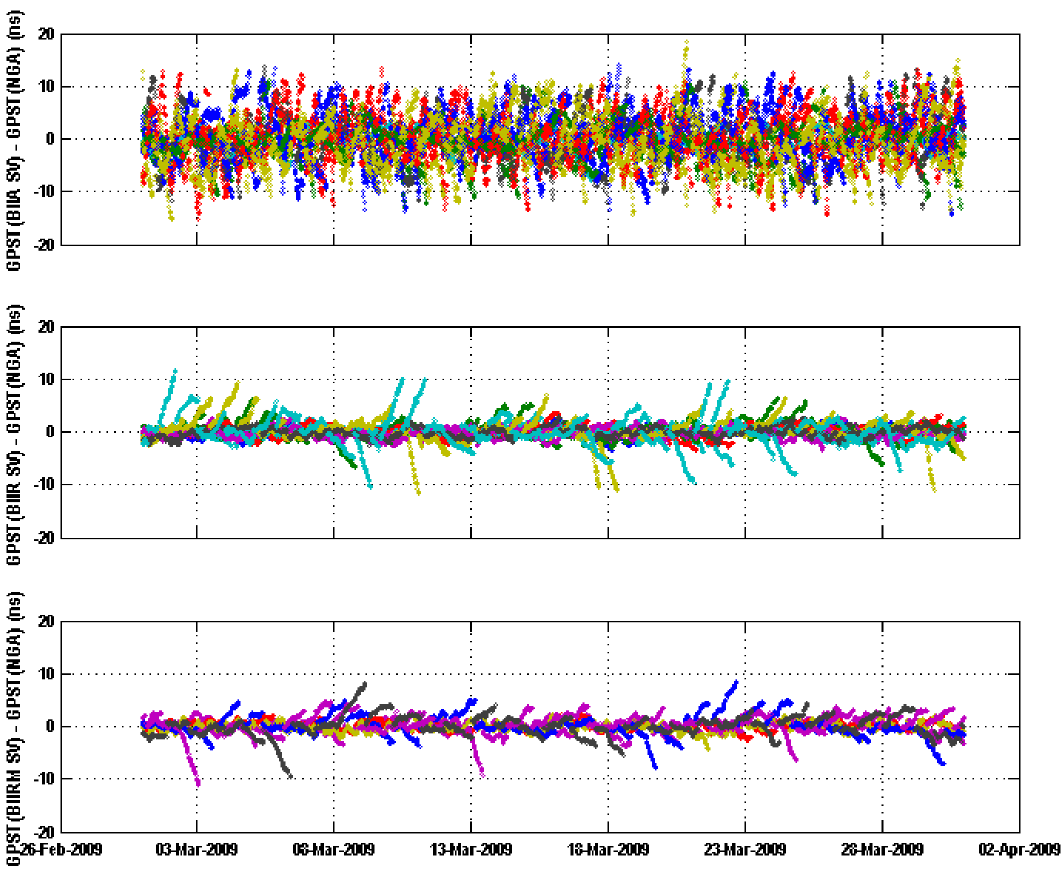


**Figure 4:** Broadcast clock predicted GPS Time minus post fit NGA GPS Time for all GPS satellites shown by Block. Broadcast values determined using precise NGA ephemerides rather than broadcast position values.

## ADVANCED DUAL-MIXER MEASUREMENT SYSTEM

Direct inter-comparison resolution can be precisely performed by the use of the dual-mixer technique, shown in Figure 5 below. The resolution of a system such as this can be shown to be considerably more precise than a phase meter only approach [14]. In addition, such a scheme does not inject any noise into the timing chain to degrade the stability characteristics. We present only the concept of a dual-mixer measurement system here. There are many options for implementation with current digital technology, which limit hardware distortions and optimize cost, weight and power [15].

The time difference, $\Delta x$, between the two oscillators in Figure 5 is defined as

$$\Delta x = \frac{\varphi_2 - \varphi_1}{2\pi \cdot \nu_0} = \frac{\Delta\varphi}{2\pi \cdot \nu_0},$$

where $\nu_0$ is the nominal frequency of the oscillators.

