Federal Aviation
Administration

Local Area Augmentation System

Performance Analysis and Activities Report

Reporting Period: January 1 – March 31, 2014

Executive Summary

The Local Area Augmentation System (LAAS) Test and Evaluation (T&E) sub-team, under the direction of the Navigation Branch in the Engineering Development Services Division under the Advanced Concepts and Technology Development Office at the FAA William J Hughes Technical Center (WJHTC) provides this LAAS Performance Analysis/Activities Report (LPAR). This quarterly report utilizes the FAA's LAAS Test Prototype (LTP) and our Ground Based Performance Monitors (GBPM) for performance characteristics. Major LAAS related research and testing activities for the reporting period are included in summary form to provide a brief snapshot of LAAS WJHTC program directives, and related technical progress.

The LTP and the GBPM are the FAA's primary LAAS Research and Development (R&D) tools and are used to test and characterize performance of a typical LAAS installation in an operational airport environment. The LTP is a government-owned suite of equipment located on the Air Operations Area (AOA) of the FAA WJHTC at the Atlantic City International Airport (ACY). The LTP is continually operational and is used for flight-testing, in addition to data collection and analysis summarized in this report. As an FAA test system, the LTP is utilized in limited modified configurations for various test and evaluation activities. This system is capable of excluding any single non-standard reference station configuration from the corrections broadcast. The performance reporting of the system is represented only from LAAS standard operating configurations. Special configurations and maintenance details are included in a separate section within this report.

There are currently six GBPM's in use. They are located in Newark New Jersey, Houston Texas, Moses Lake Washington, Rio de Janeiro Brazil, and two in Atlantic City New Jersey. The GBPM is used to monitor integrity, accuracy, availability, and continuity of the LTP and Honeywell's SLS-4000 systems. It is continuously collecting data in 24-hour intervals at a rate of five hertz from its corresponding ground station and GPS receiver. From here, one can process the data for further performance monitoring, replay the data to reconstruct output files, or refer to the live monitor web page located at http://laas.tc.faa.gov, for one-minute interval updates.

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1. Introduction

The FAA is involved in the validation of LAAS (internationally known as Ground Based Augmentation System or GBAS) performance requirements and architecture, and maintains a LAAS Test Prototype (LTP) to evaluate new concepts and resulting performance benefits. The GBAS T&E team utilizes a number of tools and methods to analyze system performance. These tools include a raw data analysis technique known as Code Minus Carrier (CMC), to closely observe errors down to a single Satellite Vehicle (SV) on a single Reference Receiver (RR). Additional system level techniques are mature enough to display key system performance parameters in real time. The GBAS T&E team has adapted the GBAS software to actively gather these key parameters for the data plots to be presented in this report.

Objectives of this report are:

a) To briefly introduce GBAS concepts and benefits.
b) To provide an LTP (LAAS Test Prototype) system level overview to aid in comprehension for persons unfamiliar with the material.
c) To present Global Positioning System (GPS) constellation, and SV availability at ACY, and any unfavorable bearing on overall system performance.
d) To document GBAS-related R&D, testing, and maintenance activities.
e) To present the GBAS system's ability to augment GPS by characterizing key performance parameters.
f) To provide a key performance summary and complete performance plots.

Figure 1 is an aerial view of the FAA's LTP taken during a GBAS flight test. This valuable FAA R&D tool provides a valid representation of an actual GBAS installation in an operational airport environment. The major system sites are identified.

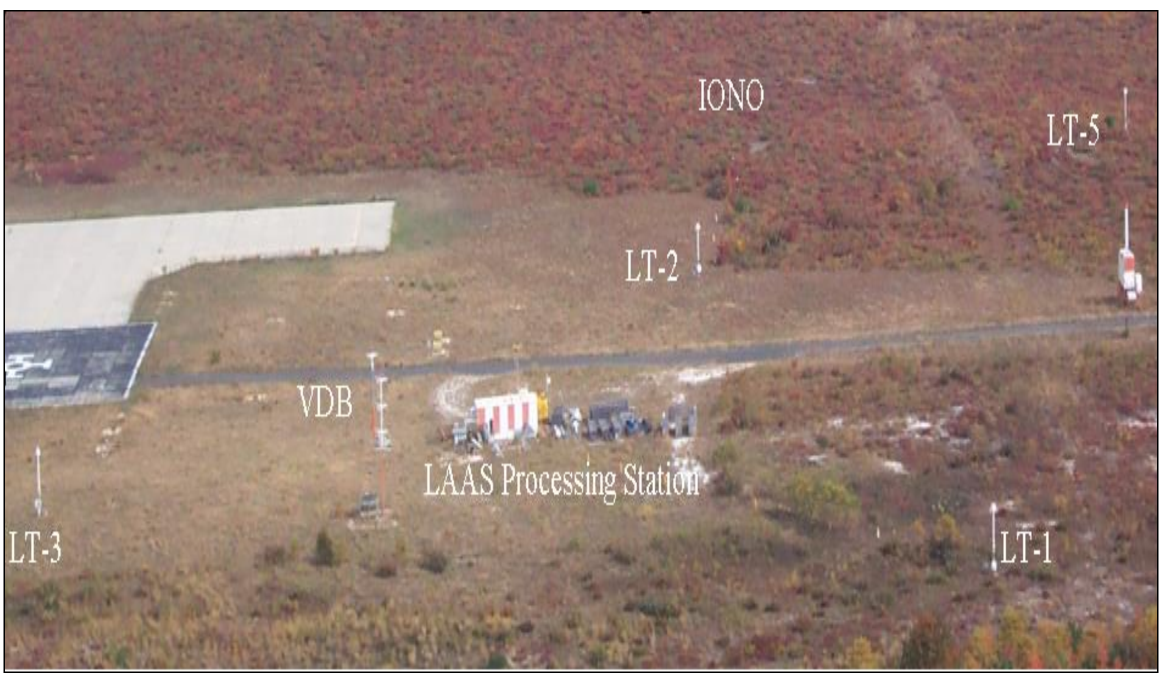


Figure 1: Aerial of LTP at ACY

2. GBAS Overview

This section is provided for persons unfamiliar with GBAS concepts and components. This brief overview is intended solely as an introduction.

A GBAS is a precision area navigation system with its primary function being a precision landing system. The GBAS provides this capability by augmenting the Global Positioning System (GPS) with real-time broadcast differential corrections.

2.1 GBAS Operational Overview

A Local Area Augmentation System (LAAS) ground facility (LGF) includes four GPS Reference Receivers (RR) / RR antenna (RRA) pairs, and a Very High Frequency (VHF) Data Broadcast (VDB) Transmitter Unit (VTU) feeding an Elliptically Polarized VDB antenna. These sets of equipment are installed on the airport property where a GBAS is intended to provide service. The LGF receives, decodes, and monitors GPS satellite pseudorange information and produces pseudorange correction (PRC) messages. To compute corrections, the ground facility compares each pseudorange measurement to the range measurement based on the survey location of the given RRA.

Once the corrections are computed, integrity checks are performed on the generated correction messages to ensure that the messages will not produce misleading information for the users. This correction message, along with required integrity parameters and approach path information, is then sent to the airborne GBAS user(s) using the VDB from the ground-based transmitter. The integrity checks and broadcast parameters are based on the LGF Specification, FAA-E-3017, and RTCA DO-253D (Airborne LAAS Minimum Operational Performance Standards or MOPS).

Airborne GBAS users receive the broadcast data and use it to compute standardized integrity results. When tuning the GBAS, the user also receives the design path for navigation with integrity assured. The GBAS receiver applies corrections to GPS measurements and then computes ILS-like deviations relative to the uplinked path providing guidance to the pilot. Airborne integrity checks compare protection levels, computed via the integrity parameters, to alert levels. Protection levels were determined based on allowable error budgets. The horizontal alert limit is 40m and the vertical is 10m at the Cat 1 decision height of 200m. If at any time the protection levels exceed the alert limits, calculated deviations are flagged and the approach becomes unavailable. With the current constellation horizontal protection levels are typically 2.3m and vertical protection levels are typically < 5m with resulting availability of 100%.

One key benefit of the GBAS, in contrast to traditional terrestrial navigation and landing systems (e.g., ILS, MLS, TLS), is that a single GBAS system can provide precision guidance to multiple runway ends, and users, simultaneously. Only the local RF environment limits this multiple runway capability. Where RF blockages exist, Auxiliary VDB Units (AVU) and antennas can be added to provide service to the additional runways.

Figure 2 is provided as an illustration of GBAS operation with major subsystems, ranging sources, and aircraft user(s) represented.

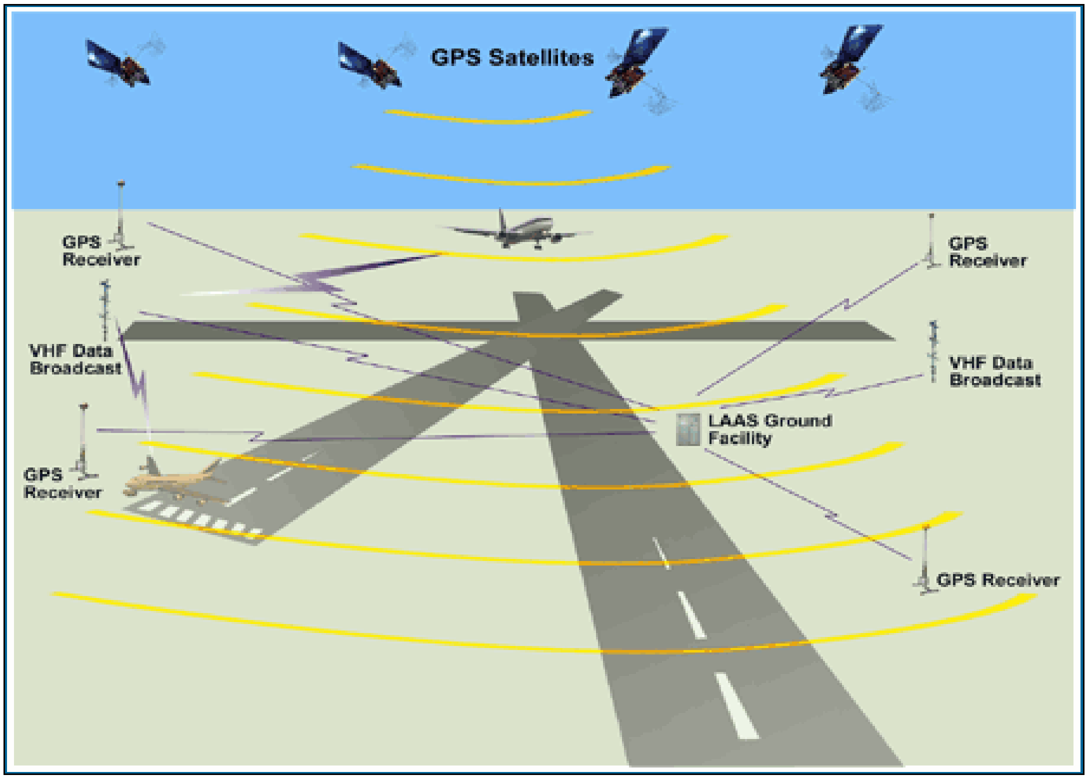


Figure 2: GBAS Simplified Architecture Diagram

3. GPS Constellation from ACY

Satellite Vehicle (SV) availability and constellation geometry have an impact on overall GBAS system performance. This section provides a snapshot of the expected constellation for the reporting period. GPS Notice Advisory to Navstar Users (NANUs) are known SV outage events that are excluded from these plots, but are included at the end of this section.

3.1 SV Availability Plot

ACY has a fairly robust available constellation expected throughout most of the sidereal day with limited periods where the observable SVs are forecasted to drop below eight.

Figure 3 is an SV availability graph representative of the reporting period. The graph does not account for any NANUs following the generation of the plot. WAAS geo-stationary satellites are not included in this plot as these ranging sources are not used by the non-fed system.

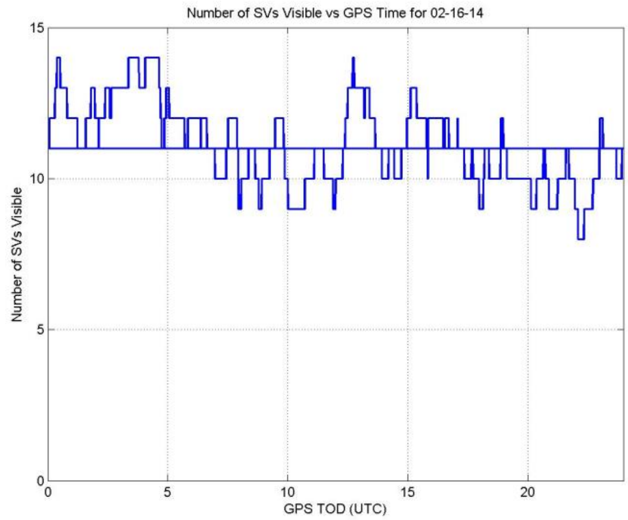


Figure 3: SV Availability

3.2 SV Elevation Plot

SV positions and the resulting constellation geometry have a bearing on the overall GBAS performance. Unfavorable GPS constellations are rare occurrences, but a prediction model of ranging source geometry, and diligent record keeping is important for long-term data collection and performance evaluation efforts. The geometry effects are generally minor, and are further minimized with the advent of the BAE systems ARL-1900 Global Navigation Satellite System (GNSS) Multipath Limiting Antenna (MLA). Section 4.2.1 outlines the capabilities of this relatively new Differential Global Positioning System (DGPS) quality equipment in greater detail.

Figure 4 is an SV elevation graph representative of the reporting period. The graph does not account for any NANUs following the generation of the plot. The graphic also does not include the WAAS SV(s).

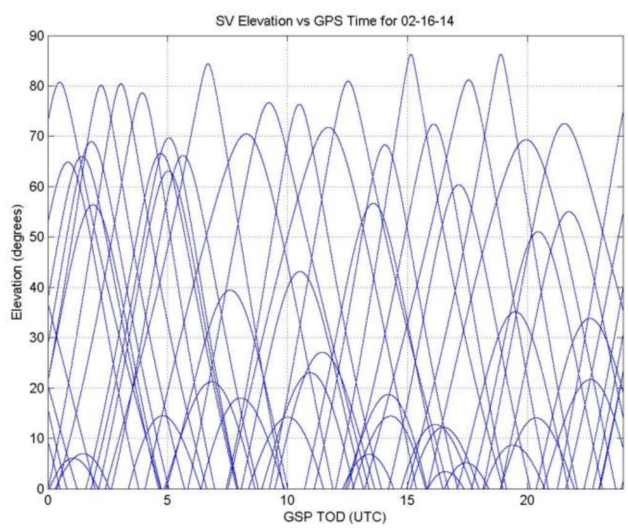


Figure 4: SV Elevations

3.3 Notice Advisory to Navstar Users (NANUs)

The GPS constellation is designed to provide adequate coverage for the continental United States for the majority of the sidereal day. A NANU is a forecasted or reported event of GPS SV outages, and could cause concern if the SV outage(s) affects the minimum required SV availability, or creates an insufficient geometry to raise the protection levels above the alert limits. See **Table 1** below for a list of NANU types.

NANUs that caused an interruption in service where Alert Limits are exceeded will be highlighted within the NANU summary (see **Table 2**). Although such an interruption is unlikely, the GBAS T&E team closely tracks the NANUs in the event that post-data processing reveals a rise in key performance parameters. Any highlighted NANUs will include additional data plots, and accompanying narrative in the “Performance Summary” section.

