Test Results for the WAAS Signal Quality Monitor

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ABSTRACT

The Signal Quality Monitor (SQM) is an integrity monitor for the Wide Area Augmentation System (WAAS). The monitor detects L1 signal waveform deformation of a GPS or a Geosynchronous (GEO) satellite monitored by WAAS should that event occur. When a signal deformation occurs, the L1 correlation function measured by the receiver becomes distorted. The distortion will result in an error in the L1 pseudorange. The size of the error depends on the design characteristics of the user receiver. This paper describes test results for the WAAS SQM conducted using prototype software. There are two groups of test cases: the nominal testing and the negative path testing.

For nominal test cases, recorded data are collected from a test facility in four 5-day periods. These four data sets include SQM correlation values for SV-receiver pairs, and satellite error bounds for satellites. They are used as input to the prototype. The prototype processes these data sets, executes the algorithm, and records test results. Parameters such as the "maximum median-adjusted detection metric over threshold" (i.e., the maximum detection test), "UDRE forwarded from upstream integrity monitors," and "UDRE supported by SQM" are shown and described. The magnitude of the maximum detection test for all GPS and GEO satellites are also shown.

For negative path testing, this paper describes two example simulated signal deformation test cases. A 2-day data set is collected from the prototype. A few example ICAO signal deformations are simulated based on this data set and are inserted in different time slots in the 2-day period. The correlator measurements for selected satellites are pre-processed to simulate the signal deformation. The results demonstrate the sensitivity of the Signal Quality Monitor to the simulated deformation, and shows when the event is detected and subsequently cleared. It also shows that the SQM will not adversely affect WAAS performance.

INTRODUCTION

The primary mission of WAAS is to provide a means for air navigation for approved phases of flight in the National Airspace System. WAAS consists of the equipment and software necessary to augment the Department of Defense-provided Global Positioning System (GPS) Standard Positioning Service (SPS). The WAAS provides a Signal-In-Space (SIS) to all aircraft with approved avionics using the system for any approved phase of flight. The broadcast SIS provides two functions: (1) messaging (data on GPS and Geostationary Earth Orbit (GEO) satellites) and (2) a ranging capability.

WAAS receives and processes GPS and GEO data at widely dispersed Wide-area Reference Stations (WRSs),which are located to provide redundant coverage over the specified WAAS service volume. These data are forwarded to Wide-area Master Stations (WMSs), which process the information to determine differential satellite corrections, GEO orbital parameters, ionospheric corrections and integrity bounds. These functions are also called Correction and Verification (C&V). The WAAS-generated information is sent from the WMSs to the GEO Uplink Subsystem (GUS) and uplinked to GEO satellites. The GEO satellites broadcast the WAAS SIS to the users with GPS type modulation. Each ground based system component communicates via a Terrestrial Communication Subsystem (See Figure 1.).

In addition to providing augmented GPS data to the users, WAAS verifies its own integrity and takes the necessary actions to ensure that the system meets the WAAS performance requirements.

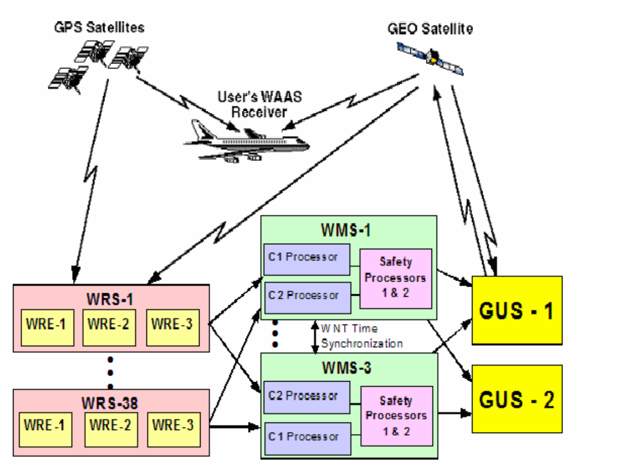

Figure 1 WAAS Overview

L1 SIGNAL DEFORMATION

An L1 signal deformation occurred on SV 19 in 1993. In March 1993 at the Oshkosh Air Show, Trimble Navigation, Ltd. noted that differential position accuracies, based on code pseudorange measurements, were less than 50 cm when not using SV19. When SV19 was included, the vertical position accuracy of the differential code phase solution degraded to anywhere from 3 to 10 meters.[1] Several candidate threat models were initially proposed to explain the SV19 event [2]. Such threats manifest themselves in the form of an anomalous correlation peak.

