GPS SIGNAL INTEGRITY DEPENDENCIES ON ATOMIC CLOCKS [*]

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Abstract

The problem of signal integrity for GPS satellites and the primary dependency upon inherent characteristics of onboard atomic frequency standards are discussed. In particular, there is a need for characterizing peak deviation of GPS clocks from prediction. Results from a preliminary study of two GPS clocks tested on the ground show that the distribution of peak deviations from prediction cannot be assumed to be Gaussian.

SIGNAL INTEGRITY FOR GPS

Navigation aids used in aviation and other safety critical applications must meet extremely stringent requirements for signal integrity, reliability, availability, and accuracy. One of the difficulties of using GPS for such applications is the need to ensure the integrity of the signals received by the user, especially since there are a number of possible failures modes, emanating from within any of the three segments comprising GPS (Space, Control, and User) **[1].** GPS is different from ground-based navigation aids, because the impact of satellites out of service is not easily identified and made known to the diverse users,

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and the areas of degraded coverage are not stationary. As a result, the current GPS by itself does not provide levels of integrity, continuity, and time-to-alert requirements adequate to permit primary reliance for safety-of-life applications.

To meet the needs of signal integrity (Integrity attributes are further discussed in the Appendix), augmentation systems such as the Local (LAAS) and Wide Area Augmentation System (WAAS) are being developed and deployed to address some of the shortcomings. However, there are inherent aspects of the current architecture that make it difficult to achieve required performance levels, as embodied in the RTCA advisory standards **[2,3]**, even with the currently planned augmentations. Note, RTCA used to stand for Radio Technical Commission on Aeronautics. However, now all their documents are marked RTCA Inc. The efforts to address limitations of the current GPS and the associated augmentation systems have resulted in increased complexity. Since an important objective for future generations of satellite-based navigation should be to meet and exceed the service guarantees of other federally provided radio navigation aids, such as the Instrument Landing System (ILS), VHF Omni Directional Range (VOR), and Distance Measuring Equipment (DME) **[4]**, overcoming the limitations of ground-based augmentation systems could be a primary requirement of a next generation GPS system.

The difficulty in meeting the integrity standards in general stems from present reliance on primarily ground-based methods, such as the Wide Area Augmentation System. The GPS signals are monitored at ground stations worldwide, from which data the clock and ephemeris solutions are generated at the Master Control Station (MCS), and then uploaded to each Space Vehicle (SV) of the constellation. This information forms the core of the L-band navigation message. If there are anomalies in the signal due to the information embedded within the message or within the satellite hardware, these can only be detected after the signals are received at monitoring locations, then evaluated for correctness at the MCS and an alarm message sent up to the SV for alerting the users. This cycle may take several minutes or even hours, depending on the location of the failed satellite. This delay, along with the extended reception path, is the reason for the complexity of ground-based solutions of this dilemma, resulting in higher costs and the difficulty in alerting users of the failure quickly, in a timely manner.

To obviate this difficulty, satellite-based monitoring schemes have been proposed to cover several possible failure modes, including excessive clock acceleration. However, the problem is compounded as signal phase deviations are generally not Gaussian and, therefore, such statistics can not be relied upon to meet probability requirements.

PRELIMINARY STUDY OF PEAK DEVIATIONS IN ATOMIC CLOCKS

Two GPS atomic clocks, using data from life-tests on the ground at the Naval Research Lab (NRL), were studied. The peak deviation from a near-optimal prediction of the time of the clocks is computed. Prediction error is a function of prediction time interval. This addresses the question: What levels of integrity can GPS clocks support? Clock signals from GPS are corrected by predictions that are uploaded. Between uploads, the peak deviation from the prediction is the worst-case level of integrity that the clock would support. Hence, the peak deviation from prediction gives a minimal level of integrity that a clock would support.

The distribution of prediction errors is computed over the following time intervals: 15 minutes, 1 hour, 2 hours, 4 hours, 8 hours, 1 day. To do this, we first near-optimally estimated the fractional frequency of each clock. The two clocks were Block IIR rubidium clocks, serial numbers R28 and R30. They were chosen as one of the worst, R28, and the best, R30, clocks from the qualification tests. The data sets were

20 s phase offsets from the reference H-Maser over MJDs 51666- 51816. We show the filtered fractional frequency on top of the fractional frequency estimates from 1st differences over 20 s in the figures below.

