Federal Aviation
Administration

Ground Based Augmentation System
Performance Analysis and Activities Report

Reporting Period: July 1 – September 30, 2014

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1. Introduction

The Ground Based Augmentation System (GBAS) team under the direction of the Navigation Branch (ANG-C32) in the Engineering Development Services Division in the Advanced Concepts and Technology Development Office at the Federal Aviation Administration's (FAA) William J Hughes Technical Center (WJHTC) provides this GBAS Performance Analysis / Activities Report (GPAR).

This report identifies the major GBAS related research, testing, and validation activities for the reporting period in order to provide a brief snapshot of the program directives and related technical progress. Currently, the GBAS team is involved in the validation of the GAST-D ICAO SARPs, long-term ionospheric monitoring, supporting system design approval activities for an update to the CAT-I approved Honeywell International (HI) Satellite Landing System (SLS-4000), and observing trends and anomalies utilizing the FAA's Local Area Augmentation System (LAAS) Test Prototype (LTP) (Internationally standardized as GBAS), six Ground Based Performance Monitors (GBPM), and prototype Honeywell Satellite Landing System here at Atlantic City International Airport (ACY).

Objectives of this report are:

a) To provide status updates and performance summary plots per site using the data from our GBPM installations
b) To present all of the significant activities throughout the GBAS team
c) To summarize significant GBAS meetings that have taken place this past quarter
d) To offer background information for GBAS

2. GBAS Updates by Site

The Ground Based Performance Monitor (GBPM), was designed and built by ANG-C32 to monitor the performance of our GBAS installations. There are currently six GBPM's in use. They are located in Newark New Jersey (EWR), Houston Texas (IAH), Moses Lake Washington (MWH), Rio de Janeiro Brazil (GIG), and two in Atlantic City New Jersey (ACY). The GBPM is used to monitor integrity, accuracy, availability, and continuity of the LTP and Honeywell's SLS-4000. The plots in each of the following sections utilize a compilation of data collected at one minute intervals. For live, up-to-date data, refer to http://laas.tc.faa.gov. A more detailed description of the GBPM configuration can be found in Appendix D of this report.

2.1 EWR SLS

- Newark has a Honeywell SLS-4000 that was granted operational approval on September 28, 2012
- Since the EWR SLS-4000 went live, United Airlines has conducted GBAS approaches 366 times as of August 2014
- British Airways has routine flights by four GLS-equipped B-787s into EWR and uses the SLS-4000 approximately twice a day

Figure 1 - EWR SLS-4000 Configuration

2.1.1 Outages and Prediction Performance

- As of September 19, the reoccurring outage in EWR has been alleviated by the launch of PRN 9
- There have been no outages or predicted outages since
- Any future outages should be handled by the Block II update currently planned for completion in the second quarter of 2015

2.1.2 Real Time Performance Data

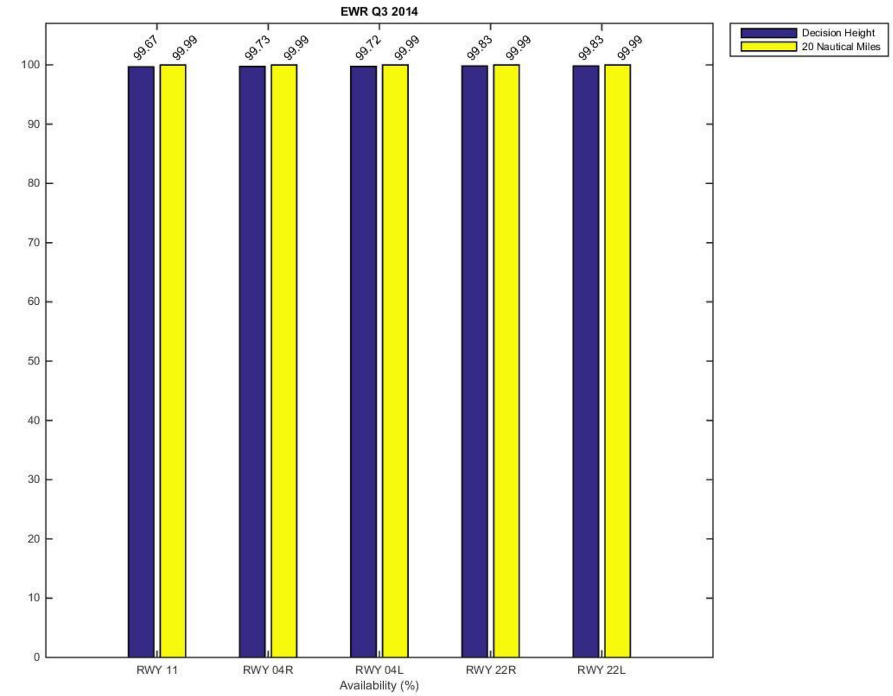

Figure 2 - EWR Availability for Q2 of 2014

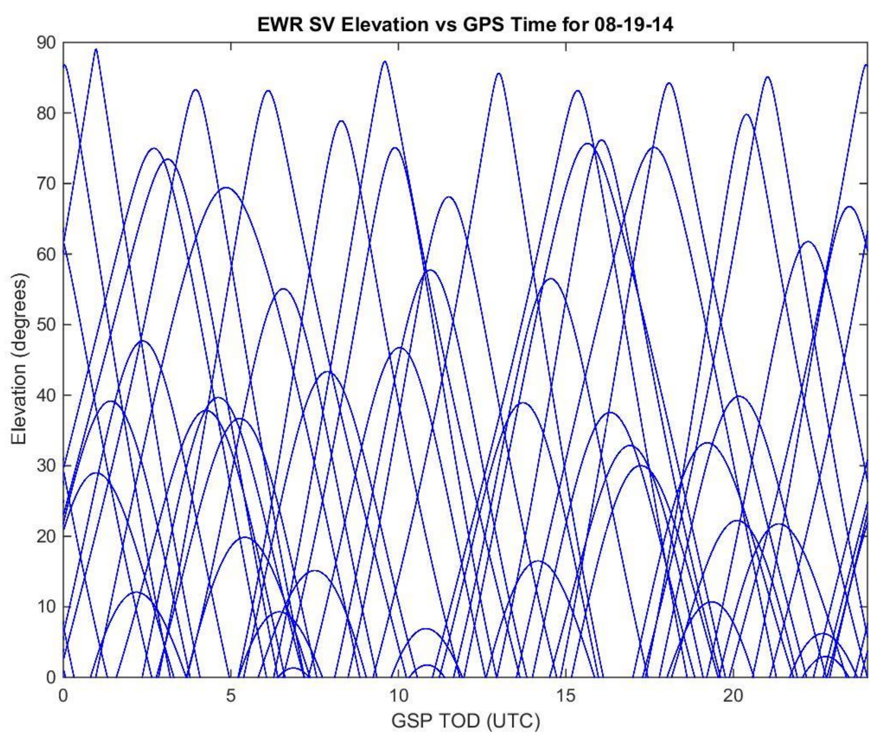

Figure 3 - EWR SV Elevation vs GPS time 5/15/14

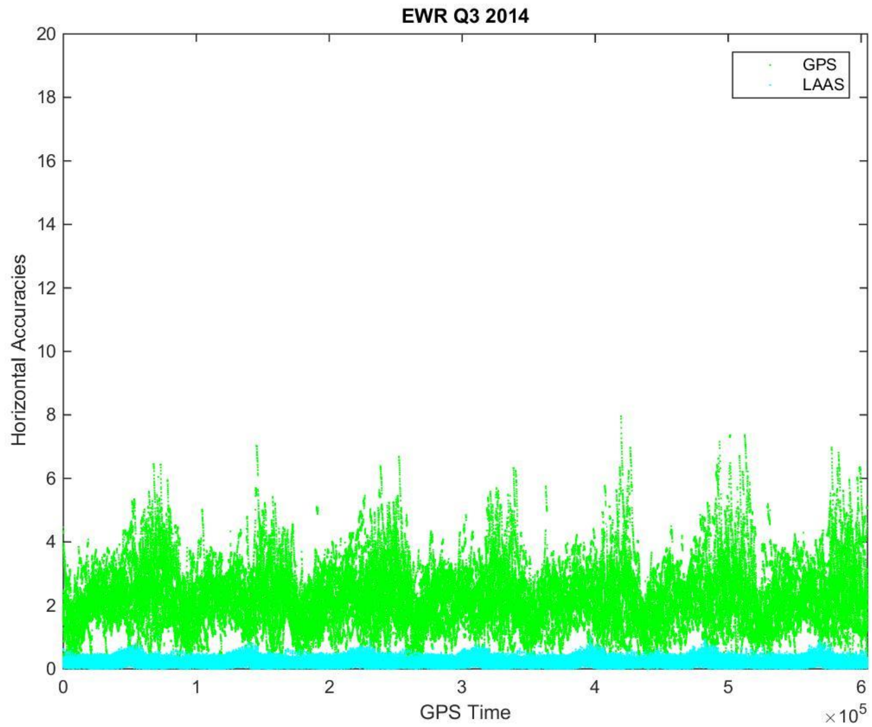

Figure 4 - EWR Horizontal Accuracy Plot

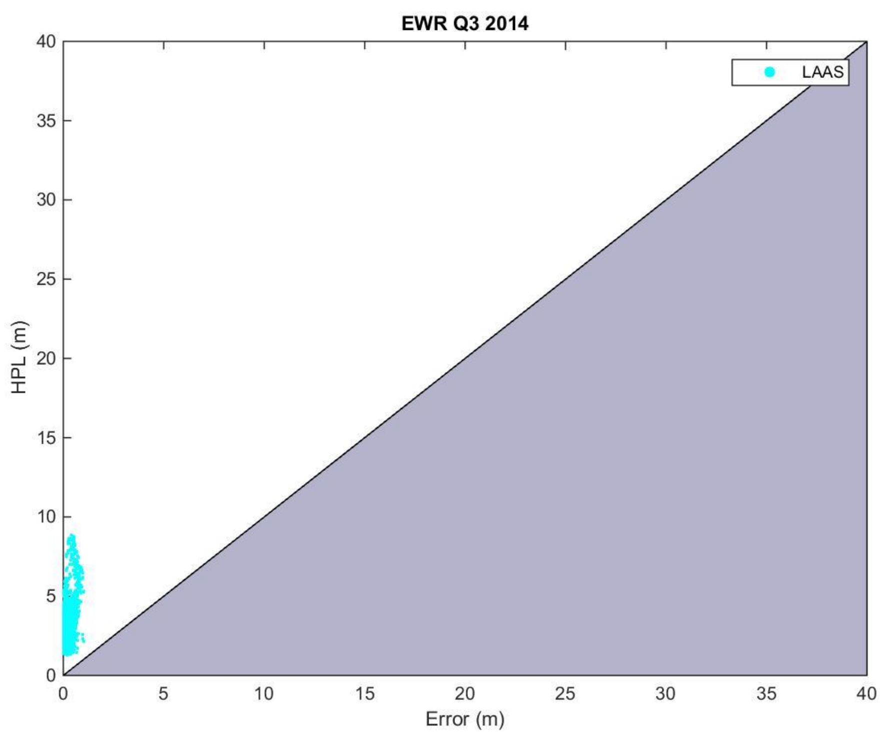

Figure 5 - EWR Horizontal Accuracy vs. Error

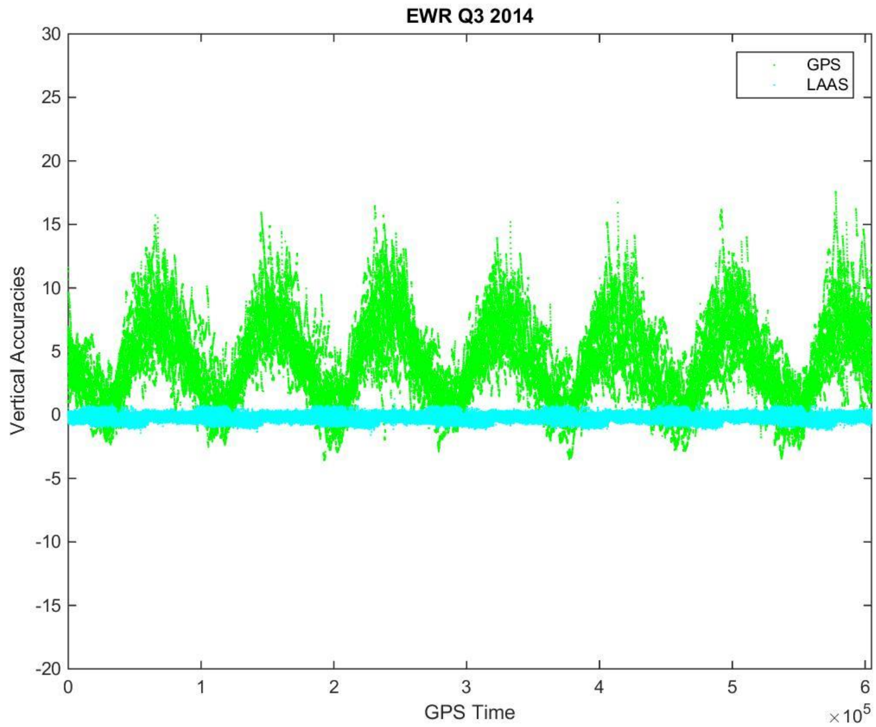

Figure 6 - EWR Vertical Accuracy

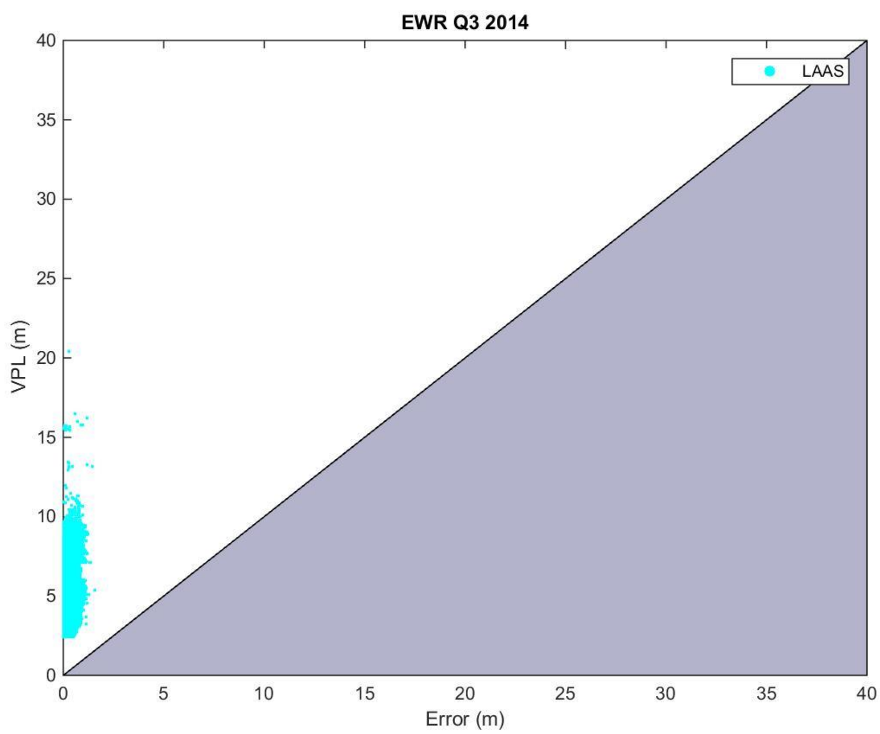

Figure 7 - EWR Vertical Accuracy vs. Error

2.2 IAH SLS

- Houston has a Honeywell SLS-4000 that was granted operational approval on April 22, 2013
- Since IAH went live, United Airlines has conducted GBAS approaches 499 times as of August 2014

