FEDERAL AVIATION ADMINISTRATION

FAA Flight Testing

6-Reference GAST-D Prototype HI SLS

FAA ANG-C32 Engineering & Development Services, Navigation Branch
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This document contains test plans and results from flight testing conducted by the FAA at the FAA Technical Center at Atlantic City International Airport (ACY). Two different avionics receivers, a GAST-C approved Rockwell Collins GNLU-930 and a GAST-D prototype Honeywell INR, were flown against the most updated version of the six-RSMU Honeywell GAST-D prototype ground station.

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1. Introduction

1.1 Background

The primary objective of the FAA's current Ground Based Augmentation System (GBAS) program is validation of the GAST-D ICAO SARPS. Much of this work is being conducted thru the development of GAST-D prototype systems.

A GAST-D avionics prototype was developed thru a cost-sharing contract with Honeywell International (HI)—GAST-D algorithms and monitors were added to HI's approved GAST-C GBAS Integrated Navigation Receiver (INR). This contract was complete as of January 2013. Details on the contract scope and schedule, work completed, flight testing conducted and results are available in the final validation report, available for download at http://laas.tc.faa.gov/documents/Docs/INR_FINAL_REPORT.pdf.

Development of a GAST-D ground prototype is also being developed thru a separate contract with HI. This contract is currently underway, with a scheduled end date in June 2015. HI is implementing GAST-D protocols and hardware changes on the FAA's SLS-4000 at Atlantic City International Airport (ACY). The most recent prototype configuration increases the number of reference station monitoring units (RSMUs) from four to six, allowing for two 'spares' which can be swapped into active use in the event a 'primary' reference receiver is taken offline by RFI or due to other failure.

1.2 Objectives

The primary goal of this set of flight tests was to verify that the introduction of addition reference receivers and reference receiver switching would not adversely impact GBAS avionics. Additionally, the tests investigated the switching of the VDB transmitters within the GBAS ground station.

A ground station with 6 reference receivers cannot provide B-values for all the reference receivers to the airborne using the current GBAS interface specification. Therefore the ground manufacturer intends to replace the broadcast B-value of a failed or unavailable reference receiver with one of the B-value from one of the reference receivers not being broadcast. When this occurs, the system will proceed through one epoch without a B-value, and then the new B-value will be broadcast in subsequent epochs. Various integrity checks on the airplane rely on the broadcast B-value, including the VPL_H1 and the RRFM. The flight tests intend to observe the performance of the airborne receiver with B-value changes due to reference receiver changes. Tests were conducted with these changes occurring both when the aircraft was inside and outside of the PAR.

Scenarios where a VDB switch was forced on the ground station were also conducted. The SLS-4000 has two VDB transmitters, with the active transmitter changing every 12 hours. This test was done to verify that the regular switching between the two ground station VDB transmitters did not cause any interruptions in service.

In addition, baseline data was collected during approaches where the ground station was in a nominal mode with its four primary RSMUs active. These are the first flight tests conducted with the ground station operating with six RSMUs and running the latest software, Build 7.

This paper contains material to be used in validation of ICAO SARPS GAST-D Baseline Section 3.6.1.2, Section 3.7.2.4.1, and Section 3.7.3.5.1. Results from these flight tests, earlier flight testing conducted during the Honeywell INR GAST-D avionics prototype development contract and documented in 'GAST-D Validation Report: Results from the HI INR Development Contract', and information on the GAST-D updates made to the prototype SLS ground station will be documented in an overall final GAST-D validation summary report due July 2015.

1.3 SARPS Requirement Change

The current version of the SARPS does not allow the broadcast of B-values for different reference receivers in the same slot during single periods of operation. This requirement is copied below for reference. In order for HI's proposed six-reference ground configuration to be approved, this requirement would need to be changed.

> 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.*

HI presented a paper explaining their need for a change to this requirement to both the ICAO NSP CSG and RTCA SC-159 WG-4 in October 2014. Their recommendations and rationales for allowing reference switching given certain conditions are currently under discussion within these groups.

2. Test Plan

2.1 Airborne Equipment Setup

Flight tests were conducted in the FAA's Convair 580 (N49) and Bombardier Global 5000 (N47), equipped with two HI INR prototype GAST-D receivers and one Rockwell Collins GAST-C approved GLNU-930 receiver.

The airborne receivers received the data broadcast from the SLS and used this information to assess the accuracy and integrity of the messages, and then computed position, velocity, and time (PVT) information using the same data. This PVT was utilized for the area navigation (RNAV) guidance and for generating instrument landing system (ILS)-look-alike indications to aid the aircraft on an approach. Use of PVT is not approved for operational GBAS systems, but remains enabled in the ACY prototype system for use in flight testing.