We estimated the linear frequency drift for each clock as a constant over the data interval. This was done using a four-point estimator, as outlined in **[5]**.

For R28, in Figure 1, we see a number of frequency steps. For R30, we note that the filtered estimate does not go through the mean or center of the 1st difference fractional frequency data. These two effects result in non-Gaussian peak deviation errors, for different reasons. Frequency steps cause peak prediction error in time data, because the predictor does not know about the step change in frequency. Hence, we find that the longer the prediction interval, the worse the error.
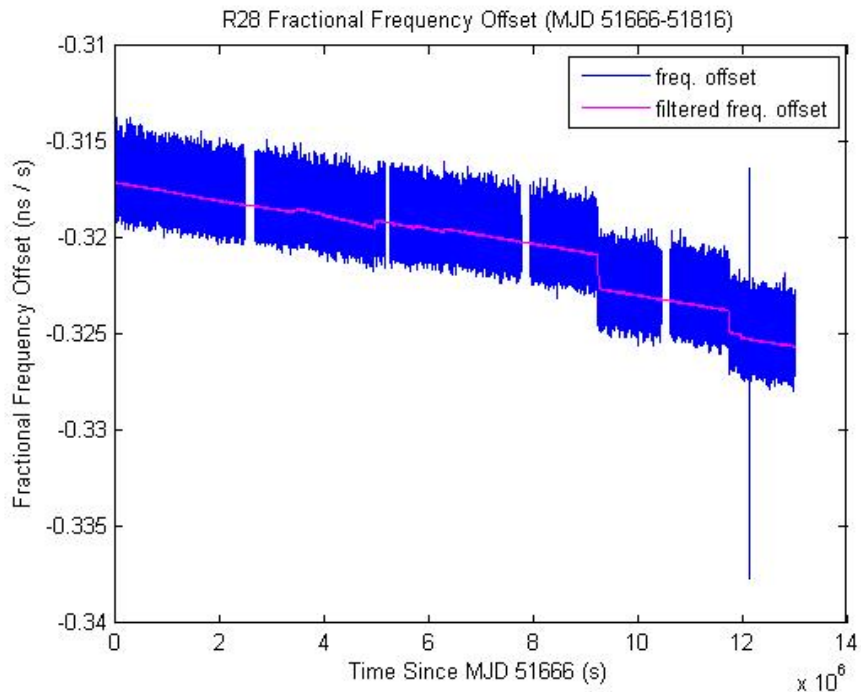

Figure 1. Clock R28 fractional frequency offset from 1st differences of 20 s measurements and from filter.
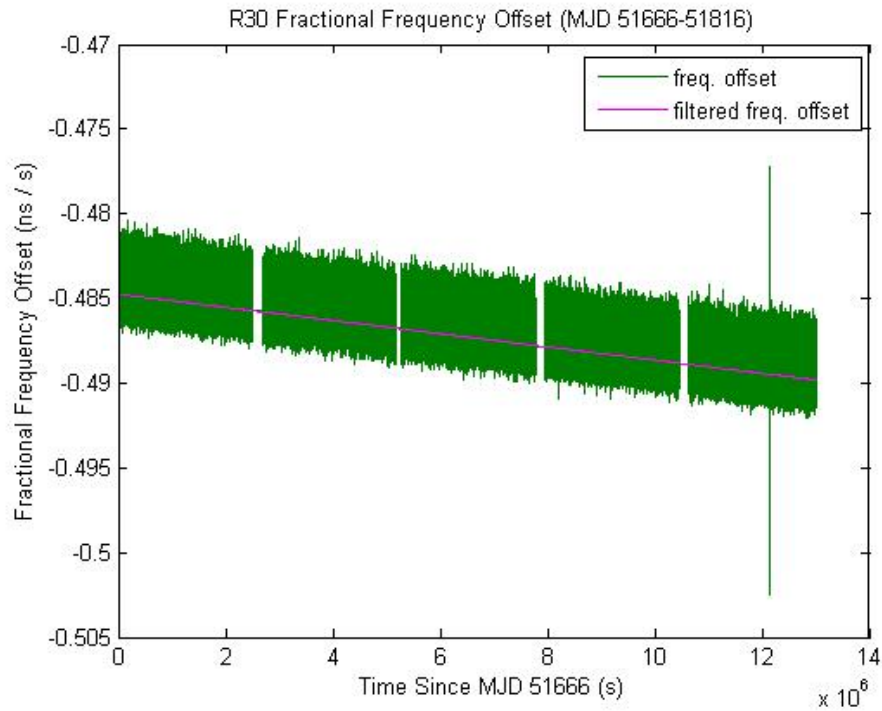
Figure 2.   Clock R30 fractional frequency offset from 1st differences of 20 s measurements and from filter.