Figure 8 - IAH SLS-4000 Configuration

2.2.1 Outages and Prediction Performance

- The recurring outage in IAH has been mitigated by the changing satellite geometry
- Any future outages should be handled by the Block II update currently expected to be complete in the second quarter of 2015
- There were seven outages caused by NANUs this quarter; six of which were accurately predicted

2.2.2 Real Time Performance Data

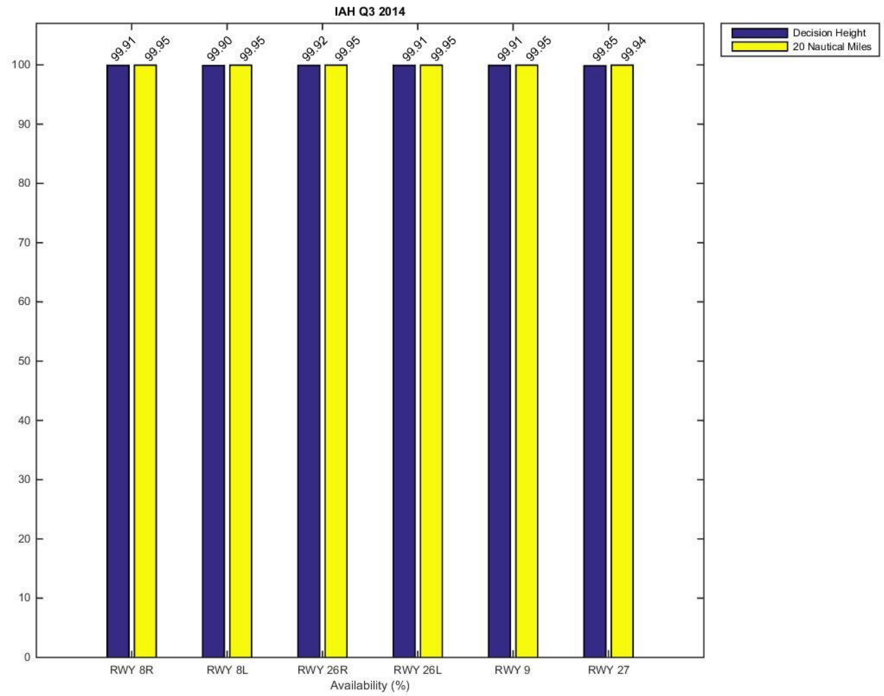

Figure 9 - IAH Availability for Q2 of 2014

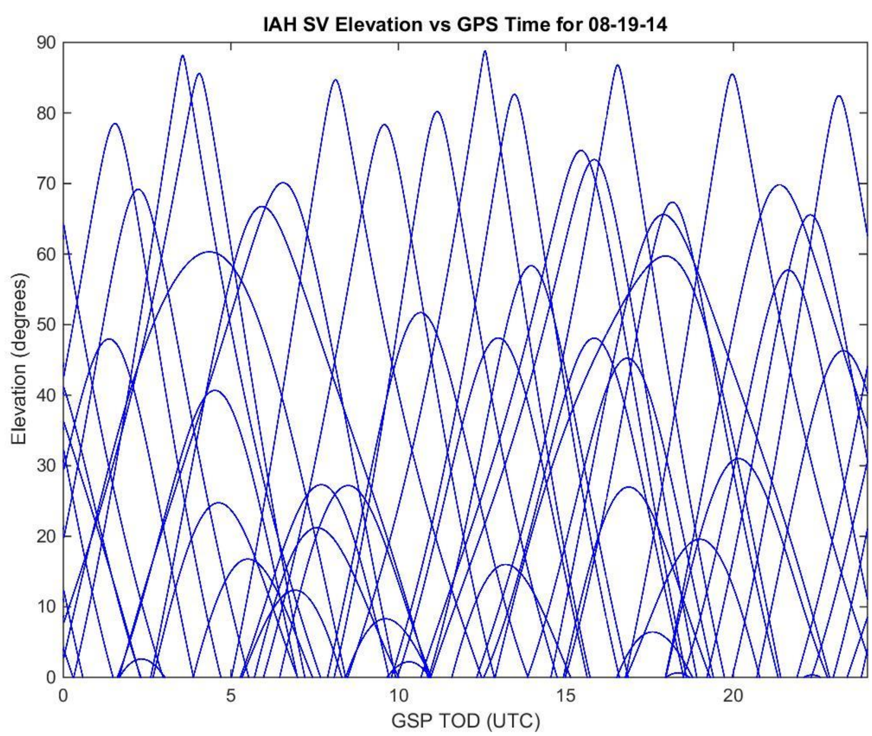

Figure 10 - IAH SV Elevation vs GPS time 5/15/14

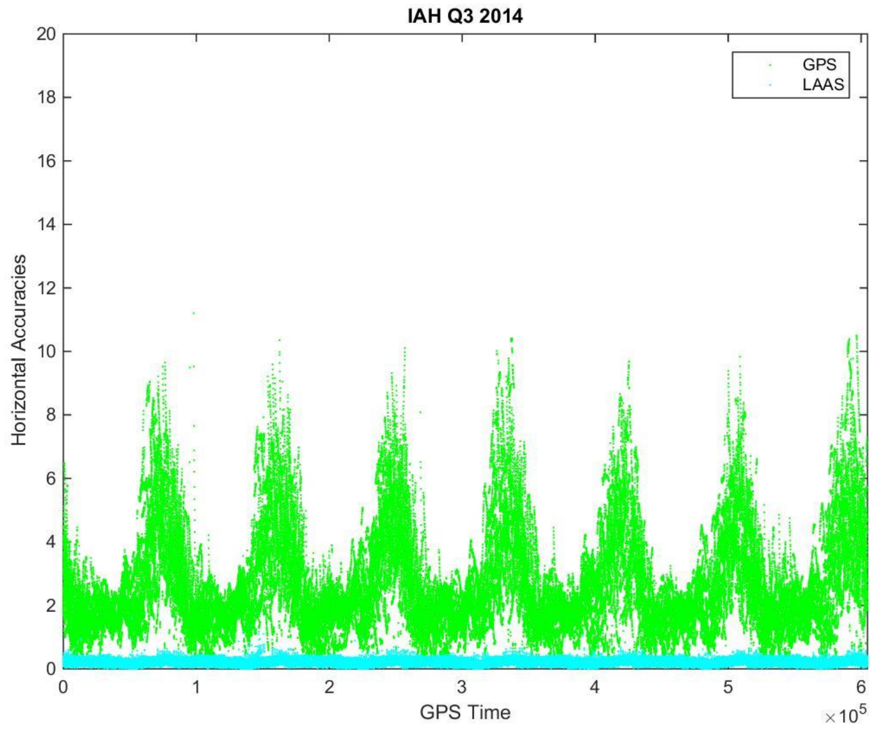

Figure 11 - IAH Horizontal Accuracy Plot

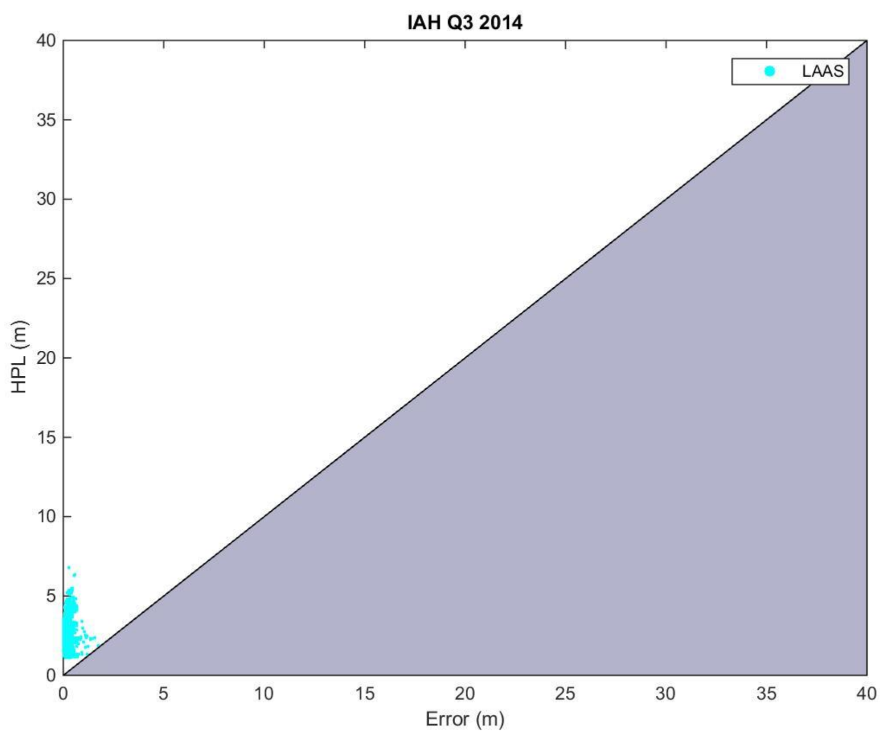

Figure 12 - IAH Horizontal Accuracy vs. Error

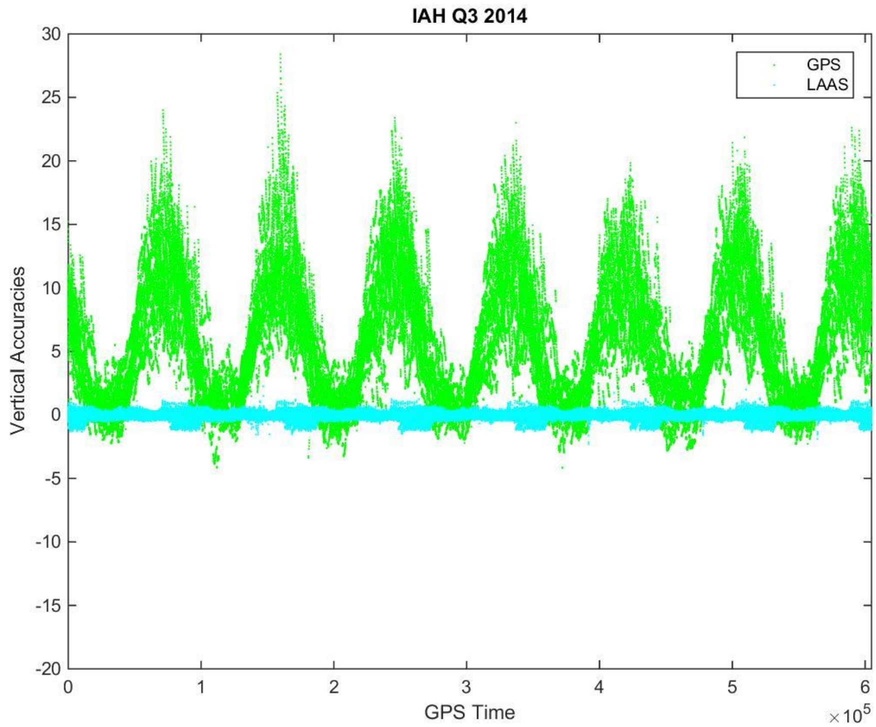

Figure 13 - IAH Vertical Accuracy

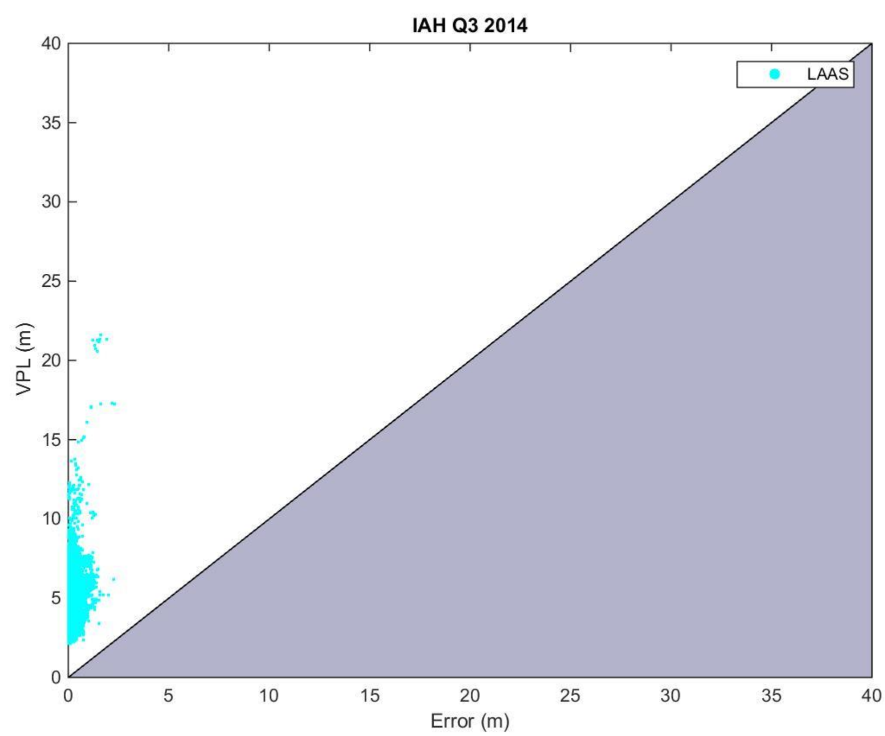

Figure 14 - IAH Vertical Accuracy vs. Error

2.3 MWH SLS

- Moses Lake has an Honeywell SLS-4000 that was granted operational approval on January 9, 2013
- Boeing uses this site for production activities
- Boeing will also operate this site in a prototype GAST-D mode for flight test to support GAST-D validation
- While Grant Country Airport (GEG) is a public use airport, it has no commercial flights