NANU Acronym	NANU Type	Description
FCSTDV	Forecast Delta-V	Satellite Vehicle is moved during this maintenance
FCSTMX	Forecast Maintenance	Scheduled outage time for Ion Pump Ops / software testing
FCSTEXTD	Forecast Extension	Extends a referenced “Until Further Notice” NANU
FCSTSUMM	Forecast Summary	Gives exact time of a referenced NANU
FCSTCANC	Forecast Cancellation	Cancels a referenced NANU
FCSTRESCD	Forecast Rescheduled	Reschedules a referenced NANU
FCSTUUFN	Forecast Unusable Until Further Notice	Scheduled outage of indefinite duration
UNUSUFN	Unusable Until Further Notice	Unusable until further notice
UNUSABLE	Unusable	Closes an UNUSUFN NANU with exact outage times
UNUNOREF	Unusable with No Reference NANU	Resolved before UNUSUFN could be issued
USABINIT	Initially Usable	Set healthy for the first time
LEAPSEC	Leap Second	Impending leap second
GENERAL	General Message	General GPS information
LAUNCH	Launch	Recent GPS Launch
DECOM	Decommission	Removed From current constellation

Table 1: NANU Types and Definitions

NANU	TYPE	PRN	Start Date	Start Time (UTC)	End Date	End Time (UTC)
2014001	FCSTDV	19	01/09/2014	20:15	01/10/2014	08:15
2014002	FCSTSUMM	19	01/09/2014	20:58	01/10/2014	02:50
2014003	FCSTDV	22	01/16/2014	17:00	01/17/2014	05:00
2014004	FCSTSUMM	22	01/16/2014	17:41	01/16/2014	22:45
2014005	FCSTDV	16	02/04/2014	15:30	02/05/2014	03:30
2014006	FCSTMX	01	02/03/2014	16:00	02/04/2014	04:00
2014007	FCSTCANC	16	02/04/2014	15:30	N/A	N/A
2014008	FCSTDV	21	02/07/2014	12:45	02/08/2014	00:45
2014009	FCSTSUMM	01	02/03/2014	16:16	02/03/2014	21:32
2014010	FCSTDV	16	02/11/2014	15:15	02/12/2014	03:15
2014011	FCSTSUMM	21	02/07/2014	13:02	02/07/2014	18:40
2014012	FCSTDV	02	02/14/2014	09:20	02/14/2014	21:20
2014013	FCSTRESCD	16	02/18/2014	15:15	02/19/2014	03:15
2014014	FCSTSUMM	02	02/14/2014	09:41	02/14/2014	15:07
2014015	FCSTUUFN	06	02/21/2014	14:30	N/A	N/A
2014016	FCSTSUMM	16	02/18/2014	15:56	02/18/2014	22:13
2014017	FCSTDV	08	02/27/2014	00:30	02/27/2014	12:30
2014018	LAUNCH	30	02/21/2014	01:59	N/A	N/A
2014019	DECOM	06	02/21/2014	15:01	N/A	N/A
2014020	FCSTSUMM	08	02/27/2014	01:01	02/27/2014	06:31
2014021	FCSTDV	05	03/05/2014	00:00	03/05/2014	12:00
2014022	FCSTDV	17	03/07/2014	03:22	03/07/2014	15:22
2014023	FCSTSUMM	05	03/05/2014	00:14	03/05/2014	07:58
2014024	FCSTSUMM	17	03/07/2014	03:55	03/07/2014	09:46
2014025	UNUSUFN	09	03/07/2014	15:08	N/A	N/A
2014026	UNUSABLE	09	03/07/2014	15:08	03/07/2014	15:48
2014027	UNUSUFN	01	03/14/2014	05:02	N/A	N/A
2014028	UNUSABLE	01	03/14/2014	05:02	03/14/2014	06:48
2014029	FCSTDV	24	03/20/2014	03:00	03/20/2014	15:00
2014030	FCSTSUMM	24	03/20/2014	03:14	03/20/2014	08:54

Table 2: NANU Summary

4. LTP Configuration and Performance Monitoring

This section provides a description of the LTP system, monitoring, and testing configurations in terms of hardware and software for the reporting period. Because the LTP is the FAA's primary R&D tool for GBAS these sections could vary somewhat between reporting periods. The majority of these changes will likely first emerge in the final sections of this report.

4.1 Processing Station

The LTP Processing Station is a complex collection of hardware and related interfaces driven by a custom software program. The processing station hardware and software operations are described in this section.

4.1.1 Processing Station Hardware

The processing station consists of an industrialized Central Processing Unit (CPU) configured with QNX (a UNIX-type real time OS). It then collects raw reference station GPS data messages while processing the data live. It also collects debugging files and special ASCII files utilized to generate the plots found in this report. These collected files are used for component and system level performance and simulation post processing.

The CPU is also configured with a serial card that communicates in real time with the four reference stations through a Lantronix UDS2100 serial-to-Ethernet converter. The reference stations continuously output raw GPS messages to the CPU at a frequency of 2 Hz. Data to and from the reference station fiber lines is run through media converters (fiber to/from copper). The CPU then generates the GBAS corrections and integrity information and outputs them to the VDB.

The VDB Transmitter Unit (VTU) is capable of output of 80 watts and employs a TDMA output structure that allows for the addition of auxiliary VDBs (up to three additional) on the same frequency for coverage to terrestrially or structure blocked areas. The LTP's VTU is tuned to 112.125 MHz and its output is run through a band pass and then through two cascaded tuned can filters. The filtered output is then fed to an elliptically polarized three bay VHF antenna capable of reliably broadcasting correction data the required 23 nautical miles (see Protection Level Maps at http://laas.tc.faa.gov for graphical representation).

Surge and back-up power protection is present on all active processing station components.

4.1.2 Processing Station Software

Ohio University (OU) originally developed the GBAS code through an FAA research grant. Once the code reached a minimum of maturity, OU tested and then furnished the code to the FAA (circa 1996). It was developed using the C programming language under the QNX operating system. QNX was chosen because of its high reliability and real-time processing capability. This LTP code has been maintained by the GBAS T&E team since that time and has undergone numerous updates to incorporate evolving requirements, such as the inclusion of Cat III.

The software stores the precise survey data of the four GBAS reference station antennas (all RRA segments). Raw GPS data (i.e., range and ephemeris info) is received via four GPS receivers. The program cycles through the serial buffers and checks for messages, if one is found, it gets passed to a decoding function. From there, it is parsed out to functions according to message type and the information from the messages is extracted into local LTP variables. Once the system has received sufficient messages, the satellite positions are calculated in relation to the individual reference receivers. Type 1, 2, 4, 11 messages containing differential corrections, integrity values, GS information, and approach path data are then encoded and sent to the VDB via a RS-232 connection. Each of the four message types are encoded separately and sent according to DO-246D standards.

4.2 Reference Stations

There are four reference stations included in the FAA's LTP as required in the GBAS specification. The LTP's reference stations are identified as LAAS Test (LT) sites; there were originally five LT sites (LT1 through LT5), excluding LT4. LT4 was originally used for the L1/L2 site (See **Figure 1**).

Each reference station consists of two major component systems. The first is a high quality, GNSS antenna (ARL-1900) manufactured by BAE Systems. The second is the reference receiver.

Figure 5: The BAE GNSS Multipath Limiting Antenna (MLA)

4.2.1 The BAE ARL-1900 GNSS Multipath Limiting Antenna (MLA)

The BAE Systems ARL-1900 (see **Figure 5**) is an innovative, single feed, GNSS antenna that is approximately 6 feet high, and weighs about 35 pounds. The receiving elements are configured in an array, and when combined allow reception of the entire GNSS (Global Navigation Satellite System) band. This antenna is also capable of the high multipath rejection as required by the LAAS specification.

Multipath is a phenomenon common to all Radio Frequency (RF) signals and is of particular concern in relation to DGPS survey and navigation. It is simply a reflection of a primary signal that arrives at a user's equipment at a later time, creating a delay signal that can distort the primary if the reflection is strong. Reflected multipath is the bouncing of the signal on any number of objects including the local water table. Signals that reflect off the earth surface are often referred to as ground-bounce multipath. In all cases, the path length is increased. This path length is critical in GPS since the ranging is based on the signal's Time of Arrival (TOA). This causes a pseudorange error, for the SV being tracked, proportional to the signal strength. The BAE provides at least 23 dB of direct to indirect (up/down) pattern isolation above 5 degrees elevation. These multipath induced pseudorange errors can translate directly into a differential GPS position solution, which would be detrimental to applications such as GBAS. Multipath limiting antennas, such as the BAE Systems ARL-1900, were therefore developed to address the multipath threat to differential GPS and attenuate the ground multipath reducing the error. The ARL-1900 antenna characteristics also mitigate specular reflections from objects. The antenna's polarization (right hand circular polarized, or RHCP), provides a pattern advantage and reflective LHCP signals, which is left hand circular polarized.

4.3 Multi-Mode Receiver (MMR) Monitoring Station

The GBAS T&E team maintains an MMR on a precise surveyed GPS antenna to monitor ground station performance and evaluate MMR software updates. The MMR drives a dedicated Course Deviation Indicator (CDI). The CDI is a cockpit instrument that indicates fly left/right and up/down information with respect to the intended flight path. A virtual runway was constructed such that the approach path goes through the MMR GPS antenna point. With the configuration, the CDI should always be centered when the MMR is tuned to the virtual runway that coincides with the antenna's survey position. **Figure 6** is a representation of a typical FAA fabricated MMR test/flight user platform. The version of MMR firmware for this reporting period was Flight Change (FC) 31.

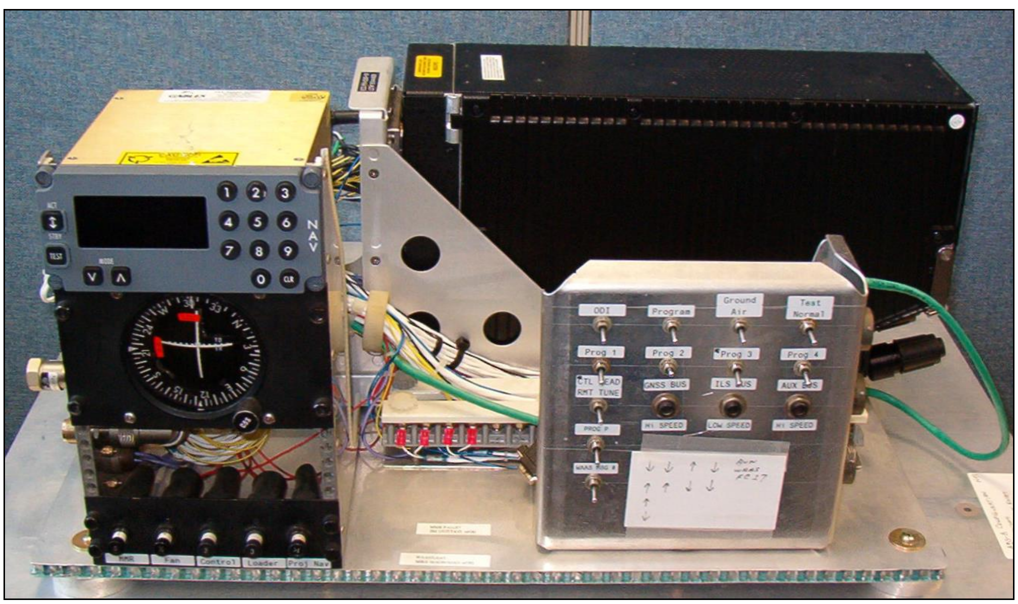


Figure 6: MMR User Platform

5. GBAS Performance and Performance Type

The GPS Standard Positioning Service (SPS), while accurate, is subject to error sources that degrade its positioning performance. These error sources include ground bounce multipath, ionospheric delay, and atmospheric (thermal) noise, among others. The SPS is therefore insufficient to provide the required accuracy, integrity, continuity, and availability demands of precision approach and landing navigation. A differential correction, with short baselines to the user(s), is suitable to provide precision guidance.

In addition to accuracy, there are failures of the SPS that are possible, which are not detected in sufficient time and can also cause hazardous misleading information (HMI). GBAS provides monitoring of the SPS signals with sufficient performance levels and time to alarm to prevent HMI.

The relatively short baselines between the user and the GBAS reference stations, as well as the custom hardware and software, is what sets GBAS apart from WAAS. Use of special DGPS quality hardware such as employment of MLA's serves to mitigate the multipath problems, while the GBAS software monitors and corrects for the majority of the remaining errors providing the local user a precision position solution.

The LAAS Ground Facility (LGF) is required to monitor and transmit data for the calculation of protection parameters to the user. The GBAS specification also requires monitoring to mitigate Misleading Information (MI) that can be utilized in the position solution. These requirements allow the GBAS to meet the accuracy, integrity, availability, and continuity required for precision approach and landing navigation.

There are three Performance Types (PT) defined within the LAAS Minimum Aviation System Performance Standards (MASPS). The three performance types, also known as Categories, (i.e., Cat I, and Cat II/III), all have the same parameters but with different quantity constraints. For the purposes of this report, the LTP assumes Cat I Alert Limits and hardware classification.

5.1 Performance Parameters and Related Requirements Overview

This section highlights the key parameters and related requirements used to depict GBAS system performance in this report. In order to provide the reader a clearer understanding of the plots provided, a little background is being provided below.

Cat I precision approach requirements for GBAS are often expressed in terms of Accuracy, Integrity, Availability, and Continuity. For clarity the use of these four terms, in the context of basic navigation, are briefly described below:

- **Accuracy -** is used to describe the correctness of the user position estimate that is being utilized.

- **Integrity** – is the ability of the system to generate a timely warning when system usage should be terminated.

- **Availability** - is used to describe the user's ability to access the system with the defined Accuracy and Integrity.

- **Continuity** - is used to describe the probability that an approach procedure can be conducted, start to finish, without interruption.

5.1.1 VPL and HPL

Vertical and Horizontal Protection Levels (VPL and HPL) parameters are actively monitored since the GBAS is required to perform with a worst case constellation and geometry scenario. VPL / HPL parameters are directly tied to constellation geometry and when combined with pseudorange errors affect the SPS position estimate and time bias. Monitoring the VPL and HPL in the GBPM gives a valid picture of what the user is experiencing. The protection levels are compared against the alert limits of the appropriate GBAS service level (GSL). In the event the protection levels exceed the alert limit, an outage will occur (See section 6 for GBAS site specific outages).

5.1.2 B-Values

B-values represent the uncorrectable errors found at each reference receiver. They are the difference between broadcasted pseudorange corrections and the corrections obtained excluding the specific reference receiver measurements. B-values indicate errors that are uncorrelated between RRs. Examples of such errors include multipath, receiver noise, and receiver failure.

5.1.3 Code-Minus Carrier and Reference Segment Status

The initial Code-Minus Carrier (CMC) quantity is computed by converting the L1 Carrier phase into a range and subtracting it from the Code range (also known as the pseudorange). Additional processing is required to isolate the code Multipath and noise components, which include subtraction of the sample-mean to remove the carrier phase integer ambiguity. Further computation is required for the removal of the ionospheric delay. The ionospheric delay is computed from the L1/L2 carrier phase measurements obtained from the L1/L2 IONO station.

The CMC values have had the effect of ionospheric delay (as determined from the L1/L2 IONO antenna data) removed from it, and has been smoothed. The CMC value can therefore be considered error that is uncorrectable, and uncommon to the ground station and airborne user. This uncorrectable error consists primarily of Multipath, noise, and hardware biases. The error is minimized by custom GBAS hardware design and adherence to the siting requirements.

Due to the configuration and siting of the reference stations of the LTP the typical antenna segment error reported has a standard deviation trace residing in the 0.05-meter region. The CMC values and statistic plots are continuously monitored to ensure minimum obtainable levels are maintained.