Airborne equipment consists of two INR shelves, a Rockwell-Collins MMR shelf, a Becker VDB Receiver shelf, two Ballard data collection systems (DCS), an ESE 291 GPS Time Code Generator, and two separate truth GPS receivers: a Z-Extreme and a Novatel DL-4. Each INR shelf contains one Honeywell INR receiver, a control head used to tune the receiver and a Sandel navigation electronic display used to show CDI deviations. The INR receiver requires a 429 input from an Inertial Reference System to provide the PVT output. The Convair uses a custom Honeywell HG-1095 Laser Ref IRS which used two extra bits of data resolution in place if SDI bits. This requires the Ballard DCS to take the output of the IRS, modify the 429 words and retransmit to the INR. Each INR shelf outputs two 429 channels and one RS-232 channel to be collected by the Ballard DCS.

The Rockwell-Collins MMR shelf consists of the MMR, a Gables Control Head for tuning and a standard analog electromechanical CDI display. The MMR outputs three 429 channels plus one RS-422 channel to be collected and time stamped by the Ballard DCS.

The Becker VDB shelf receives the ground station VDB transmission and outputs the received data on a RS 422 data bus which is collected and time stamped by the Ballard DCS.

The Ballard DCS consists of a twelve channel 429 receive module, four channel 429 transmit module and a 4 channel rs-232/422 receive module and an ESE-291 GPS based time code generator. All 429 and RS-232 ports transmitted from the INR were collected and time stamped by the DCS and saved on a four gigabyte compact flash card. The DCS has an additional function of modifying some of the INR 429 messages and transmitting them to the Convair's MLS port to be displayed on the ship's CDI. This is the only way of displaying CDI information to the pilots.

In addition to the 429 bus data described, the HI INR GAST-D prototype also supplies data from the new GAST-D monitors and algorithms on the 232 bus. This data is used to analyze the performance of the DSIGMA monitor, the RRFM monitor, the differential correction magnitude monitor, the CCD monitor, and GAST-D protection levels. Information on signal levels and faults is also supplied by this bus.

The Z-Extreme is a dual frequency receiver that provides truth GPS measurements on the test aircraft and ground, independent of the GBAS equipment. A ground-based Z-extreme is used for reference and will be connected to a precision surveyed antenna. Post-processing of the data collected by this system provides accurate aircraft position over the course of a flight. A second truth system, the Novatel DL-4 is used as a backup truth system.

All GPS-based equipment is connected to one amplified antenna output patch panel. The GPS antenna is a Sensor Systems S67-1575-96 L1/L2 dual band active GPS antenna and is located on the top center of the aircraft. The VDB antenna on the plane uses the VOR/LOC antenna. From there the signal is split twice before being connected to the equipment. One splitter is used to send the VDB signal to the one rack containing the INR receivers and the other rack containing the MMR and the Becker VDB receiver. At each rack another splitter is used to send the VDB signal to the individual equipment.

2.2 Ground Equipment Setup

2.2.1 SLS Configuration

The HI GAST-D SLS prototype at ACY, with six reference station monitoring units (RSMUs) was the GBAS tuned for all approaches during this set of flight tests. At this time the SLS was running software Build 7, which broadcasts GAST-D messages (i.e. Type 11, Type 3, and additional data blocks in Type 2), as well as both GAST-C and GAST-D approaches in the Type 4 messages, and includes updated GAST-D monitors for excessive acceleration, code-carrier divergence (CCD), signal deformation, and cycle-slip detection and repair. Implementation was also added to control the switching between primary and secondary RSMUs. A switch of active RSMUs does not lead to a change in the broadcast ground reference point in the current implementation of the GAST-D SLS prototype. Figure 1, below, illustrates the physical configuration of the system and demarcates which reference stations were assigned as primary and secondary at the time of these flight tests.

