The Integrity Monitor Testbed and Multipath Limiting Antenna Test Results

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ABSTRACT

The Integrity Monitor Testbed (IMT) is a prototype of the Local Area Augmentation System (LAAS) Ground Facility (LGF). It is used to evaluate the integrity and continuity requirements on the LGF for Category I precision approach and as a research platform for Category II/III development. With support from the U.S. Federal Aviation Administration (FAA), Stanford University has developed IMT algorithms and has implemented them in real-time software with special emphasis on automated fault diagnosis and recovery. The IMT prototype platform is built from standard off-the-shelf hardware.

Multipath Limiting Antennas (MLA) are expected to be an integral part in future LAAS systems in order to meet continuity and availability. In order to verify that Multipath Limiting Antennas do not pose any integrity threats and meets and/or improve the LGF requirements, Stanford has developed a interface to replay data collected from the FAA Technical Center's LAAS Test Prototype (LTP). The LTP is used to evaluate the LAAS architecture and it is properly sited and equipped with four Multipath Limiting Antennas. However, currently it does not contain a full set of IMT integrity monitors. Applying the IMT algorithms to data collected using the FAA's LGF prototype will provide insight into thresholds that could be expected from an actual LAAS installation.

The paper briefly summarizes the Multipath Limiting Antennas and "virtual receiver" concept and how the LTP-IMT replay data interface is designed together with test results. Integrity test statistics and thresholds are compared using both SU/IMT data (survey grade antenna) and FAA/LTP data (MLA antenna) and examples of failure testing are presented.

1.0 INTRODUCTION

The U.S. Federal Aviation Administration (FAA) is developing the Local Area Augmentation System (LAAS) to support aircraft precision approach. The LAAS architecture (Figure 1) consists of three components:

I. The Space Segment (GPS)
II. The Users (aircraft)
III. The Local Ground Facility (LGF)

This local-area differential GPS ground-based system places the responsibility for detecting and alarming space-segment and ground-segment failures on the LAAS Ground Facility (LGF), which is also responsible for generating and broadcasting carrier-smoothed code differential corrections and approach-path information to user aircraft [1]. The LGF must insure that all ranging sources for which LAAS corrections are broadcast are safe to use. If a failure occurs that threatens user safety, the LGF must detect and alert users (by not broadcasting corrections for the affected ranging source) within three seconds. Category I precision approaches have a six seconds time-to-alarm and the LGF has three of those seconds while the user is allocated the other three seconds.

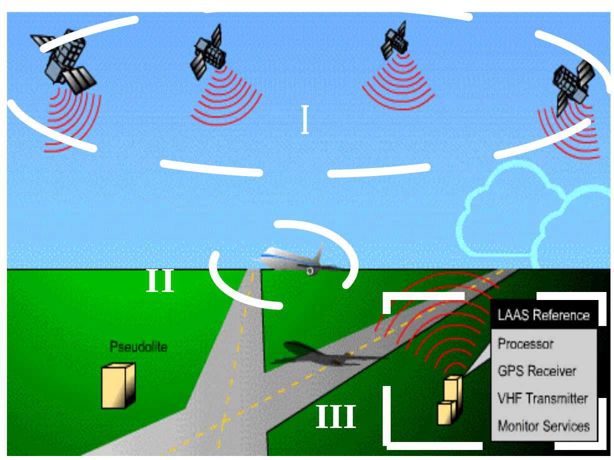

Figure 1 LAAS Architecture

2.0 STANFORD IMT

Stanford University researchers have developed an LGF prototype known as the Integrity Monitor Testbed (IMT) that focuses on the data processing algorithms [4, 5]. The LGF must apply several different types of monitoring algorithms to detect a varied array of possible failures. In order to coordinate the LGF response to detected failures (some of which may trigger more than one monitoring algorithm), complex failure-handling logic must be included in the LGF. The IMT includes a comprehensive set of monitoring algorithms and Executive Monitoring (EXM) logic (figure 3) to isolate failed measurements and reintroduce these measurements after the failure is clearly determined to be over.