In order to observe overall system performance, the CMC, **number of samples (N)**, and **carrier-to-noise** (**C/No**) ratio values from all four reference station MLAs are averaged together so as to create a single representation of data/performance for all SVs, from the original four DGPS sensors (BAE MLA). C/No is critical to optimum reference receiver (RR) performance and is closely monitored. The C/No is a density ratio, with units in dB-Hz, driven by the amount of total signal power that is permitted to enter two RF inputs of the RR. The GBAS T&E team maintains proper total input power through external attenuation the value of which is obtained by performing an AGC calibration. The number of samples also serves as a representation of RR performance and health. System level number of samples for a given elevation bin is reasonably repeatable for a given GPS constellation. Marked changes in the number of samples, without a constellation change, would prompt the GBAS T&E team to investigate and address the potential cause.

The standard deviation of the CMC estimate of pseudorange error is compared to the Ground Accuracy Designator (**GAD**) **"C"- curve**. These deficiencies are repeatable and will not improve/degrade without human/environmental intervention. This is when the GBAS team inspects the RR/RRA environment and hardware to address the problem.

5.1.4 Clock Error

The average Clock Error is important to monitor since rapid changes in the ionosphere can drive the clock error to unusual levels. Clock error will invariably rise when the Total Electron Count (TEC) of the ionosphere is high (day), and fall when the TEC is lower (night). The derived average system clock error is correctable and in general amounts to between 5 and 15 meters (between 0.166 and 0.550 nano-seconds). Much larger clock biases are tolerable as well. The reference receiver clock biases are largely removed from the pseudorange correction (PRC) before these corrections are sent to the airborne equipment.

5.1.5 Performance Analysis Reporting Method

For a given configuration, the LTP's 24-hour data sets repeat performance, with little variation, over finite periods. The GBAS T&E team can make that statement due to the continual processing of raw LTP data and volume of legacy data that has been analyzed from the LTP by the FAA and academia. Constellation and environmental monitoring, in addition to active performance monitoring tools such as the web and lab resources provide the GBAS T&E team cues for closer investigation into the presence, or suspicion, of uncharacteristic performance.

Data sets from the LTP ground and monitoring stations are retrieved on a weekly basis and processed immediately. A representative data-day can then be drawn from the week of data to be formally processed. The resultant performance plots then serve as a snapshot of the LTP's performance for the given week. These weekly plots are afterward compared to adjacent weeks to select a monthly representative set of plots.

6. GBAS Updates by Site

The LTP is an AOA-installed operational GBAS system and requires the same type of airport maintenance activities required for other AOA-installed systems, though it is not certified for operational use. The Navigation Branch has also installed multiple GBPM's over the years to monitor our LTP and the SLS-4000 systems. Both the LTP and GBPM systems' components do occasionally falter, requiring replacement.

The following sections include maintenance, performance plots, and predictions/outages for each individual site.

The Ground Based Performance Monitor (GBPM) is the primary performance monitoring tool for the LTP and the Honeywell SLS-4000 systems. The system uses the received VDB broadcast type 1, 2, 4, and 11 messages from the ground station being monitored along with raw GPS data in order to compute the position of the monitor station. The position calculated from this data is compared to the position of the precision-surveyed GBAS grade GPS antenna, which is used to identify positioning errors.

The GBPM's Novatel OEM-V receiver logs range and ephemeris messages, which provide the necessary pseudorange and carrier phase measurements, as well as satellite position information. VDL messages are then received and separated into each of the DO-246D GBAS message types and decoded.

Data is collected in 24-hour intervals at 5Hz and saved to a .raw file without interruption. This data is used to post-evaluate system performance. In addition to the raw file, every minute live data is transferred from each offsite monitor to the local database. Users can then access the data through an interactive website by means of tables, graphs, and maps hosted by the Navigation Branch at the FAA. The web address for this service is http://laas.tc.faa.gov.

Analysis of GBPM data is critical for closely observing the LTP and SLS performance behavior. The GBPM data output package contains several plots that can quickly illustrate the overall performance picture of the GBAS. The most useful plots available for performance summary purposes are *Vertical and Horizontal User Error versus Time*. These two plots are often used for preview performance analysis because the "user" GPS sensor position is known and stationary. The known position (precision survey) of the GBPM GPS sensor is compared directly to the computed user position. Typical LTP Vertical and Horizontal user error has an average well within the +/- 1-meter range.

Figure 7 is one of the GBPM's that was built by the Navigation Branch. Some of the major components include a retractable KVM to check the current status of the monitor, CISCO router with a T1 line back to our lab at ACY for data collection and maintenance, Power Distribution Unit (PDU) for a means remote access to bring power outlets back up if they become unresponsive, Novatel GPS Receiver, Becker VDB Receiver, QNX CPU, and an uninterruptable power supply.

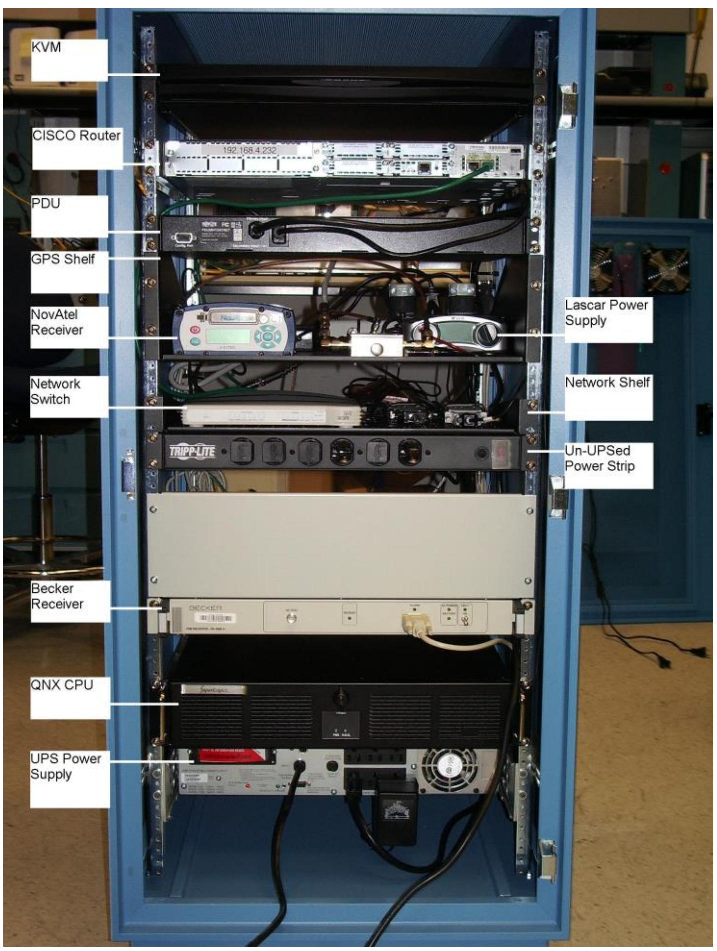


Figure 7: Ground Based Performance Monitor (GBPM)

6.1 LTP ACY

- The LTP has been down all of this quarter due to damaged fiber connections and bad MLA antennas

6.2 ACY SLS

- The SLS is currently set up with six references for CAT III testing. See section 8.1 for further information

