ENHANCING GPS TIMING ENGINES USING WAAS SIGNALS

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Abstract

Accurate timing sources are becoming a very important issue in the development of networked telecommunication systems. Since the early 1990's, GPS has been exploited for this purpose. The common GPS time transfer technique is mostly used to minimize the timing error caused by satellite clock and ephemeris errors, and Selective Availability. This technique provides a typical timing accuracy of 50 nanoseconds (1 sigma).

Currently, a new WAAS (Wide Area Augmentation System) is being developed under the authority of the FAA (Federal Aviation Administration). This system is a Satellite-Based Augmentation System (SBAS) which will be used to enhance signal continuity, availability, and integrity to GPS receivers. WAAS is scheduled to be officially commissioned in the summer of 2000.

This paper describes the features and performance of a GPS/WAAS Timing Engine developed by Marconi Canada. The paper will discuss the features of the WAAS system and how it can be used to dramatically decrease the timing errors of a GPS engine. Results obtained using a GPS simulator and live signals will be analyzed. Comparative results between a GPS only and a GPS/WAAS Timing Engine will be presented. Finally, additional features of the GPS/WAAS Timing Engine, such as TRAIM (Time Remote Autonomous Integrity Monitoring), will be discussed.

INTRODUCTION

This article is concerned with the use of the FAA's Wide Area Augmentation System (WAAS) signal by a low-cost GPS receiver in order to provide a stable and accurate 1 Pulse-Per-Second (1PPS) timing signal aligned on UTC time.

Precise timing using GPS has become increasingly popular in the past years due to the low cost of commercial-grade GPS receivers implementing time transfer techniques. Marconi Canada has recently developed a GPS/WAAS timing engine based on its popular Superstar low-cost GPS receiver. In this article, an overview of the use of a GPS receiver as a source for precise timing will be given, followed by an overview of the WAAS system and the added value that it brings to a GPS timing engine. The features of the Superstar receiver will then be presented. The next part of the article will be concerned with our test set-up and a discussion of obtained results.

GPS TIMING OVERVIEW

A GPS receiver can produce precise timing information by implementing a time-transfer technique. This technique attempts to replicate the highly stable atomic clocks residing within the GPS satellites. It yields accurate absolute timing information and usually a one order of magnitude higher level of accuracy in relative mode.

The fundamental concept behind the time-transfer technique is simple. It requires that the exact position of the GPS receiver be known. The receiver computes the position of the satellites via the received navigation message; hence, a range estimate between the receiver and the satellite is obtained for each satellite. Then, since the time of the satellite signal's transmission is provided again through the navigation message, the signal's reception time is deduced, as follows:

$$t_r = t_t + R / c \tag{1}$$

where R is the computed range in units of meters, c is the speed of light, and t_t is assumed to be perfectly synchronized to GPS time, after use of the satellite clock modeling parameters. The receiver is then capable of generating a 1PPS signal with its rising edge synchronous to the UTC second edge by aligning t_r on UTC. To achieve this, the receiver's clock, that is used to sample the GPS measurements and to generate the 1PPS signal, must be steered towards the GPS clocks. A receiver typically accomplishes this by computing a clock bias estimate for each satellite measurement, as follows:

$$\Delta t_u[i] = R / c - \rho[i] \tag{2}$$

where Δt_u is the user's clock bias and $\rho[i]$ is the receiver's pseudo-range measurement for satellite i, and where

$$\rho = \hat{t}_r - t_t \tag{3}$$

$\hat{t}_r$ represents the estimate of the receiver's true GPS time of reception.

The set of clock bias estimates are then averaged out and the resulting estimate is used to drive the receiver's clock such that it will best approximate the true GPS time. Typical performances that can be expected from GPS time transfer are presented in [1].