We compute the distribution of peak prediction errors as follows:

1) Pick a prediction interval, τ, among: 15 minutes, 1 hour, 2 hours, 4 hours, 8 hours, 1 day.

2) For each 20 s measurement at time t, take the phase offset from the reference at that time, $x(t)$, and use the filtered fractional frequency at that time, $y(t)$, and estimated linear frequency drift, d, to predict time forward as a quadratic over the given prediction interval from 1). This is the predicted time:

$$P(t+\tau)= x(t)+ y(t)* \tau+ d*\tau^2$$

3) The peak deviation error at $t+\tau$, over the prediction interval τ, is the difference between the predicted time and the measured time:

$$PeakDev(t, \tau) = P(t+\tau) - x(t+\tau)$$

4) We collect the *PeakDev(t, τ)* for all of the possible values of t in the data set. Plotting these as a histogram gives the distribution function.

The plots below show how prediction error arrived for different prediction intervals for R28.
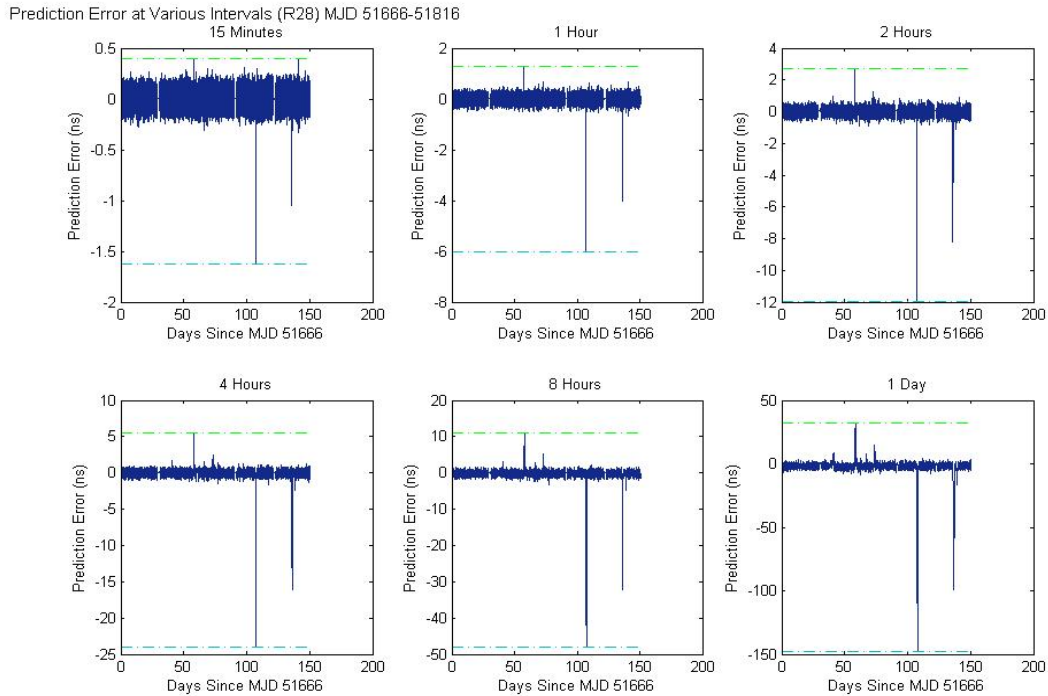
Figure 3. Prediction error for various prediction intervals, showing when the errors occur.