6.2.1 Outages and Prediction Performance

- There are no outages reported for this quarter outside of CAT III testing

6.2.2 Real Time Performance Data

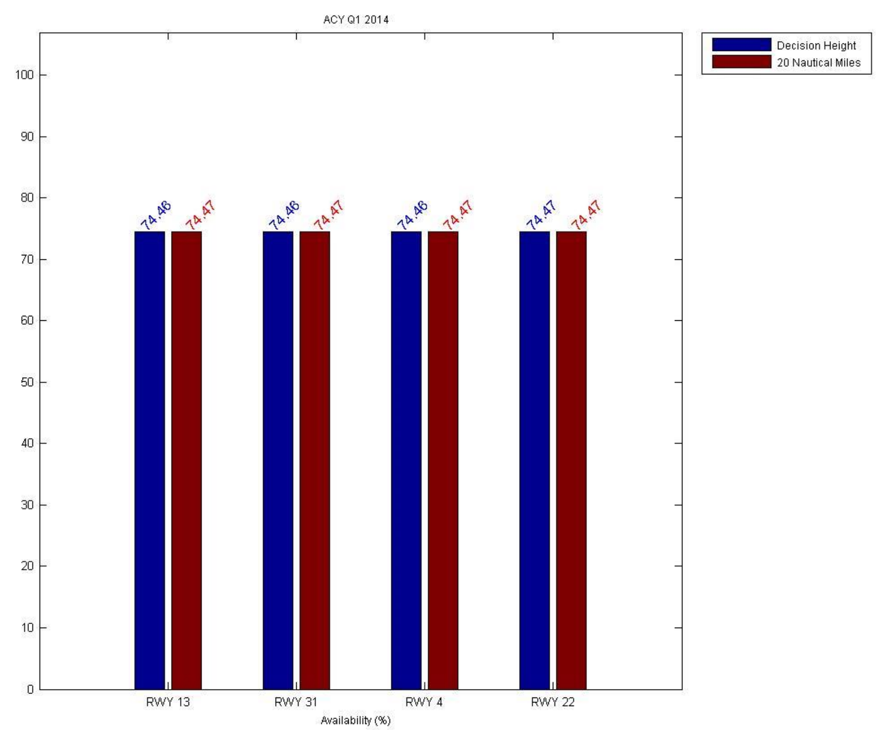


Figure 8: ACY SLS Availability

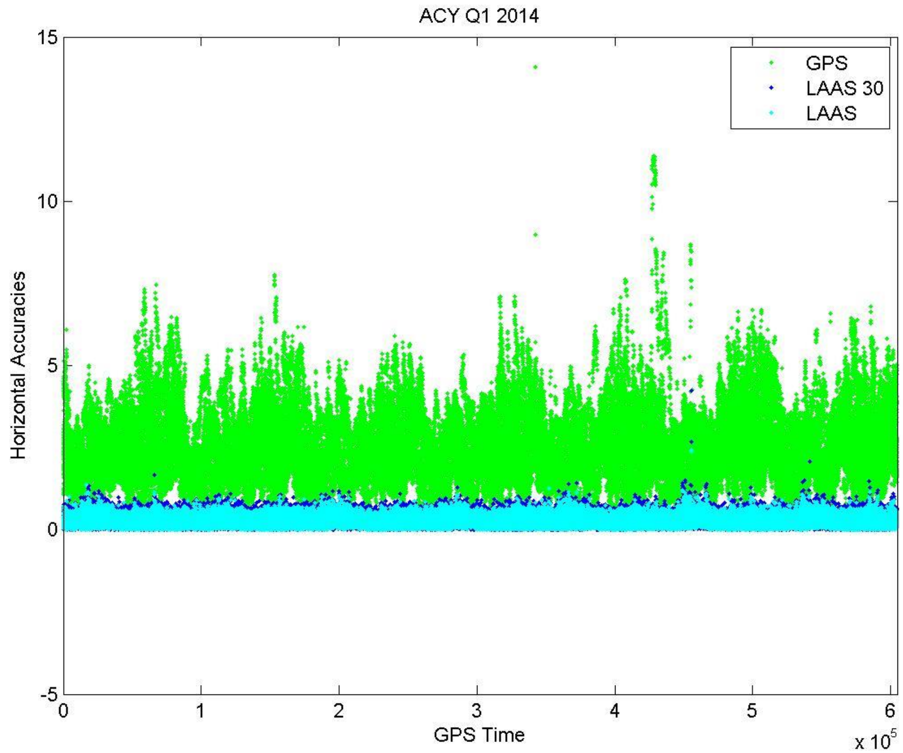


Figure 9: ACY SLS Horizontal Accuracy Ensemble Plot

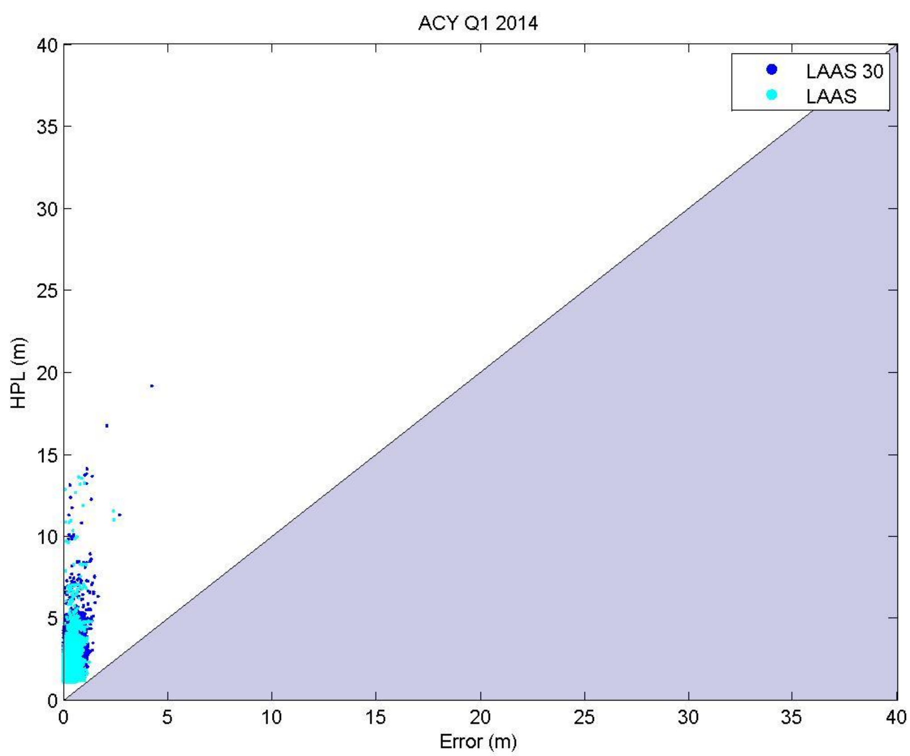


Figure 10: ACY SLS Horizontal Accuracy vs. Error Bounding Plot

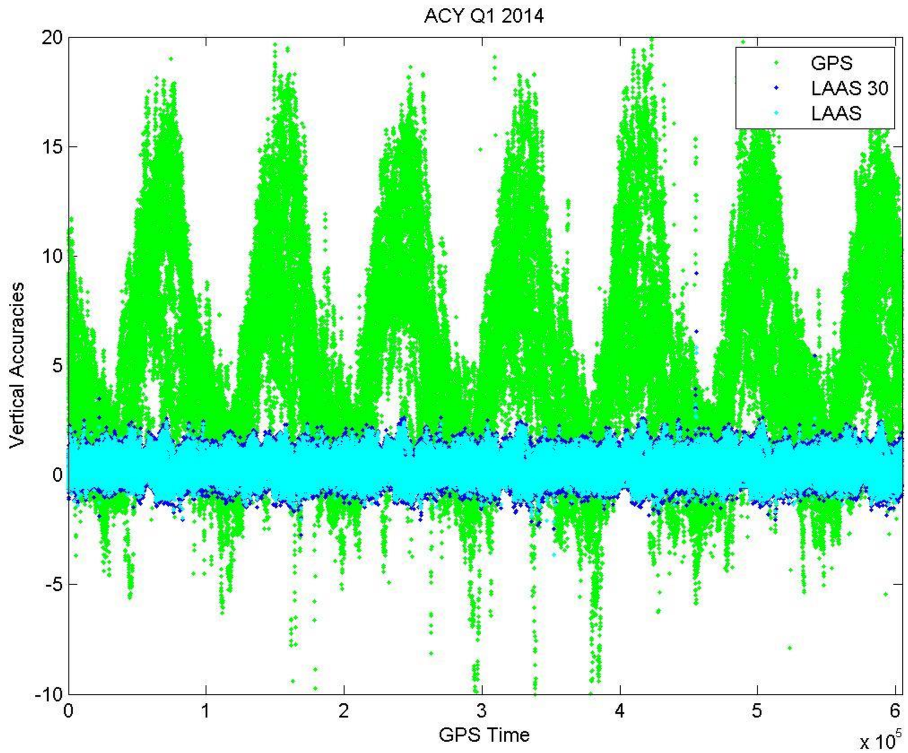


Figure 11: ACY SLS Vertical Accuracy Ensemble

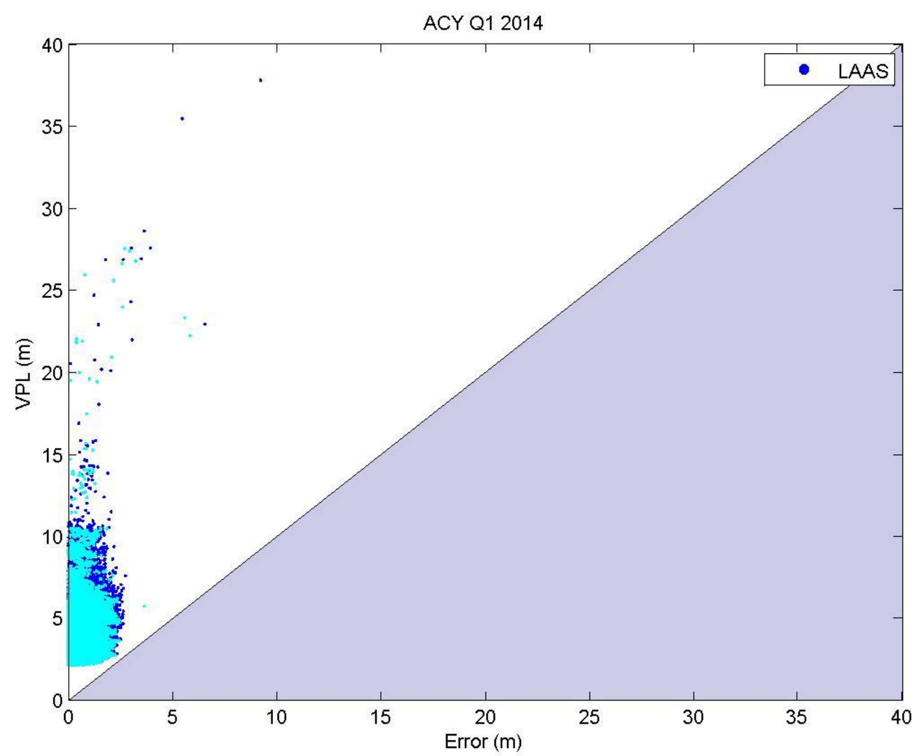


Figure 12: ACY SLS Vertical Accuracy vs. Error Bounding Plot

6.3 EWR SLS

- No new status updates at this time

6.3.1 Outages and Prediction Performance

- There is a predictable reoccurring outage each day lasting approximately twenty minutes that should be alleviated by the planned Block II update

6.3.2 Real Time Performance Data

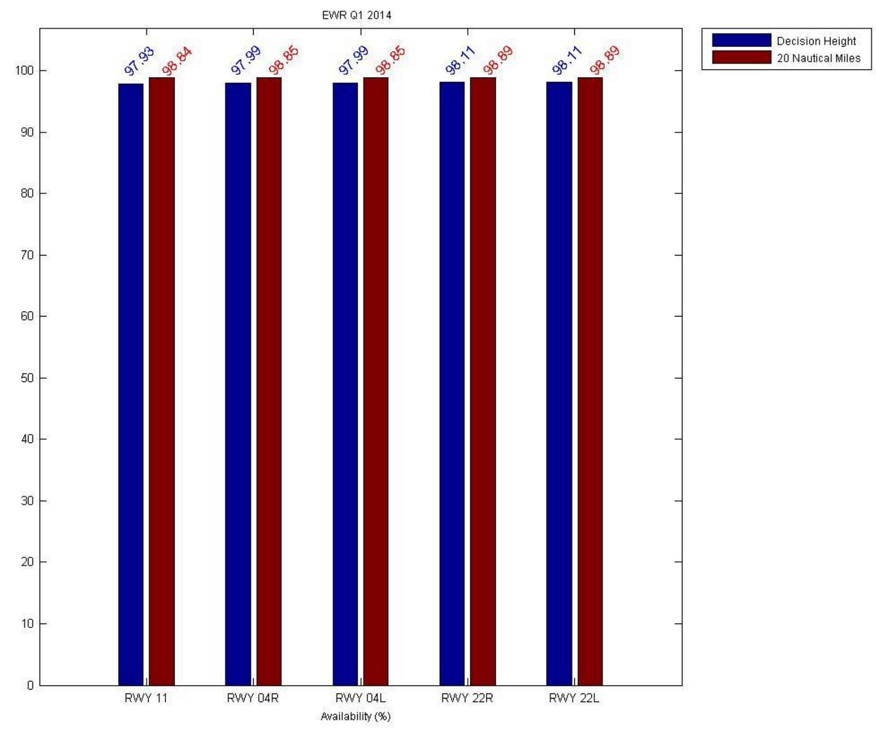


Figure 13: EWR Availability

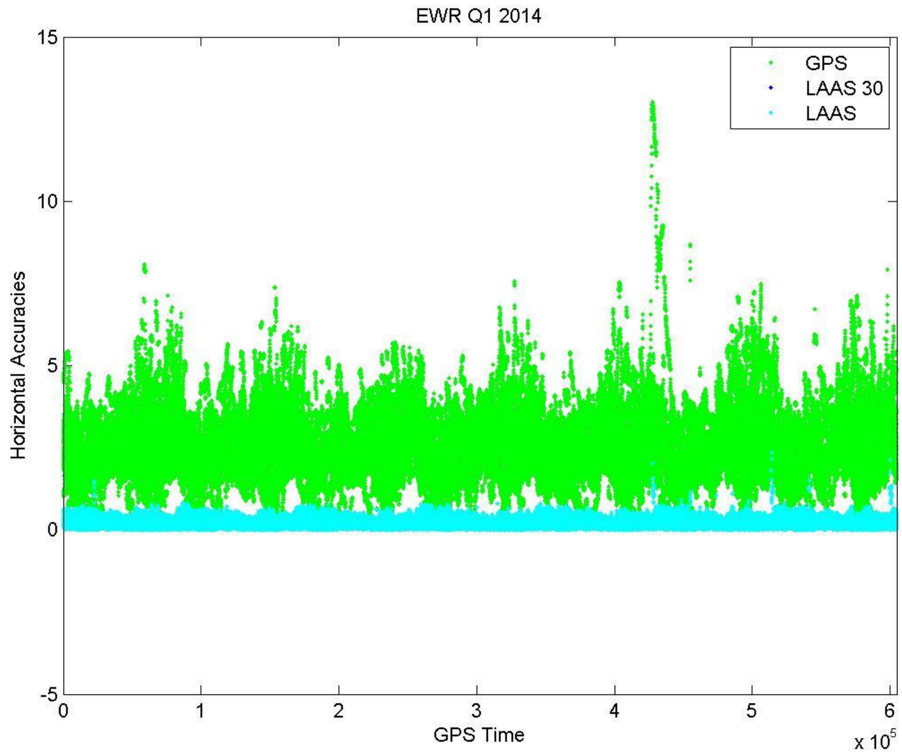


Figure 14: EWR Horizontal Accuracy Ensemble Plot

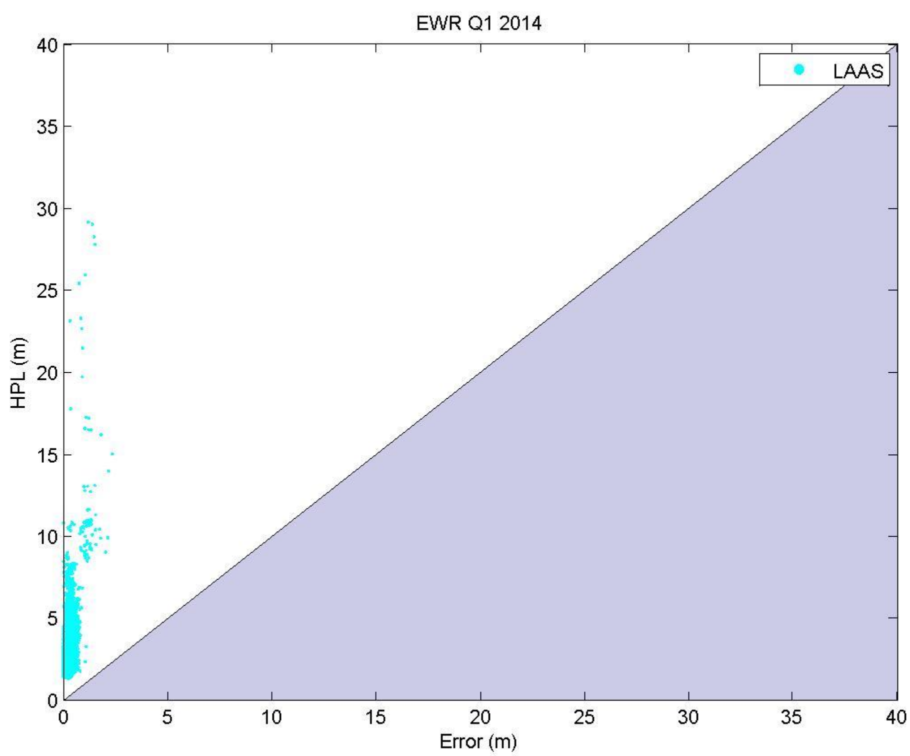


Figure 15: EWR Horizontal Accuracy vs. Error Bounding Plot

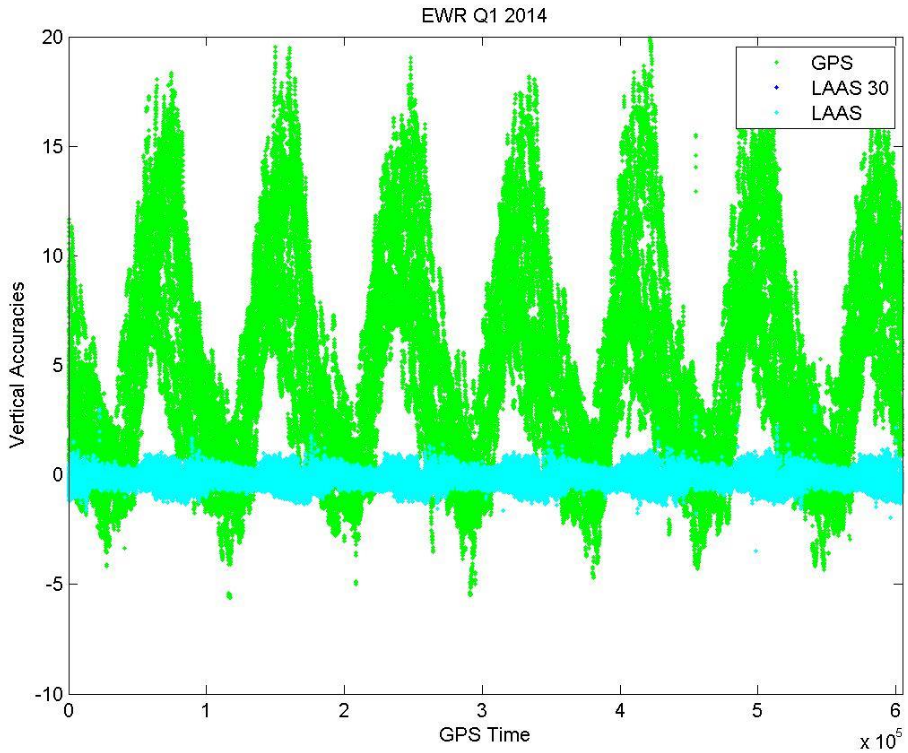


Figure 16: EWR Vertical Accuracy Ensemble Plot

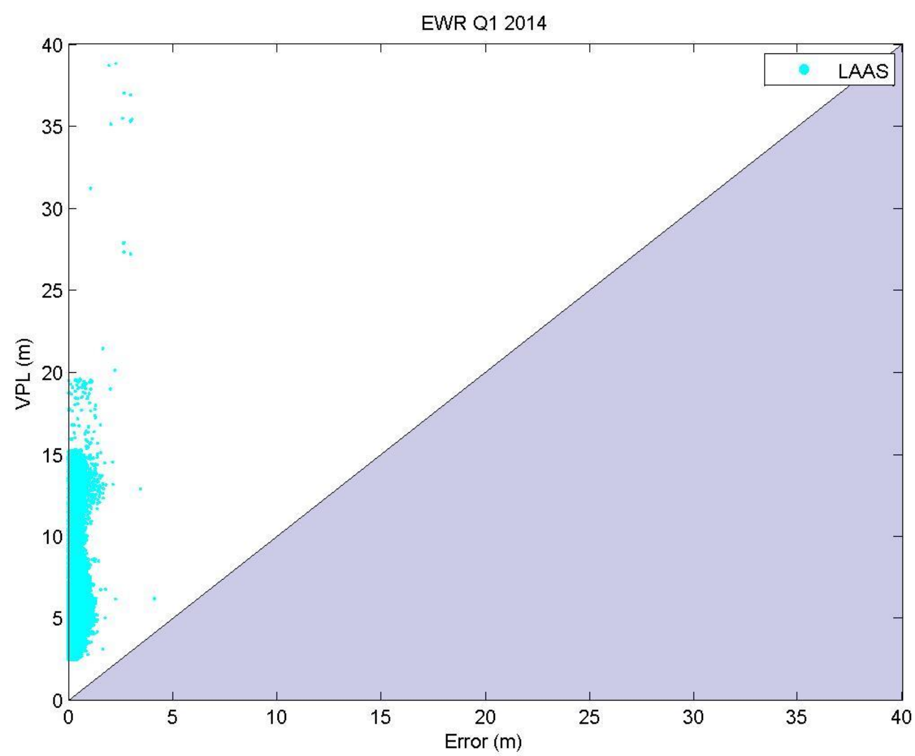


Figure 17: EWR Vertical Accuracy vs. Error Bounding Plot

6.4 IAH SLS

- No new status updates at this time

6.4.1 Outages and Prediction Performance

- There is a predictable reoccurring outage each day lasting approximately fifteen minutes that should be alleviated by the planned Block II update