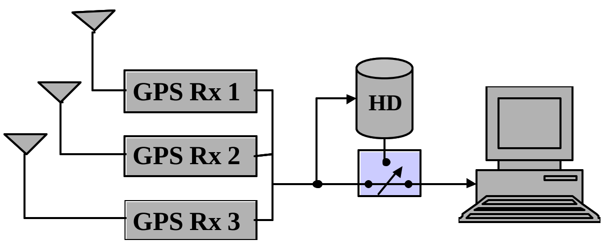

Figure 2 IMT Hardware Components

During the past year the IMT platform (figure 2) was upgraded with state of the art off-the-shelf RF/GPS hardware and a powerful computer platform to allow for CAT II/III research and development [3]. Three NovAtel Pinwheel (survey grade) antennas are in close proximity on the roof at Stanford University and each antenna is connected to a NovAtel OEM4 receiver. The measurements are processed in a single computer where algorithms are developed and tested. The IMT system is a prototype sufficient for development but the environment, or siting, and to a lesser extent, the antennas are not of the design expected to be fielded in an actual LAAS system. Hence thresholds computed based on the IMT collected data are significantly worse and are not representative of an actual LAAS installation.

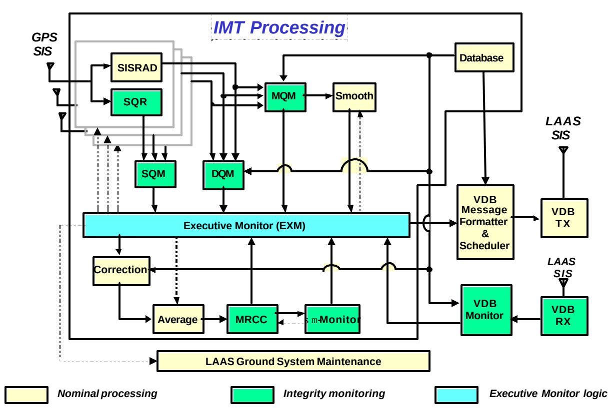

Figure 3 IMT Functional Block Diagram

3.0 FAA TECHNICAL CENTER LTP

The LAAS Test Prototype (LTP) has been developed by the FAA Technical Center to verify the LAAS architecture. The LTP consists of an LGF with VDB functionality (VHF Data Broadcast, provides corrections to aircraft using a VHF data link) and an airborne (LAAS user) system. The LTP has been used for flight-testing, but it does not contain a full set of LAAS integrity monitor algorithms which is the function of the IMT.

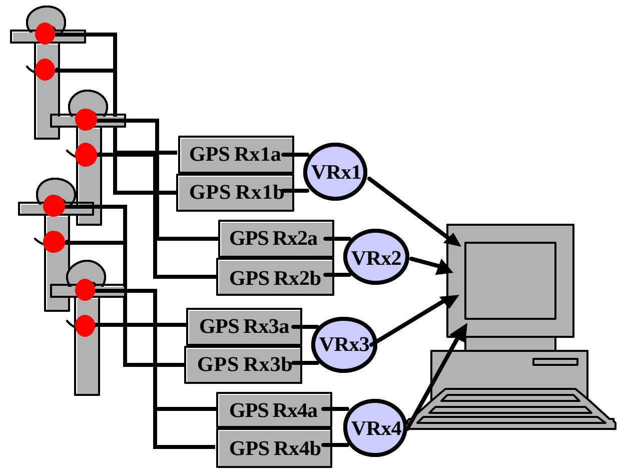

Figure 4 LTP LGF Component

The LTP uses four properly sited reference stations equipped with special Multipath Limiting Antennas. The MLA increases accuracy by reducing multipath and it is the antenna design expected to be part of the future LAAS system. The antenna component is the primary difference between the LTP and IMT systems.