WAAS OVERVIEW

WAAS is a wide area differential system developed by the FAA to meet the stringent accuracy, integrity, and continuity requirements of the avionics community. It is composed of 25 ground stations (dubbed WAAS Reference Stations - WRS) spread over the United States territory that continuously track GPS satellites. The information is then relayed in real-time to a master station (dubbed WAAS Master Station - WMS). By collating measurements from the WRS, the WMS derives two kinds of information: system errors and ionospheric delays. The former consists of S/A (Selective Availability) components, satellite clock errors, and ephemeris errors. The multi-site observations and the geographic distribution of the WRS allow the WMS to separate the three components enumerated above and estimate each one. The ionospheric delays measured by the dual-frequency receivers at the WRS sites are remapped to provide the vertical ionospheric corrections at the pierce point location, which is defined as the intersection point between the satellite's signal and the ionosphere layer. From the set of pierce point locations and observed vertical ionospheric corrections, a map of ionosphere corrections for the entire service area of the network is computed in the form of a grid. The grid's resolution is 5° between latitudes of ±55° and 10° for latitudes between 55° and 75°. The polar region is mapped with only four values. The WMS estimator also provides a variance for the estimated parameters.

The computed corrections and corresponding variances are relayed to a geo-synchronous (GIC) satellite. The satellite packages the information into a set of WAAS data frames. A frame is composed of a preamble (8 bits), data (226 bits), and a CRC (24 bits). The frames are 2-1 convolutionally encoded and have a constraint length of 7 to provide additional coding gain. The 500 bits are then radiated onto a carrier modulated by a Pseudo-Random Noise (PRN) number, similar to the ones used by the GPS satellites. Therefore, both the GPS signals and the differential link can be received on a single antenna.

PRECISE TIMING USING WAAS

As mentioned above, typical GPS time transfer techniques average out the sum of S/A, tropospheric, and ionospheric errors. The relative accuracy of the 1PPS signal generated by two receivers separated by relatively short distances (25-50 km) can be in the order of 20 nsec, providing an adequate steering algorithm. The main advantages of WAAS are that:

- It allows for high absolute timing accuracy with respect to UTC;
- For relative timing purposes, two L1 GPS receivers tracking a WAAS satellite and separated by a large distance will have their 1PPS synchronized within a few nsec. The only constraint is that both receivers must be contained within the WAAS network.

SUPERSTAR WAAS TIMING ENGINE OVERVIEW

The Superstar is a low-cost, single-frequency (L1) GPS receiver developed by Marconi Canada for embedding in Original Equipment Manufacturer (OEM) systems. It measures 2.8"W x 1.8"L x 0.51"H and consumes 1.2 W. Details of its use, performance, and specifications are presented in [2]. The WAAS Timing Engine version of the Superstar is capable of using the corrections and integrity data transmitted by the WAAS satellites and produces an accurate and stable timing signal aligned on UTC.

FEATURES

The accuracy of the 1PPS signal, that is, the alignment of its leading edge with respect to the UTC second boundary, is as follows:

- ±30 nsec (1σ), or ±50 nsec (peak-to-peak), without S/A (using DGPS or WAAS corrections)
- ±45 nsec (1σ), or ±120 nsec (peak-to-peak), with S/A.

Via a command message, the user can request the receiver to self-survey its position. The accuracy of the position resulting from this process is sufficient for providing a precise timing signal. During this process, the computed position is averaged out and a Figure-Of-Merit (FOM) reflecting its accuracy is maintained. This process continues until expiry of the desired survey FOM. When this occurs, the surveyed position is stored in Non-Volatile Memory. The receiver then automatically switches to timing mode using the surveyed position.

Several of the receiver parameters are user-configurable. The noteworthy ones are:

- Cable Delay: Allows the user to compensate for the length of the antenna cable, since this cable introduces a delay in the 1PPS signal output. The range of possible values ranges from 0 to 1 msec, in units of 1 nsec.
- 1PPS Offset: Allows the user to offset the 1PPS signal from the UTC second edge. The range of possible values ranges from 0 to 1 second, in units of 100 msec.
- 1PPS Output Control: Allows the user to specify under which conditions the 1PPS output should be disabled. For example, when no satellites are being tracked, when an alarm has been raised by TRAIM (see section below), etc.