6.4.2 Real Time Performance Data

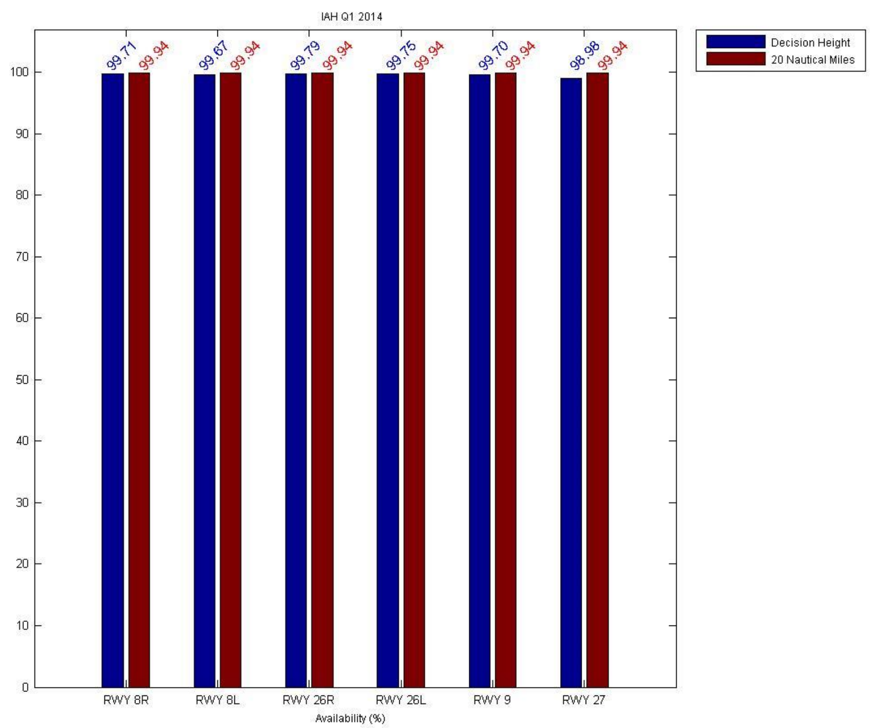


Figure 18: IAH Availability

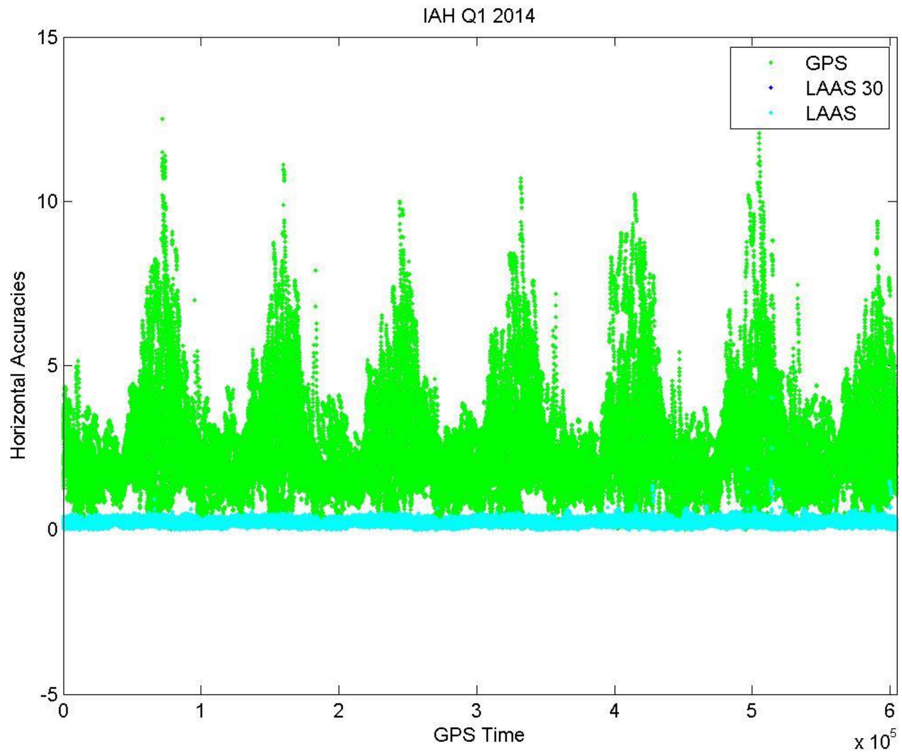


Figure 19: IAH Horizontal Accuracy Ensemble Plot

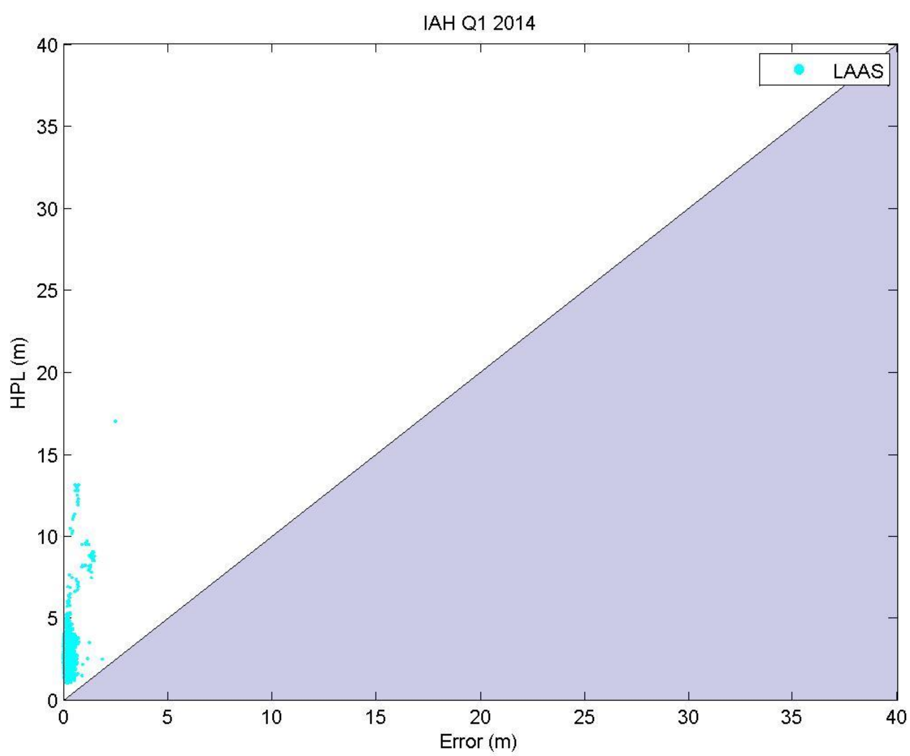


Figure 20: IAH Horizontal Accuracy vs. Error Bounding Plot

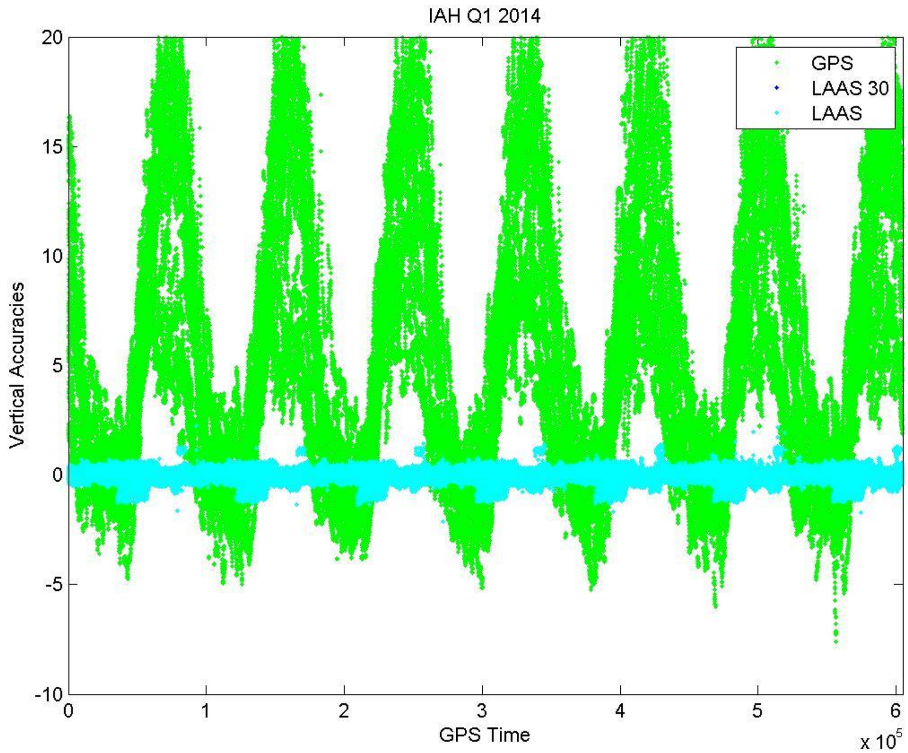


Figure 21: IAH Vertical Accuracy Ensemble Plot

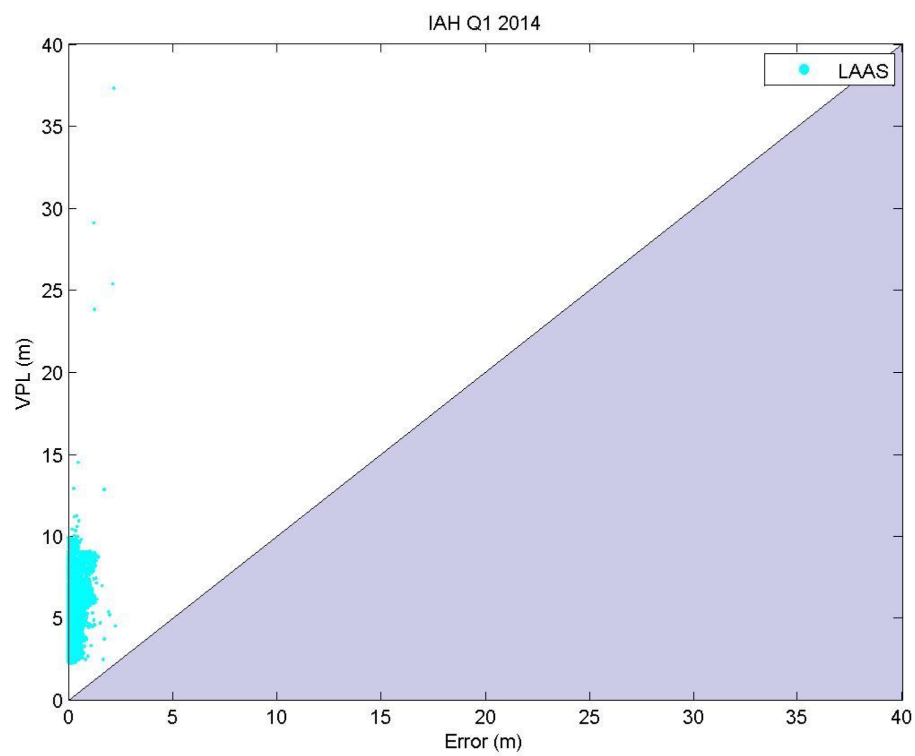


Figure 22: IAH Vertical Accuracy vs. Error Bounding Plot

6.5 MWH SLS

- No new status updates at this time

6.5.1 Outages and Prediction Performance

- There is a predictable reoccurring outage each day lasting approximately two minutes that should be alleviated by the planned Block II update