These plots lead to the distribution functions for R28 in Figure 4. The dashed lines are a best-fit Gaussian distribution to the data.
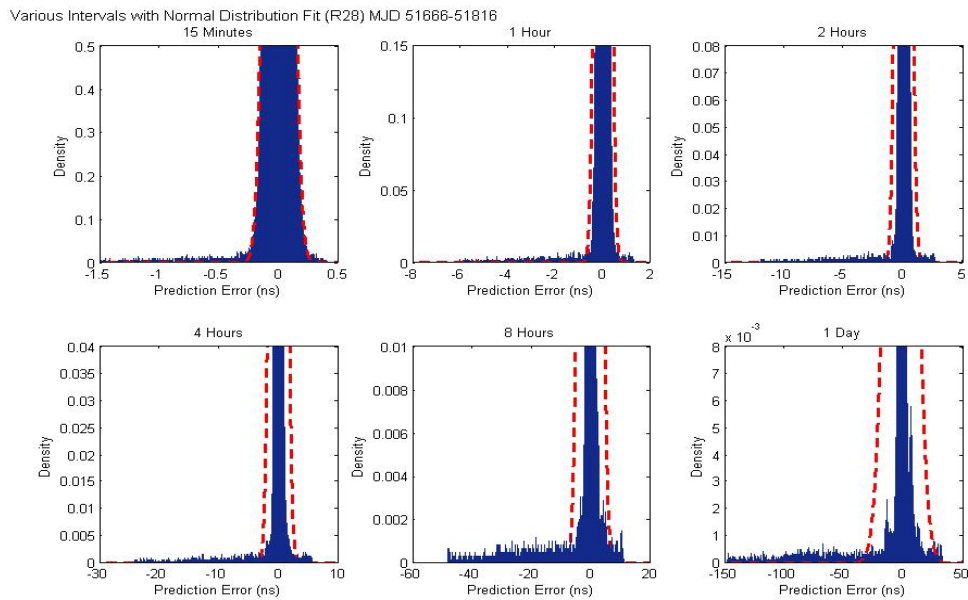

Figure 4.   Prediction error for various prediction intervals, showing the distribution of errors. The dashed lines show best fits for Gaussian distributions.

For R30, we found a different effect, than for R28. R30 had no significant frequency steps over the study interval. However, as we noted above, the filtered fractional frequency estimate did not go through what appeared to be the center of the fractional frequency from 1st differences of measurements. To understand this, we looked at the distribution of all of the residuals of fractional frequency from 1st differences of measurements differenced from the filtered estimates. See Figure 5 below.
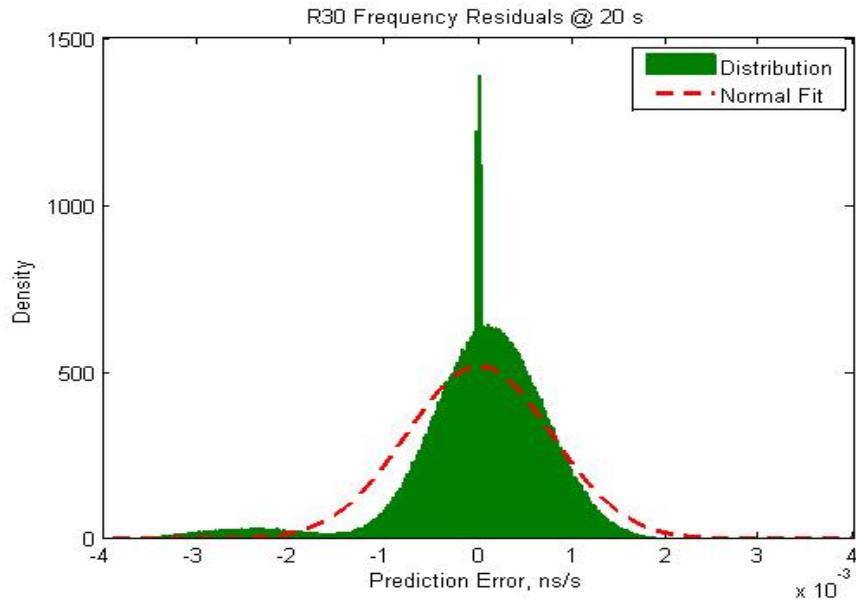

Figure 5. Fractional frequency residuals for clock R30 showing the bimodal behavior of the clock. The dashed line is a best fit for a Gaussian distribution.