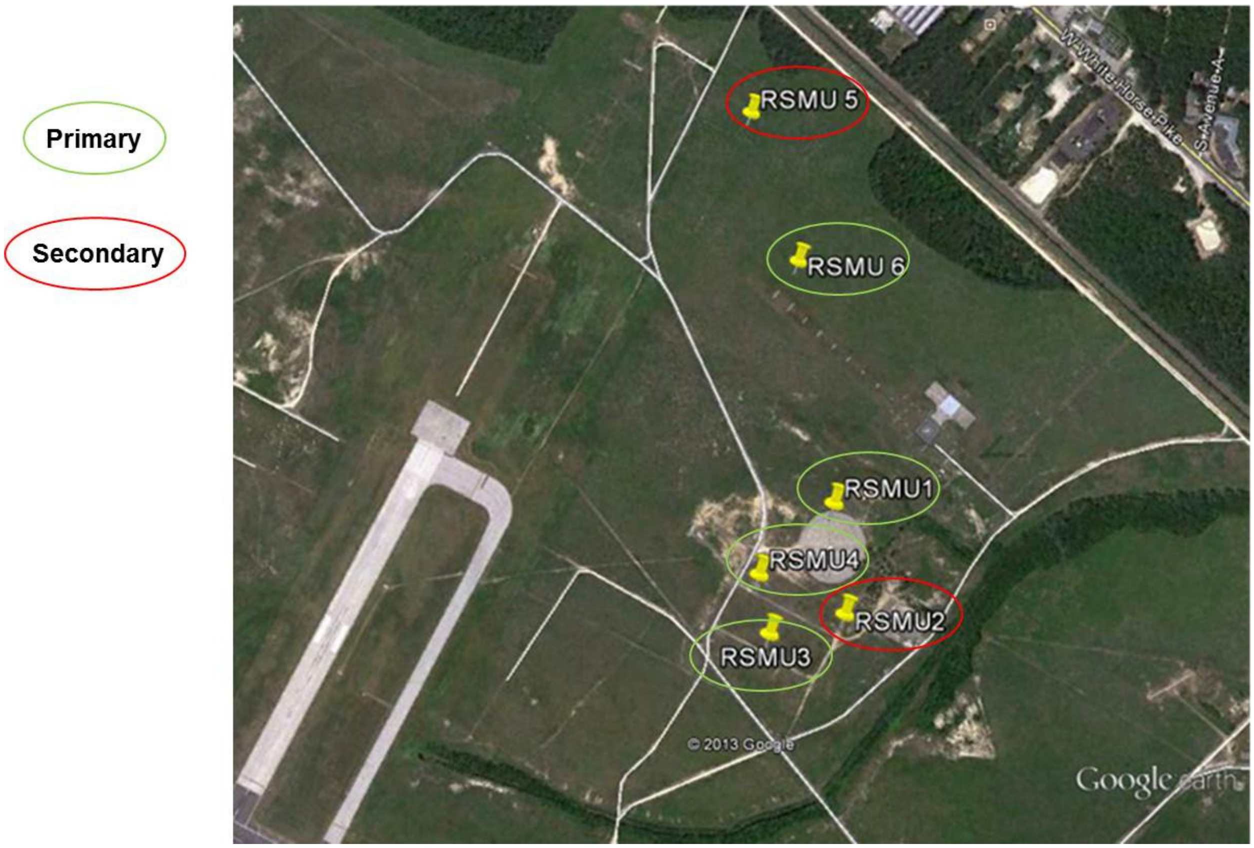

Figure 1: Current HI SLS GAST-D Prototype Layout at ACY

2.2.2 Reference Switching Scenarios

A variety of reference switching scenarios were tested during this set of flight tests. Personnel on the ground forced data outages on given reference receivers to force the switches, later re-including them to force the switch back to a nominal configuration. Table 1 below shows the configurations changes planned. During early flight tests, these changes were made post-approach, so that the system would change which reference B-values were in a given slot in between approaches. During later tests, the intention was to switch while the aircraft was on final approach. However, due to issues with timing and communications between ground and air personnel, nearly all switching during these later flight tests occurred just after the plane turned to approach the airport and outside of the PAR.

Scenario #	Test #	B1 RR#	B2 RR#	B3 RR#	B4 RR#	Scenario #	Test #	B1 RR#	B2 RR#	B3 RR#	B4 RR#
1	Baseline	1	3	4	6	19	7	X	3	4	2
2	Baseline	1	3	4	6	20	7	X	3	4	2
3	1	1	2	4	6	21	Baseline	1	3	4	6
4	Baseline	1	3	4	6	22	9	2	3	5	6
5	2	1	2	5	6	23	9	2	3	5	6
6	2	1	2	5	6	24	Baseline	1	3	4	6
7	Baseline	1	3	4	6	25	10	X	3	5	6
8	3	1	X	5	6	26	10	X	3	5	6
9	3	1	X	5	6	27	Baseline	1	3	4	6
10	1	1	2	4	6	28	11	4	3	5	6
11	4	X	2	5	6	29	11	4	3	5	6
12	4	5	2	X	6	30	Baseline	1	3	4	6
13	Baseline	1	3	4	6	31	12	4	X	5	6
14	6	2	3	4	6	32	12	4	X	5	6
15	6	1	2	4	6	33	Baseline	1	3	4	6
16	6	1	3	2	6	34	Switch VDB	1	3	4	6
17	6	1	3	4	2	35	Switch VDB	1	3	4	6
18	Baseline	1	3	4	6	36	Baseline	1	3	4	6

Table 1: System Configurations

2.3 Flights

2.3.1 Approach Profiles

Approaches flown during this flight test are 3-degree straight-in ILS lookalikes. A majority of approaches are conducted from 10-nmi out, while at least one approach from 23-nmi out is flown to each runway used during the test period. Approaches are alternately flown manually and with autopilot enabled.

2.3.2 Schedule

Table 2 shows the dates flight testing was conducted, aircraft in use, and flight profiles completed, as well as providing notes as to the intentions of the flight and any issues encountered.