4.0 MULTIPATH LIMITING ANTENNA (MLA)

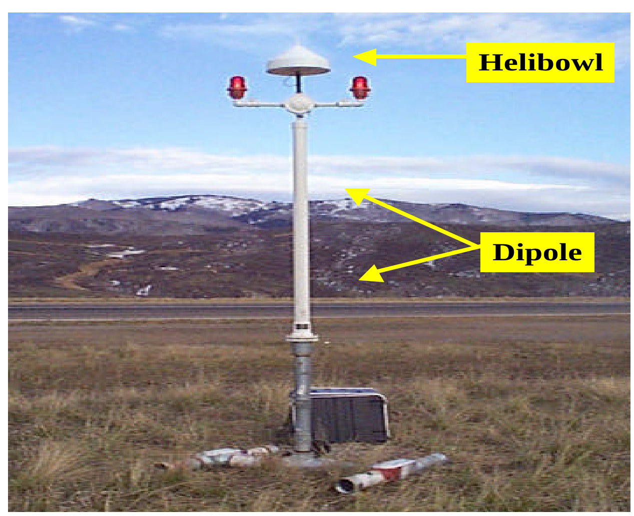

Figure 5 Picture of the MLA
(not at the LTP operating test environment)

Multipath Limiting Antennas consists of two distinct antennas, one helibowl antenna used for high elevation satellites (> 30 degrees) and one dipole antenna array used for low elevation satellites (5-35 degrees). Both the helibowl and the dipole antenna are each connected to a 12 channel GPS receiver (both receivers are using a common clock) and software is used to combine pseudorange and carrier phase measurement of the two antennas/receivers into one "virtual receiver" measurement. The software performs a calibration of the elevation dependent phase center of the two antennas. The MLA and virtual receiver concept provides less noisy measurements for low elevation satellites. When this fact

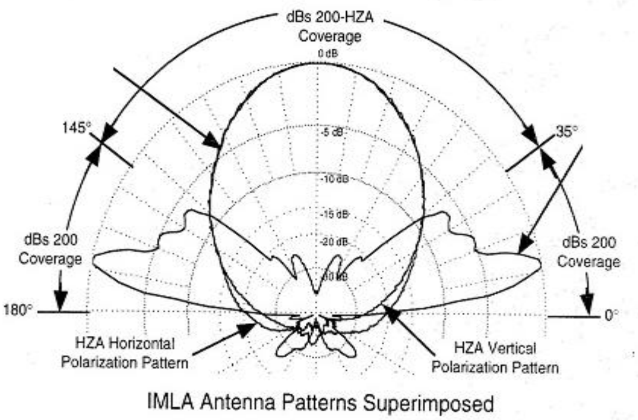

Figure 6 MLA Gain Pattern
(courtesy dBsystems Inc.)

is and combined with a pre-site multipath model, the antenna accuracy performance is very good. In this paper, the MLA and the "virtual receiver" is used as a "black-box" (only the output of the virtual receiver is used) and no attention has been on for example how the phase center is calibrated inside the "virtual receiver" [12].

4.0 LTP-IMT INTERFACE

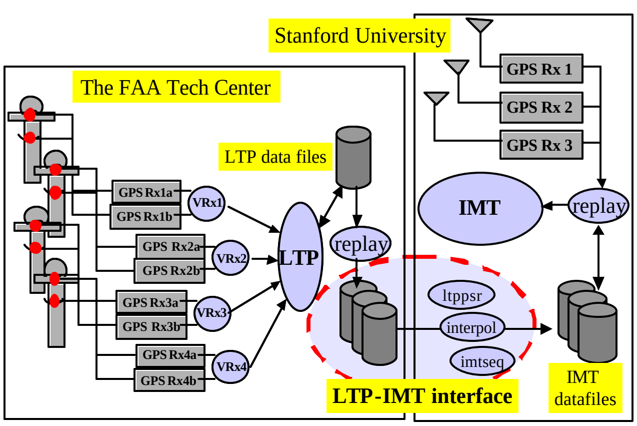

Figure 7 LTP-IMT Interface

A post-processing LTP-IMT interface has been developed in conjunction with the FAA Technical Center to replay recorded virtual receiver data from the LTP system. The LTP-IMT interface consists of three programs that converts and synchronizes any three of the four LTP MLA virtual receiver data files (the IMT currently uses three reference stations, not four) into IMT input data files. The interface makes it possible to collect data with the LTP system and replay the data with the IMT for integrity validation.