If the user's application has stringent requirements on the upholding of the timing reference during possible GPS outages (e.g. when the antenna is masked), a more stable voltage-controlled oscillator may be used. In this case, a Superstar without an on-board oscillator is provided, with a connector for input of the external 10

MHz oscillator. Since timing using GPS is very stable in the long term, a highly stable oscillator can be used for short-term GPS outages. The Superstar provides the user with the oscillator's bias and drift, which in turn may be used to steer the oscillator towards an exact 10 MHz beat frequency.

WAAS IMPLEMENTATION

A block diagram of the WAAS message processing as implemented in the Superstar is depicted in Figure 1. The 500-symbol WAAS message is demodulated by the signal processing module, and the 250-bit WAAS message is recovered with a Viterbi decoder implemented in software. The Viterbi decoder and a lock detector quickly resolve bit polarity and symbol alignment for fast bit acquisition. The basic 1-second WAAS frame is then de-assembled according to the DO-229A specification [3]. The S/A, satellite clock, and ephemeris errors are computed and removed from the pseudo-ranges. The local ionosphere correction for each pseudo-range is also computed. A troposphere model is used to estimate the satellite signal's delay as it travels through it. An α-β type filter is used to derive rate corrections to be applied to the delta-ranges. This is necessary because, unlike differential messages such as RTCM-104 [4], there are no delta-range corrections encoded in the WAAS message.

The associated variance for each error type is also extracted from the WAAS message. When WAAS is not active, the pseudo-range and delta-range variances are computed as a function of satellite elevation, Signal-To-Noise Ratio, and the URA contained in the ephemeris message. The corrected pseudo-ranges and delta-ranges and associated variances are then used to update a Kalman filter-based estimator that computes the clock bias and clock drift. A Time Figure-Of-Merit (TFOM) of the clock bias is computed and scaled by the magnitude of the residual clock bias; it provides an estimate of the spread of the measurements.

TRAIM CONCEPT

Integrity of the receiver-generated 1PPS signal is becoming an increasingly important issue. A faulty synchronization signal may have disastrous consequences on the network operation and cause expensive down-time periods. In the avionics community, the subject of integrity has drawn a considerable amount of attention and has spurred algorithm developments to support the industry's safety requirements. The same formal approach that has been developed by this industry can also be used to provide integrity for the purpose of time-transfer applications. Some basic concepts will be briefly elaborated here. The reader should refer to [5] and [6] for further details.

Accuracy basically refers to the confidence interval of the estimate given by an estimator. Integrity refers to the capability of the same estimator to provide a timely warning when a solution is outside a given limit and is called, in this context, a Time Integrity Level (TIL). The integrity algorithm uses the redundancy in the measurements to confirm the integrity of the timing solution. TIL depends mostly on the number of satellites being tracked and the a-priori statistics of the measurements. Unlike GPS navigation receivers that must estimate four parameters, namely 3-D position and time, a timing engine would only solve the user clock parameters (bias and drift). This provides more "observability" to detect a faulty timing estimate. Furthermore, the estimated clock bias and drift are not geometry-dependent and most parameters required to implement an effective integrity algorithm can be pre-computed and stored within the receiver.

The Time Receiver Autonomous Integrity Monitor (TRAIM) is split into two functions: Detection and Isolation (refer to Figure 2). The detection function detects the presence of any anomalies that may have caused a spreading of the residuals that is incompatible with a-priori statistics of the residual errors. It uses a mapping function to carry out a statistical test for each residual. The mapping is selected such that the signature of a failure is maximized in one direction. If at least one of the residuals exceeds a pre-computed threshold, a fault detection condition is raised. The computed TIL is increased to reflect that condition.

The isolation function attempts to identify one faulty measurement. A set of (n-1) statistics is computed for each of the n residuals. If all statistics for one given residual exceed a threshold and all tests fail for the remaining residuals, the faulty measurement has thus been successfully identified. The measurement for this satellite is removed from the solution. The process is applied to both pseudo-ranges and delta-ranges.

There may be an elapsed time between fault detection and fault isolation. For example, if the user programmed an incorrect position in the receiver, the fault detection condition would be raised and the isolation function would be unable to isolate a single faulty satellite, since all residuals are off. When this condition persists, the timing service is interrupted and the receiver executes a self-survey process prior to returning to its normal timing operation.