6.5.2 Real Time Performance Data

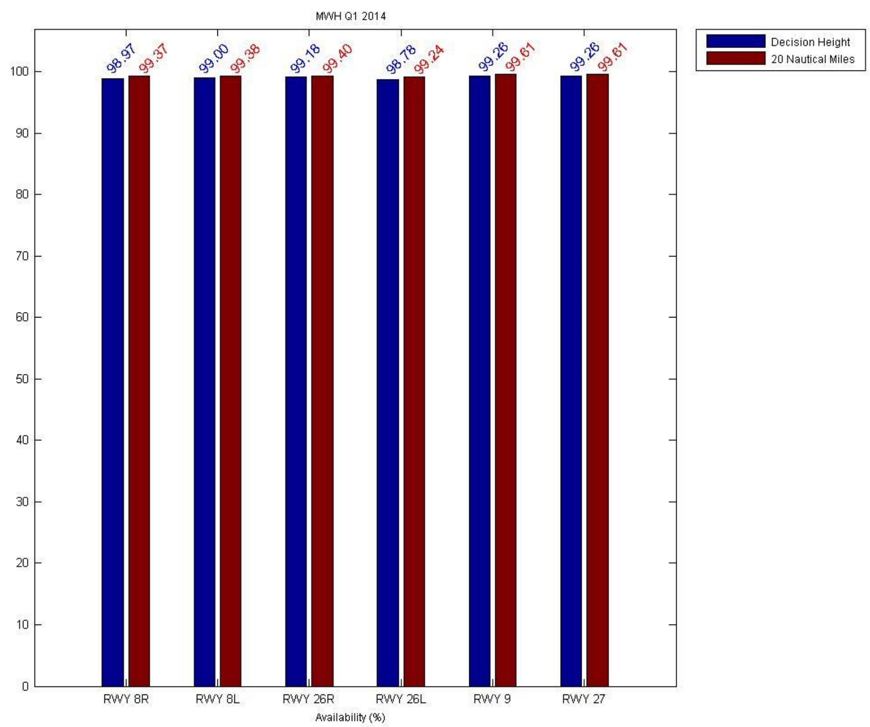


Figure 23: MWH Availability

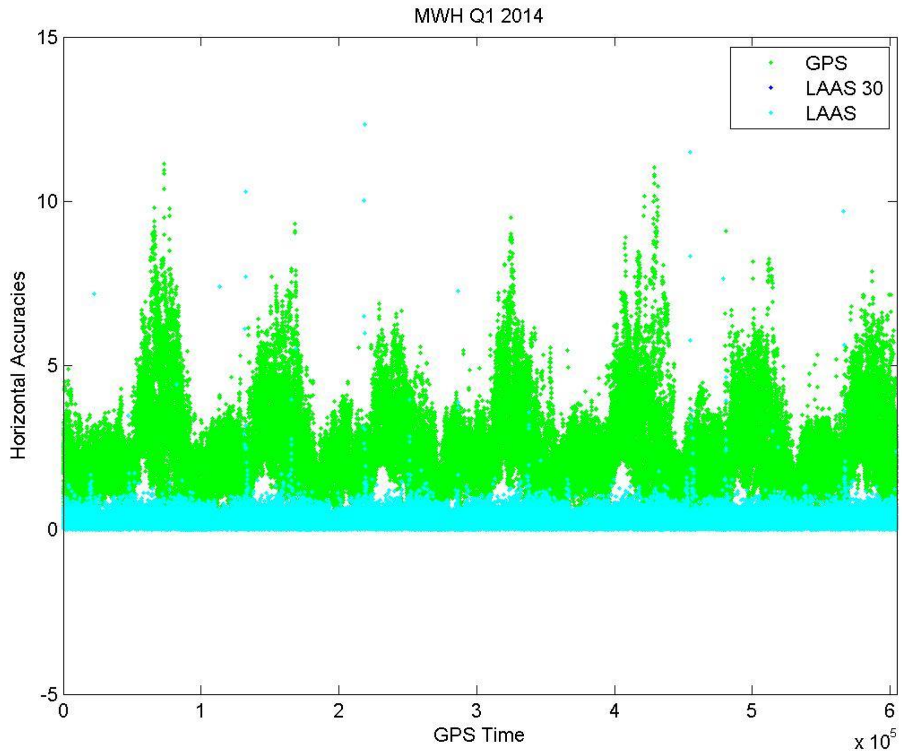


Figure 24: MWH Horizontal Accuracy Ensemble Plot

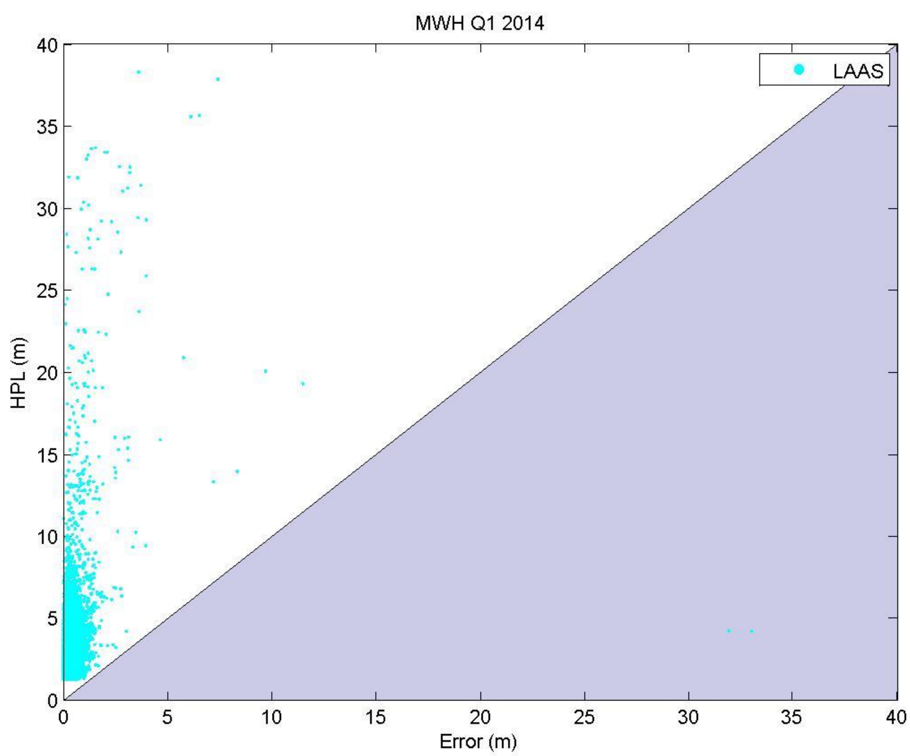


Figure 25: MWH Horizontal Accuracy vs. Error Bounding Plot

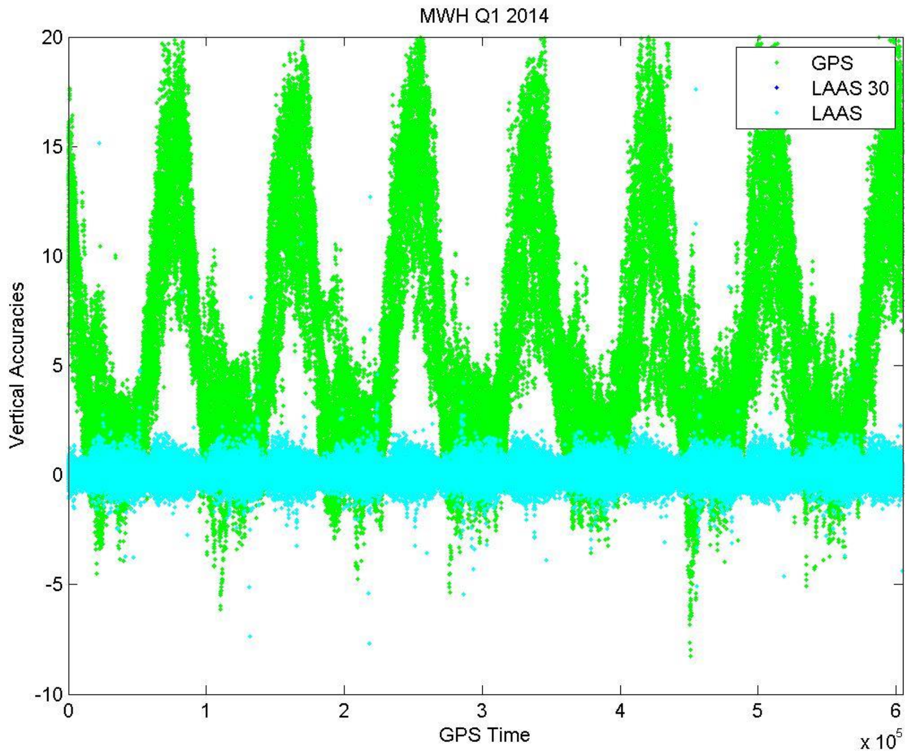


Figure 26: MWH Vertical Accuracy

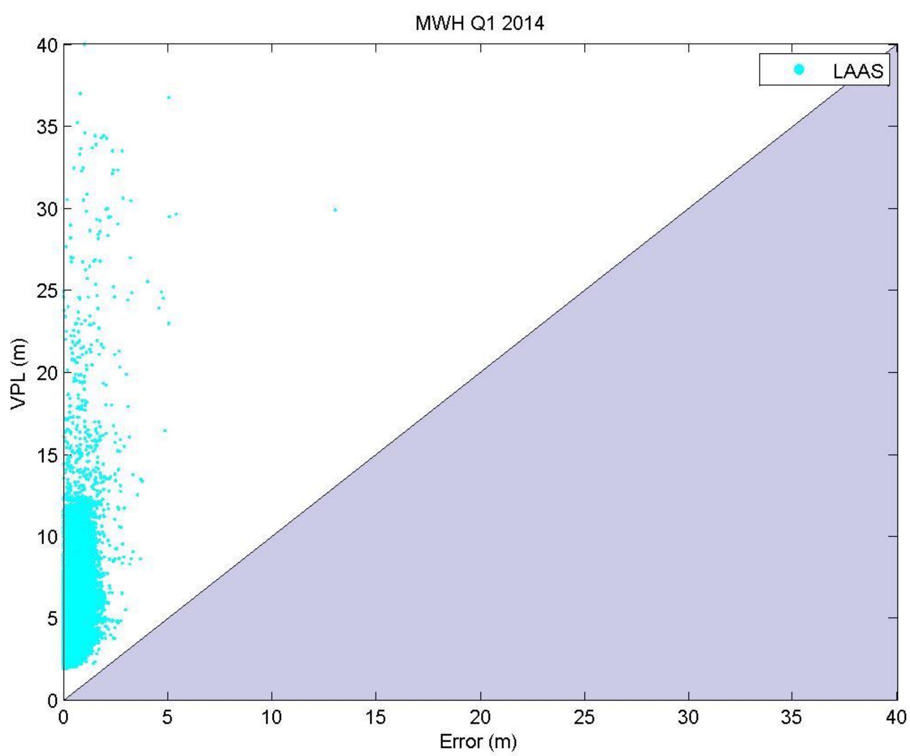


Figure 27: MWH Vertical Accuracy vs. Error Bounding Plot

6.6 Rio de Janeiro Brazil

- The Brazil monitor has been restored, and is currently available to view on our website as of March 31, 2014. Plots and status updates will be presented in the next quarterly report.

7. FAA Long-Term Ionospheric Monitoring (LTI) Activity

Large spatial variation in Ionosphere delay of Global Positioning Systems (GPS) signals occurs during severe Ionosphere storms. A threat model was developed to access and search for the maximum error possible. This allows GBAS to provide the appropriate corrections to an aircraft should an Ionosphere wave front (modeled as a spatially linear semi-infinite wedge parameterized by the gradient or “slope” of the ramp and its width moving with a constant speed) overtake that aircraft while on precision approach, even under the most detrimental conditions.

The current threat model for the mid-latitude Continental United States (CONUS) was derived by processing data corrected from local clusters of Continuously Operating Reference Stations (CORS) and Wide Area Augmentation System (WAAS) reference stations. This threat model was used for safety assessment and System Design Approval (SDA) of the Honeywell SLS-4000 LAAS (Local Area Augmentation System) Ground Facility (LGF) by the Federal Aviation Administration (FAA) for use in CONUS.

The bounds of the threat model (Figure 28) were determined by processing the worst anomalous days during the last solar maximum in 2000-2003. Continued monitoring of the Ionosphere to ensure gradients larger than those included in the threat model are not present is imperative to GBAS operations, as we are now in the next solar maximum period (14 year cycle). From 2011-2014, we expect to see an increase in solar activity, which may include but is not limited to Coronal Mass Ejections (CMEs), Solar Flares, and other space weather phenomenon. Figure 29 illustrates the current mid-latitude CONUS threat model, which includes confirmed gradients (in mm/km) from the 2003 solar cycle.

Max. Front slope (mm/km)	Low elevation (<15°)	375
	Medium elevation (15° <el<65°)	375+50(el-15)/50
	High elevation (>65°)	425
Front width (km)	25 – 200	
Front speed (m/s)	0 – 750	
Max. differential delay (m)	50	

Figure 28: Parameters for Mid-latitude CONUS Threat Model

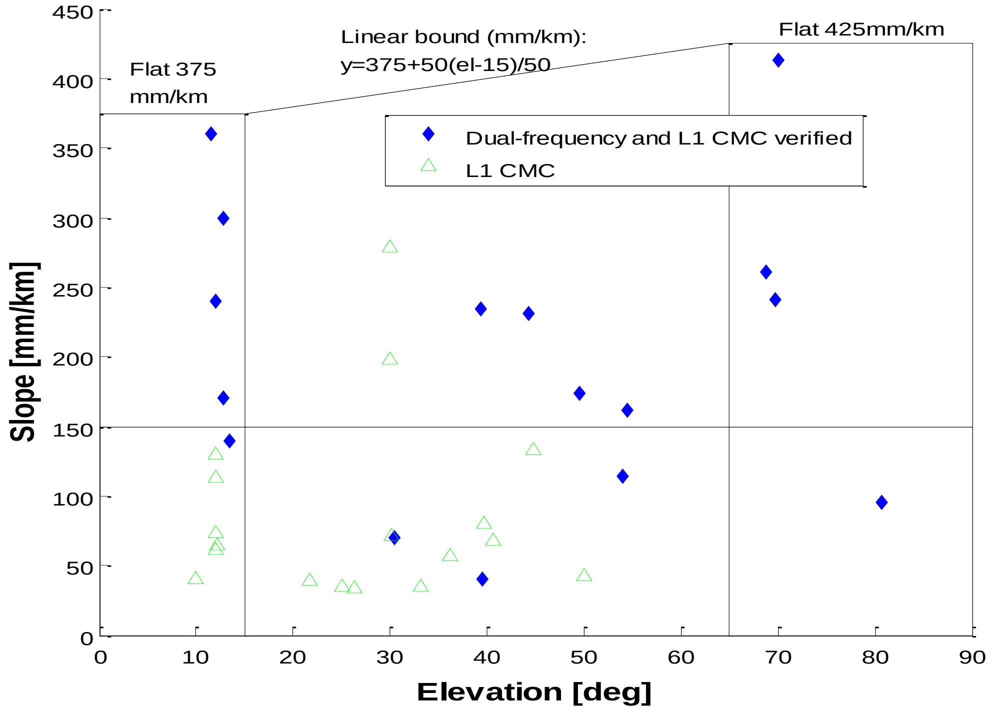


Figure 29: Mid-latitude Conus Threat Model, shown with confirmed gradients (mm/km) from 2003

Scope of Work:
The tool/software package being used to validate Ionospheric data is identified as the Long-Term Ionosphere Anomaly Monitor (LTIAM) and was originally developed by Dr. Jiyun Lee of the Korean Advance Institute of Science and Technology (KAIST), Dr. Sam Pullen of Stanford University, and their respective teams. The LTIAM consists of MATLAB code that will detect and report Ionospheric anomalies with data collected from NOAA, CORS, and WAAS. Our ultimate goal is to insure that Ground-based Augmentation systems that enhance the performance of GPS are robust to Ionospheric anomalies and irregularities. With regards to CONUS, we also want to continue population of the threat model, evaluate its validity over the life cycle of the system, and to continuously update the threat model if necessary.

The LTIAM tool contains two primary modules: Ionospheric Event Search (IES) and GPS Data Process (IACS). The Ionospheric Event Search block is used to check for potential occurrences of an Ionosphere storm based on space weather indices Kp and Dst (Planetary K and Disturbance Storm Time respectively). The GPS Data Process block is used to read input data (in RINEX format) and derive Ionospheric delay and gradient estimates, as well as generate Ionospheric anomaly candidate pairs. Station pairs are determined by the baseline distance (maximum separation between any two stations), which can be manually entered by the user. As a GBAS model, the first station represents an aircraft on approach and the second station simulates the LAAS Ground Facility.

The LTIAM is capable of producing plots that include slant Ionosphere delay, L1 L2 dual-frequency gradient estimation, L1 CMC gradient estimation, and SV elevation track. We define slant Ionosphere delay as an estimation of GPS measurement caused by the Ionosphere between the receiver and the SV. Gradient estimation, or slope (in mm/km), is the difference of slant Ionosphere delay between the candidate station pair, divided by the baseline distance. LTIAM estimates slope using both L1 L2 dual-frequency (L1 carrier – L2 carrier) and L1 code-minus-carrier (L1 code – L1 carrier) measurements. Due to the low amount of noise in the dual-frequency measurement, we expect the dual-frequency gradient estimation to be our "best guess". The L1 CMC measurement is "more noisy", due to the nature of L1 code (large multipath). However, the L1 CMC measurement is not affected by normal L2 tracking anomalies and errors, which gives a good comparison against the dual frequency measurement. The most crucial aspect of manual validation comes from the comparison of these two different measurements. If the trends of both measurements match well, then this is a good indication of how trustworthy, and ultimately how real, the gradient estimation is. When processing CORS data, a baseline distance of < 100 km for GBAS operations is used (larger baselines are used for Brazil, see background information below).

Progress Report:
As of December 2013, the FAA team has entered into a cooperative project with the Brazilian Team (DECEA) to build an equatorial-based Ionosphere threat model. Although experience gained from the CONUS threat model is valuable, the exact process will differ for developing a threat model in the equatorial region (within 25 degrees latitude of the geomagnetic equator) due to the more variable and more extreme Ionospheric behavior, specifically, those of plasma bubbles and depletions that do not apply to mid-latitude regions (such as CONUS).

Brazilian data is collected from the Instituto de Geografia e Estatística (IBGE), which includes the Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS (RBMC), which covers Brazil with about 100 receiver stations as of 2010. Other networks include the widespread (but less dense) networks of IGS and LISN in South America. Selected days of high scintillation are retrieved for study and processed using LTIAM, which has been modified to process Brazilian data (referred to as LTIAM_Brazil Patch). As of March 2014, we have identified two major groups of data, which are as follows:

- Group 1: December 29-31, 2013 January 01-02 2014
- Group 2: October 21-24, 2013

This data has been processed by LTIAM and manual validation of these results is completed. An additional 100 days of data has been identified and is ready for processing with LTIAM. This large data set will be divided among the various organizations of the project, which includes: FAA, KAIST, Stanford University, Boston College, Mirus, and DECEA.

As noted above, a significant amount of work has been completed thus far, with contributions from the FAA, KAIST, Stanford University, Boston College, Mirus, and DECEA. A working threat model for confirmed gradients (from Group 1 and Group 2 data sets) is shown below in Figure 30.