Three basic correlation peaks pathologies are envisioned: dead zones, distortions, and false peaks. The deadzones or plateaus atop the correlation peak are regions of zero discriminator gain. The airborne and reference receiver correlator pairs may "track" in different portions of this region. The distortions are asymmetries caused by underdamped oscillations in the correlation function. They may affect the airborne receivers differently than the reference station. Even using multiple correlators, monitor receivers may not detect these distortions. The false peaks result from significant distortions of the correlation peak. They may cause some receivers to track the distorted peak (a raised oscillation) instead of the true one.

To address these three peak pathologies, the ICAO threat model approximates three specific classes of failure modes: digital, analog, and combination (analog and digital) failure modes. This model assumes the anomalous waveform is some combination of second-order ringing (an analog failure mode) and lead/lag (a digital failure mode) of the pseudorandom noise code chips. The model includes parameter bounds for F_d (damped natural frequency), σ (damping), and Δ (lead/lag). The WAAS Signal Quality Monitor (SQM) would detect any and all such deformations that would result in unacceptably large differential pseudorange errors. (See Figure 2). Note that this SQM design and approach replaces the previous one implemented for the initial operation of WAAS. [4]

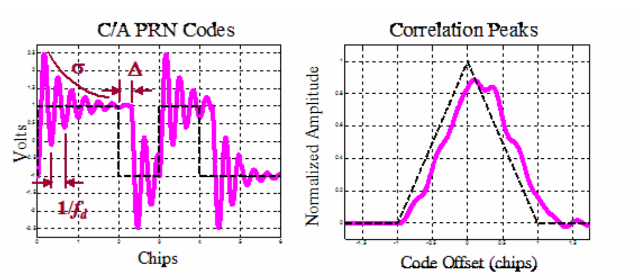

Figure 2 Combination of Analog (F_d and σ) and Digital (Δ) Failure Modes (Ideal (Dashed) and Distorted (Solid) Waveforms Shown.)

SQM PROCESSING OVERVIEW

SQM is responsible for detecting signal deformations on the GPS L1 C/A code or GEO WAAS SIS and for ensuring that the broadcast UDREs (User Differential Range Error)—a key measure for determining WAAS performance—are sufficient to bound the error caused by signal deformation given the monitor's current observability. The UDRE is a one-sigma error bound on the errors associated with the satellite corrections. The UDREI is an index used to identify which UDRE is in effect for a given SV at any given time.

With a rate of once per second, the WRS receivers measure the values at 9 different locations of the ideal correlation function for each SV in view. These 9 locations are -0.1, -0.075, -0.05, -0.025, 0, 0.025, 0.05, 0.075, and 0.1 chip offsets from the center of the peak respectively. The value measured at the center (zero-offset) is called the prompt correlator measurement.

To perform the task of monitoring for hazardous signal deformations, the monitor processes the above 9 correlator measurements produced by the reference station receivers and calculates statistics based on the observed performance compared against undistorted signal correlation peaks. This results in an estimate of the overall deformation per satellite signal. The calculated deformation level is then compared against UDREI-dependent threshold values. If the threshold is breached, the monitor trips for the given satellite, the SV UDRE is set to 'Don't Use' (i.e., an alarm is triggered to alert users).

The probability of missed detection is also considered based on the quality of the satellite signal measurements. If this probability is determined to be too high, the threshold and, hence, the SV UDREI, is raised accordingly. Note that the SQM also depends on other WAAS monitors to screen out anomalous measurements. This helps ensure that the SQM responds only to actual signal deformations rather than to local environmental effects (e.g., large multipath).

The SQM processing can be summarized in the following steps:

1) Pre-screen the correlation input to exclude invalid data, then normalize the measurements by the prompt correlator.
2) Smooth the 9 correlator measurements and map them into 4 raw detection metrics for each SV-receiver pair.
3) Screen the smoothed metrics based on their expected standard deviations and compute the inter-receiver biases.
4) Remove the inter-receiver biases (IRBs) and average the metrics across receivers.
5) Remove the type bias of the mean detection metric
6) Subtract the median across the mean detection metrics of all the SVs in view from the mean detection metric of this SV.
7) Compare the absolute value of this median-adjusted detection metric to a UDRE-dependent threshold for each of the 4 metrics.

In Steps 1 and 2, the SQM algorithm obtains data from the WAAS network of SQM-capable receivers at all WRSs for both GPS and WAAS GEO satellites. The algorithm prescreens, normalizes and smoothes this measurement data and then linearly combines the nine—four early, four late, plus prompt—correlator inputs from each channel of a receiver to form a total of four detection metrics. [3] The four detection metrics are formed for each of N satellites with measurements from each of J total reference receivers.

In Step 3, metrics are further screened by looking across receivers for each satellite and metric using median edit processing to remove outliers. The remaining metrics from this screening are combined (averaged) for each satellite with an elevation angle-based weighting. These mean metrics per satellite are used in estimating individual metric biases for each receiver (referred to as the inter-receiver biases).