TEST SETUP

Extensive testing has been performed on the WAAS Timing Engine using both a GPS/WAAS signal simulator and live signals. The purpose of the simulator tests was to verify the intrinsic accuracy of the receiver under ideal conditions. Since the errors due to the simulated S/A are perfectly modeled in the WAAS correction message, and no other errors are imposed on the signal, the error on the 1PPS output is due to the receiver. The test setup using the GPS/WAAS signal simulator is shown in Figure 3. The universal counter measures the time interval between the rising edges of both 1PPS signals. It was observed that the 1PPS generated by the simulator is not accurately aligned to UTC: successive steps of 700 nsec build-up at each second, after which a correction of a few microseconds is applied to the 1PPS. Hence, the simulator has an *average* 1PPS output rate of 1 Hz. However, this is transparent to the receiver, since the simulator's measurements are synchronous with the 1PPS output. A personal computer is used to log these time intervals along with other timing information (receiver clock error estimates, UTC time, etc.), after which processing is performed with the MATLAB™ data analysis tool.

A similar series of tests was performed using live GPS and WAAS signals. A rubidium clock was used as the reference against which the receiver's 1PPS is compared. As shown in Figure 4, the atomic clock is fed into a frequency divider, which generates a square wave signal.

Another test setup was used to verify the proper functionality of the receiver using an external 10 MHz input. In this case, the rubidium clock was fed directly into the receiver as shown in Figure 5.

RESULTS

Results of various tests are presented in this section. The test environment provided us with relative timing accuracy results only, since calibration of all signal delays was not performed due to the unavailability of an absolute UTC timing reference. Therefore, all plots are centered on an arbitrary initial timing error of zero seconds.

GPS/WAAS SIMULATOR TESTS

Tests were performed on the Superstar using a GSS® GPS/WAAS simulator, model STR2760. A full S/A model as per the DO-229A specification [3] was selected. The simulator generated ionosphere and troposphere error models. A typical antenna pattern was also simulated. The 1PPS misalignment error was recorded for a 55-hour period. The purpose of this test was to validate the Superstar and the simulator. The plot shown in Figure 6 illustrates well that all the error models are correctly encoded by the simulator and correctly decoded and applied within the receiver. The uniform distribution of the 1PPS error is well contained within ±50 nsec, that is, the intrinsic resolution of the receiver's hardware timer. This 50 nsec quantization error (see Figure 7) is made available to the host after each 1PPS output via a data message.

LIVE SATELLITE TESTS WITH AND WITHOUT WAAS

Figures 8 and 9 show comparative plots when the Superstar tracks the WAAS satellite and when it doesn't. The first plot is_without WAAS. It is observed that the 1PPS drifts due to the effects of S/A, with a mean of about zero. The second plot is with WAAS.

Preliminary analysis of the WAAS signal's message has shown that the correction variances it reports are sometimes very large. They had to be limited in software so they did not exceed the ones used in the non-differential model; otherwise, mixing of non-differential and differential measurements would lead to incorrect clock bias and clock drift estimates.

TRAIM TESTS

Figure 10 better illustrates the principle of TRAIM.

In this example the following design parameters were used:

- Probability of False Alarm: 2.7e-06
- Probability of Missed Detection: 0.0001
- RMS Residual Error: 33.0 meters and correlation time of 120 seconds.

The receiver is tracking four satellites with WAAS being inactive. At time t=100 seconds, a ramp of 1 m/s is injected on one satellite. The error will slowly corrupt the clock bias and,consequently, the accuracy of the 1PPS. At this point, the computed TFOM increases slowly and the computed TIL is about 300 nsec. As the true error approaches the TIL, the faulty satellite is detected and isolated. After isolation, the TIL is about 400 nsec and the clock error induced by the faulty measurement fades away. The reader is reminded that this is one instantiation of the process.