The down-conversion process preserves the phase information, so that

$$\Delta x_{beat} = \frac{\Delta\varphi}{2\pi \cdot \Delta\nu},$$

where $\Delta\nu$ is the beat frequency between the nominal frequency of the oscillators and the frequency of the offset oscillator. The time difference $\Delta x_{beat}$ is therefore

$$\Delta x_{beat} = \frac{\nu_0}{\Delta\nu} \cdot \Delta x,$$

where the effective down-conversion gain of the measurement is $K_{dc} = \frac{\nu_0}{\Delta\nu}$. If the nominal frequency is $\nu_0$= 10 MHz and the beat frequency $\Delta\nu$ = 10 Hz, then the down-conversion gain is $K_{dc} = 1 \times 10^6$. If $\Delta x_{beat}$ is measured with a Time Interval Counter (TIC) having a resolution of $\Re(\Delta x_{beat})$ = 20 ns, the measurement of $\Delta x$ implies an equivalent resolution of

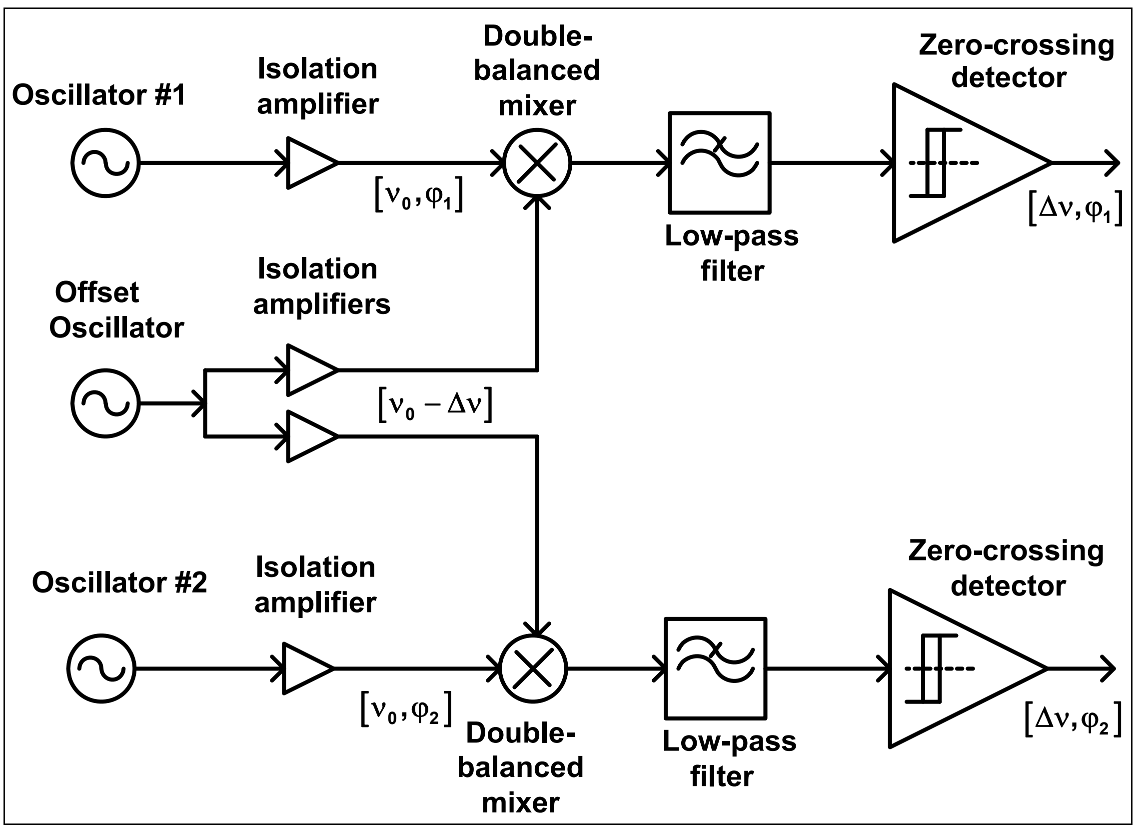


**Figure 5**: Dual mixer technique for phase measurement

$\Re(\Delta x)$ = 20 fs. While the hardware realization of this mathematical idealization may have effects which limit the accuracy, nevertheless, the dual-mixer approach provides a high-accuracy measurement system that allows the characterization of AFS performance in space.