The inter-receiver biases due to hardware (receiver/antenna) variability must be compensated for in SQM processing in order to accurately observe actual satellite-induced signal deformations. Each inter-receiver bias is smoothed and the time constant for this filter is commensurate with expected hardware temperature variation.

In Steps 4 and 5, detection metrics from each satellite and receiver are adjusted for inter-receiver bias and corrected for PRN type biases. These are PRN-dependent biases that characterize the shape of the correlation peaks. The PRN type biases are computed offline and coded in the prototype as operational specific parameters (OSPs).

Step 6 computes the median across the *N* satellites in view of the WAAS network for each metric and removes this quantity from each metric. In other words, in this step the algorithm centers each metric on each respective median metric across the SVs. This effectively makes this instantaneous median the reference from which potentially-hazardous deformations are subsequently measured.

Step 7 computes the monitor thresholds for each metric based on *a priori* noise characteristics and satellite elevation angles. It then normalizes the metrics by this threshold. This forms the four final detection tests—the ratio of the detection metric to its corresponding threshold. Accordingly, the monitor "trips" whenever any one of these metrics exceeds unity and declares that signal deformation has occurred on this SV. If the monitor trips, it sets the UDRE for that SV to "Don't Use", an indication to all WAAS users to stop using the satellite.

A high-level block diagram of the SQM processing is shown in Figure 3.

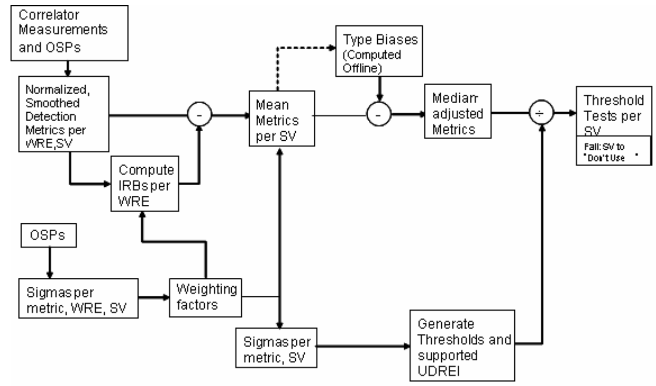

Figure 3 SQM Algorithm and Processing Overview (Note OSPs, or Operational System Parameters are constants defined at initialization.)

SQM PROTOTYPE

Raytheon Company has developed a software prototype for the WAAS SQM algorithm. It is a subset of the software functions in the WAAS Integrity Software Prototype. The prototype also contains other integrity monitors for the Integrity Data Monitoring capability in the WAAS. This prototype is used for SQM algorithm tuning and validation.

NOMINAL TEST SCENARIOS

Four 5-day data sets were recorded by a test facility in Raytheon Company. This test facility receives data from WRSs including live correlator measurements at real time. It performs the C&V functions for testing purposes. These 5-day data sets are used for the complete SQM validation test. For each of these 5-day tests, the SQM prototype was "cold started" (i.e., no warm up time was assumed.) Various SQM parameters were generated as the algorithms were performed. These parameters are recorded for post-analysis. Examples of these parameters are Median-Adjusted Detection Metric over Threshold Ratio (i.e. the detection tests), Supported UDREI, etc. There is no signal deformation simulated in theses test cases.

NOMINAL TEST RESULTS

As examples, several parameters for two GPS satellites (PRN 1 and 23) and one GEO satellite (PRN 135) for 10/01/2007 are shown here.

A detection test for a satellite, $|_{m,adj}D|/\,_{m}T$, is computed by dividing the absolute value of the Median Adjusted Detection metric, $_{m,adj}D$, by the Detection Threshold, $_{m}T$. The subscript m is the metric number (from 1 to 4). Throughout the four nominal tests, the maximum Median-Adjusted Detection Metric over Threshold Ratio for all satellites is less than 1. In other words, there were no false alarms.

The Median-Adjusted Detection Metric (${}_{m,adj}D$) for PRNs 1, 23, and 135 (a GEO satellite) are shown in Figures 4 through 6. There are 4 curves in each of these figures. Each curve represents one metric. The Detection Thresholds for all 4 metrics for those satellites are shown in Figures 7 through 9. They are driven by elevation angle-dependent *a priori* sigmas across all receivers tracking the satellite.

When a satellite just rises above 5-degree elevation angle, the detection threshold is at its highest. The high threshold bounds the multipath error embedded in the correlator measurements at low elevation angle. When the satellite is at the highest elevation angle relative to most receivers tracking the satellite, the Detection Threshold reaches its floor. Note that the Detection Threshold for a GEO satellite stays at a steady level since the elevation angles of the GEO satellite relative to the receiver antennas remain relatively stable. (The number of receivers tracking PRN 1, PRN 23, and PRN 135, whose correlator measurements pass the pre-screening tests, are shown in Figures 10 through 12.)