DATE	AIR CRAFT	FLIGHT PROFILES	NOTES
04/28/2014	N47	1 20-nmi orbit 1 23-nmi approach to RWY 22 5 10-nmi approaches to RWY 22 1 23-nmi approach to RWY 31 5 10-nmi approaches to RWY 31	Baseline - No ground configuration changes made
04/29/2014	N47	1 23-nmi approach to RWY 04 5 10-nmi approaches to RWY 04	Baseline - No ground configuration changes made
05/01/2014	N47	5 10-nmi approaches to RWY 13	Baseline - No ground configuration changes made
05/20/2014	N47	12 10-nmi approaches to RWY 04	Ground configuration changes made just after approach was completed
05/21/2014	N47	9 10-nmi approaches to RWY 04	Ground configuration changes made just after approach was completed
07/29/2014	N49	8 10-nmi approaches to RWY 04	Ground configuration changes made just after the aircraft turned towards the approach direction

07/30/2014	N49	6 10-nmi approaches to RWY 04	Ground configuration changes made just after the aircraft turned towards the approach direction *INR #1 faulted for duration of flight- data not included in analysis
08/01/2014	N49	8 10-nmi approaches to RWY 04	Ground configuration changes made just after the aircraft turned towards the approach direction
08/04/2014	N49	8 10-nmi approaches to RWY 04	Ground configuration changes made just after the aircraft turned towards the approach direction *Only 7 approaches recorded on the GNLU-930 due to recording issue
08/05/2014	N49	8 10-nmi approaches to RWY 04	Ground configuration changes made just after the aircraft turned towards the approach direction
08/06/2014	N49	8 10-nmi approaches to RWY 04	Ground configuration changes made just after the aircraft turned towards the approach direction
08/07/2014	N49	6 10-nmi approaches to RWY 04	Ground configuration changes made just after the aircraft turned towards the approach direction
08/19/2014	N49	8 10-nmi approaches to RWY 04	INR GAST-C/GAST-D comparison data. No ground configuration changes made. (Test to troubleshoot tracking issues on INR GAST-D prototype receiver.)
08/20/2014	N49	8 10-nmi approaches to RWY 04	INR GAST-C/GAST-D comparison data. No ground configuration

			changes made. (Test to troubleshoot tracking issues on INR GAST-D prototype receiver.)

Table 2: Flight Test Schedule

2.4 Data Collection and Analysis

This section describes the succession of procedures used to collect, reduce and analyze data from each Ground Based Augmentation System (GBAS) flight test performed by the Williams J. Hughes FAA Technical Center ANG-C32 Navigational Branch. There are two major input sources to this process:

- Time Space Position Information (TSPI). The TSPI utilizes differential GPS and its final solution is based on precise carrier phase measurements. TSPI processing requires one GPS receiver on the aircraft and a second receiver placed at a known survey point. The two receivers run simultaneously, collecting GPS satellite data to calculate their position. The GPS receiver placed at the survey point compares its known position with its calculated position, and determines any anomalies caused by ionospheric conditions and/or selective availability. TSPI data is then post-processed for correction and used as a truth-tracking source. It is available in Geo (WGS84) or Earth-centered Earth-fix (ECEF) coordinates at 1-Hz and 5-Hz rate, but is most often used at 1-Hz. Based on the one sigma distribution of the TSPI tracking accuracy at Atlantic City Airport when near the threshold, the 95% accuracy is estimated to be better than 40 centimeters.

- Data Collection Area Navigation. The DCAN receives the air segment computer GPS time, aircraft position, and velocity data via an RS-232. It also obtains aircraft attitude information through ARINC 429, or through the aircraft's analog gyros. Using the aircraft's approach profile, the DCAN generates horizontal and vertical errors. These errors, called localizer and glideslope deviations, are generated in +/- 300 millivolt and ARINC 429 digital formats. Once generated, the errors are fed to the appropriate aircraft guidance systems, such as the CDI or the FMS. All data collected and generated by the DCAN are time stamped and recorded to a 100-Megabyte removable hard drive.

Aircraft GPS and truth-tracking data come from the same aircraft GPS antenna, alleviating the need for lever arm corrections by combining all measurements to the same reference point. Generally, the input file coordinate position format of the data collected is on Geoid (WGS84) or Earth-centered Earth-fix (ECEF) coordinates, but the DAS is capable to handle other formats.

During the Final Approach Segment (FAS) the input coordinates are translated and rotated to a common xyz coordinate system using the Landing Threshold Point coordinates (LTP) plus Threshold Cross Height (TCH) aim-point as the origin. The x-axis aligns with the runway, indicating a negative number before the aim-point and positive thereafter; the y-axis indicates a positive number to the right of the runway and negative to the left; and the z-axis indicates a positive number up from the runway, and negative down.

Once all data sources are in FAS coordinates the truth-tracking source and navigation airborne data is merged by time. The truth-tracking source time is always recorded at the top of the second; if the GPS data time is not recorded at the top of the second, the truth-tracking source is interpolated to the GPS data time. After the navigation airborne data source and truth-tracking source are matched in time, the Sensor Errors are calculated:

- Navigational Sensor Error (NSE): the GPS Data Source minus the actual aircraft position (truth-tracker position)
- Total System Error (TSE): the actual aircraft position (truth-tracker position) minus the Desired Flight Path
- Flight Technical Error (FTE): Total System Error minus the GPS Data Source

A variety of plots are generated and compiled to assist with the analysis of the flight test. Sensor Errors plots can be generated for a single approach or an ensemble, per mission(s), RPDS#, guidance, and/or GPS data source. The x-axis can be modified to any specific range, in nautical miles, seconds, or meters. Overlaying multiple fields (VPL, Flags, RMS, Ground Speed, Number of Satellites, etc.) with sensor errors on a single plot has helped to reveal possible problems with the system.