The basic configuration of the dual-mixer shown above can be extended to measure three or more oscillators simultaneously. Such a configuration can measure the time difference $\Delta x_i$ between the reference oscillator and all the remaining N oscillators: $\Delta x_i = x_i - x_0$, or:

$$\Delta x_{i,\text{beat}} = \frac{\nu_0}{\Delta\nu} \cdot \Delta x_i = \frac{\Delta\varphi}{2\pi \cdot \Delta\nu} = \frac{\varphi_i - \varphi_0}{2\pi \cdot \Delta\nu}$$

This arrangement provides an effective high-resolution, multi-channel measurement system. Time-differences obtained from this system can be used for the following:

a) detect anomalies in phase, frequency and frequency drift in the output signal;

b) provide a means to estimate systematic parameters, phase and frequency offset, and frequency drift of each clock with respect to a particular clock, or provide a statistical average of all the clocks against a reference, such as the ensemble average;

c) provide a measure of the stability of the clocks with respect to the reference for diagnostic or predictive applications;

d) provide the capability to control the phase and frequency of an output VCO in a phase-locked loop configuration.

To effectively measure and isolate anomalous behavior over a prediction interval from 15 minutes out to one day, at least three independent timing sources are required. As already discussed, three or more are necessary to separate the individual contributions of the clocks and determine uniquely the one that is responsible for the anomaly. Phase jumps can be measured in real time. Frequency changes require integration, which can be optimized with an accurate measurement system. The system could also monitor the short-term stability (Allan variance) of the onboard clock, thereby providing an additional measurement useful to monitor the on-line clock performance.

## INTEGRITY BOUND AND THE CLOCK STABILITY MEASUREMENT

When considering clock monitoring for anomaly detection and integrity assurance, a number of dependent factors need to be considered for trade-offs and accommodation. First, note that atomic clocks are fundamentally frequency devices. At best, the clock would provide a Gaussian distribution of deviations around its true frequency, with a noise spectrum consistent with a white-noise model of frequency modulation. Even in this ideal case, white noise in frequency would integrate to a random walk in the time of the clock. Thus, even an ideal clock would randomly walk off from prediction at some rate.

Heightening this problem is the fact that GPS atomic frequency standards rarely produce a Gaussian distribution of deviations from prediction [16, 17]. This includes the Rubidium vapor cell standard design in use for Blocks IIR and IIF and planned for Block III. Distribution of clock deviations depends on the statistics that characterize both the steady-state performance of the clock, as well as occasional frequency departures that are not steady-state. It may be that a good model involves separate steady-state statistics from anomalous behaviors in operating clocks. A complete evaluation of this problem for GPS clocks needs to be done.

With a Gaussian model a probability of $10^{-7}$, as required for CAT-I, is reached by allowing data within 5.33 standard deviations. Since the existing clock data are not Gaussian, and since we are planning for the performance of clocks not yet made, the resulting distribution cannot be known. To allow some analysis of clock requirements relative to an integrity error threshold, we select a value of 10 times the deviation as a reasonable guess.

A second concept crucial to understanding on-board clock monitoring is the relationship between clock stability, or predictability, and the update interval. The longer the update interval, the more stringent are the requirements for clock performance. For integrity monitoring, the update interval must be realizable with the stringent reliability requirements for aviation integrity. Advanced cross-link data systems may achieve uploads every hour or even every 15 minutes, but perhaps not reliably enough in a new system. Given the current rate of one upload per day, it is prudent to design to meet the present baseline until future systems are proven.

A third assumption is that of the integrity failure threshold. This would be a value for range error that should not be exceeded without an integrity alert. For our analysis, we take the value of 0.7 m, as specified in the GPS System Specification [18], as a somewhat reasonable value to provide aircraft integrity alerting for precision approach.

Figure 6 combines these concepts to illustrate their interaction graphically. The figure compares the deviation of various advanced clocks with 1/10 of the required performance to meet a 0.7 m prediction error threshold. The vertical axis is the Hadamard deviation of a clock, a statistic chosen because it aliases the linear frequency drift of a clock. Thus, assuming the drift can be removed operationally, we compare the predictability of clocks with and without drift. The horizontal axis is the time interval between updates. Thus we see the stability of each clock as a function of the interval the clock would be required to hold performance. A clock supports the error threshold in the plot when its stability curve lies below the red line.