Figures 13 through 15 show the Median-Adjusted Detection Metric over Threshold Ratio for GPS satellite PRN 1, PRN 23, and GEO satellite PRN 135 on 10/01/2007, in the middle of one of the 5-day scenarios. The maximum of the 4 detection tests, $\max(|{}_{m,adj}D|/{}_{m}T)$, for each satellite is well below 1. However, the margin of the $\max(|{}_{m,adj}D|/{}_{m}T)$ below 1 varies from satellite to satellite. It is obvious that PRN 1 has more margin than PRN 23. This indicates the presence of larger nominal signal deformations on PRN 23.

The Requested UDREI is the index equivalent to the UDRE forwarded by the upstream monitors in the WAAS processing. Currently, the Requested UDREI floor for GPS satellites is 5 (equivalent to 0.9-meter σ_{UDRE}). For GEO satellites, the Requested UDREI floor is 10 (equivalent to 2.3-meter σ_{UDRE}). In this test, the Requested UDREI is the index equivalent to the UDRE forwarded by the upstream monitors in the system prototype. The Supported UDREI is the UDREI that is supportable by the SQM. It is always desirable for the (SQM) Supported UDREI to be less than or equal to the (system) Requested UDREI. These two parameters are shown in Figures 16 through 18.

During normal rising on 10/01/2007, the Supported UDREI for PRN 1 converges to zero after it is viewed by a number of receivers. This is true for all the GPS satellites in view of WAAS. For GEO satellite, the Supported UDREI is steady at 0 throughout the day since the GEO satellite are viewed by a fixed (and substantial) number of receivers. Note that after a cold start of the prototype in this test, the Supported UDREI converges slower than the Requested UDREI. This is because the metric sigmas for the satellite/receiver pairs are inflated initially, and it takes a period of time to decay. This process slows down the transition of the Supported UDREI toward the floor. In the actual WAAS, this would limit performance somewhat by forcing a slightly higher-than-normal UDREI, However, this condition would only occur during start-up.

At steady state throughout the test, the Supported UDREI for a GPS satellite is almost always less than or equal to the requested UDREI. This is true for 10/01/2007. For the entire day, there are only four brief occurrences (one second each) of the SQM Supported UDREI being greater than Requested UDREI. This confirms that the SQM would have a negligible adverse effect on the performance of WAAS.