CONCLUSION

WAAS was originally designed for aviation purposes. It has been shown in this article that the WAAS network also proves to be a valuable asset for precise timing applications. It particularly helps in increasing absolute timing accuracy and in increasing relative timing accuracy for widely separated receivers. The Superstar WAAS Timing Engine developed by Marconi Canada takes advantage of the WAAS signal to achieve these benefits. When high reliability is required, the Superstar receiver can be stripped from its on-board oscillator and fed with an external, highly stable, voltage-controlled oscillator. In this configuration, the long-term stability of the external oscillator is ensured by its continuous calibration by the Superstar. In case of intermittent GPS outages, correctly signaled by the TRAIM, the calibrated external oscillator will continuously provide an accurate 1PPS signal. As well, this configuration yields a near perfect 10 MHz reference. Also, provided with the user clock error estimates that are accurate within 10 nsec, the host application could remove the 50-nsec jitter intrinsic to the Superstar's hardware timer and generate a timing signal well within 10 nsec.

For wide-area network synchronization systems, the expected dominating errors will be those induced by the residual errors in the troposphere corrections. At this time, the Superstar receiver uses a simple Hopfield model. More elaborate models such as those discussed in [7] could be implemented in the receiver to further reduce the contribution of the troposphere error.

REFERENCES

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[2] Superstar Users Manual, Marconi Canada publication no. 1230-GEN-0101.

[3] RTCA DO-229A, "*Minimum Operational Performance Standards for the Global Positioning System / Wide Area Augmentation System Airborne Equipment*," RTCA Inc, Washington, DC, June 8, 1998.

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[6] A. Ray and R. Luck, "*An Introduction to Sensor Signal Validation in a Redundant Measurement System*," IEEE Control Systems Magazine, Vol. 11, No. 2, pp. 44-49, 1991.

[7] A Tropospheric Delay Model for the User of the Wide Area Augmentation System, Final contract report for NAV Canada Satellite Navigation Program Office, Engineering Technical Report No. 187, University of New Brunswick, Fredericton, New Brunswick, Canada, September 1997.