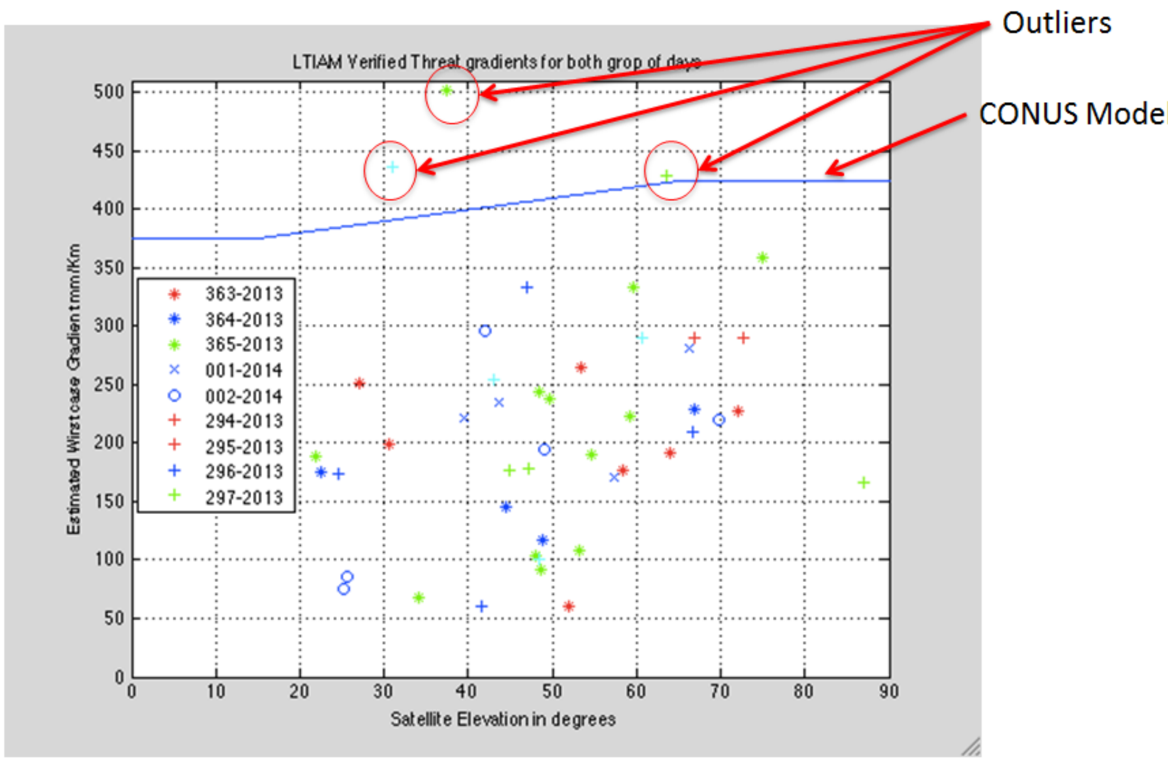
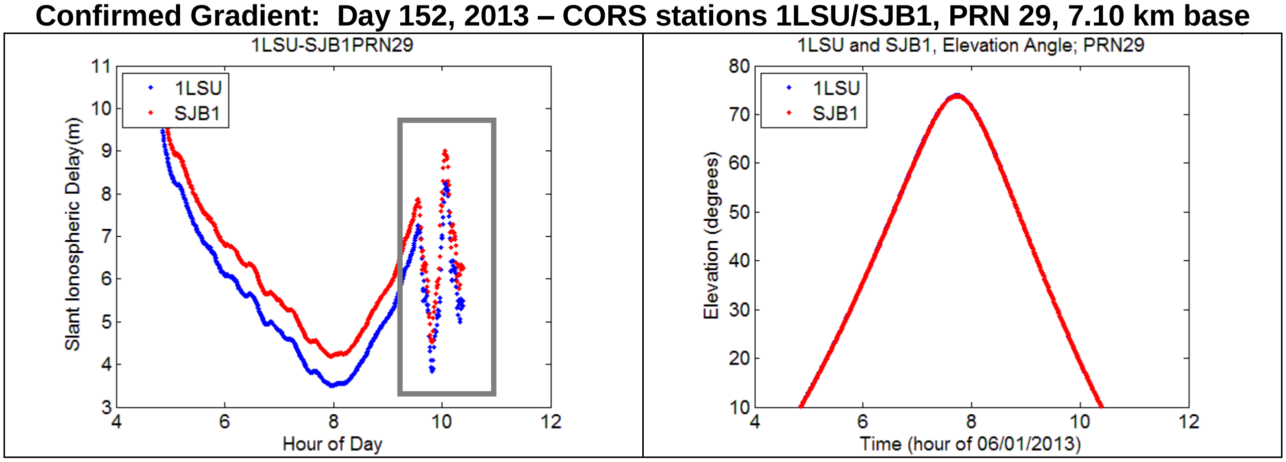


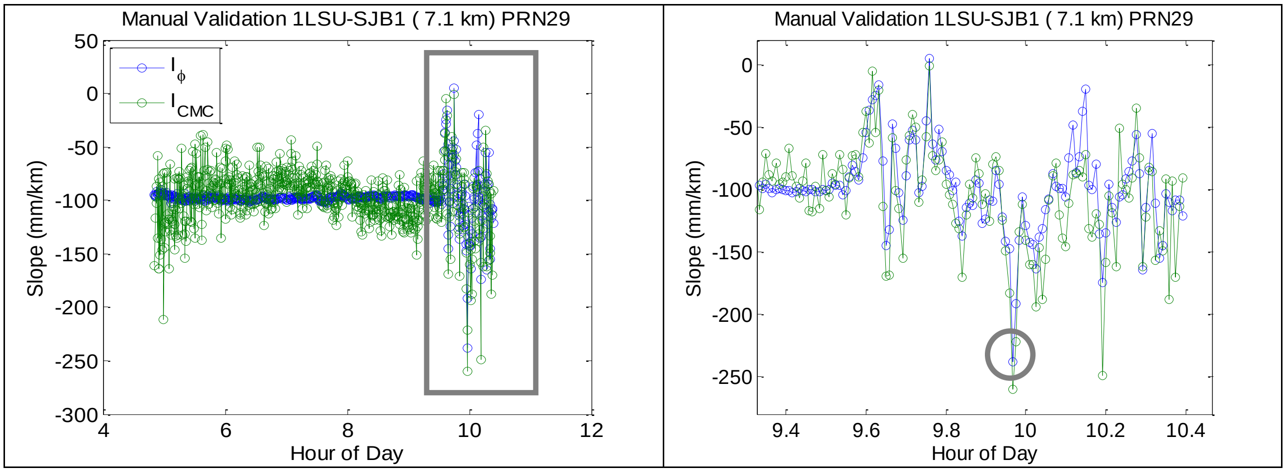
Figure 30: Working Threat Model of Brazilian Threat Space

Additional work has been done in the mid-latitude CONUS region as well. Several days have been identified using LTIAM. These days are classified as "anomalous" based on space weather indices Kp and Dst (Planetary K and Disturbance Storm Time respectively). If these indices are found to be above a set threshold (Kp >= 6 and/or Dst <= -200), then LTIAM flags the selected days of interest as potentially experiencing severe Ionospheric activity (or as being *anomalous*). The following three days have been selected for LTIAM processing: June 1 - 2013, February 27 - 2014, and February 28 - 2014. In this LPAR report, an example gradient will be presented from June 1, 2013. LTIAM processing for February 27-28 is currently underway. Additional examples from the June 1st event are available upon request.

Confirmed Gradient: Day 152, 2013 – CORS stations 1LSU/SJB1, PRN 29, 7.10 km base



The anomaly begins approximately at Hour 9.5; notice the consistent bias between the two receivers throughout the day. This bias has an extremely long duration and is abnormal in behavior. Most likely, this bias is the cause of the -100 mm/km offset in the slope estimation (below). We can remove this offset from the final gradient estimation. Lower elevation equates to higher slant delay. As elevation increases (and LOS improved), the slant delay decreases. In the example, we can see slant delays of 3.5 - 10 meters.



(Above) The left plot shows the dual frequency estimate (blue curve) and the L1 CMC (green curve). Notice that both curves follow a similar trend, which is more apparent at the start of the anomaly. Due to the nature of L1, we can clearly see that the green curve is estimated higher than the blue curve (L1 CMC is more noisy). We expect this, and it is our goal is to compare these two different curves based on this knowledge.

(Above) The right plot (zoomed in on the square clearly shows how well the two curves match in trend. Green points are shown to be estimated higher than blue points in most cases (as expected). The gray circle highlights the point of highest magnitude using the dual frequency estimate (-240 mm/km, L1 CMC is slightly higher), taking into account the -100 mm/km offset, our final gradient = ~140 mm/km.

This concludes the FAA long-term Ionosphere monitoring activity for this reporting period. Additional explanation or manually validated examples are available upon request.

8. Research, Development, and Testing Activities

The GBAS T&E team is responsible for directing and supporting GBAS related R&D engineering activities. The team also is engaged in verifying the performance of experimental GBAS hardware and software configurations. Any changes in configuration, or degradations in performance, are captured and rigorously analyzed. This section outlines GBAS engineering and testing activities for the reporting period.

8.1 CAT III Configuration and Testing at ACY

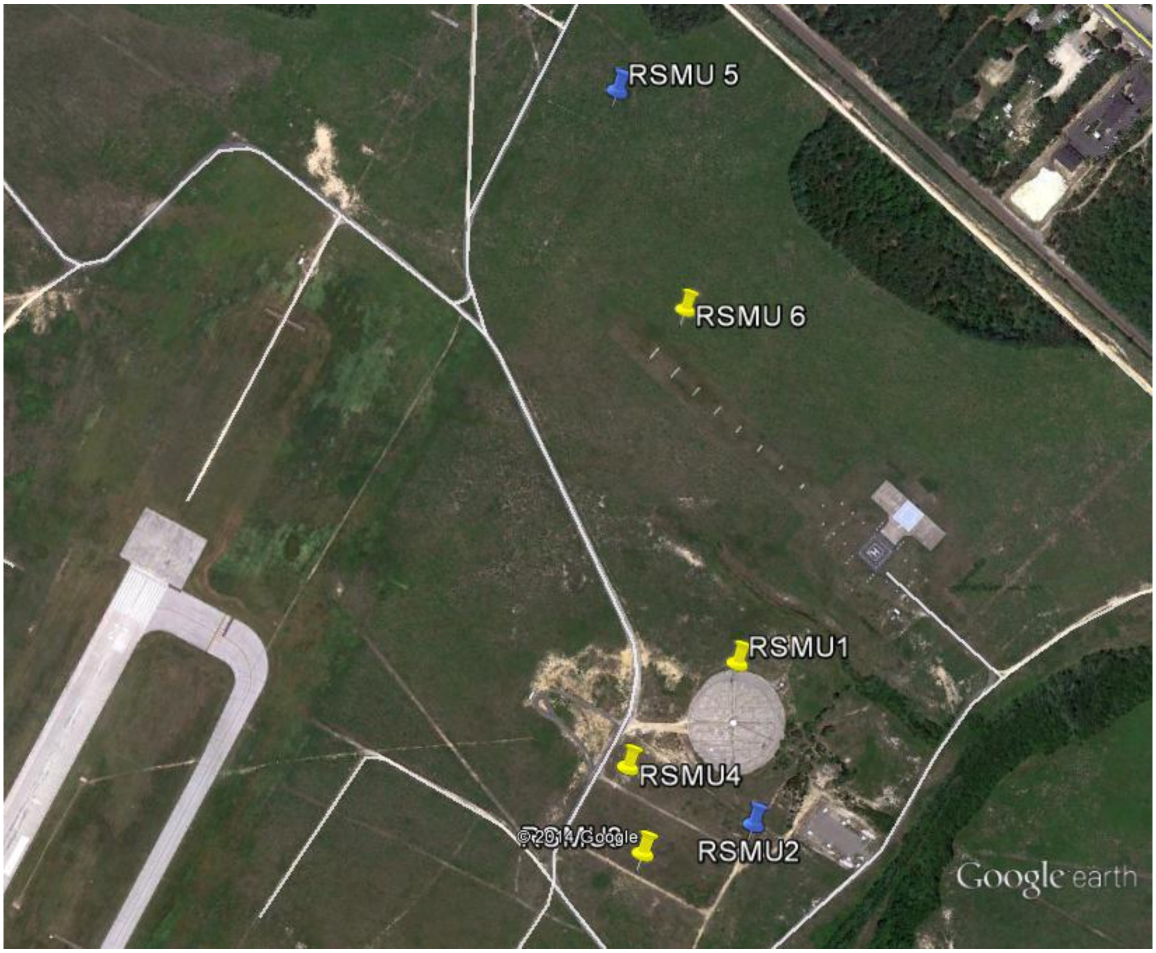


Figure 31: ACY CAT III Configuration

The picture above shows the current locations of all 6 reference receivers available under the newly designed CAT-III configuration. This configuration uses 4 Primary references (yellow pins), and 2 substitutes (blue pins) that can be interchanged under certain circumstances that cause one of the Primary sites to be unavailable. Monitoring, such as the IONO Graident Monitor (IGM), is also performed using the 6 reference receivers. The additional references also allow for more, and longer baselines during the various monitoring processes.

There was also the start of Ground testing of different GBAS operational scenarios, conducted to demonstrate some possible conditions that might occur with the system during normal operation. Test data was collected using the GBPM, a Rockwell MMR, and a Honeywell INR. That data, as well as the raw GBAS station data, is currently being analyzed in preparation for Flight Tests, which are to be conducted in the late April-early May timeframe.

8.2 Newark RFI Outages / Mitigation

On September of 2009, a full Category I System Design Approval (SDA) for the Non-Federal GBAS system was given at Newark International Airport (EWR) for the SLS-4000. This would be the first approved GBAS and was also intended to be the first operational GBAS in the

National Airspace System (NAS). On November 23rd, several days after initial stability tests began on the installed system, the SLS-4000 was found to be in an alarmed state. GPS Receiver satellite tracking was interrupted, with the station not broadcasting. As the data being collected by the station was analyzed, it was observed that the event that caused the system outage to occur had an impact on the carrier-to-noise (CN_0) causing a dramatic loss of satellite acquisition. Though the initial probability was considered low, the reality was that the SLS-4000 at Newark International Airport experienced its first major Radio Frequency Interference (RFI) impact.

As the system is designed with redundant implementation of hardware and software, RFI detection and protection, it appropriately stopped transmitting information with an alarm indication being displayed. Through further analysis of the SLS-4000 collected data and an assortment of monitors and systems used to observe RFI events, it was discovered that the outage in Newark was not an isolated event to GBAS and that various systems currently in operation have also seen RFI.

On February 17, 2010 ANG-C32 coordinated a multi-organizational mitigation group consisting of various RF experts adverse in RFI observation, detection and protection in order to further study these RFI events and come to a swift resolution. Through the efforts of the RFI joint mitigation organization, a better understanding and characterization of these events were implemented and on September 28th 2012 the SLS-4000 became operational to the public, with United Airlines flying its first GLS capable Boeing 737 on GBAS.

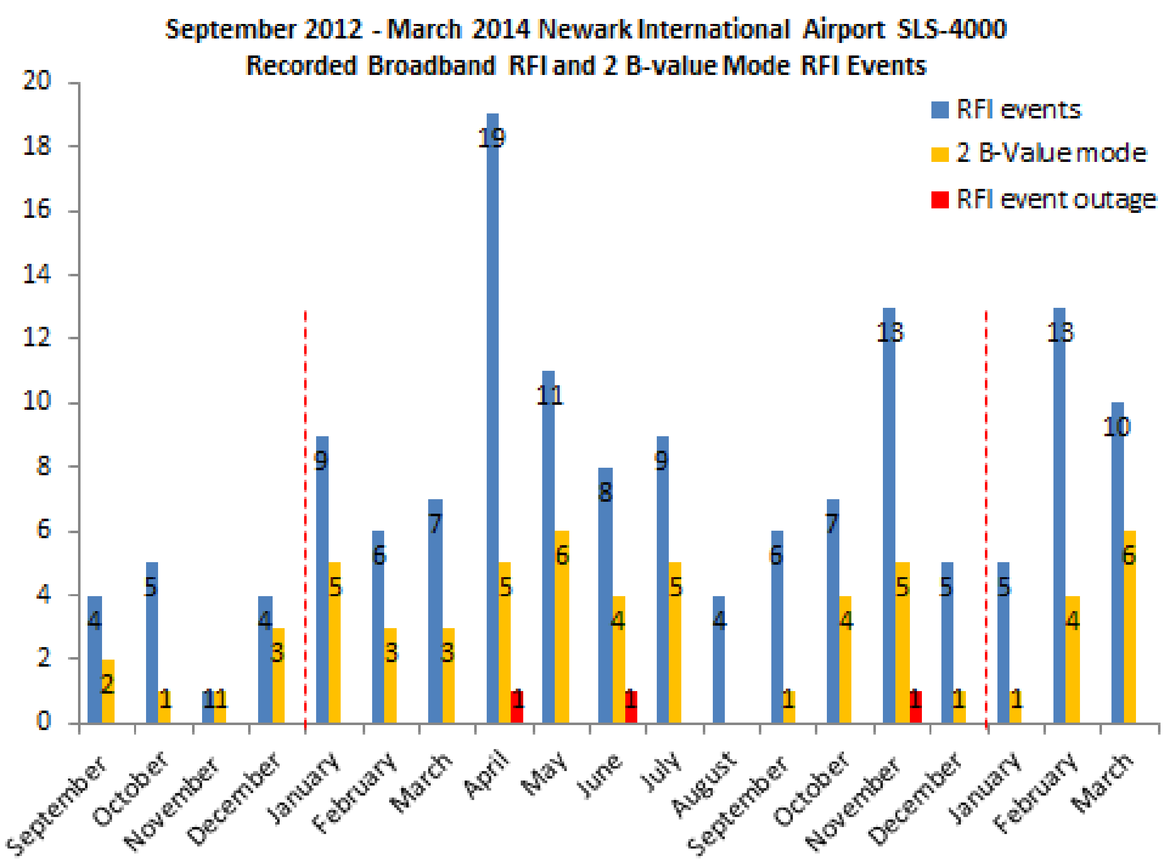


Figure 32: The above graph depicts approximately how many RFI events happened between the September "go live" date in 2012 up until the end of December 2013

The RFI threat is still imminent not only at Newark International Airport or GBAS, but to any system using digital guidance for differential GPS to provide precision. Since the September 28th 2012 “go live” date, due to the efforts of the RFI joint mitigation group, the SLS-4000 at Newark International Airport has only been affected by three RFI events that caused the system to perform in an RFI state, needing manual maintenance intervention to verify the RFI issues were resolved.