Figure 15 - MWH SLS-4000 Configuration

2.3.1 Real Time Performance Data

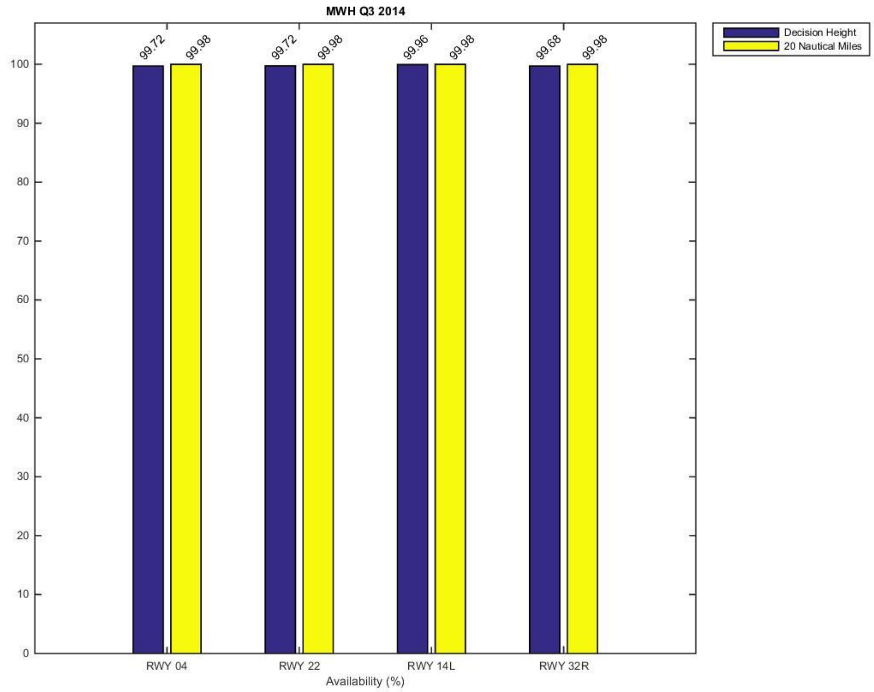

Figure 16 - MWH Availability – The data shown is based upon times when the SLS was transmitting corrections

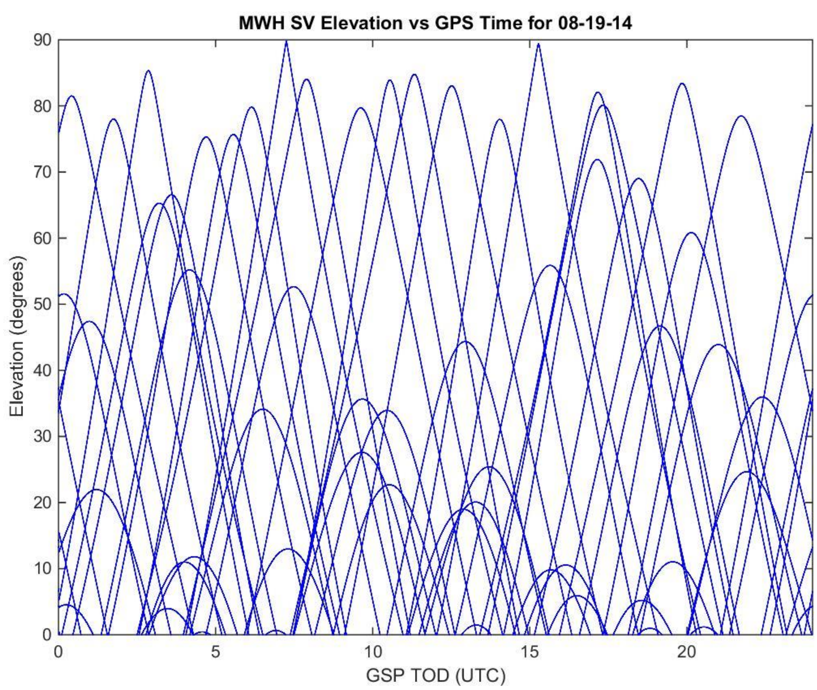

Figure 17 - MWH SV Elevation vs GPS time 5/15/14

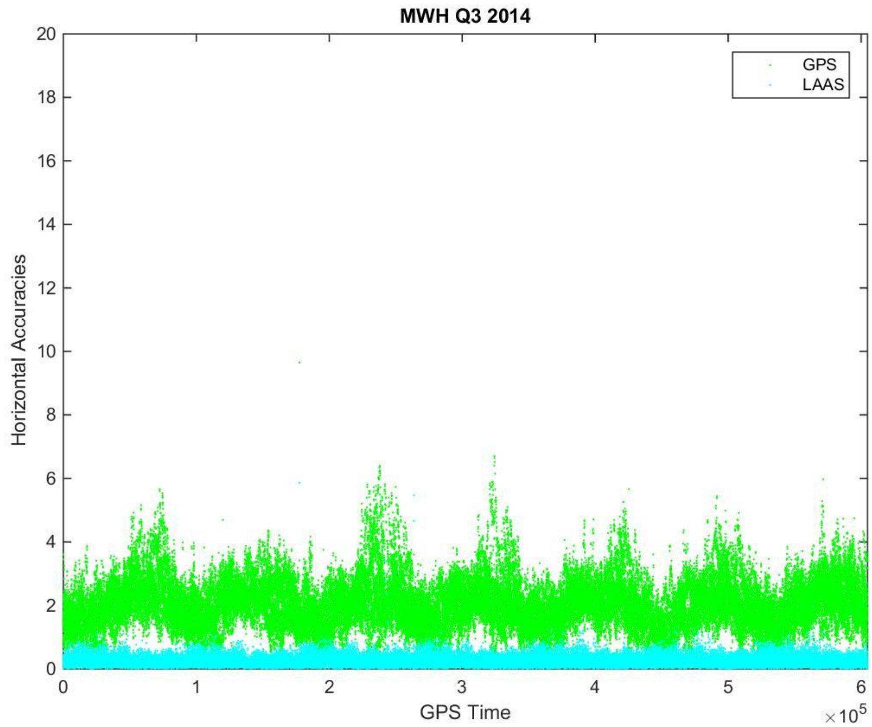

Figure 18 - MWH Horizontal Accuracy Ensemble Plot

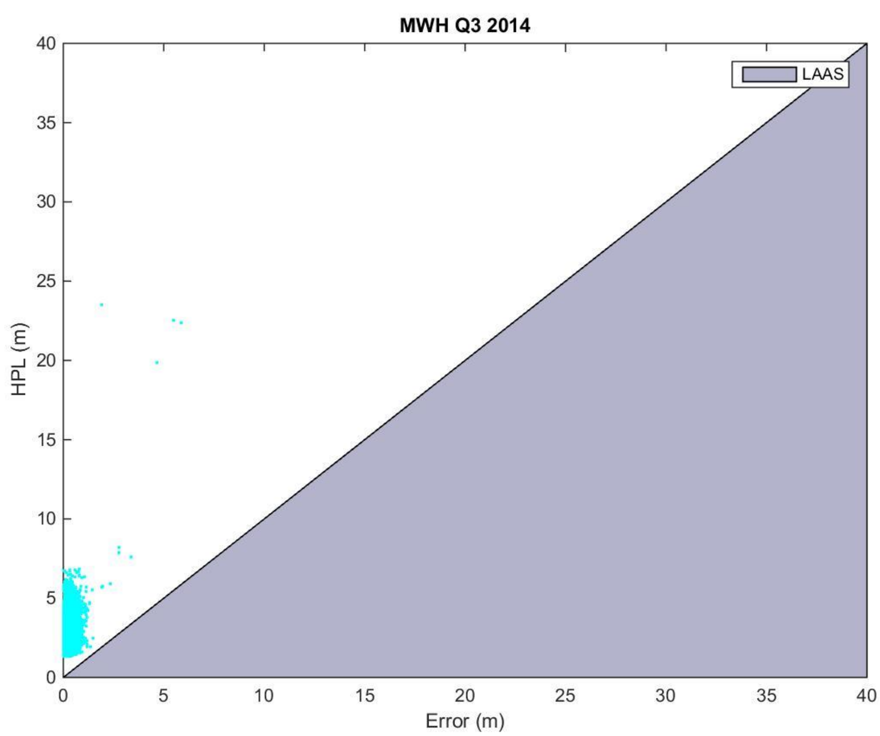

Figure 19 - MWH Horizontal Accuracy vs. Error Bounding Plot

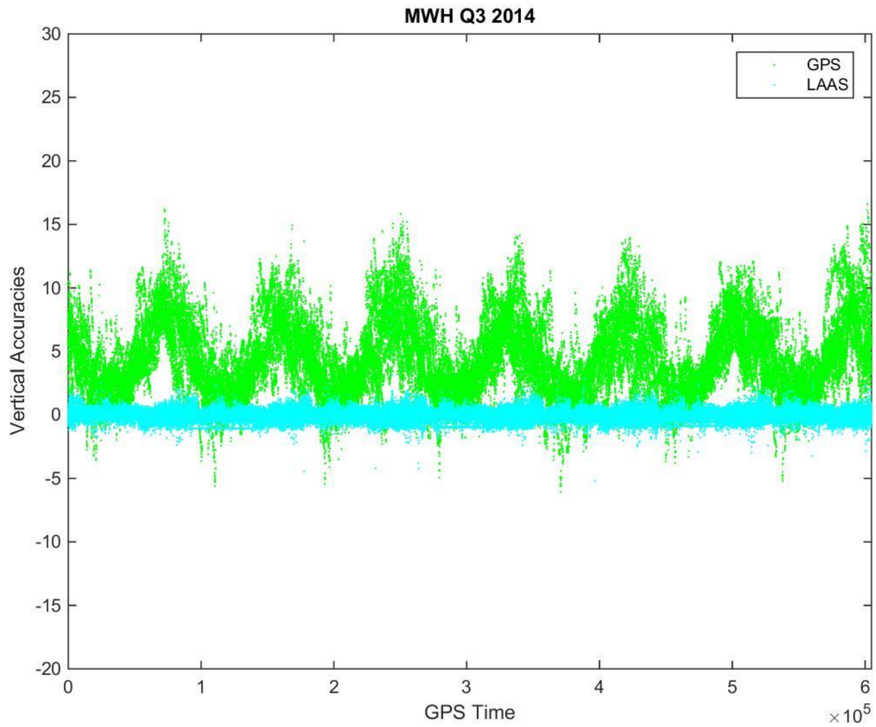

Figure 20 - MWH Vertical Accuracy

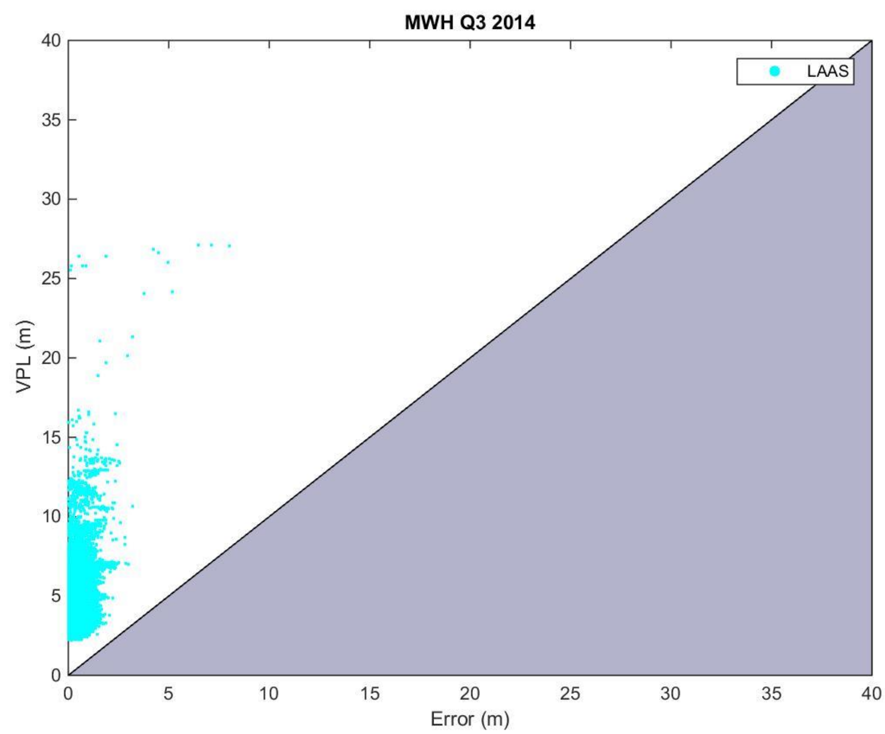

Figure 21 - MWH Vertical Accuracy vs. Error Bounding Plot

2.4 Rio de Janeiro Brazil

- System is a Honeywell SLS-4000 operating in a GAST-C Block II prototype mode
- The antenna on the Brazil monitor is less robust than the other sites, therefore satellites below 11 degrees may not be tracked as reliably