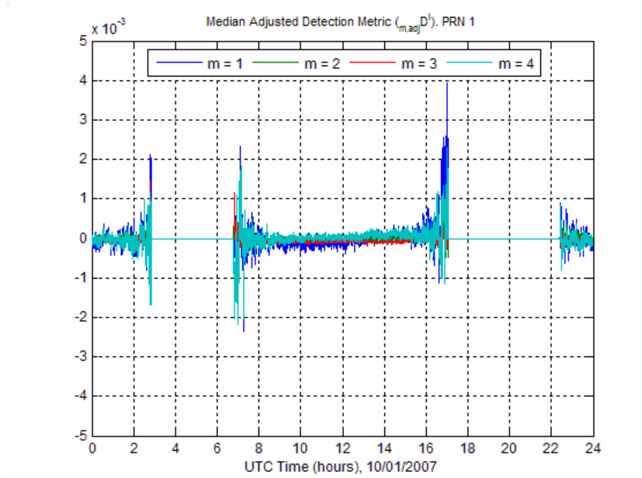

Figure 4 Median-Adjusted Detection Metric, PRN 1

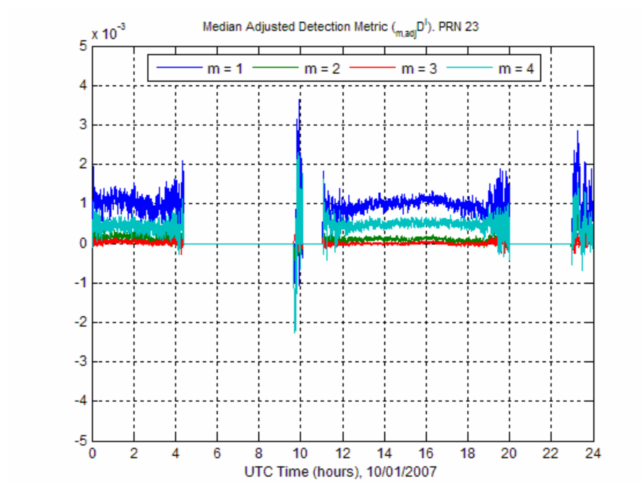

Figure 5 Median-Adjusted Detection Metric, PRN 23

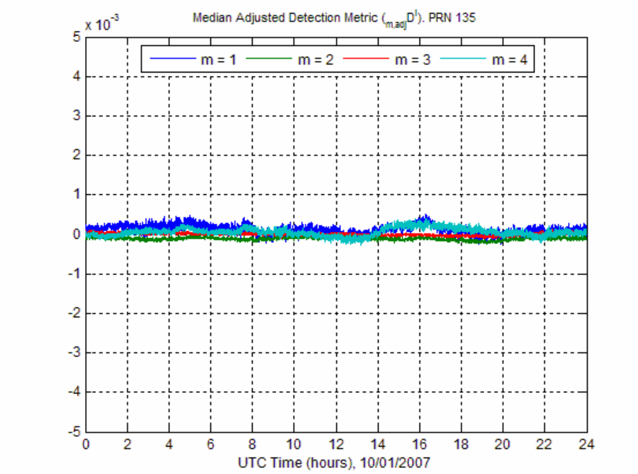

Figure 6 Median-Adjusted Detection Metric, PRN 135

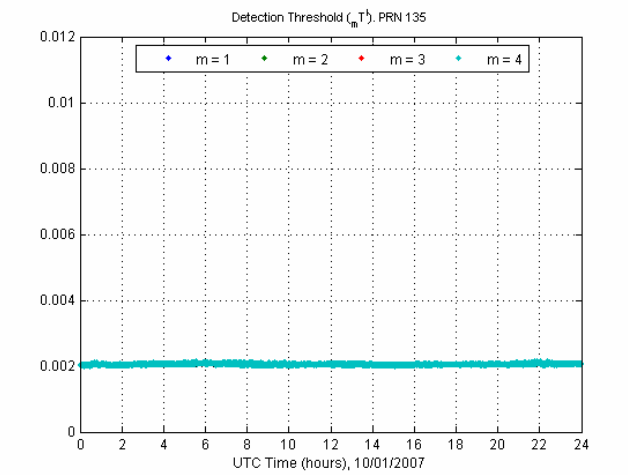

Figure 9 Detection Threshold, PRN 135

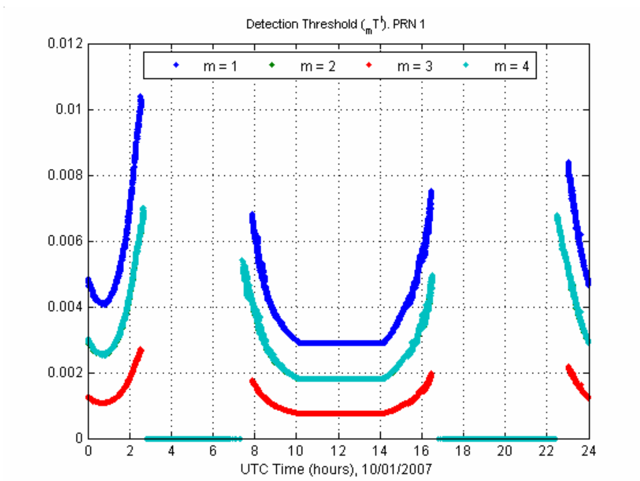

Figure 7 Detection Threshold, PRN 1

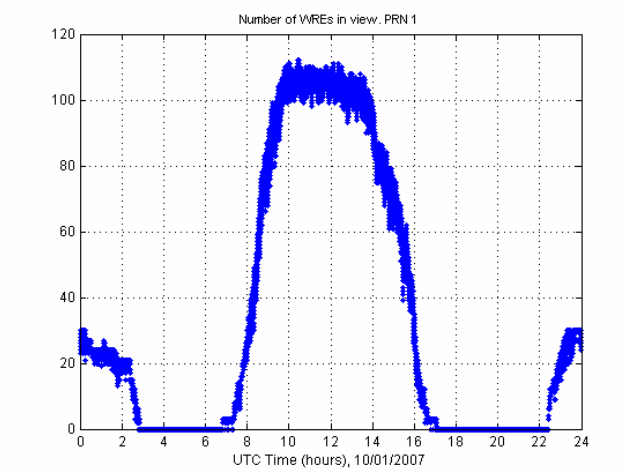

Figure 10 Number of WREs (i.e., WAAS receivers) in View, PRN 1

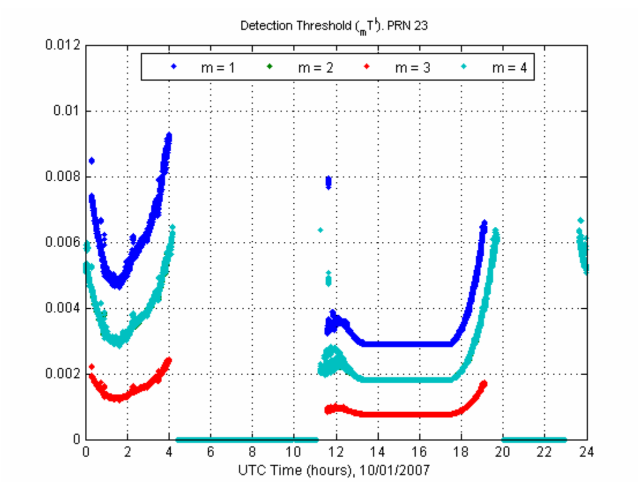