3. Results

3.1 Rockwell-Collins MMR GNLU-930 (GAST-C Approved)

3.1.1 Baseline Data Collection

Baseline approaches were conducted on 4/28, 4/29, and 5/1/2014. Five 10-nmi to each of ACY's four runway ends were conducted, as well one 20-nmi approach to three of the runway ends and one 20-nmi orbit. The GNLU-930 behaved as expected, with no fault flags observed and nominal errors. The ensemble plots below show MMR data from 21 of the approaches completed in this phase. Data from two approaches was removed due to pilot error--these approaches were cut too short causing excessive outlier errors in the NSE via deviations data. This is due to the effects of data latency being magnified when the aircraft is not in a straight-on segment. There is delay between the time that deviations are computed and the time they are displayed. The data shown in Figure 2 and Figure 4 is horizontal and vertical Navigational System Error (NSE) vs. Distance to Threshold, with error based on deviations. Figure 3 and Figure 5 show horizontal and vertical NSE vs Distance to Threshold as well, but this time using the PVT outputs as the position source instead of deviations. This removes the effects of latency from the situation, resulting in very minimal errors. Mean and standard deviation for the NSE errors at the 200’ decision height are shown on the right-hand axes of the plots.

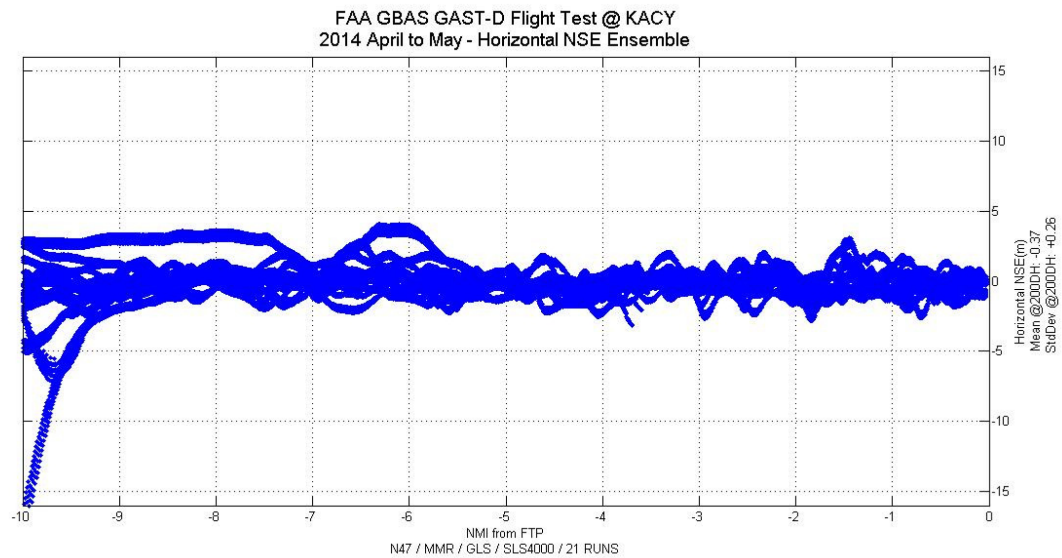

Figure 2: MMR Baseline Approach Data-Horizontal NSE (Deviations)

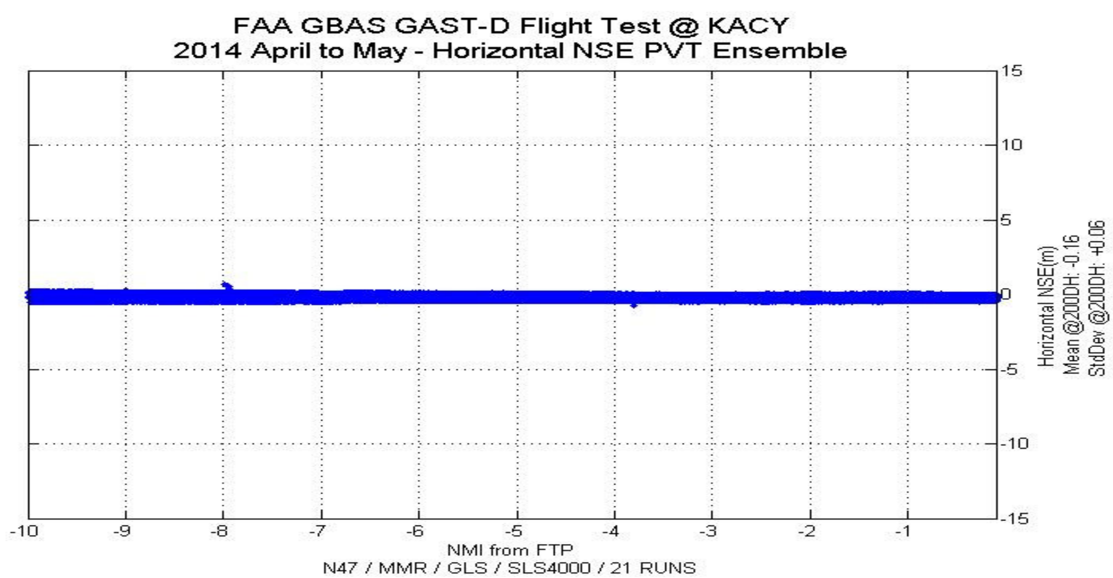

Figure 3: MMR Baseline Approach Data-Horizontal NSE (PVT)