2.4.1 Real Time Performance Data

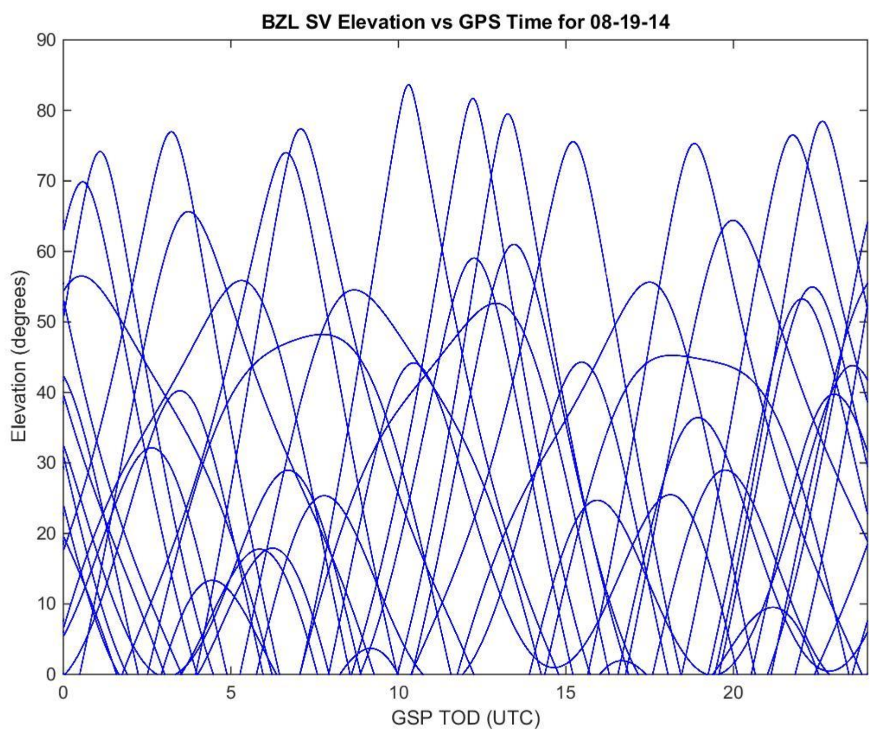

Figure 22 - BZL SV Elevation vs GPS time 5/15/14

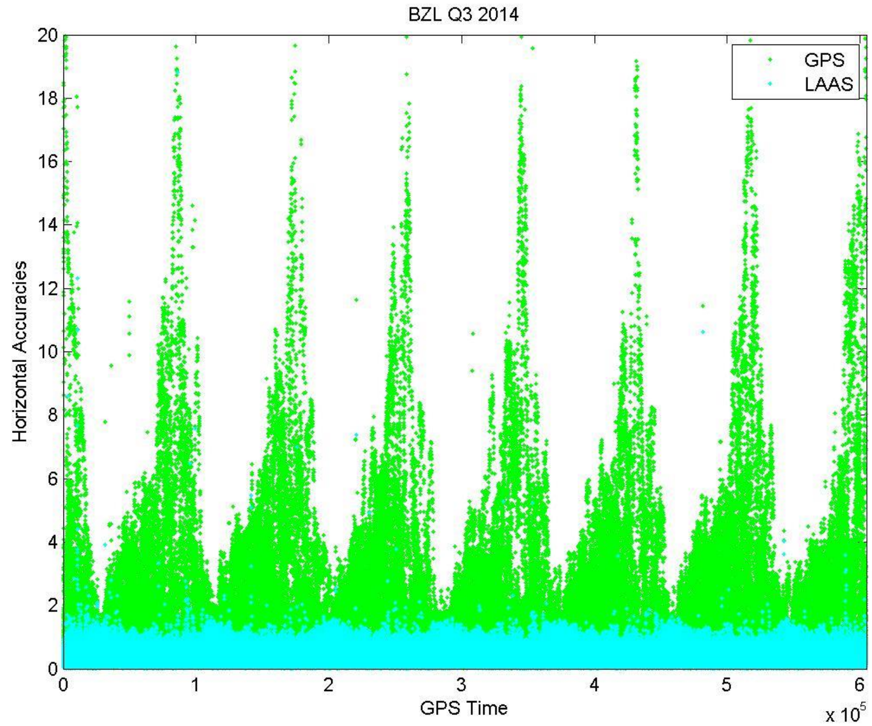

Figure 23 - BZL Horizontal Accuracy Ensemble Plot

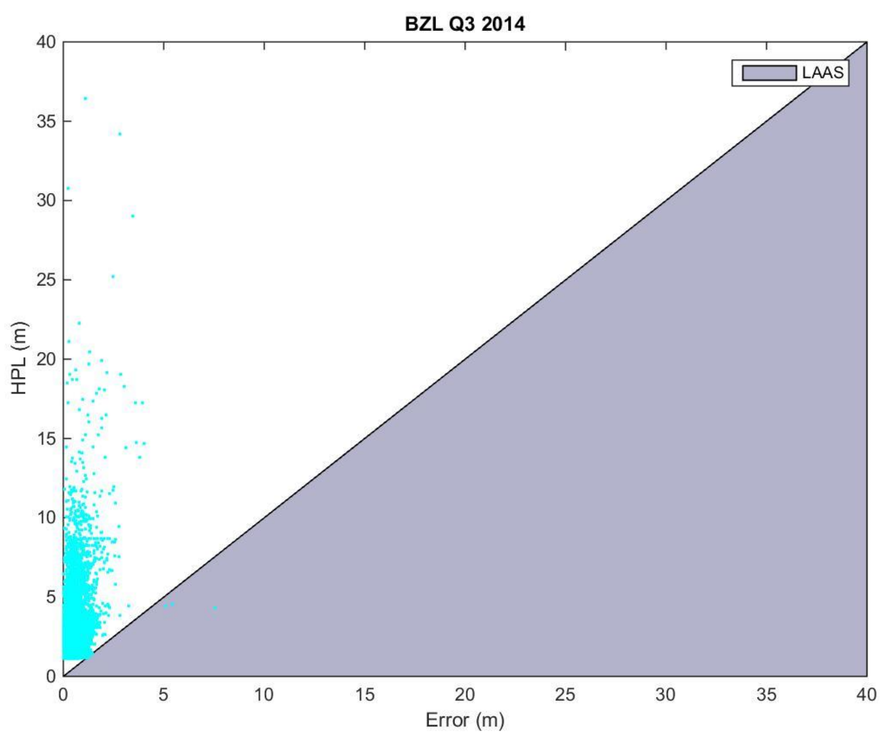

Figure 24 - BZL Horizontal Accuracy vs. Error Bounding Plot

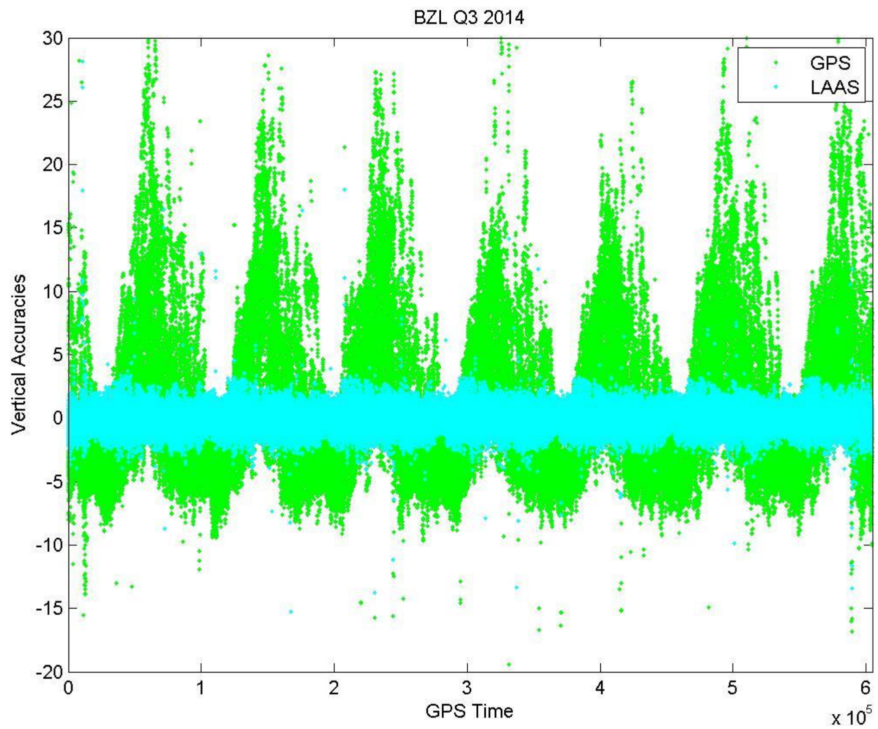

Figure 25 - BZL Vertical Accuracy

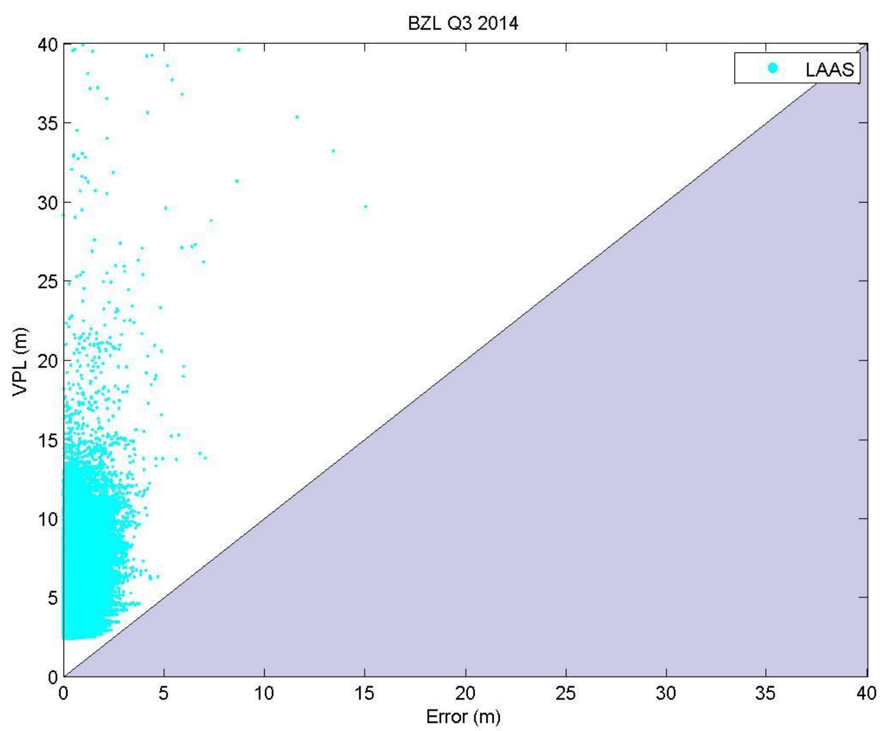

Figure 26 - BZL Vertical Accuracy vs. Error Bounding Plot

2.5 ACY SLS

- The SLS is currently configured in GAST-D prototype mode
- See the below image and description for complete details on the configuration and testing being done

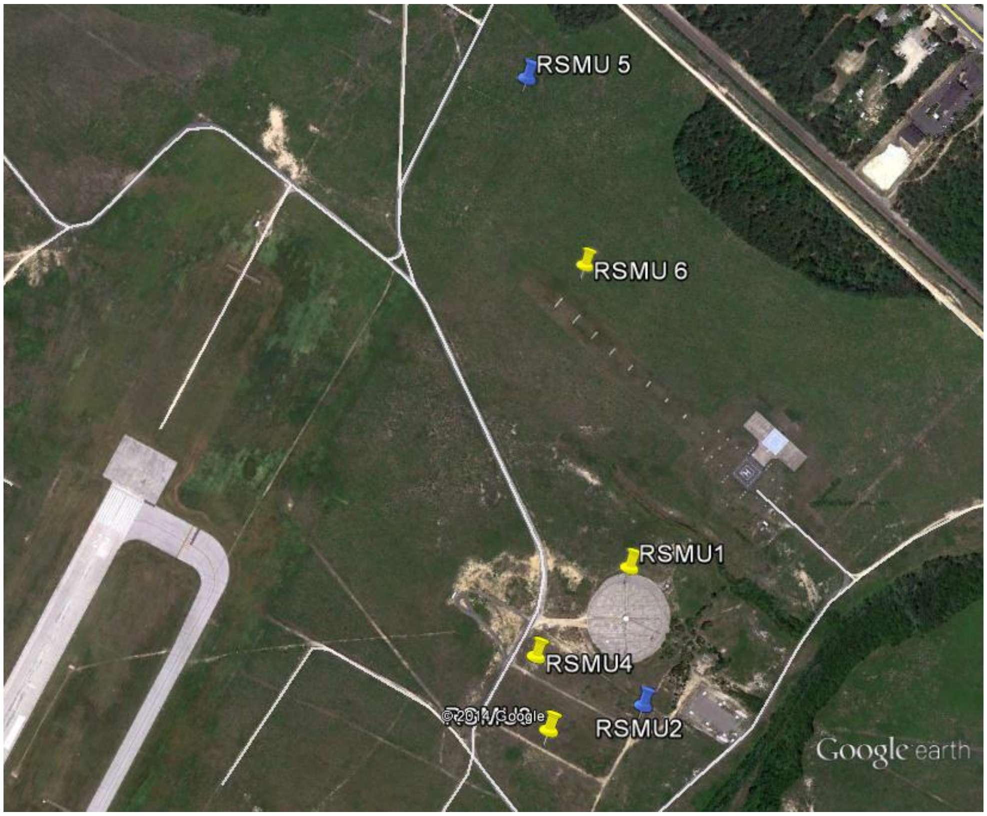

Figure 27 - ACY GAST-D Configuration

The picture above shows the current locations of all 6 reference receivers available under the new prototype GAST-D 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 Ionosphere Graident Monitor (IGM), is also performed using the 6 reference receivers. The additional references also allow for more, and longer baselines for IGM.