Figure 8 Detection Threshold, PRN 23

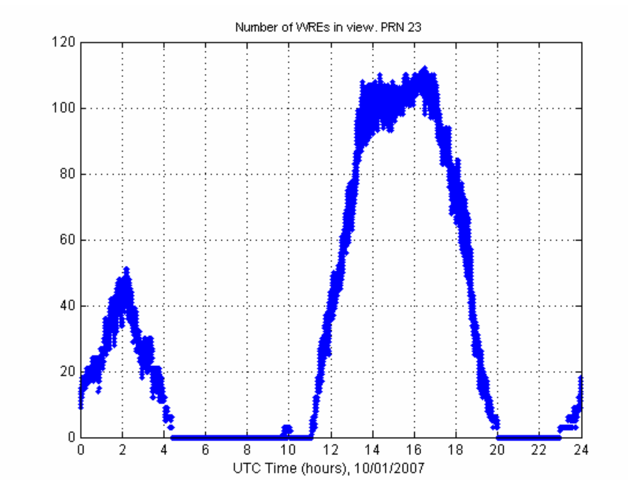

Figure 11 Number of WREs (i.e.,WAAS receivers) in View, PRN 23

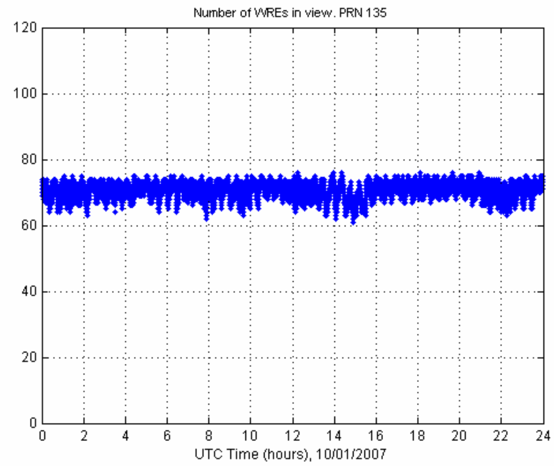

Figure 12 Number of WREs (i.e., WAAS receivers) in View, PRN 135

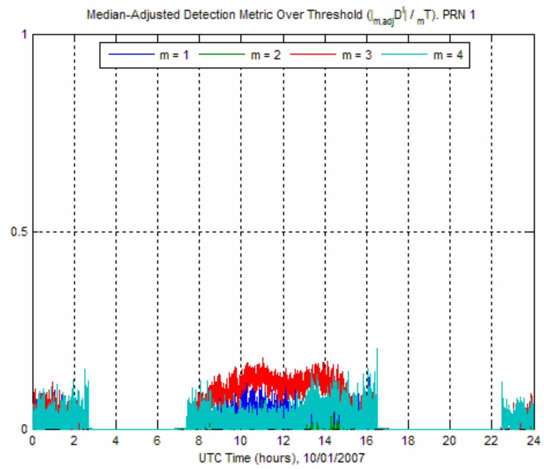

Figure 13 |Median-Adjusted Detection Metric|/ Threshold Ratio, PRN 1

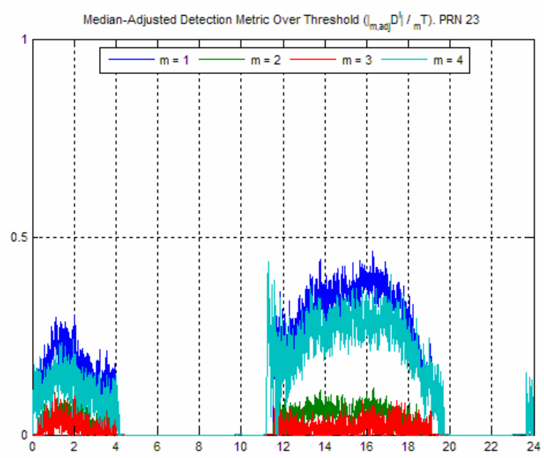

Figure 14 |Median-Adjusted Detection Metric|/ Threshold Ratio, PRN 23

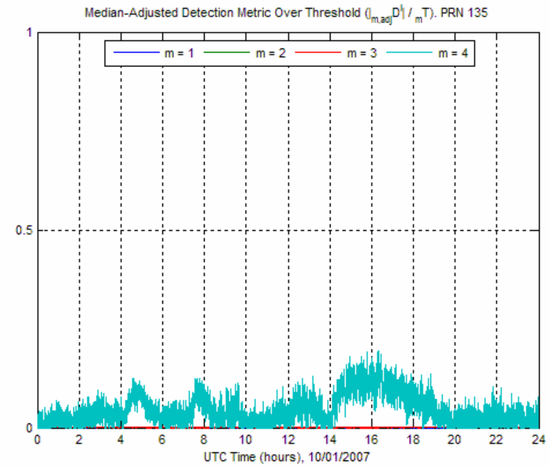

Figure 15 |Median-Adjusted Detection Metric|/ Threshold Ratio, PRN 23