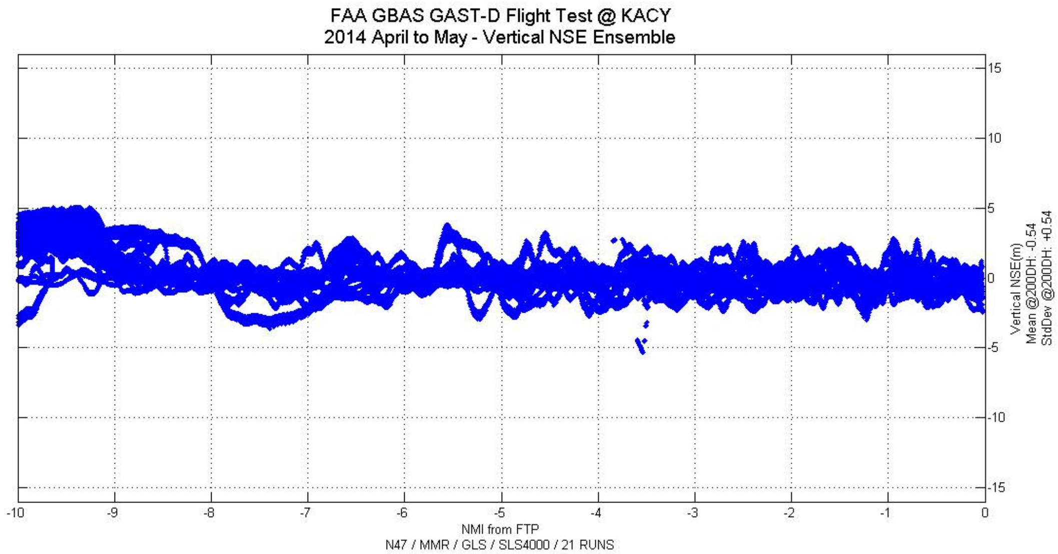

Figure 4: MMR Baseline Approach Data-Vertical NSE (Deviations)

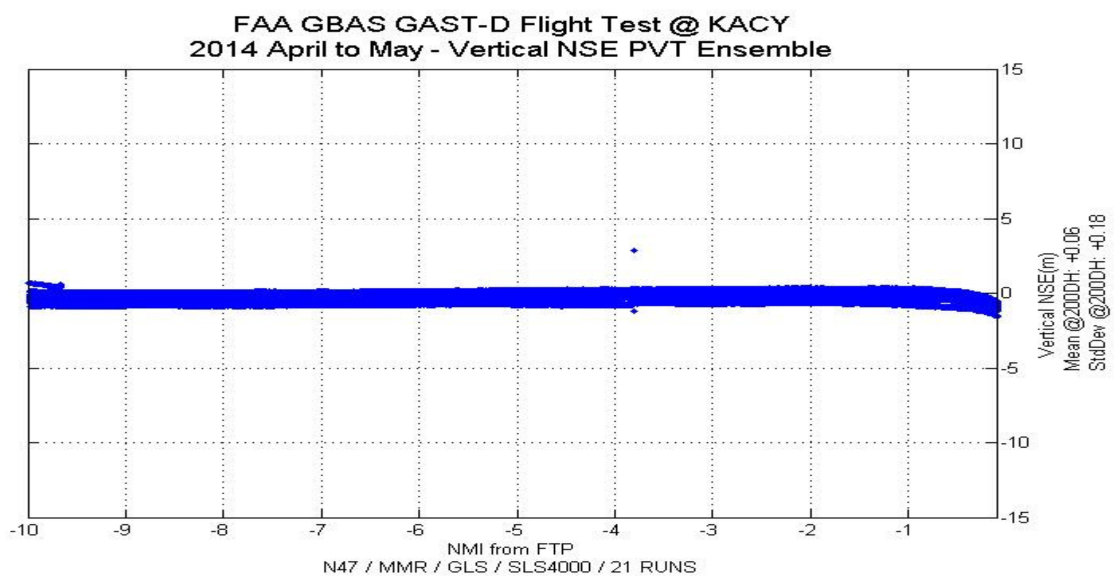

Figure 5: MMR Baseline Approach Data-Vertical NSE (PVT)

3.1.2 Reference Switching Scenario Data Collection

Although nearly all of the RSMU switches on the ground station occurred outside of the PAR, the data collected on flights between 5/20 and 8/7/2014 do represent scenarios in which the SLS-4000 was using various combinations of either three or four RSMUs. Ensemble plots of

GNLU-930 NSE data from these 72 approaches to ACY RWY 04 are shown in Figure 6 thru Figure 9, below.