2.5.1 Real Time Performance Data

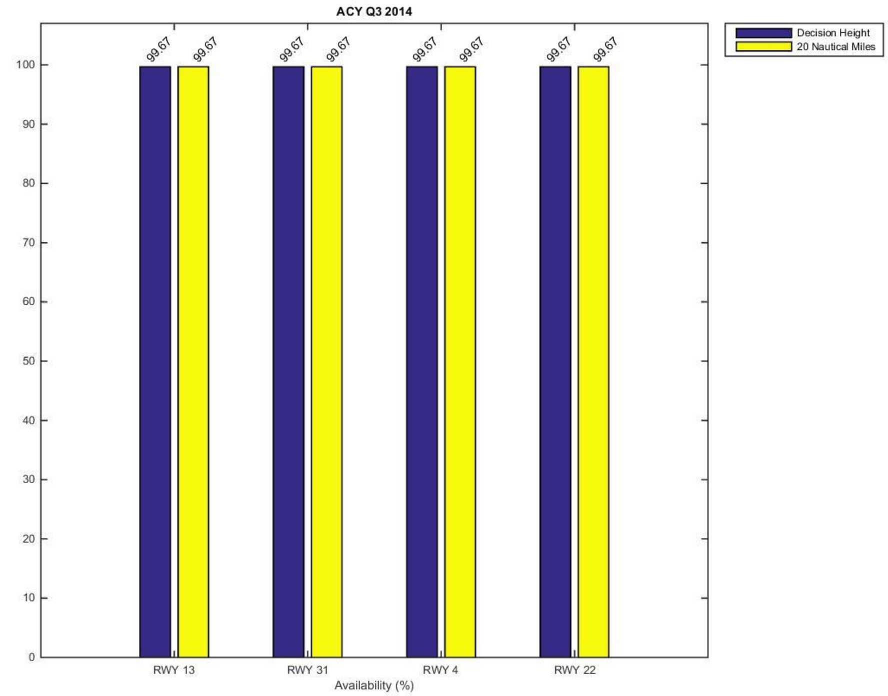

Figure 28 - ACY Availability

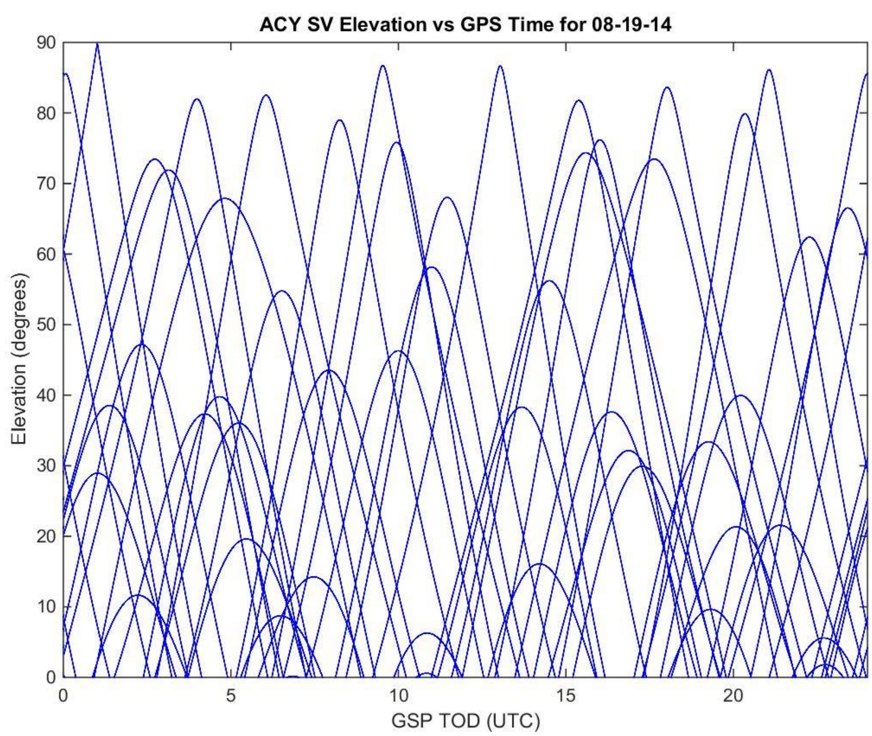

Figure 29 - ACY SV Elevation vs GPS time 5/15/14

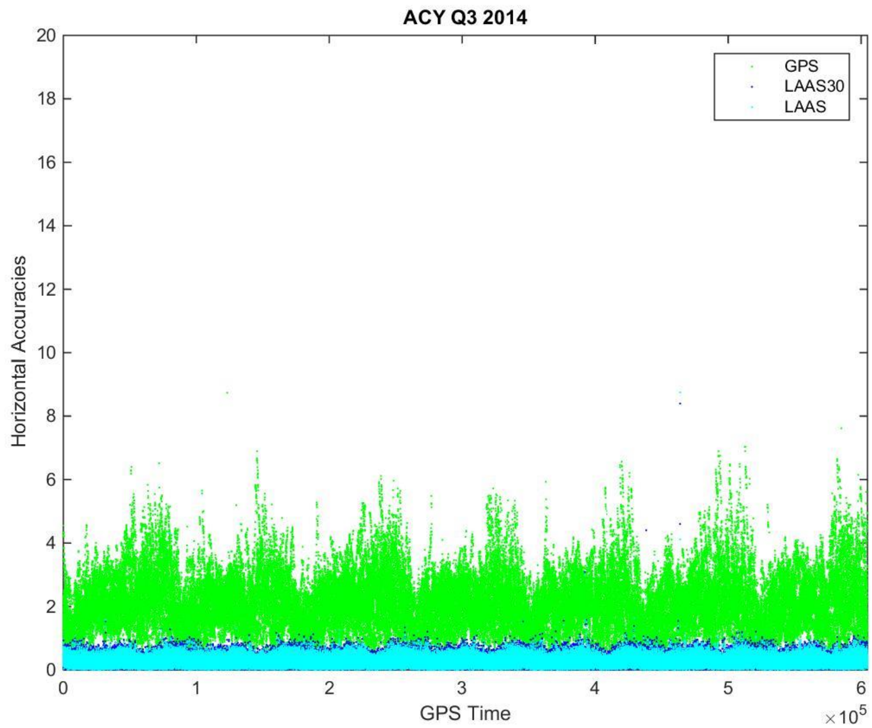

Figure 30 - ACY SLS Horizontal Accuracy Ensemble Plot

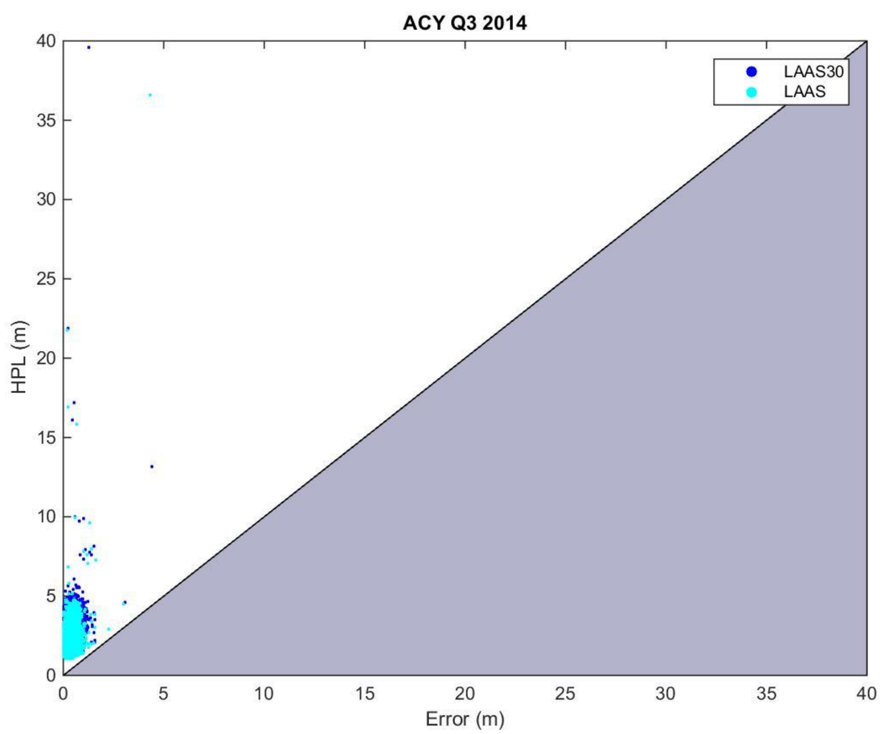

Figure 31 - ACY SLS Horizontal Accuracy vs. Error Bounding Plot

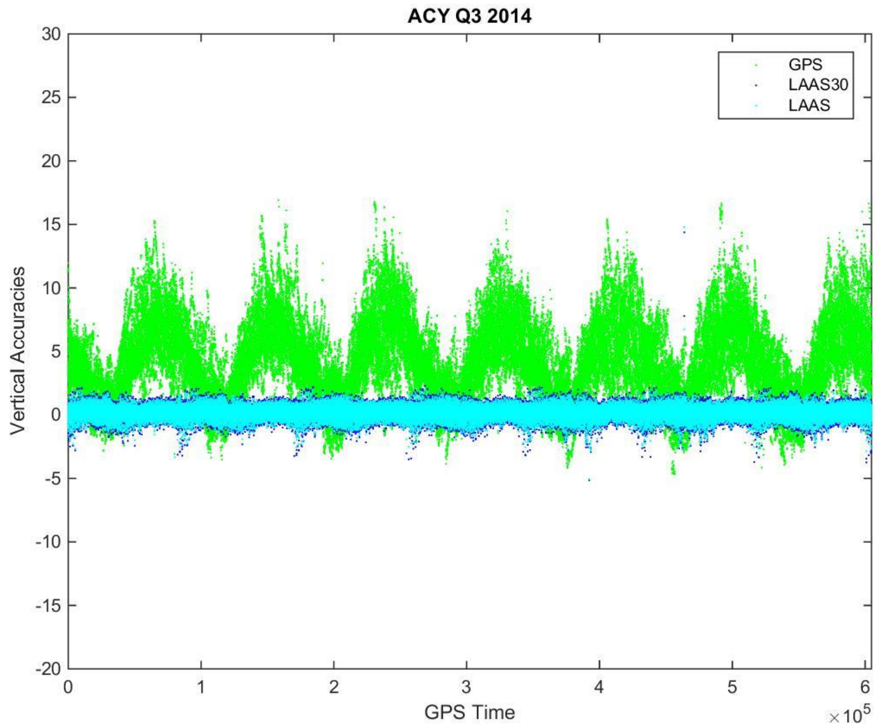

Figure 32 - ACY SLS Vertical Accuracy Ensemble

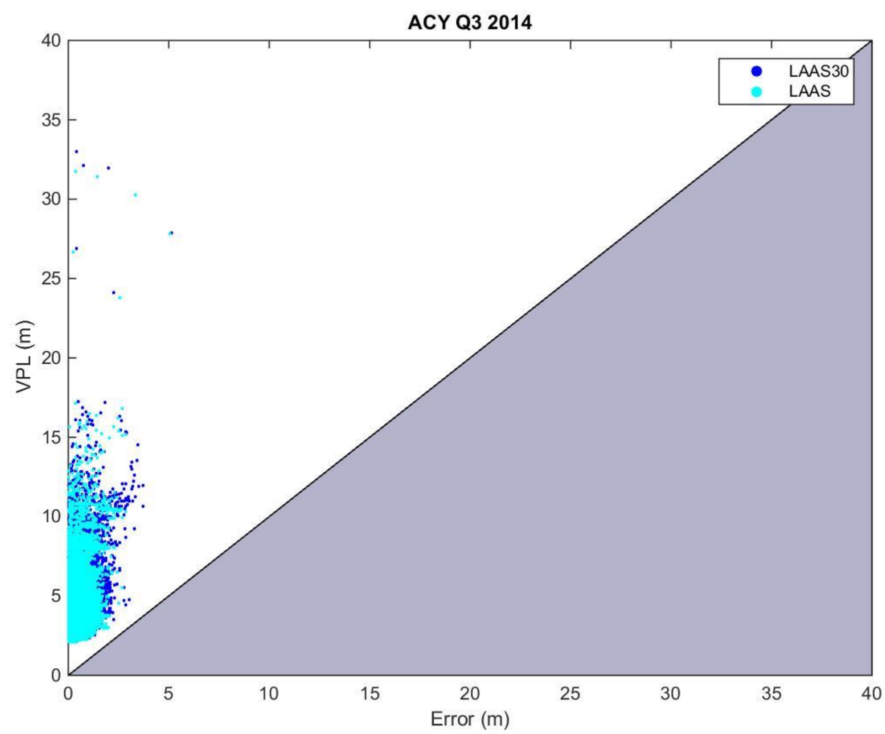

Figure 33 - ACY SLS Vertical Accuracy vs. Error Bounding Plot

2.6 LTP ACY

- The LTP has not been operational this quarter due to damaged fiber connections and other hardware components
- LTP hardware has been repaired, which includes repairs to fiber communication to 3 of 4 references, coaxial cable repairs to VDB antenna, as well as computer repair and network switch replacement. Software updates being conducted with various other configuration changes
- See Appendix C for a full description of the LTP configuration

Figure 34 - Aerial View of LTP Configuration

3. Research, Development, and Testing Activities

3.1 FAA Long-Term Ionospheric Monitoring (LTI) Activity

During severe ionospheric storms, the potential for large gradients in ionospheric delay between the GBAS and the airborne user exists. The current ionospheric threat model for 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 threat model provides the information necessary for a GBAS to apply appropriate error bounding to guarantee the required integrity for a precision approach.

The bounds of the threat model (**Figure 35**) were determined by processing a set of anomalous days during the last solar maximum in 2000-2003 (based on Kp and Dst). The Navigation Branch continues to process ionosphere data to ensure gradients larger than those included in the threat model are not present in 2014, the current 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 36** illustrates the current mid-latitude CONUS threat model, which includes confirmed gradients (in mm/km) from the 2003 solar maximum.

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 35 - Parameters for Mid-latitude CONUS Threat Model

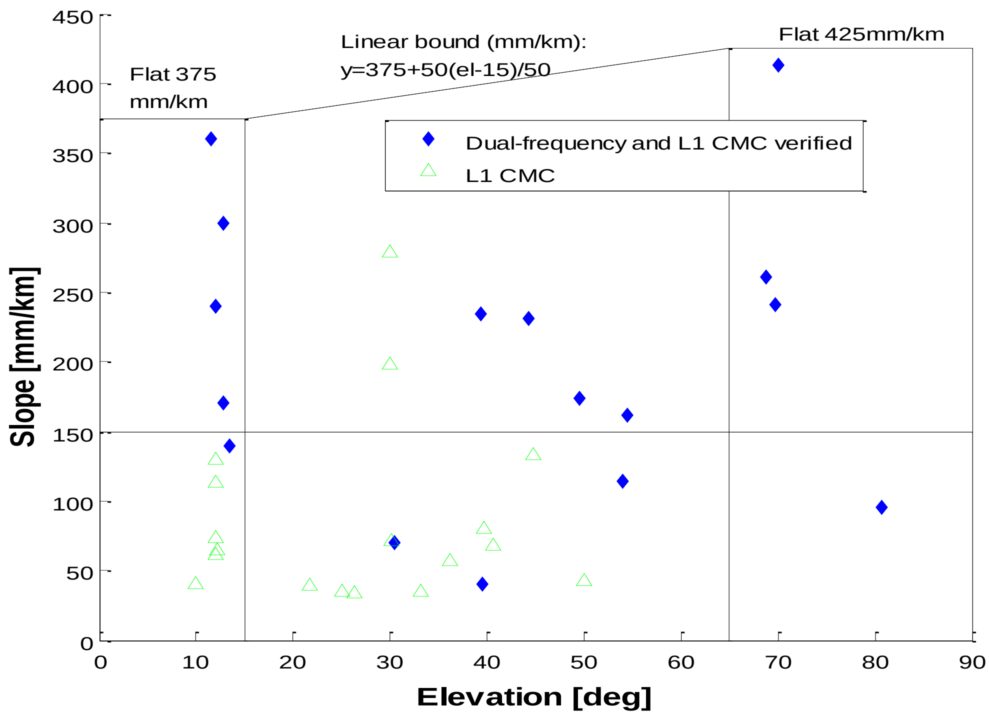

Figure 36 - Mid-latitude CONUS Threat Model with confirmed gradients (mm/km) from 2003

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. With regards to CONUS, we aim 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). For the CONUS region, an ionospheric storm is caused by interactions of solar induced radiation on the Earth's atmosphere, which in turn causes irregularities in the TEC of the ionosphere. These irregularities in the atmosphere can cause events of high or low TEC densities around the world and can extend for hundreds of Km and can last from minutes to hours. Ionospheric storms are threatening to GBAS and can cause a severe integrity threat.

The GPS Data Process block is used to read input data (in RINEX 3.11 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. Representative of a GBAS model, the first station represents an aircraft on approach and the second station simulates the GBAS 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 carrier measurement; we expect the dual-frequency gradient estimation to be the most accurate. The single frequency L1 CMC estimation is noisier, due to the nature of the code measurement; however, this measurement is not affected by L2 tracking anomalies and errors, which gives a good comparison against the dual frequency estimation. The most crucial aspect of manual validation comes from the comparison of these two different measurements. If the trends of both measurements match well (among other factors), then we can say with a high level of confidence that the observable gradient is caused by the ionosphere and not caused by receiver error (or other phenomenon).