Currently, Honeywell is working on a software solution which has been stated, will resolve the RFI problems in Newark by providing better tolerance of the system in order to operate consistently during periods where RFI activity is strong.

- The RFI events listed are approximately how many RFI events happened within a given month as noted by the SLS-4000. The systems behavior is recorded via text spreadsheet known as System Event log and is stored locally by the station and gathered on a regular basis by local maintainers.

There are several monitors independent of the SLS-4000 that also monitor and record RFI events. One of these is the Ground Based Performance Monitor (GBPM) that in addition to monitor RFI has its primary function of monitoring GPS frequency and “listen” to the SLS-4000 system.

- 2 B-Value mode – When affected with a strong enough Broadband RFI, the number of common satellites drop below 4 (SV < 4). As a GPS receiver needs at least 4 or more satellites to provide trilateration, in turn providing optimal precision, the SLS-4000 will go into a protected state, in which it will begin operating in a 2 B-value mode, as recorded in the Systems event log. In this state, the station will remain in Normal mode but cease broadcasting corrections until the number of common SVs is 4 or more (SVs >= 4).

- RFI outage – When the SLS-4000 is impacted by a strong RFI event that it must operate in 2-B Value mode, the station will broadcast corrections within 200 seconds as longs as the conditions are optimal for its performance. In cases where the system cannot operate due to its continual protection from RFI and to continue to uphold its integrity from being used under these conditions, we call this an RFI outage. During these instances, manual intervention will be needed to help validate the outage and remove any potential threat in order for the system to continue its performance. As of March 2014, there have only been 3 reported instances of these RFI outages since the station has been given operational approval on September 28th 2012.

8.2.1 RFI Outages in Detail at EWR

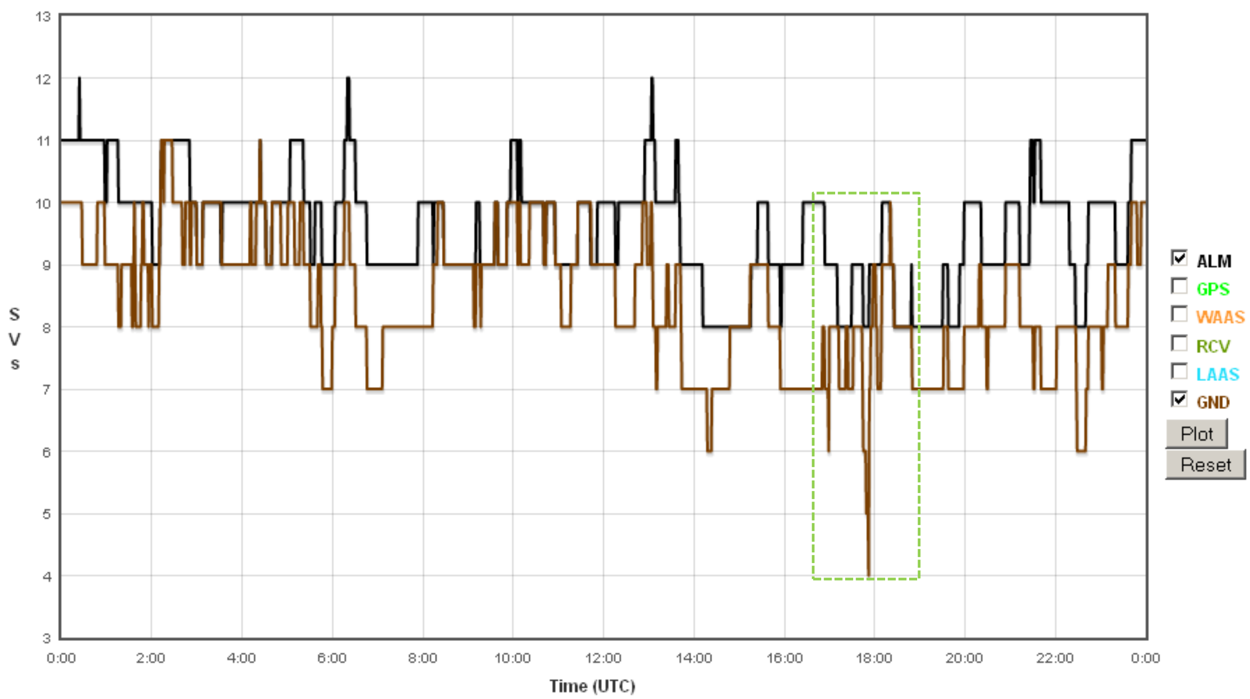


Figure 33: 1st RFI EWR Event Outage 4-17-2013

Figure 33 depicts the first RFI event that provided outage to the SLS-4000 since the "go live" date. The black horizontal line represents GPS almanac and its behavior. The Brown line represents how the SLS-4000 is behaving. Within the dotted green box the observance of the dramatic decrease in satellite acquisition is apparent. This particular outage lasted 30 seconds.

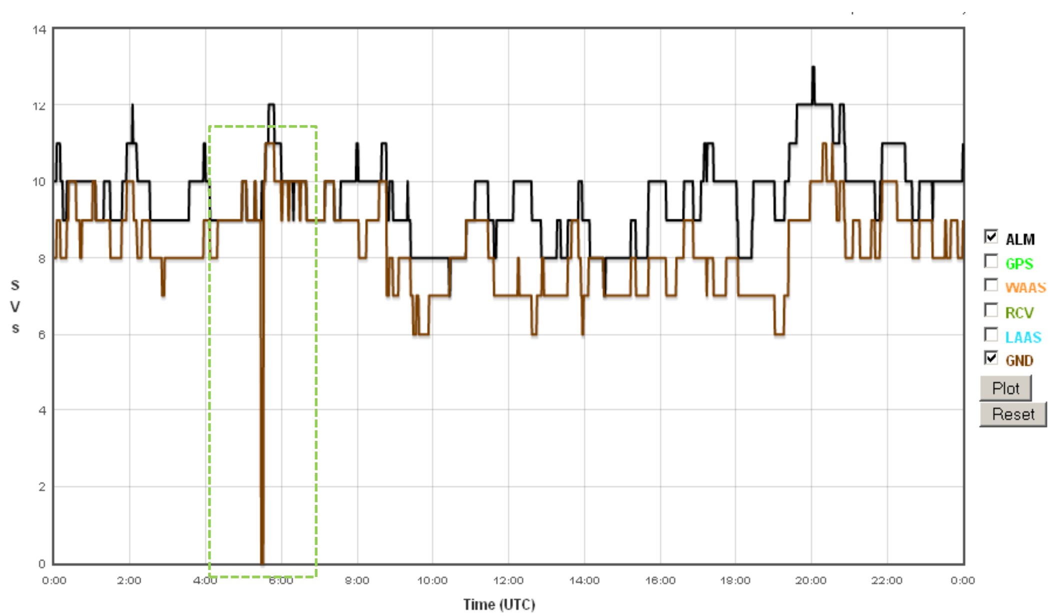


Figure 34: 2nd RFI EWR Event Outage 6-19-2013

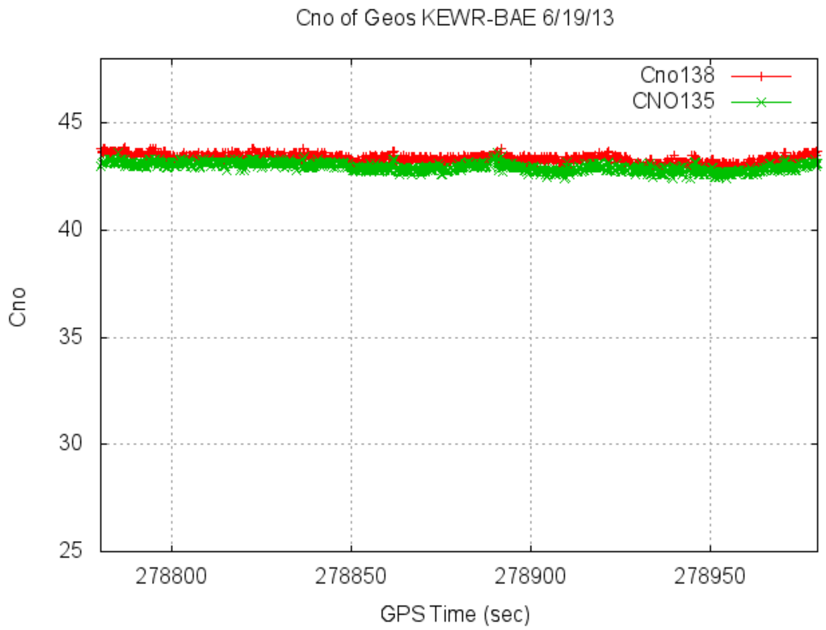


Figure 35: 2nd RFI EWR Event Outage 6-19-2013 as recorded by Ground Based Performance Monitor (GBPM)

There are several independent systems that are used in monitoring and characterizing RFI. One of these systems is the GBPM and although it is not the primary function of the GBPMs, it is a tool often referenced. Figure 36 depicts the GBPM observation of the RFI event that transpired on June 19th. Interestingly to note, the CN_O was not affected by the RFI event as opposed to what is depicted on from the SLS. This can still portray much information from comparison, as it was later hypothesized that the RFI event was more local to the SLS-4000 and not from a traveling vehicle on the highway.

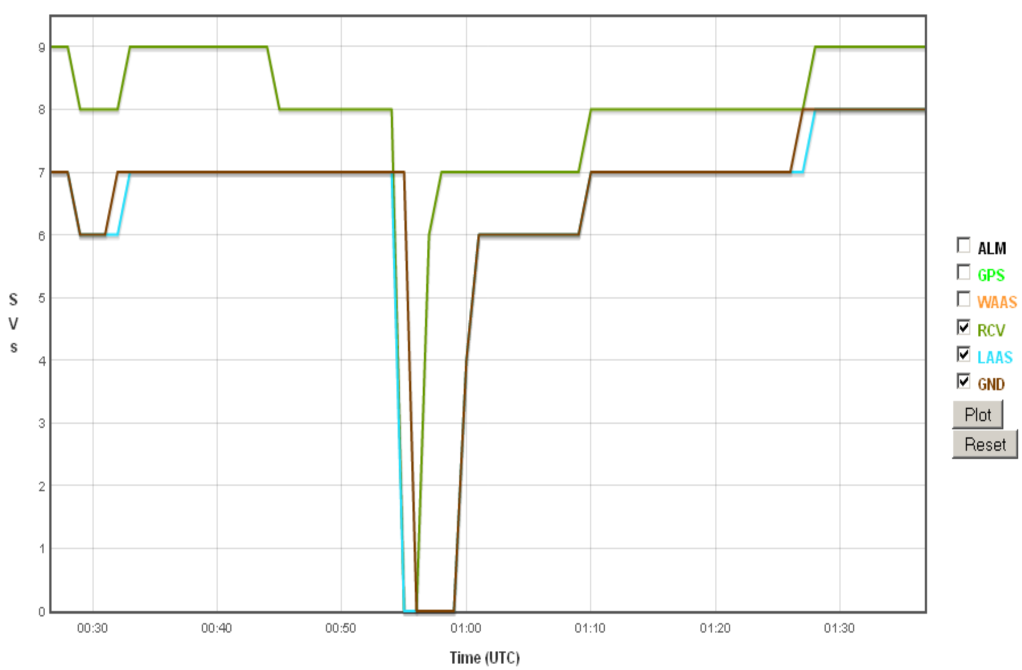


Figure 36: 3rd RFI EWR Event Outage 11-3-2013

The characteristics of the GBAS performance can be easily obtained from looking at current and historical data from the LAAS website, as depicted in Figure 36 along with the previous observed outages listed. The brown vertical line represented as GND is the SLS-4000 performance, the light blue LAAS representation is of the GBPM behavior, the dark green RCV is the GPS receiver behavior of the GBPM. This shows that the RFI impacted the GBAS monitor first, which is located in a separate facility, further north of the SLS-4000, followed by the GBAS station.

Since the 3rd RFI event, there have been no RFI outages during the first quarter.

8.3 Newark Chronos Testing

Figure 37: Chronos Jammer Detector

In a continued effort by the Port Authority of New York and New Jersey (PANYNJ) to protect GPS and NAVAIDS using GPS from the threat of RFI influence and in order to continue commercial operations and the safety of its personnel, implementation of RFI detector instruments have been deployed and are currently installed in various guard post locations around Newark International Airport in which there may be high areas of risk areas of strong concentrated RFI activity local to the airport.

The Chronos CTL3520 is a portable handheld GPS RFI instrument that is designed to both detect and locate the presence of RFI relative to Personal Privacy Devices (PPDs) located in vehicles. The Chronos detector uses a display that indicates the direction of the jammer with a visual marker. In addition, it uses eight LEDs which represent signal strength dependent on how strong the RFI present is. It will also use an audible alarm to detect any RFI local to the device. The device also allows even logging by time stamping events which are internally stored, and can be exported to any current windows based platform. It is sensitive enough to detect many low power RFI devices and can be fine-tuned to detect stronger RFI, excluding the low powered ones based on individual needs.

Currently, the PANYNJ have implemented the Chronos detector during their reconstruction of runway 4-left and will continue to use these handheld devices to closely detect RFI.

9. Glossary of Terms

—A—

ACY
Atlantic City International Airport 2

AOA
Air Operations Area 2

—C—

CDI
Course Deviation Indicator 12

CMC
Code Minus Carrier 4

CPU
Central Processing Unit 10

—D—

DGPS
Differential Global Positioning System 7

—E—

EWR
Newark Liberty International Airport 20

—G—

GBAS
Ground Based Augmentation System 4

GNSS
Global Navigation Satellite System 11

GPS
Global Positioning System 4

GSL
GBAS Service Level 14

—H—

HPL
Horizontal Protection Level 14

—I—

IAH
George Bush Intercontinental Airport 23

IMLA
Integrated Multi-Path Limiting Antenna 7

—L—

LAAS
Local Area Augmentation System 2

LHCP
Left Hand Circular Polarized 12

LPAR
LAAS Performance Analysis Report 2

LT
LAAS Test 11

LTP

10. Index of Tables and Figures

11. Key Contributors and Acknowledgements

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