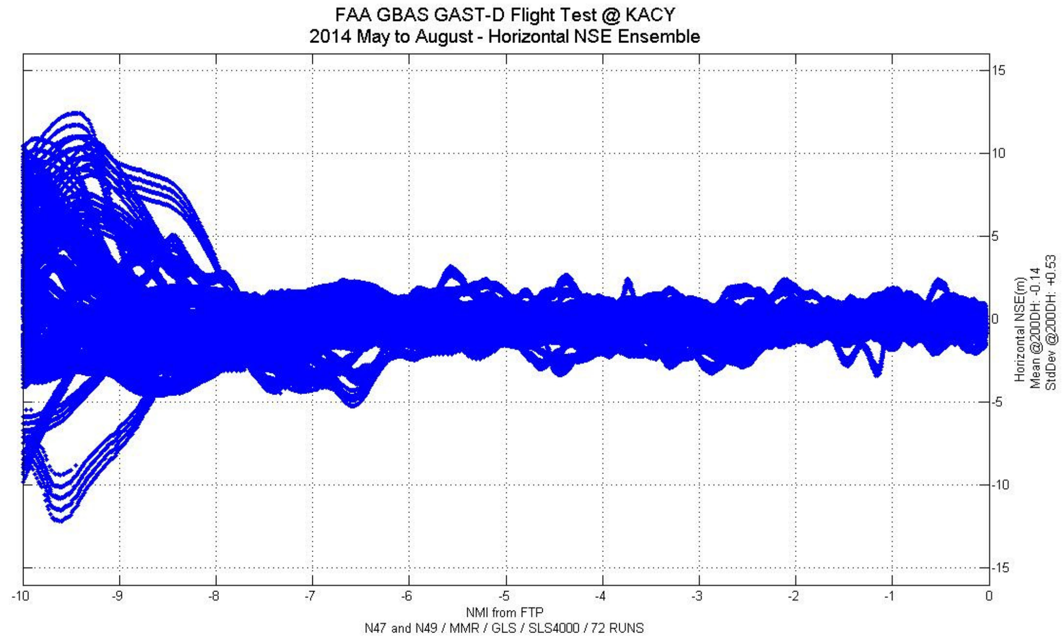

Figure 6: MMR Reference-Switching Approach Data - Horizontal NSE (Deviations)

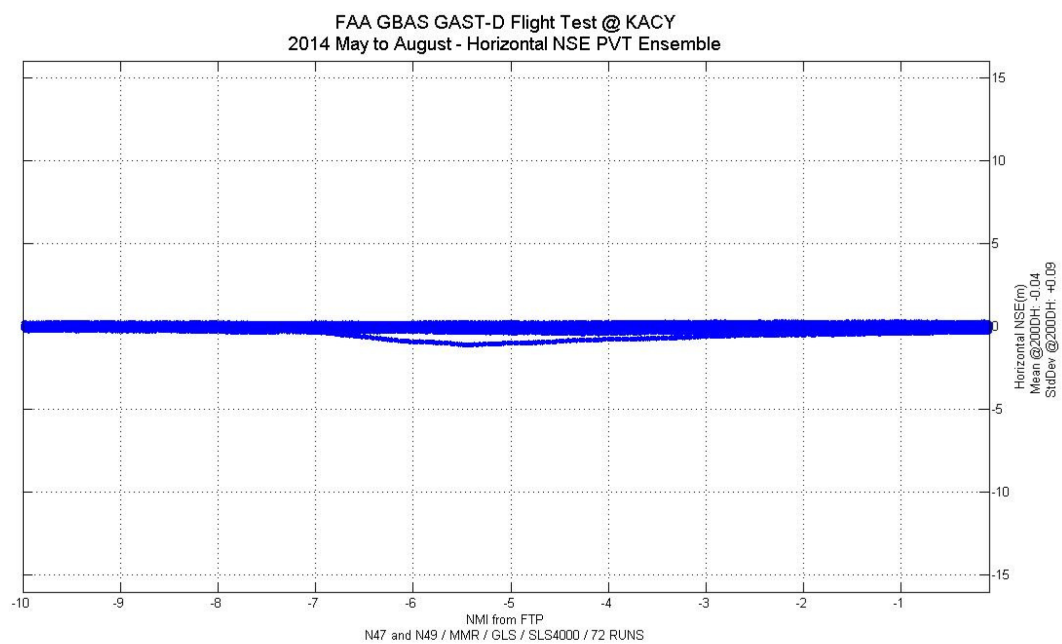

Figure 7: MMR Reference-Switching Approach Data - Horizontal NSE (PVT)