Progress Report: Brazilian Threat Model Effort

The Navigation Branch entered into a cooperative project with the Brazilian Team (DECEA) to build a complete low latitude Ionosphere threat model. Of the three ionospheric regions, the largest is the equatorial (low latitude) region, the effects of which can be measured up to $\pm 30°$-$40°$ geomagnetic latitude, which comprises 50% of the earth's surface and covers much of the Brazilian Airspace. The equatorial region, located at approximately $\pm 20°$ on either side of the magnetic equator, has the highest values of Total Electron Content (TEC) directly proportional to ionospheric range delay in the world [1]. Unlike the CONUS (mid latitude) region, the process to build a low latitude threat model is more difficult 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). It should be noted that plasma bubbles have been observed to move from west to east along the geomagnetic dip, this effect can be utilized to our advantage when studying the speed and width of the bubbles.

In order to develop such a threat model, the Brazilians and Boston College developed a list of 100+ days that were considered threatening to GBAS users. The selection of days was based upon the scintillation index s4, as well as Kp and Dst indices over the past three years of the current solar cycle (Solar Cycle 24). The geomagnetic index Kp is a global average of horizontal component of earth's magnetic field ranging between 0 and 9. Disturbance, Storm-Time (Dst) is measured as the hourly averaged difference in nano-Tesla (nT) from the daily mean. Whereby, the lager deviation from the mean in Dst is indicative of the strength of the storm at any given location [1]. Dual frequency GPS data, from various CORS equivalent networks in Brazil was gathered for those identified days and then analyzed using LTIAM. The results included gradients above that of the CONUS Threat Model and commonly occurred during the post sunset hours, local time.

The list of roughly 120 days consists of data recorded from the following networks of CORS equivalent stations in Brazil:

1. RBMC - Brazilian Network for Continuous Monitoring of GNSS Systems consists of a network of 100+ dual frequency receivers that collect GPS data at 1 sample every 30 seconds.

2. LISN - Low-Latitude Ionospheric Sensor Network, the purpose of which is to study the low latitude ionosphere and upper atmosphere above Brazil. The stations include receivers designed to record Total Electron Content (TEC), as well as amplitude and phase scintillation measurements.

3. SIPEG - Integrated Positioning System for Geodynamic Studies

4. CIGALA - Concept for Ionospheric scintillation mitiGAtion for professional GNSS in Latin America, which aims to study low latitude ionospheric scintillation and to develop methods to mitigate the adverse effects on GPS signals.

5. Instituto de Controle do Espaço Aéreo (ICEA) operated Trimble and Septentrio receivers, useful for observing the ionospheric impact on GNSS signals in space.

The days that were selected include 8 non-scintillating days, 85 days with heavy scintillating days (based primarily on the number of satellites experiences scintillation during the day at various locations in Brazil), 7 storm days based on Kp, and 23 days of high geomagnetic activity based on Dst.

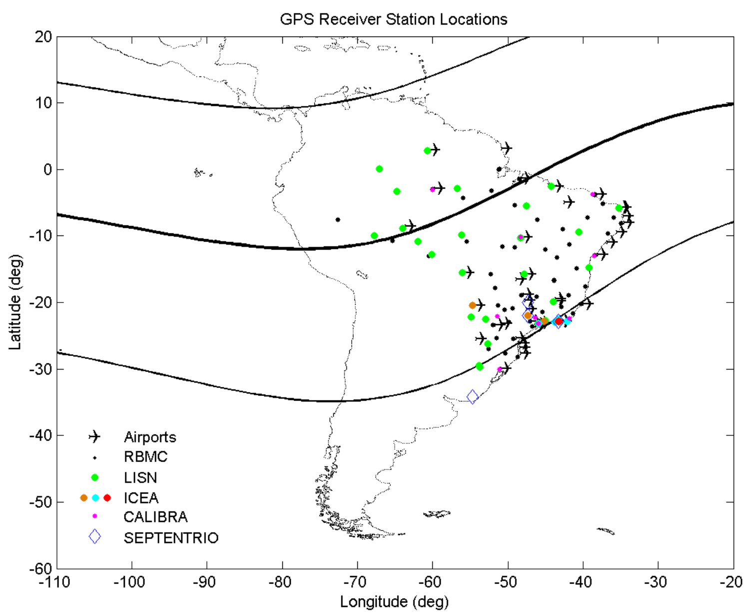

Figure 37 - Data coverage in Brazil [1]

The current working low latitude threat model is shown below in **Figure 38**, which shows the observed gradients with respect to the elevation of the satellites for all stations-satellite pairs. We have found several occurrences of gradients larger than those present in the CONUS Threat Model, the highest of which is measured to be ~625 mm/Km near Rio de Janeiro on March 7, 2014. An interesting point to note is that most of the largest observed gradients occurred within the Salvador region of Brazil, but we have determined that occurrence is not location dependent.

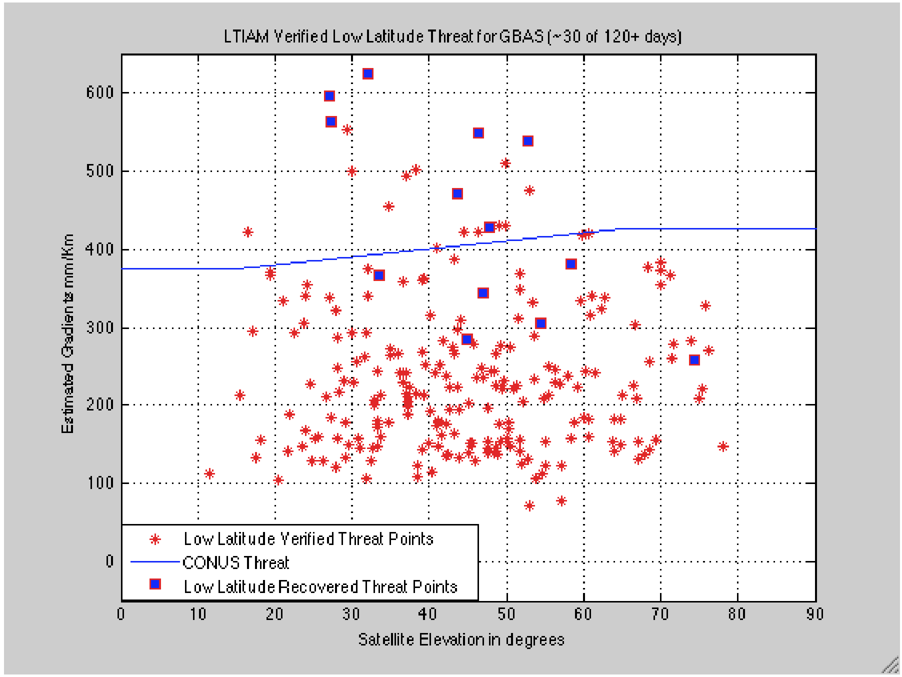

Figure 38 - Low latitude Threat Model [1]

It should be noted from the above figure that the blue points are representative of additional analysis and team scrunity to ensure the validaty of these observed gradients. Effort to calculate the speed and width of these gradients is still ongoing.

The time of occurance of all significant gradients fell within 2100 and 0500 UT (post sunset hours), where the strongest of those gradients occuring between 0000 – 0400 UT. This occurance coincides with the occurance of recorded scintialltion on the L-band frequencies. Additionally, the largest gradients were detetced by stations oriented in the Northest and Southwest direction, which indicate that the bubbles are moving from West to East [1]. **Figure 39** below shows the time of occurrence of all observed gradients.

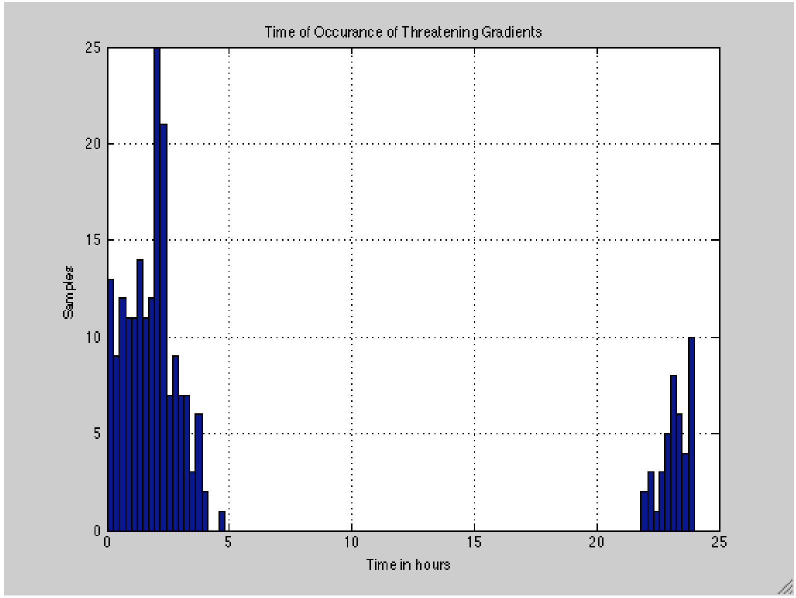

Figure 39 - Time of Occurance for Observed Gradients [1]

References:
[1] N. Mathur, R. Cole, "Effects of Southern Hemisphere Ionospheric Activity on Global Navigation Satellite Systems (GNSS) Based Augmentation System," *Southern Latitude Threat Model Report*, September 2014, DRAFT.

3.2 GAST-D Validation

3.3.1 GAST-D Validation Activities Overview

A key goal of the FAA's GBAS program is validation of the GAST-D ICAO SARPS. Much of this work is being accomplished through prototyping contracts for ground and airborne systems, both with Honeywell International. Planned GAST-D avionics prototyping was completed in January 2013, while ground prototype development continues. Validation is scheduled to be officially completed by ICAO in February 2015. HI has already applied for SDA support for a GAST-D system, with a target completion date in 2018.

Avionics
A cost-sharing contract to create a GAST-D avionics prototype was awarded to HI in August 2010 and was complete as of January 2013. Under this contract HI implemented GAST-D algorithms and message types as described in the LAAS Minimum Operational Performance Standards (MOPS) (DO-253C) and the LAAS ICD (DO-249D) on their commercially available GAST-C platform, the Integrated Navigation Receiver. The objectives were to confirm that the various monitor thresholds set forth in the MOPS were appropriate and that all MOPS requirements were clearly and correctly defined. Incorporation of new GAST-D algorithms occurred over several software builds within three task areas, as shown in the table below.

Task	INR Version	Delivery Date
Task Area I		
Delivery of 3 Baseline Receiver (INR) Units	E100	11/2010-2/2011
Delivery of Bench Test Interface Software	E100	12/2010
Delivery of CAT-I Compliance Report	E100	9/2010
Task Area II Phase I		
Implement CAT III Message Format (DO-246D LAAS ICD)	E101	3/2011
Implement 30-second pseudorange smoothing (DO-253C LAAS MOPS Section 2.3.6.6.1)	E101	3/2011
Implement dual weighing matrix (DO-253C LAAS MOPS Sections 2.3.9.2.1-3)	E102	6/2011
Implement second solution (DO-253C LAAS MOPS Section 2.3.9.2.3)	E102	6/2011
Implement DSIGMA (DO-253C LAAS MOPS Section 2.3.9.3)	E102	6/2011
Task Area II Phase II		
Activate and update software baseline from Phase 1	E200	1/2012
Implement Divergence Monitoring Function (DO-253C LAAS MOPS Section 2.3.6.11)	E201	5/2012
Implement Differential Correction Magnitude Check (DO-253C LAAS MOPS Section 2.3.9.5)	E202	5/2012
RAIM Algorithm, Analysis & Test Report	N/A	3/2012
Implement B-Value Monitoring (DO-253C LAAS MOPS Section 2.3.11.5.2.3)	E202	5/2012
Implement Fault Detection and Provide Results Data (DO-253C LAAS MOPS Section 2.3.9.6)	E202	5/2012
Task Area II Phase III		
Activate and update software baseline from Phase II	E300	8/2012
Implement VDB Message Authentication (DO-253C LAAS MOPS Section 2.3.7.3)	E301/E302	10/2012

Table 1 - GAST-D Avionics Prototype Software Builds

During the course of the contract, several deficiencies were found in the MOPS as they were written. These have been presented at RTCA for amendment and are summarized here:

- Airborne Code Carrier Divergence Filtering (CCD) [DO253-C Section 2.3.6.11]
    - Filter output can be positive or negative, but MOPS defines the threshold as positive.
    - CCD output will be in meters, but the MOPS defines the threshold as m/sec.

- The MOPS does not specify any re-inclusion criteria for an SV excluded by the CCD monitor. Should IN PAR and IN AIR sates be monitored?
- Due to the 20 minute waiting period for SV inclusion, receiver start-up performance will be different for AEC-D equipment than AEC-C equipment, even when operating in GAST-C mode.

- Differential Correction Magnitude Check (HPCM) [DO253-C Section 2.3.9.5]
  - There is an extra term in the computation for the total correction to the measured PR for SV 'i'.
  - More clarity on when to use 100-second or 30-second smoothed PRs for computation of HPDCM is required.
- Reference Receiver Fault Monitoring (RRFM) [DO253-C Section 2.3.11.5.2.3]
  - Computations for the standard deviations of D_v and D_L are not defined. Acceptable assumptions for manufacturers to use when computing these values should be stated.
- Fault Detection [DO253-C Section 2.3.9.6]
  - The MOPS requires fault detection (FD) only for GAST-D systems. HI believes FD would be beneficial in detecting local conditions that could lead to faulted measurements.
- Fault Detection for Satellite Addition [DO253-C Section 2.3.9.6.1]
  - More clarity is needed on when FD for SV is required
  - How to handle situations where multiple SVs which were failed for CCD in the past 20 minutes become available at the same time
- VDB Authentication [DO253-C Section 2.3.7.3]
  - No guidance is provided for clearing a fault after an authentication failure.

Not all of the GAST-D updates found in the LAAS MOPS (DO253-C) were completed. Notably absent is the implementation of airborne geometry screening. VDB Authentication protocols were also only partially completed, as the hardware changes necessary to successfully implement those protocols which require detection of the slot a message was received in fell outside the scope of this contract. A follow-on contract to address these items has not been possible due to funding.

A complete report on the GAST-D avionics prototype contract, including detailed results of the six sets of flight testing completed by ANG-C32 during development, is available at http://laas.tc.faa.gov/documents/Docs/INR_FINAL_REPORT.pdf.