6.0 THRESHOLD DERIVATION

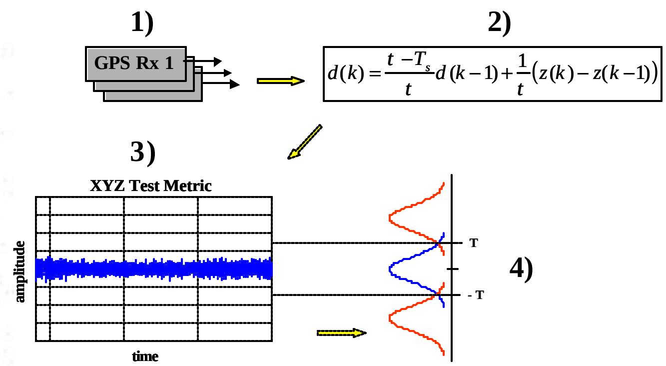

Figure 8 Threshold Derivation Example

The goal is to design monitors that can detect "anomalous" behavior in a satellite or reference receiver. The key is to determine what is "anomalous" behavior of the system that would result in an integrity or safety risk. More important is that reliance is not accomplished only on theoretical bounds since data/test statistics will be highly system dependent (antenna siting, gain pattern, and operating environment). Thresholds for the monitors must be derived and verified using real data. In most cases the "tails" of the distribution must be overbounded (typically through sigma inflation).

Figure 8 illustrates an example of how thresholds are established.

1) GPS receivers provide measurement observables
2) The observables are combined mathematically to provide a meaningful test metric for a possible fault case
3) The metric is evaluated over time, often as function of elevation angle, calculating the standard deviation of the noise statistics
4) Thresholds are established for the metrics based on the collected data and the expected fault cases under a Gaussian noise assumption

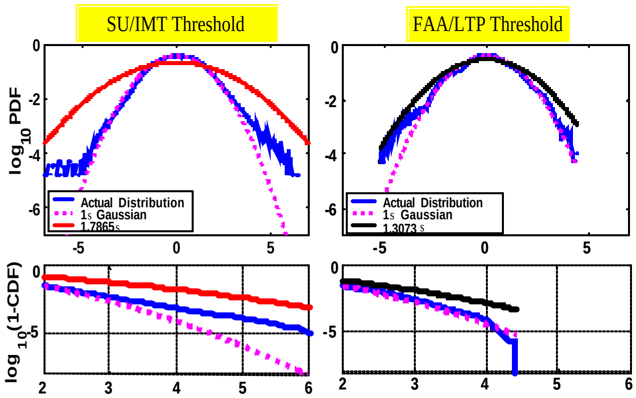

Figure 9 Example of “Ramp” Monitor Sigma Inflation (SU/IMT data on left and FAA/LTP data on right)

Figure 9 illustrates an example of the carrier-phase “Ramp” monitor threshold for data collected using both systems. For this particular example the sigma inflation factor for the FAA/LTP is smaller (1.31) then the SU/IMT sigma inflation factor (1.79) but this does not hold for all test statistics (not a general result).

7.0 INTEGRITY MONITOR TEST STATISTICS

Data has been collected at each site (Stanford University/IMT and FAA Tech Center/LTP) using different antennas and siting. Both data sets are six hours long and the SU/IMT dataset was collected 6-Dec-2001 and the FAA/LTP dataset was collected 6-May-2002. Identical IMT processing algorithms have been applied to the data sets to compare integrity monitor test statistics. For comparison, two different PRNs with similar elevation angle profiles in both datasets have been identified. A subset of the different IMT integrity monitor outputs are examined side-by-side in the following figures.