Thus we see that all of the clocks illustrated lie below the ten-deviation requirement out to almost 1 day. This model implies that a more advanced clock would be required to support a true 1-day update rate. The estimated IIF Rubidium Atomic Frequency Standard (RAFS) and the performance required for the Advanced Technology Atomic Frequency Standard (ATAFS) clocks lie below the red bound for a 15-minute update and stay below out to about a half-day update. With a more stable advanced clock it would be possible to achieve the required stability with the present operational mode of 1-day updates.

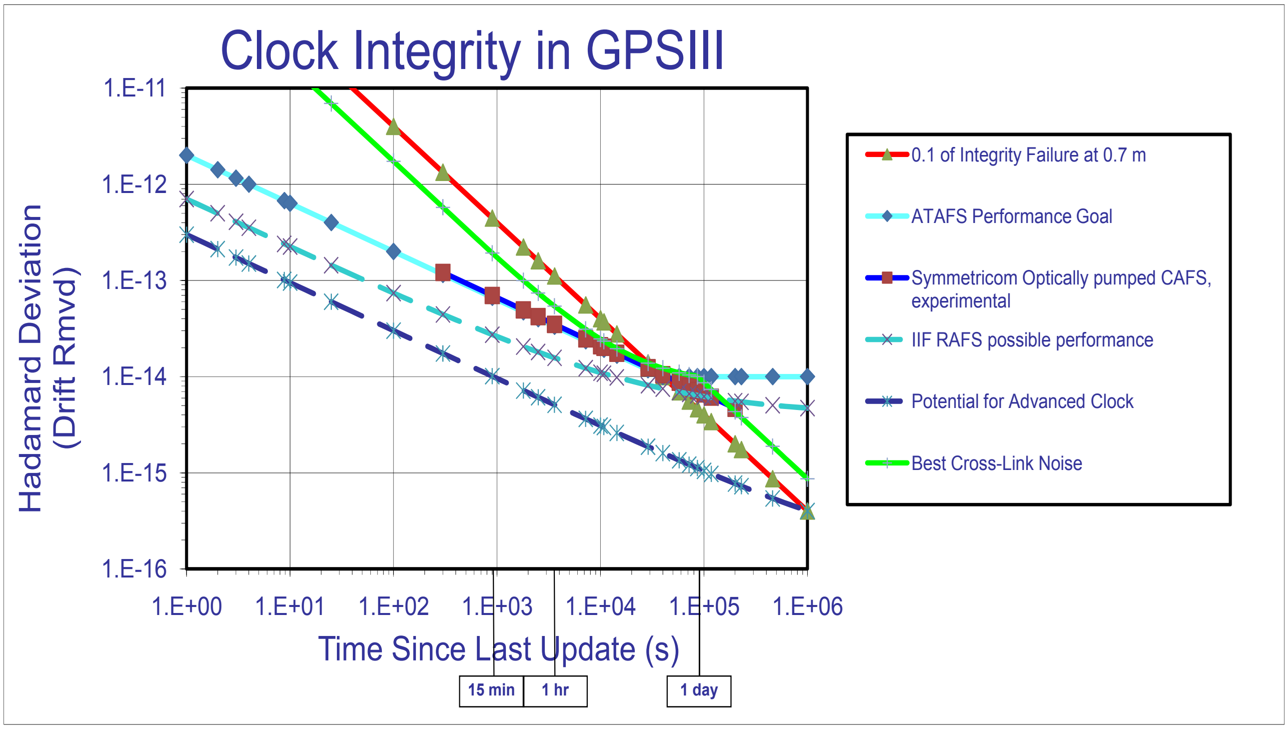


**Figure 6**: Clock stability and cross-link measurement in support of GPS III integrity. A clock holds stability in support of 0.7 m error threshold when its stability lies below the red line, as discussed in the text.