The high peak at around 0 is simply because of data gaps. We interpolated ten the filter and measurement were aligned. However, note the bimodal nature of the distribution. The clock appears to have two modes separated by almost 3×10^{-12} in fractional frequency. This results in the distributions of time deviations having a nonzero mean. See Figure 6 below.

CONCLUSIONS

We conclude that one cannot assume that Gaussian statistics are valid for Peak Deviation of atomic clocks from prediction. Hence we cannot look at a Root-Mean-Squared measure of clock performance, such as the Allan variance, and use that to predict probabilities of peak time deviations. To determine failure probabilities for integrity, it will be necessary to characterize the distribution of peak deviation from prediction errors for the design clocks. It will also be necessary to incorporate peak testing into acceptance tests.
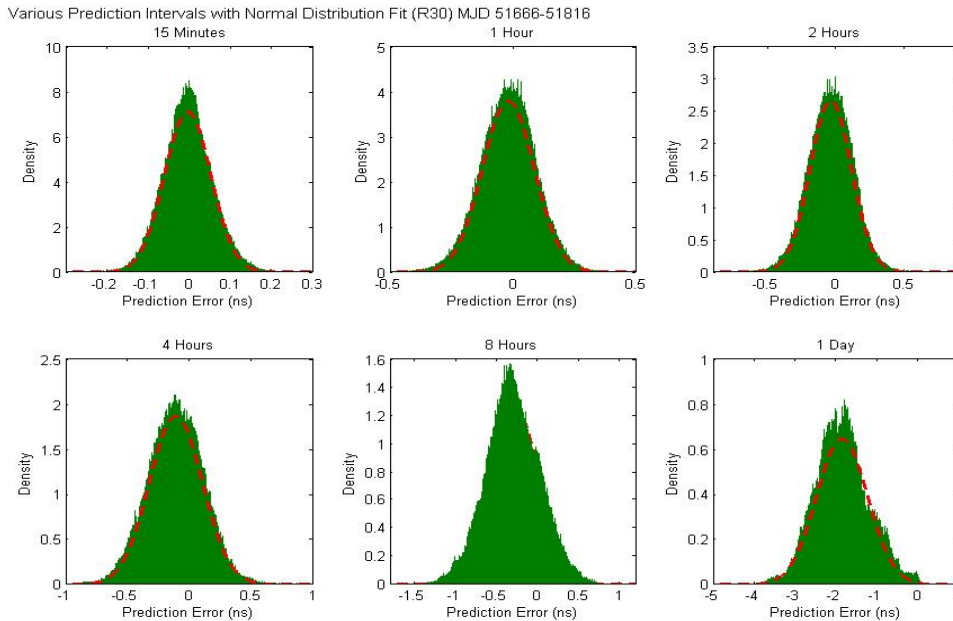
Figure 6. Prediction error for various prediction intervals, showing the distribution of errors.

APPENDIX

The key requirement of signal integrity refers to "the measure of the trust that can be placed in the correctness of the information supplied by the total system" **[6]**. Integrity includes the ability of a system to provide timely and valid warnings to the user (alerts) when the system must not be used for the intended operation (or phase of flight)." This means the necessity of providing timely warning to the users when a particular sub-system is degraded or when the system should not be used. Loss of Integrity is defined as the occurrence of an unsafe condition, known as hazardous misleading information (HMI), without intimation to the user for a time longer than the required time to alert. Hazardous misleading information is defined to occur when the true error resulting from the broadcast message exceeds the specified alert limit. The alert limits and the times to alert in Table 1 define the boundaries of safety threats in terms of error magnitudes that can be tolerated and the notification delays.

The Civil navigation requirements listed in Table 1 are categorized by phase of flight and the necessary navigation attributes **[7]**. Signal Integrity is the foremost and encompassing consideration, as safety is paramount in aviation operations. Time to Alert and Alert limit are two of the facets that constitute Integrity. To ensure that the position error is acceptable, an alert limit is defined that represents the largest position error allowable for a safe operation. The position error cannot exceed this alert limit without annunciation for a time longer than the required time to alert. This is analogous to ILS, in that the system can degrade so that the error is larger than the 95th percentile, but within the monitor limit.