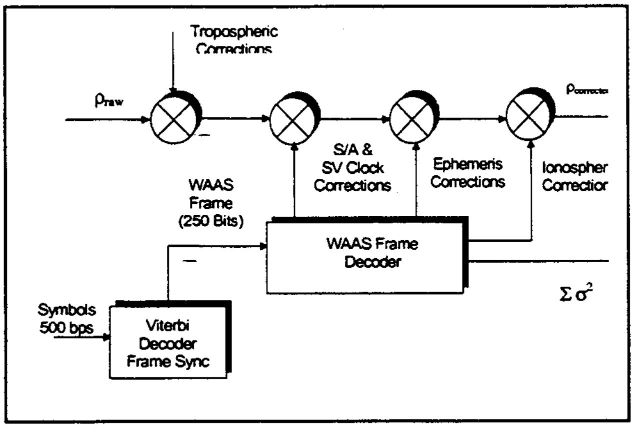


Figure 1: WAAS Message Processing

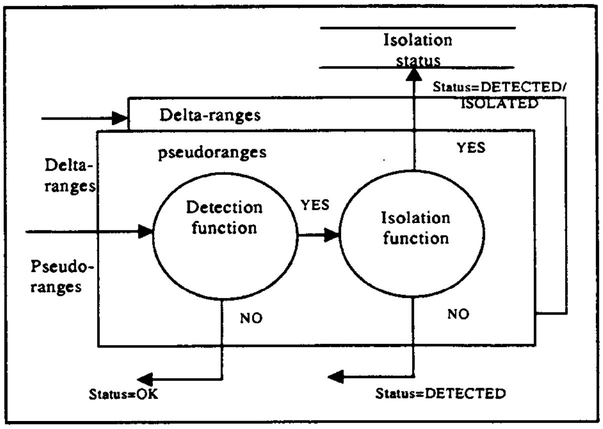


Figure 2: TRAIM Block Diagram

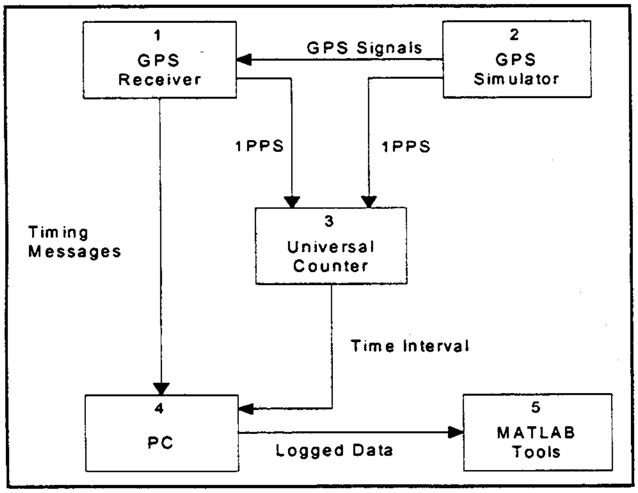


Figure 3: GPS/WAAS Simulator Test Setup

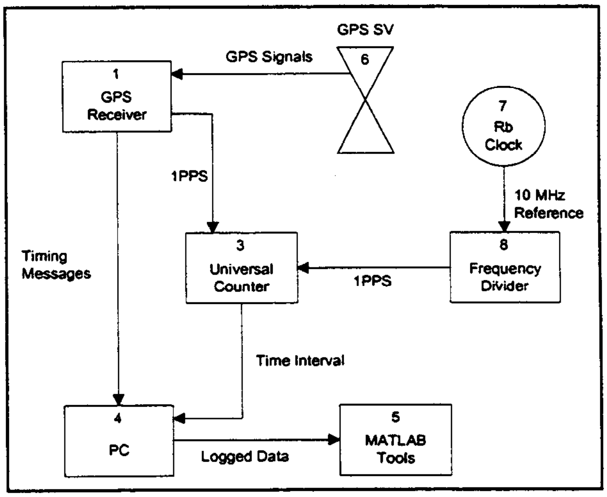


Figure 4: Live Signal Test Setup

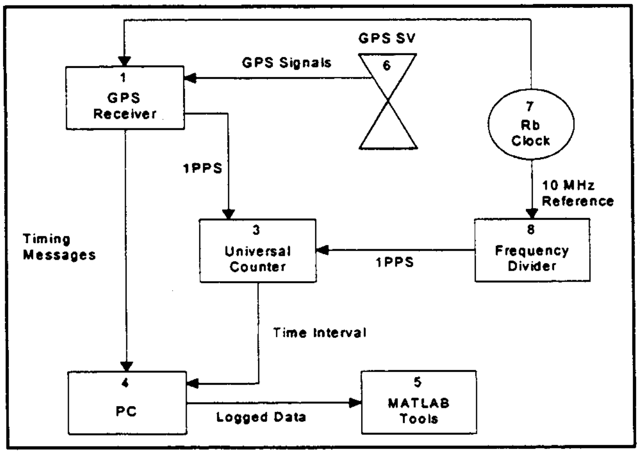
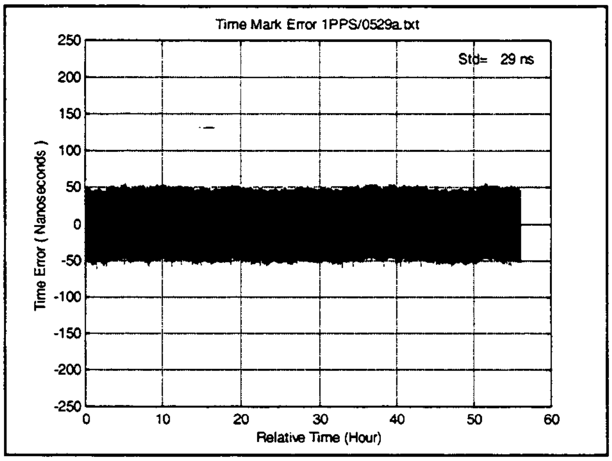