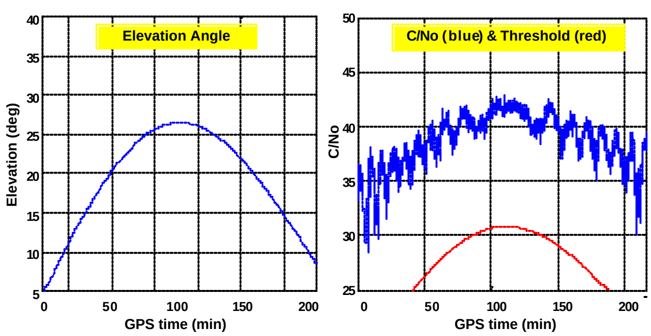

Figure 10 SU/IMT Elevation Angle.Signal Power Test

A fairly low-elevation profile was chosen for comparison since the MLA is designed to perform much better with low-elevation satellites compared to “standard” antennas. Figure 10 shows the PRN 22 elevation angle profile for the SU/IMT dataset and figure 11 shows the PRN 5 elevation angle profile for the LTP/MLA dataset. Tests on PRN 22 and PRN 5 from the two datasets will be used for comparison in figure 12-14.

The signal power test designed to assure that the received signal power is within SPS specifications. Figure 10 and 11 clearly shows the different gain pattern of a standard survey grade antenna and the MLA. The C/N_o clearly shows the MLA’s higher signal power at low elevation and allows for increased thresholds. The thresholds derived using SU/IMT data is plotted in red and thresholds derived using the FAA/LTP data is plotted in black.

Measurement Quality Monitors (MQM) carefully examines the pseudorange and carrier phase measurement from the reference receivers. The carrier smoothed code

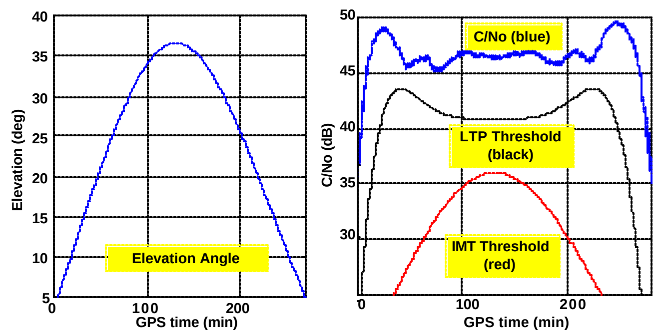

Figure 11 FAA/LTP Elevation Angle/ Signal Power Test

(CSC) innovation test (figure 12) is designed to detect impulse and step errors on raw pseudorange measurements. The LTP/MLA Innovation test appears to be smoother, but a positive/negative bias is showing. Both the pseudorange and the carrier phase measurement is used in this test and the bias could be a result of geometry difference/calibration of the phase-center of the code & carrier.

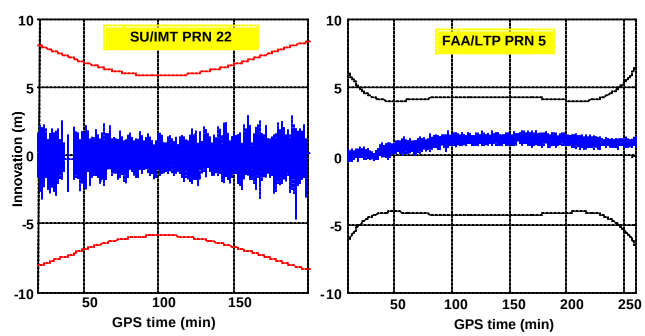

Figure 12 MQM CSC Innovation Test

The step test (figure 13) is designed to detect rapid changes in carrier-phase measurement and appears cleaner for low elevation satellites.