Integrity attribute may be quantified in terms of Protection Levels, horizontal and vertical thresholds, and associated time to alert that the navigation system can conform against a specified, low probability of hazardously misleading information (HMI) corresponding to each phase of flight.

Loss of Integrity can occur in two ways. It is possible that under nominal conditions, with all equipment operating properly and within specification, an error occurs that exceeds the alert limit for that phase of flight. It is also possible an anomaly within the signal-in-space is not detected within the time to alarm, thus leading to errors exceeding the alert limit. Note that if the error is detected in time and the operation is aborted, then integrity is maintained, but signal continuity is lost. However, if the anomalous element is detected, properly identified and excluded within the time to alert and all the navigation requirements are still met despite the failed element, then the aviation operation can continue safely – with maintenance of both Integrity and Continuity.

Continuity refers to the likelihood that an operation that met all navigation requirements will be successfully completed. Loss of Continuity is defined as the occurrence of an anomaly that causes loss of safe navigation performance before the operation is completed.

Loss of Continuity can happen in two ways: a component failure that is evident or is detected by onboard Integrity monitoring. If the source of failure can not be diagnosed with near certainty, then a general alarm is issued and the operation is aborted. Here, continuity is sacrificed to protect integrity.

Service Availability refers to the likelihood that the navigation system meets all requirements for an intended operation. Availability is, thus, contingent on meeting the accuracy, integrity, and continuity requirements, and is important for air traffic control purposes. The Availability requirements are expressed as a long-term probability that all requirements are met over all possible conditions, including varying GPS satellite geometries, outages, variations in error magnitudes, etc.

Since Service availability expresses the probability that a given operation can be carried out, it is a useful performance indicator for assessing navigation system architectures to support civil users. The service availability requirements shown in the enclosed Table 1 express the desired probabilities of being able to provide guidance in the various phases of flight.

Table 1. Civil navigation requirements.

Phase of Flight	Accuracy (95% error)	Integrity Time to Alert	Integrity Alert Limit	Integrity Prob (HMI)	Continuity Prob. (Loss of Navigation)	Availability Threshold	Availability Objective
Oceanic Enroute	H: 12.4 nmi	120 s	H: 12.4 nmi	$10.^{-7}$/hour	$10.^{-5}$/hour	0.99	0.999 - 0.9999
Domestic Enroute	H: 2.0 nmi	60 s	H: 2.0 nmi	$10.^{-7}$/hour	$10.^{-5}$/hour	0.99	0.9999
Terminal Area	H: 0.4 nmi	30 s	H: 1.0 nmi	$10.^{-7}$/hour	$10.^{-5}$/hour	0.99	0.99999
Non-Precision App.	H: 220 m	10 s	H: 556 m	$10.^{-7}$/hour	$10.^{-5}$/hour	0.99	0.99999
LNAV/VNAV	H: 220 m	8 s	H: 556 m V: 50 m	$10.^{-7}$/hour	$5. \times 10.^{-5}$/hour	0.99	0.99999
APV	H:16 m V: 7.6 m	6 s	H: 556 m V: 20 m	$2.x\ 10.^{-7}$ /approach	$5. \times 10.^{-5}$/hour	0.99	0.99999
Cat I Precision Approach	H: 16 m V: 4.0-7.6 m	6 s	L: 40 m V: 10-12 m	$2.x\ 10.^{-7}$ /approach	$5. \times 10.^{-5}$/hour	0.99	0.99999
Cat II Precision Approach	H: 6.9 m V: 2.0 m	2 s	H: 17.3 m V: 5.3 m	$2.x\ 10.^{-9}$ /approach	$4.x10^{-6}$/ 15 s	0.99	0.99999
Cat IIIa Precision Approach	H: 6.0 m V: 2.0 m	1-2 s	H: 15.5 m V: 5.3 m	$2.x\ 10.^{-9}$ /approach	L: $2. \times 10^{-6}$/30 s V: $2. \times 10^{-6}$/15 s	0.99	0.99999

Notes on Table 1:

LNAV   Localizer Performance with Vertical Guidance
VNAV   Vertical Navigation
APV   Approach with Vertical Guidance
LNAV/VNAV essentially adds vertical guidance to existing non precision approach
APV may be seen as a "relaxed" version of Category I precision approach

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