Figure 5: External Oscillator Test Setup



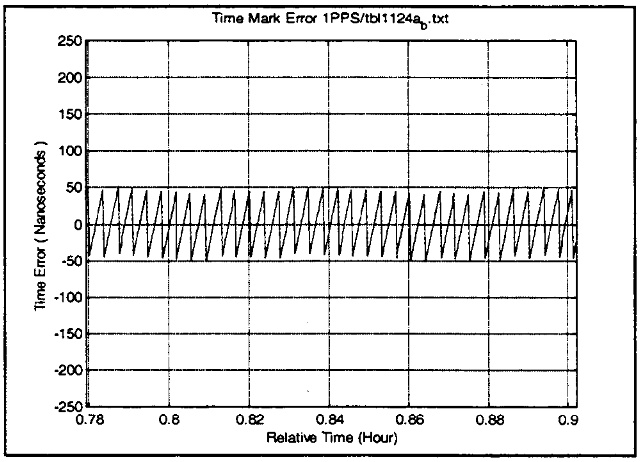
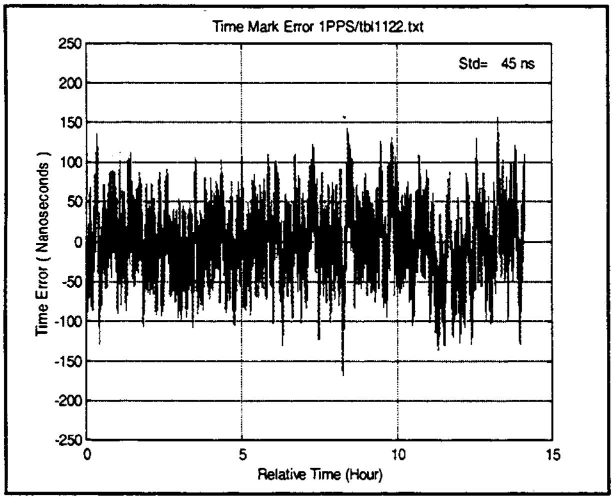


Figure 6: 1PPS Error Using Simulator

Figure 7: Receiver Quantization Error on 1PPS



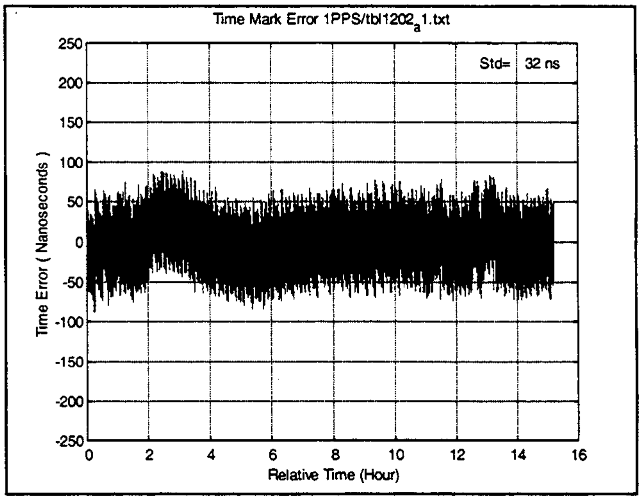


Figure 8: 1PPS Error With Live GPS SVs Only

Figure 9: 1PPS Error With Live GPS/WAAS SVs

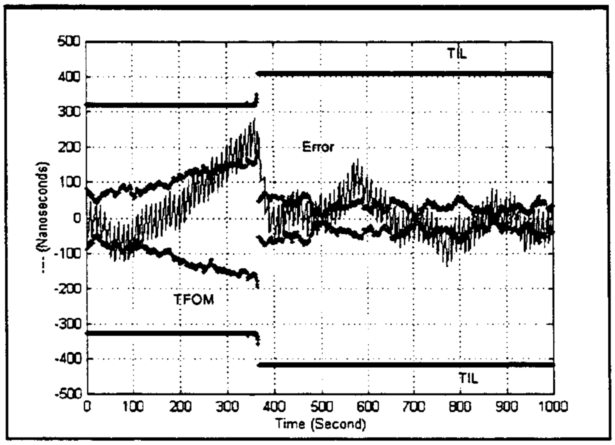


Figure 10: TRAIM Detection and Isolation