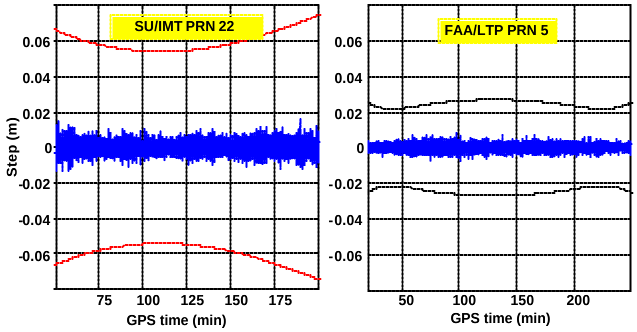

Figure 13 MQM Step Test

The Multiple Receiver Consistency Check (MRCC) expresses the consistency of the corrections produced for each satellite across all reference receivers. The B-value test is a consistency test of the candidate pseudorange corrections generated for each satellite and each receiver.

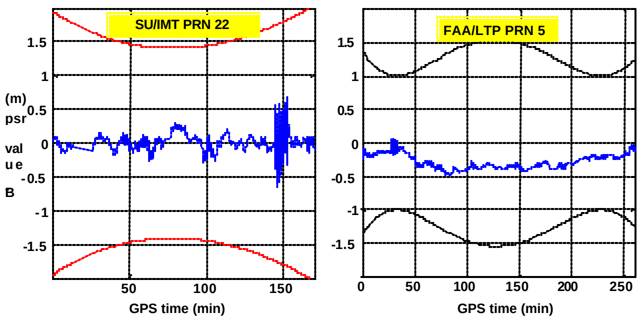

Figure 14 MRCC B-Value Test PRN22/PRN6

B-values are critical component as they are broadcast to users (they are needed for users to compute "H1" protection levels) and to isolate any receivers or receiver channels that create anomalously large errors in the corrections.

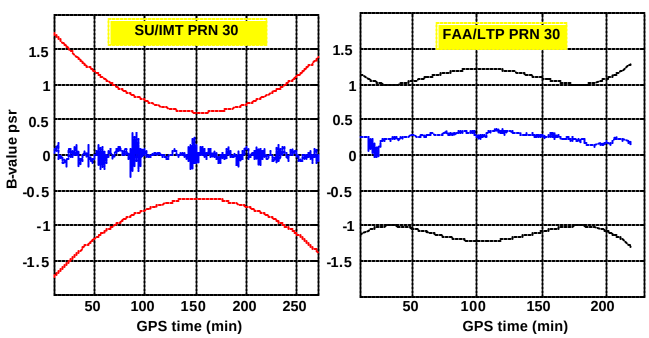

Figure 15 MRCC B-Value Test PRN30/PRN30

The B-values are a very good quality measurement of a system. The FAA/LTP B-values appear smoother then the SU/IMT (which is expected) but with a positive/negative bias. Ongoing work is being performed to track down the cause of the bias. The bias is geometrically dependent and it is suspected that the elevation angle dependent phase calibration of the code and carrier-phase plays a role. The FAA Technical Center processing efforts do reveal see this B-value bias in the processed LTP data, nor do the IMT processed result show this bias using SU/IMT data. Hence there could be a observation difference between the LTP and IMT in how and what measurements are processed.