Ground System

The FAA is currently conducting contracts with Honeywell International (HI) to implement GAST-D GBAS ground requirements on the HI GAST-C GBAS system, the SLS-4000. Tasking under the original contract is complete. This work included modifications for RFI robustness, as well as necessary updates to existing GAST-C monitors and the addition of an ionospheric gradient monitor (IGM). Modeling and system safety analysis work for the various monitors implemented was also completed.

All updates have been implemented on the FAA's SLS-4000 at Atlantic City International Airport (ACY). Hardware changes have included the switch from copper to fiber connectivity to the reference stations from the main processing unit and the addition of two 'secondary' reference receivers (RRs). These extra RRs will be used to help mitigate RFI as well as to provide longer baselines for ionospheric gradient monitoring. A description of the GAST-D software updates to the ACY SLS-4000 is provided in **Table 3**.

A new contract modification was recently awarded to HI to allow for more work, primarily on ionospheric gradient monitoring. As work progressed on the original GAST-D contract, it was found that non-ionospheric elements of the atmosphere could also cause delays that could cause blinding or false tripping of the developed gradient monitor. Further study of this issue led to concerns with the ground ionospheric gradient monitoring requirement as it is written in the current SARPS. Details on the data collected and suggested changes to this requirement are available in working papers presented by the FAA and HI at this meeting [1, 2]. Although HI led the effort to build and validate the ground IGM, this work was sponsored by the FAA. Validation material for the IGM was collected under the prototyping contract and was overseen by the FAA, and the LAAS Integrity Panel (LIP) has reviewed and concurred with the data collection.

Software Build	Updates	Date Delivered
1	Display Type 11 Msg	12/2010
2	Implement 30 second smoothing Populate Type 11 msgs Updates to Message Types 2 & 3 Incorporation of iono gradient monitor	6/2011
3	Incorporation of CAT-III Excessive Acceleration (EA) monitor	7/2012
4	Updates to manage 6 RRs	9/2012
5	Incorporation of CCD monitor updates Incorporation of Ephemeris monitor updates Incorporation of Signal Deformation Monitor (SDM) Updates	12/2012
6	Measured site data updates for 6 RRs	3/2013
7	Addition of RR selection logic RFI monitoring updates	7/2013
8	6 RR updates for SDM, CCD, IGM, and carrier rate monitors	Expected 11/2014

Table 2 - GAST-D Ground Prototype Software Builds

3.3.2 GAST-D Flight Testing Summary

The final round of planned GAST-D flight testing was conducted at ACY this quarter. The GAST-D prototype ground station was the modified Honeywell SLS-4000 in six reference-receiver configuration. Avionics receivers were two Honeywell Integrated Navigation Receivers

(INRs) with GAST-D prototype modifications, and one Rockwell Collins MMR GNLU-930 (approved for CAT-I use). During this set of flights, tests were conducted to demonstrate that Honeywell's plan to "hot-swap" backup references in cases such as RFI or RSMU failure would not cause anomalous behavior in the avionics. Allowing this behavior in an operational system would require changes to the SARPS and to the LAAS MOPS (DO253-C). The affected SARPS requirement is quoted here:

> Annex 10, Appendix B, 3.6.4.2.3 (Type 1 Corrections)
>
> *B1 through B4:* are the integrity parameters associated with the pseudo-range corrections provided in the same measurement block. For the ith ranging source these parameters correspond to Bi,1 through Bi,4 (3.6.5.5.1.2, 3.6.5.5.2.2 and 3.6.7.2.2.4). The indices "1-4" correspond to the same physical reference receiver for every epoch transmitted from a given ground subsystem during continuous operation.
>
> Coding: 1000 0000 = Reference receiver was not used to compute the pseudo-range correction.
>
> *Note. — Some airborne receivers may expect a static correspondence of the reference receivers to the indices for short service interruptions. However, the B value indices may be reassigned after the ground subsystem has been out of service for an extended period of time, such as for maintenance.*

Data processing for this set of flight tests is in the final stages. First looks at the data collected on the GAST-D INR prototype receivers showed worse than expected performance. Further analysis showed that this was caused by a combination of low elevation satellites being blocked by the wings during periods of high roll angle on the aircraft and the long settling time of the prototype's CCD filter (caused by a bug in the implementation which was documented in the INR Validation Final Report).

Thus far, as expected, no anomalies have been observed due to the intentional switching between primary and back-up RSMUs. Example data from an approach during which a primary RSMU was returned to service, replacing a back-up in one B-value slot, is shown below. **Figure 40** shows the navigational sensor error calculated for one of the INRs under test during final approach, as well as VPL and LPL values. Note that this error includes the effects of latency in the receiver, which accounts for the brief periods where error exceeds protection level. This is expected and not an issue. The red vertical line on the plot indicates the moment when RSMU 1 was returned to its regular place in the first B-value slot, replacing back-up RSMU 2. As expected there is no detectable jump in error or protection levels.

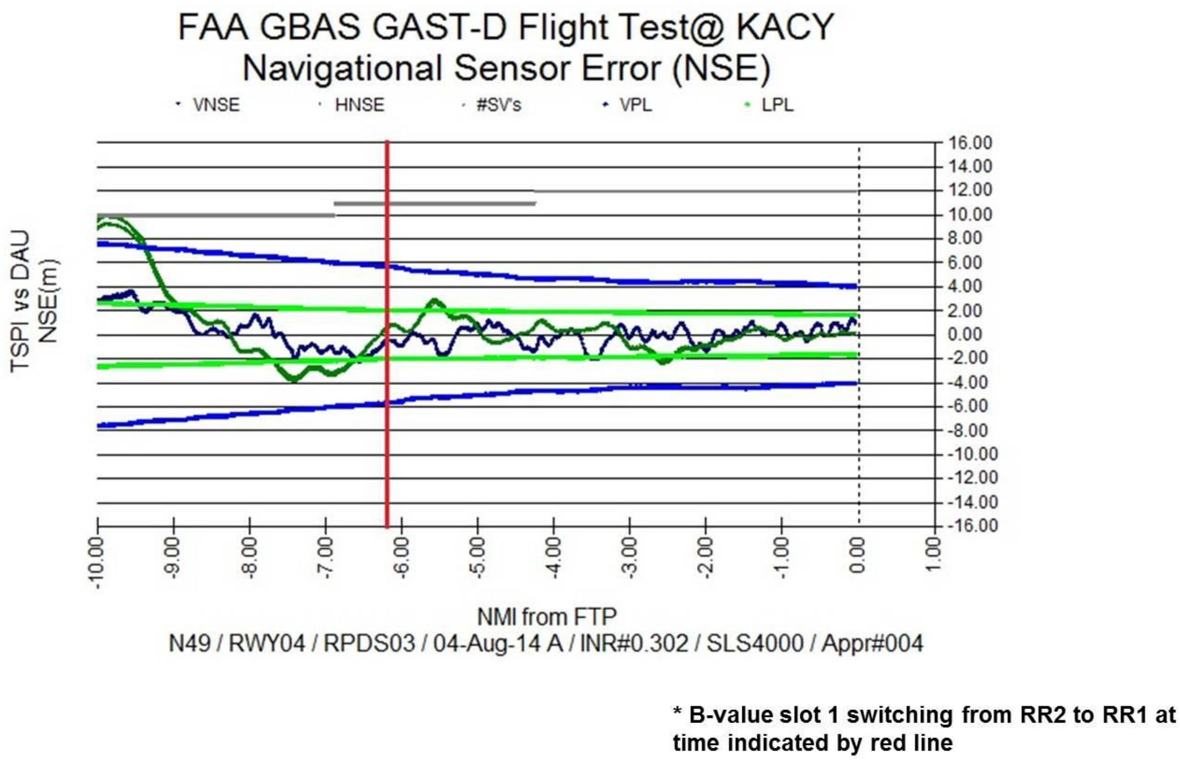

Figure 40 - NSE v. Distance to Threshold

Figure 41 shows results from the GAST-D airborne reference receiver fault monitor (RRFM). This monitor's outputs are most directly affected by the B-values received from the ground. During this approach in nominal conditions, we would expect the B-values between the primary and back-up receivers to be comparable and should not note any major jumps in value when the RSMU switch takes place. This plot confirms this to be the case.

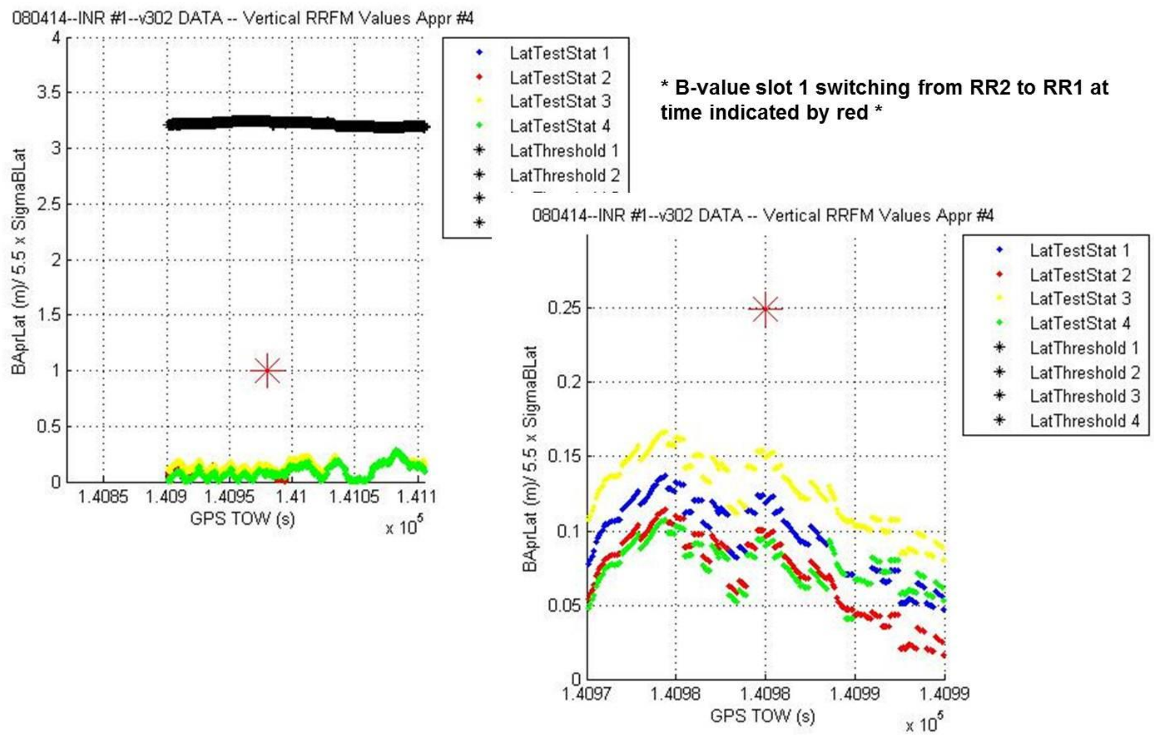

Figure 41 - Vertical RRFM results v. GPS TOW

Complete results from this set of flight tests will be compiled in a report to be posted by the end of October 2014 at laas.tc.faa.gov/Documents.

3.3 CAT I Block II SDA

The FAA is currently supporting system design approval activities for an update to the CAT-I approved Honeywell International SLS-4000 system. This software update is known as “Block II” and includes changes that will improve system availability in the NAS and allow for use in low-latitude areas such as Rio de Janiero, Brazil. The table below provides an overview of the major updates to be made in Block II from the previously approved Block I and Block 0 versions.

Configuration Attributes	GBAS Configuration		
	YG4031EA01 Block 0	YG4031EA02 Block I	YG4031EA03 Block II
CAT-I Integrity/Continuity	☑	☑	☑
Robust to Personal Privacy Devices (a.k.a., GPS jammers)		☑	☑
P-Value & Kmde moved to a site specific parameter file (facilitates extended service volume without a "code" change)			☑
SDM Natural Bias Update (Enables the use of PRN 11 and 23)			☑
Increase the number of selective masks (Improve granularity of masks to improve availability)			☑
Updates to Data Recorder and FAS Input File (Supports ED-114A compliance)			☑
Facilitates Low-latitude Operations (Scintillation monitor added, configurable scintillation thresholds, etc.)			☑
Number of Approaches Supported	26	26	48

Table 3 - Block II Updates

The current target for design approval is Quarter 2 of 2015, with FAA design approval limited to use in CONUS. Verification and analysis of the work done to allow operations in low-latitude regions will be left to authorities in those regions.

3.4 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) creates an insufficient geometry to keep the protection levels below the alert limits. See **Table 4** 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 5**). Although such an interruption is unlikely, the GBAS team closely tracks the NANUs in the event that post-data processing reveals a rise in key performance parameters.