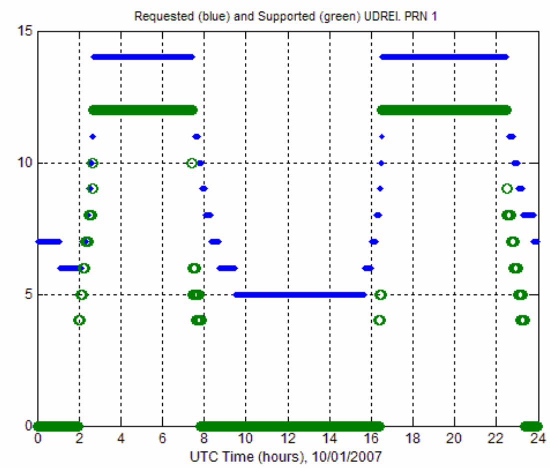

Figure 16 Requested and Supported UDREI, PRN 1

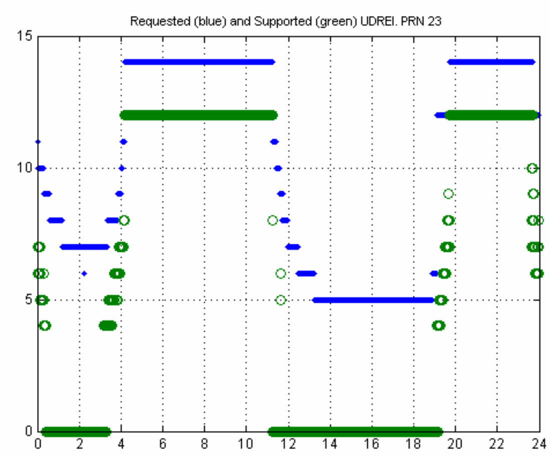

Figure 17 Requested and Supported UDREI, PRN 23

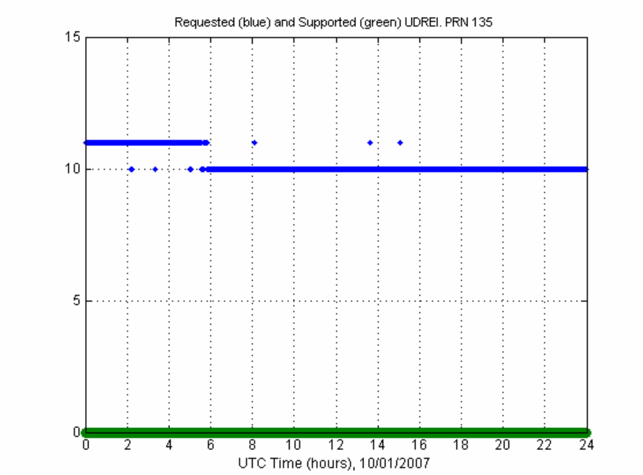

Figure 18 Requested and Supported UDREI, PRN 135

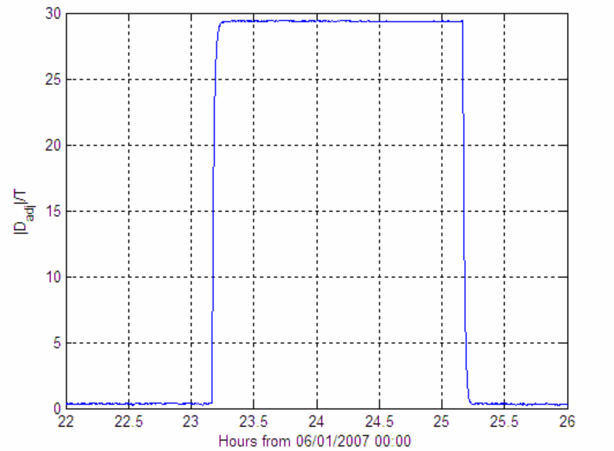

Figure 19 $\max(|_{m,adj}D|/_{m}T)$ **for PRN 23 in Simulated Signal Deformation Test**

SIMULATED SIGNAL DEFORMATION TEST for GPS SATELLITE PRN 23

(1) DEFORMATION SIMULATION

The simulated deformation is of Type C, with fd = 10.23 MHz, σ = 7.8 nepers/second, and Δ = +2% of a chip.