8.0 FAILURE TESTING

It is possible to inject a failure in the collected data and reprocessed the files to emulate an actual fault. This "software" injection of faults into collected data allows for an easy way of simulating different types failure and

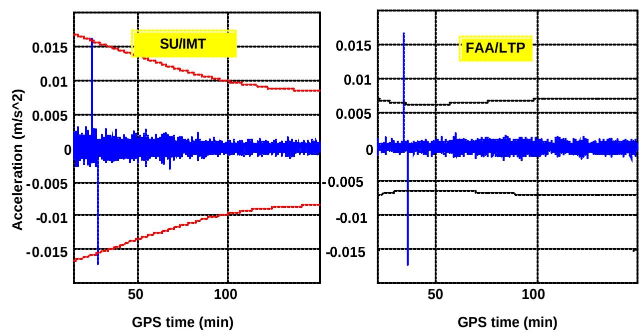

Figure 16 MQM Acceleration Monitor Detection

verifying the expected responses of the monitors. For this example, an error of equal magnitude was injected into both data sets. The thresholds are set at predefined levels derived using nominal data and the failure is injected into a low elevation angle satellite (approximately 15 degree elevation). The injected error is an ionosphere divergence ramp of 0.05 m/s for approximately 3 minutes. This error simulates an ionosphere front approaching over an LGF reference antenna and impacts the pseudorange and carrier phase measurements with opposite sign.

The carrier-phase acceleration test (figure 16) clearly detects the 0.05 m/s ramp using the MLA thresholds while the IMT thresholds are much looser.

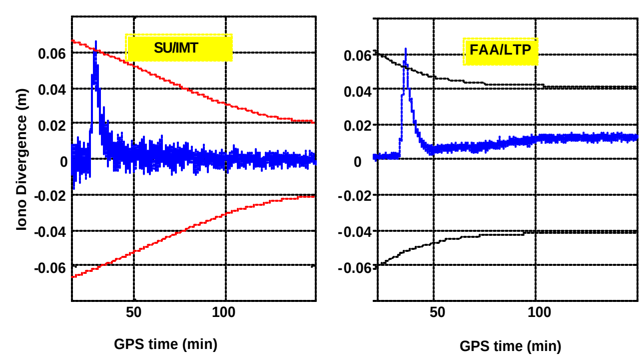

Figure 17 Ionosphere divergence monitor detection

The Code-Carrier Divergence test (figure 17) narrowly detects the 0.05 m/s ramp (with both the IMT and MLA thresholds). The ionosphere divergence test is designed to detect slower ionosphere divergence over time, and does not respond as quickly as the carrier-phase acceleration monitor.

9.0 CONCLUSIONS AND FUTURE WORK

This paper has investigated the integrity performance of the Multipath Limiting Antenna using the Stanford Integrity Monitor Testbed (IMT). Two datasets have been processed and compared using the same IMT algorithms, one dataset collected with the Stanford University IMT system equipped with survey grade antennas and one dataset collected with the FAA LAAS Test Prototype (LTP) equipped with special Multipath Limiting Antennas (MLA). Replaying MLA data with the IMT integrity monitors will provide insight into performance that can be expected from a true LAAS installation.

The results meets theoretical expectations; anomalies, particularly in low elevation satellites, can be detected more reliably by using an MLA. An MLA allows for reduced thresholds for most integrity monitors. Thus, by limiting ground multipath, the MLA enhances nominal accuracy for low elevation satellites (increasing availability) as well as integrity via improved continuity.

The level of scrutiny applied by the Stanford IMT processing algorithms provides additional insight into the operation of the MLA. An interesting observation is that there appears to be a slight bias in some of the outputs of the virtual receiver. This could be due to the elevation dependent calibration of the code and carrier phase center or some geometric difference between how the measurements are processed in the IMT and the LTP. The FAA Technical Center results do not see this B-value bias in the LTP data, despite applying the same algorithms for the calculation. Nor does the IMT processing see this bias using SU/IMT data. Work is ongoing to determine the source of the bias.

ACKNOWLEDGEMENTS

The authors would like to give thanks to people in the Stanford GPS research group for their advice and interest. Special thanks to John Warburton and his group at the FAA Technical Center for help in providing the FAA/LTP data. Funding support from the FAA Satellite Navigation LAAS Program Office (AND-710) is appreciated. The opinions discussed here are those of the authors and do not necessarily represent those of the FAA and other affiliated agencies.

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