We see also in Figure 6 that an advanced cross-link ranging system could support a 1/10 of 0.7 m threshold by comparing clocks among adjacent satellites at update rates of up to 1/day. The noise of cross-link measurements may be closer to Gaussian than is clock noise. We discuss measurement noise more specifically in relation to Figure 7.

Figure 7 shows that a high-precision, low-noise, cross-link ranging could perhaps support an integrity bound of 0.7 m up to about 1 day. This assumes that the short term noise of cross-link ranging is 100 ps or 3.3 cm, and is white phase noise out to almost one day, and that the distribution is Gaussian. This last assumption may be very optimistic. Whereas clocks rarely show Gaussian distributions if one includes their occasional non-steady-state behavior, measurement systems are more well-behaved. However, cross-link ranging will incorporate noise elements of the satellite ephemeris error. With Gaussian performance, the probability of exceeding five standard deviations in the measurement is 6 x $10^{-7}$. In order to ensure that the measurement system does not exceed the threshold during normal performance with a probability of (1.0 – $10^{-7}$ = 0.9999999), we need better than five times the deviation ( 5 σ ) to remain below the threshold. Similarly, we assume that the noise of the troposphere in measuring any satellite from the ground is 20 cm or 700 ps. In this case, 5 σ brings the noise level up to the threshold. Thus, achieving a 0.7 m threshold with ground measurements would have difficulty maintaining the probability of false failure detection at or below 1.e-7 with 99.99% availability. This supports the argument that on-board detection of anomalies is needed to meet TTA levels of 6 s or better.