The simulated deformation is applied to the correlator measurements for all the WREs viewing PRN 23 in the following time duration:
First time stamp: 6/1/2007 23:10:00
Last time stamp: 6/2/2007 01:10:00

This scenario covers the case of a nominal type GPS SV that is subject to signal deformation for 2 hours when it has high elevation angle (greater than 45 degrees) relative to most receiver antennas.

(2) TEST RESULTS

The plot for maximum detection test, $\max(|_{m,adj}D|/_{m}T)$, is shown in Figure 19. $\max(|_{m,adj}D|/_{m}T)$ goes above one at 23:10:01, triggering the detection of signal deformation. The recorded SQM Trip status for PRN 23 indicates "Tripped," and the UDRE forwarded to the downstream integrity monitors of the prototype is set to "Don't Use". At 1:12:46, 166 seconds after signal deformation ends, $\max(|_{m,adj}Dj|/_{m}T)$ drops below 1. The 166-second delay is due to the 50-second correlator filtering time constant and the large $\max(|_{m,adj}D|/_{m}T)$ value. Due to hysteresis added by design, the SQM would actually remain in the Tripped state for another 3600 seconds before its state returns to "Not Tripped."

SIMULATED SIGNAL DEFORMATION TEST for GEO SATELLITE PRN 135

(1) DEFORMATION SIMULATION

The simulated deformation is of ICAO threat Type C, with fd = 10.23 MHz, σ= 7.8 nepers/second, and Δ = +2% of a chip.

The deformation is applied to the raw detection metric in the following time duration:
First time stamp: 6/1/2007 14:00:00
Last time stamp: 6/1/2007 15:00:00

This negative path scenario covers the case when a GEO SV is subject to signal deformation for 1 hour.

(2) TEST RESULTS

Figure 20 shows the plot of maximum detection test, $\max(|_{m,adj}D|/_{m}T)$, the parameter used in determining SQM tripped status.

Tripped state is reported at UTC 14:00:03, 06/01/2007, when $\max(|_{m,adj}D|/_{m}T)$ exceeds 1. The UDRE forwarded to the downstream monitors is set to "Don't Use". The 3-second lag time between the beginning of the deformation and the detection is due to the first-order filter (with a time constant of 50 seconds) applied to the measurements.

When signal deformation ends at UTC 15:00:00, 06/01/2007, $\max(|_{m,adj}D|/_{m}T)$ starts dropping off significantly. This quantity drops below 1 at 15:02:18, 138 seconds after the simulated deformation ended. The 138-second lag time is again due to the first-order filter and the magnitude of the deformation. SQM remains in tripped state for 3600 seconds after $\max(|_{m,a}djD\_adj|/_{m}T)$ drops below 1, and the UDRE remains "Don't Use". When one hour has elapsed since the max($|_{m,adj}D|/_{m}T$) drops below 1, the SQM Trip state for the satellite becomes "Not Tripped," and the UDRE forwarded to the downstream monitors becomes valid again.

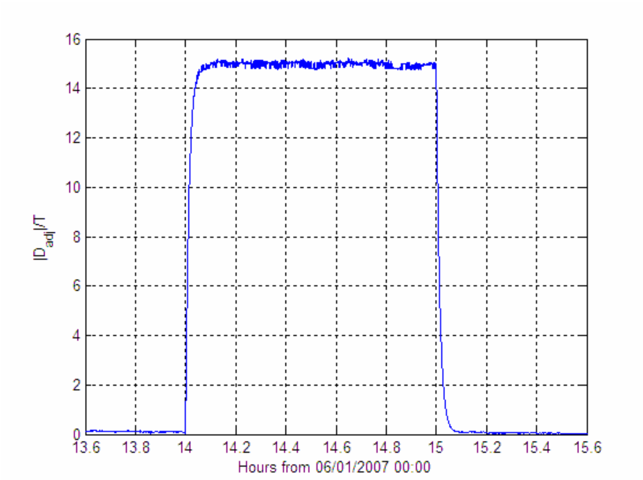

Figure 20 max($|_{m,adj}D|/_{m}T$) **for PRN 135 in Simulated Signal Deformation Test**

CONCLUSION

This paper presents test results for WAAS SQM using software prototype. The results demonstrate that the processing of the SQM does not adversely affect the performance of WAAS. The test results also show that the signal deformation can be detected by the SQM, and when the onset is over, the Trip state is exited properly.

ACKNOWLEGEMENTS

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