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 4 - NANU Types and Definitions

NANU	TYPE	PRN	Start Date	Start Time (UTC)	End Date	End Time (UTC)
2014052	UNUSUFN	30	07/03/2014	12:11	N/A	N/A
2014053	FCSTDV	10	07/10/2014	11:30	07/10/2014	23:30
2014054	UNUSABLE	30	07/03/2014	12:11	07/03/2014	22:50
2014055	FCSTDV	06	07/17/2014	09:30	07/17/2014	21:30
2014056	FCSTSUMM	10	07/10/2014	11:52	07/10/2014	17:41
2014057	FCSTSUMM	06	07/17/2014	09:50	07/17/2014	15:07
2014058	UNUSUFN	19	07/21/2014	16:12	N/A	N/A
2014059	UNUSABLE	19	07/21/2014	16:12	07/21/2014	19:02
2014060	FCSTUUFN	03	08/01/2014	14:30	N/A	N/A
2014061	FCSTDV	08	08/07/2014	12:30	08/08/2014	00:30
2014062	LAUNCH	09	08/02/2014	03:23	N/A	N/A
2014063	DECOM	03	08/02/2014	22:00	N/A	N/A
2014064	FCSTSUMM	08	08/07/2014	12:52	08/07/2014	18:56
2014065	FCSTMX	04	08/12/2014	16:00	08/13/2014	04:00
2014066	FCSTDV	13	08/14/2014	07:00	08/14/2014	19:00
2014067	FCSTSUMM	04	08/12/2014	16:47	08/12/2014	22:14
2014068	FCSTSUMM	13	08/14/2014	07:33	08/14/2014	13:30
2014069	GENERAL	03	09/05/2014	N/A	N/A	N/A
2014070	FCSTDV	13	09/19/2014	07:00	09/19/2014	19:00
2014071	USABINIT	09	09/17/2014	20:26	N/A	N/A
2014072	FCSTSUMM	13	09/19/2014	07:13	09/19/2014	14:30

Table 5 - NANU Summary

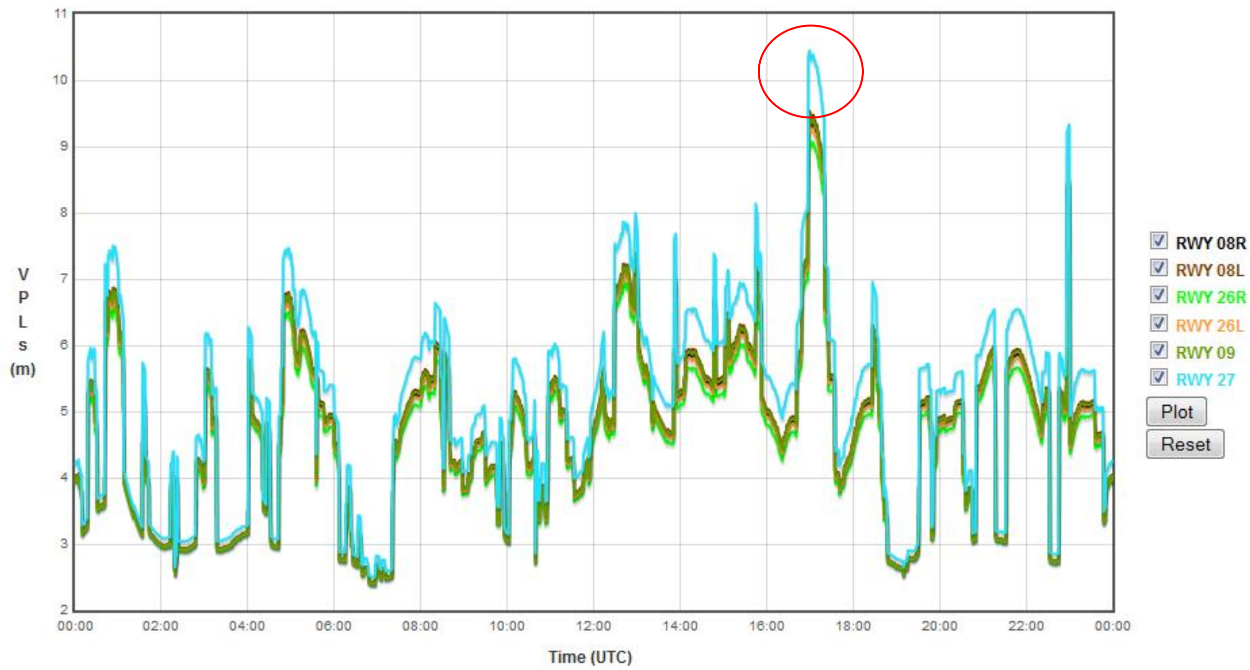

Figure 42 - Outage at IAH on RNWY 27 by NANU 2014065 FCSTMX on PRN 04 - 8/12/2014

4. GBAS Meetings

4.1 GBAS Block II Operational Evaluation / System Verification Meeting

GBAS team members met August 12th through August 14th to discuss the Op Eval and System Verification of Block II for the SLS-4000. The primary goals were to review the list of Honeywell Block II Change Requests (CR), assign POC's and brainstorm possible test cases to the viable CRs, and to review the Honeywell tools for reviewing test cases, test procedures, and test results.

4.2 ICAO CSG Summary

The ICAO Navigation Systems Panel (NSP) Category II/III Subgroup (CSG) met on September 29 - October 1, 2014 in conjunction with the NSP meeting at ICAO headquarters in Montreal, Canada. At this meeting, the CSG continued coordination of the operational validation phase for the GAST-D GBAS SARPS.

A significant item addressed during the meeting was proposed modifications to GAST D anomalous ionospheric monitoring requirement in the GAST-D SARPs. Much of the work accomplished for this was sponsored by FAA ANG-C32. The proposed change would enable increased design and siting flexibility for ground manufacturers while maintaining the roles and responsibilities of the ground and airborne systems in their shared mitigation of the anomalous ionospheric gradient threat. A related item discussed was how to address ionospheric gradients caused by plasma bubbles that occur in low latitudes. A paper was submitted that proposed updating the ionospheric threat model, taking account of bubble gradients. That will be the subject on ongoing work.

The next CSG meeting is planned for February 2015, in Ishigaki, Japan. The goal of the CSG is to complete validation of the GAST-D SARPs in April 2015.

Appendix A – GBAS Overview

A.1 GBAS Operational Overview

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 GPS with real-time broadcast differential corrections.

A GBAS ground station 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 approach 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 GAST-C 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 42 is provided as an illustration of GBAS operation with major subsystems, ranging sources, and aircraft user(s) represented.

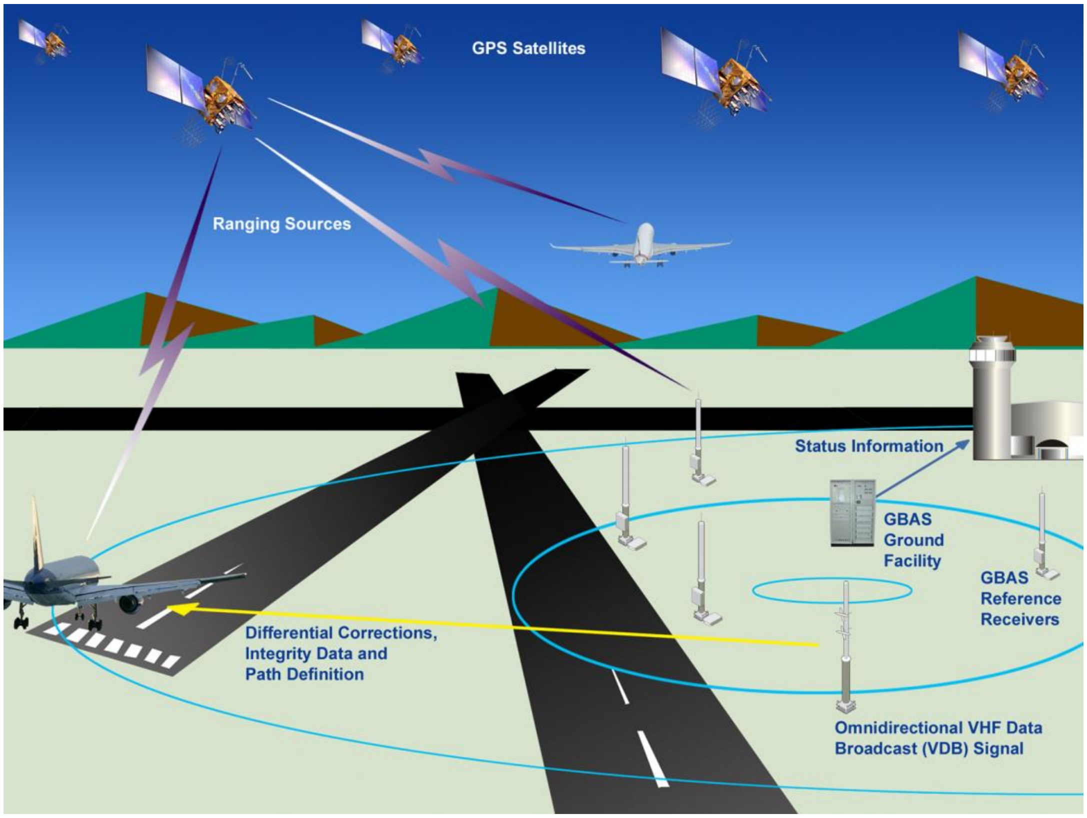

Figure 43 - GBAS Architecture Diagram

Appendix B - GBAS Performance and Performance Type

B.1 Performance Parameters and Related Requirements Overview

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 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.

B.2 Performance Parameters

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.

B.2.1 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).

B.2.2 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.

B.2.5 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 indications 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.

Appendix C - LTP Configuration and Performance Monitoring

C.1 Processing Station

The LTP Processing Station is an AOA-installed operational GBAS system. It 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 GBAS standard operating configurations.

C.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.

C.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.

C.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 (**Figure 43**).

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 44 - The BAE GNSS Multipath Limiting Antenna (MLA)

C.2.1 The BAE ARL-1900 GNSS Multipath Limiting Antenna (MLA)

The BAE Systems ARL-1900 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.

C.3 Multi-Mode Receiver (MMR) Monitoring Station

The GBAS 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 44** 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.

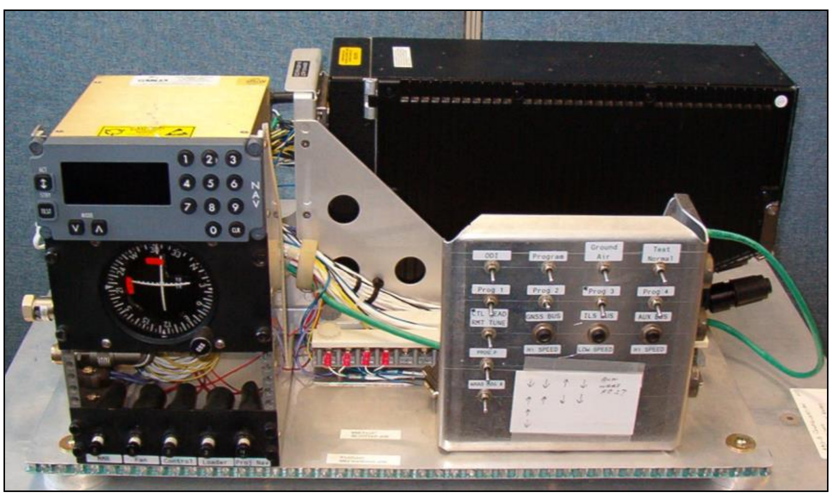

Figure 45 - MMR User Platform

Appendix D - GBPM Configuration and

The Ground Based Performance Monitor 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 and saved to a .raw file without interruption. This data is used to post-evaluate system performance. In addition to the raw file, live data is transferred from each offsite monitor once per minute to our local database. Users can then access the data through an interactive website by means of tables, charts, and graphs 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 45 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.

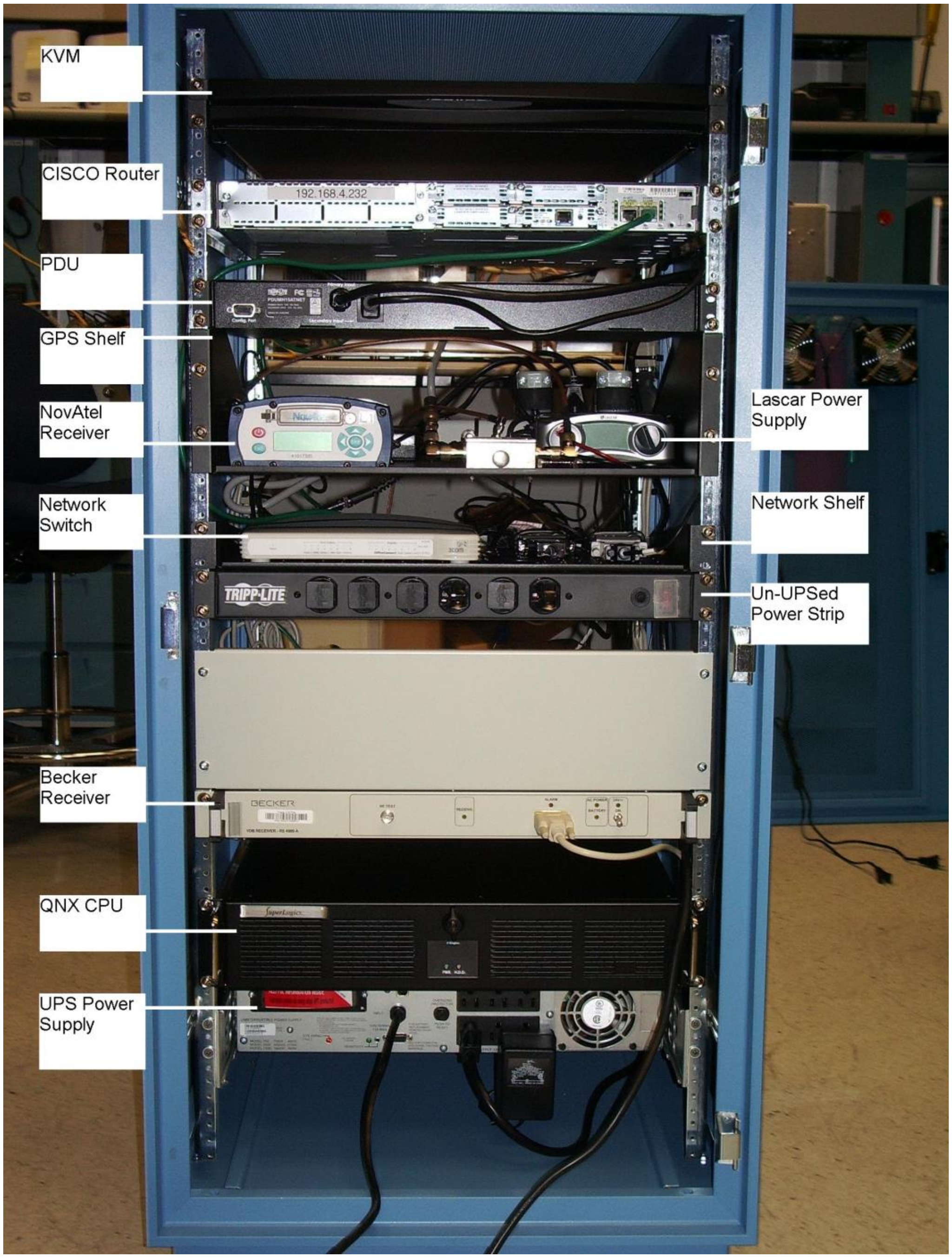

Figure 46 - Ground Based Performance Monitor (GBPM)

Glossary of Terms

—A—

ACY
Atlantic City International Airport ... 3, 4

—C—

CCD
Code Carrier Divergence ... 30

CDI
Course Deviation Indicator ... 47

CMEs
Coronal Mass Ejections ... 24

CONUS
Continental United States ... 24

CORS
Continuously Operating Reference Stations ... 24

CPU
Central Processing Unit ... 45

CSG
Category II/III Sub-Group ... 37

—D—

DECEA
Department of Airspace Control ... 26

—E—

EEC
Experimental Centre ... 38

ESV
Extended Service Volume ... 39

EWR
Newark Liberty International Airport ... 4

—F—

FAA
Federal Aviation Administration ... 3

FD
Fault Detection ... 31

—G—

GBAS
Ground Based Augmentation System ... 3

GBPM
Ground Based Performance Monitor ... 3

GIG
Galeão International Airport ... 4

GNSS
Global Navigation Satellite System ... 47

GPAR
GBAS Performance Analysis Report ... 3

GPS
Global Positioning System ... 24

GSL
GBAS Service Level ... 44

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