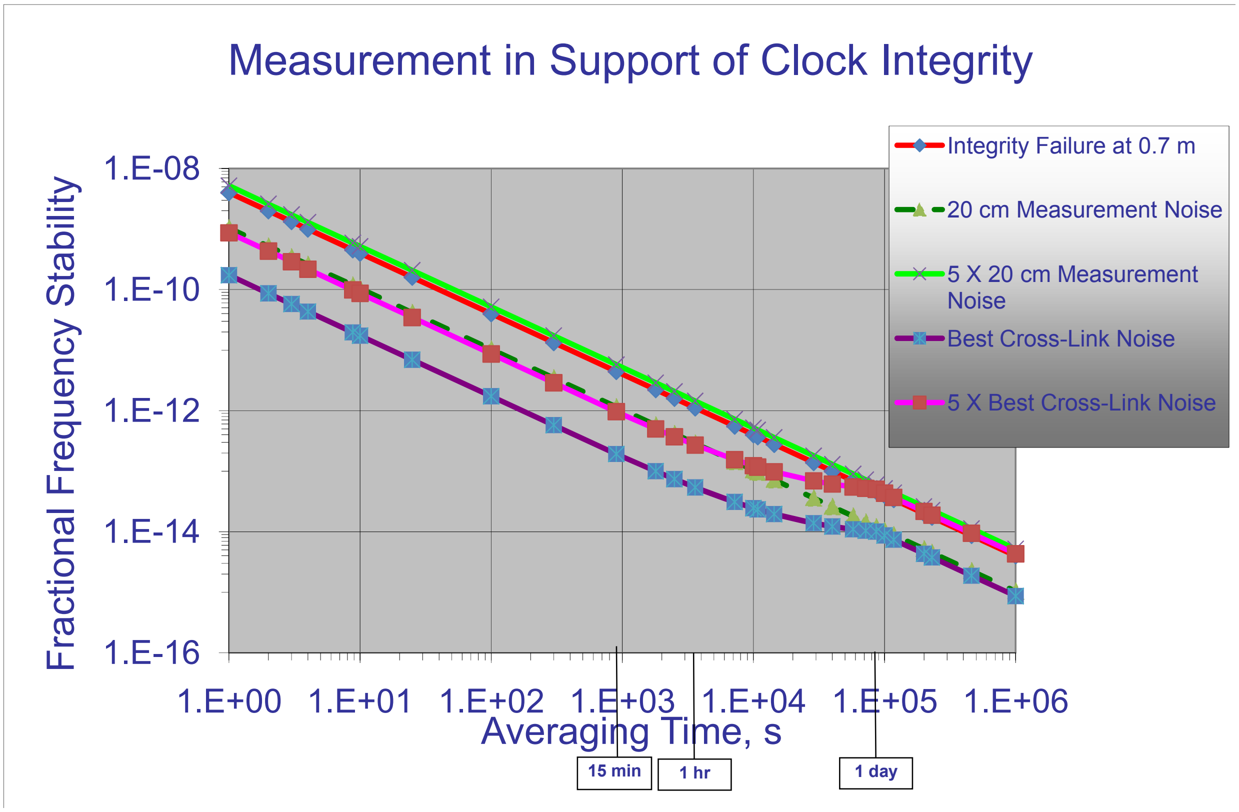


**Figure 7:** Measurement noise characteristics in support of clock integrity

## ANOMALY DETECTION WITH THE NIST TIME SCALE

The NIST time scale, AT1 [19], can give an example of how clock anomalies can be detected by comparison with an ensemble of clocks. Figure 8 below shows the performance of a somewhat troubled hydrogen maser, maser number 2 at NIST from modified Julian day (MJD) 55100 (September 26, 2009) to 55200 (January 4, 2010). The arrows indicate periods of time scale resets detected for this clock. The time scale system automatically detects a time reset when the clock exceeds four times the estimated time deviation of the clock. The model for these resets is that the clock has suffered a simple time step, with neither degradation of performance nor with a frequency change. When other anomalies occur, this model can be less effective. In some cases, human intervention is required. Sudden changes in the plot of H-maser 2 in Figure 8 indicate periods where the clock's predictability wanes. This is analogous to potential threshold violations in signal integrity for GPS. Figure 4 illustrates heuristically how a chosen model and threshold for error allows some unpredictability to continue unabated, but limits performance worse than the threshold and consistent with the model. Sudden changes in value or slope that are marked with an arrow would correspond to an event that would be removed in GPS.

We show the fractional frequency of H-Maser 2 against the AT1 scale in Figure 9 below. We have removed a single set of deterministic parameters in this plot, i.e. we have removed an estimate of linear frequency drift. We have also removed the time step values estimated by the resets that the scale found. The resulting data are clearly not consistent with a Gaussian distribution. There are departures from linear drift in frequency, as well as a number of specific events.

## EVOLUTIONARY APPROACH

Elements of this design could be added incrementally as they are tested and approved. GPS III already requires the ability to run and measure two or more clocks. Anomaly detection algorithms, while providing another layer of protection, could be tested in the existing system. This on-board integrity approach can at first simply assist ground-based augmentation systems. Only after elements are proven, should an on-board system be relied upon.

To evaluate the capability of upload verification with alternative ephemerides data and computation on-board, the algorithms necessary to process the measurements, computation data and output results will need to be validated and tested with as close as possible to the actual hardware to be used.

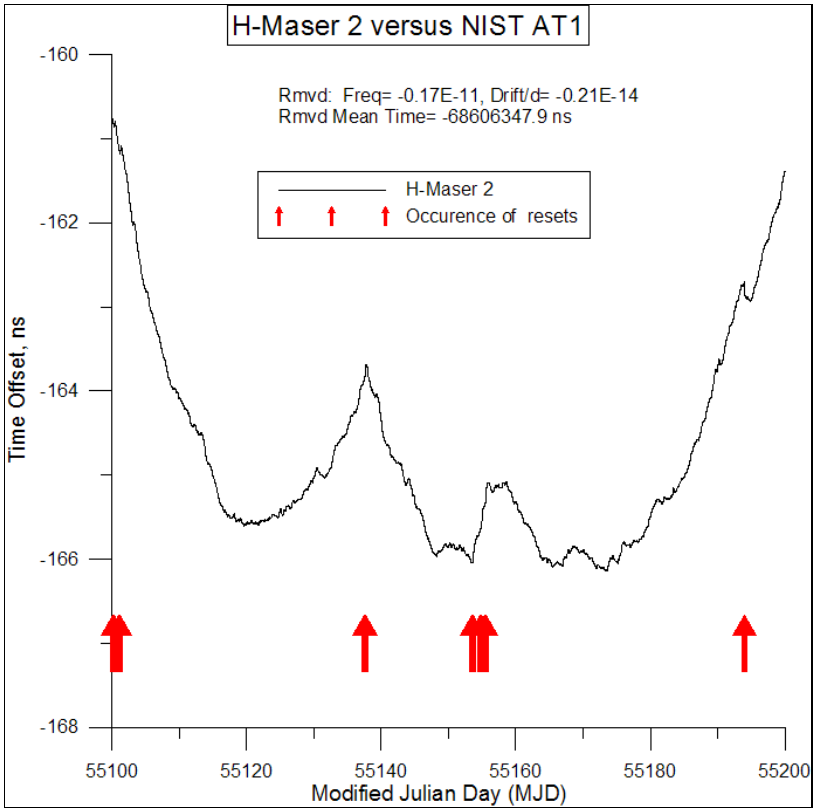


**Figure 8**: The NIST time scale, AT1, automatically detects anomalous behavior in this clock, and removes its effect from the system by use of resets.

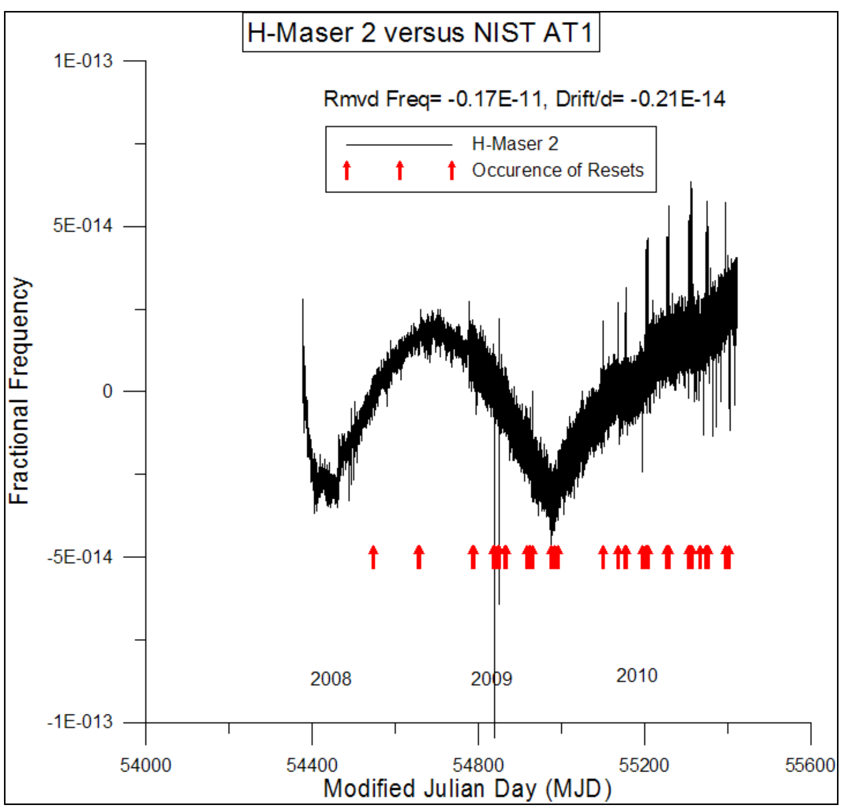


**Figure 9:** The deviation of this clock from prediction can be seen in this plot. We see considerable non-Gaussian effects over the 1087 days of this plot.

## CONCLUSIONS

We have presented concepts for GPS signal integrity assurance directly from the satellites. A cautious development approach might yield considerable advantages for users requiring integrity assurance.

Achieving GPS III signal integrity requires a robust cross-link system, more stable atomic frequency standards, or both for risk mitigation. Providing Cat-I directly from GPS requires providing automatic anomaly detection on-board the space vehicle (SV). Key to this function is the stability of the on-board clock between uploads, as well as providing an on-board measurement system capable of precisely measuring multiple clocks.

Currently, the Control Segment operational mode is normally to upload from the ground once per day. Reducing this upload interval significantly would require a more precise and reliable cross-link system. However, to depend on cross-link uploads in order to maintain integrity would require a high degree of robustness for the new cross-link system. The concept could be validated by a relatively small development effort demonstrating that a time keeping system could be employed to support Cat I criteria. This system could continue to depend on one-day uploads, but with higher accuracy, signal integrity and quality, while providing enhanced robustness, redundancy and risk mitigation.

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