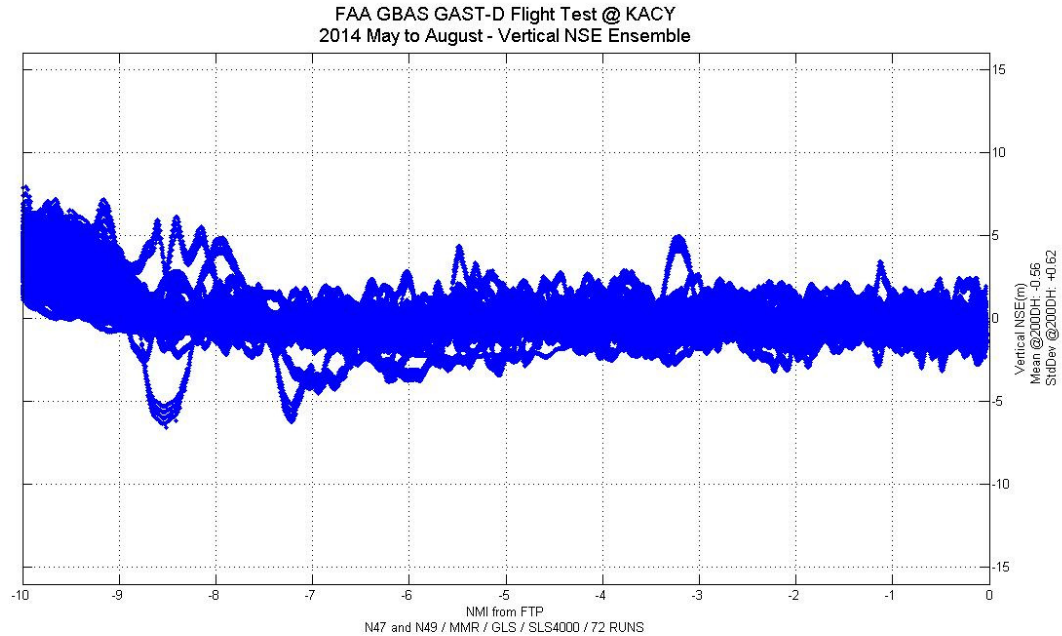

Figure 8: MMR Reference-Switching Approach Data - Vertical NSE (Deviations)

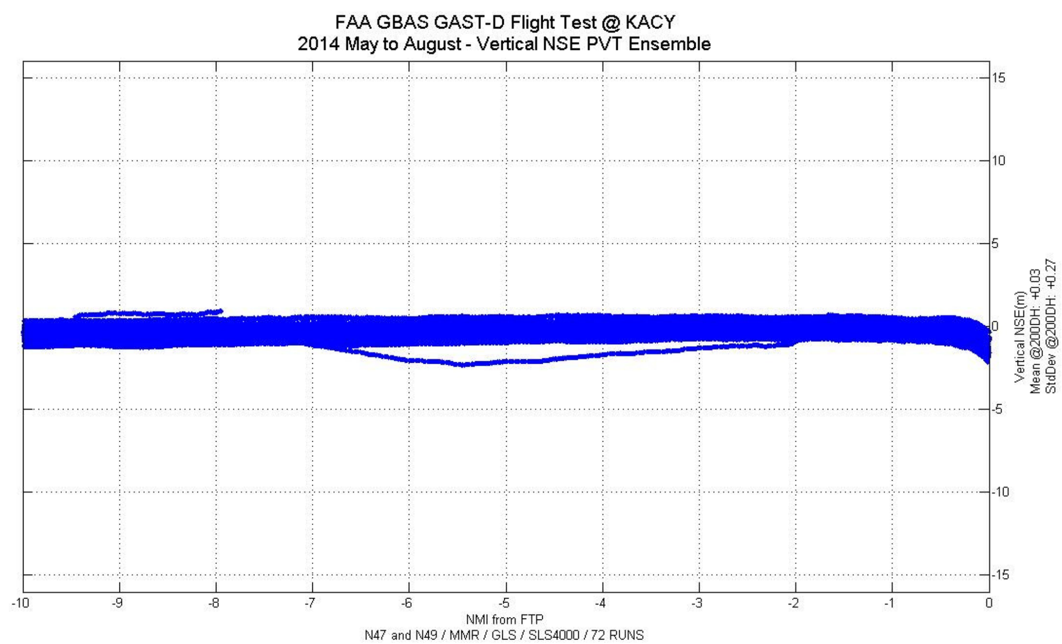

Figure 9: MMR Reference-Switching Approach Data - Vertical NSE (PVT)

3.1.3 VDB Switching Scenarios

Approaches where switches between the two available VDB transmitters of the SLS-4000 took place were conducted on 5/21/2014 and 8/5/2014. On 5/21 the VDB was manually switched from VDB #1 to VDB #2. This test was intended to mirror what would happen during the routine switch between VDB transmitters that is scheduled every 12 hours. During the 8/5 approach VDB #1 was de-powered such that the system was responsible for switching to transmitting on VDB #2. This test was meant to mimic how the ground system might behave during an actual VDB failure.

Analysis of the data collected on the airborne MMR indicated no gaps in guidance or other anomalous behavior as a result of the manual switch on 5/21/2014. VDB transmission data recorded by the SLS on the ground also showed that there were no gaps in Type 1 message transmission—messages were sent once per frame throughout the entire approach.

During the 8/5/2014 approach, where the VDB was de-powered forcing the SLS to swap to the secondary VDB transmitter automatically, the VDB transmission data indicated that one frame of data was lost. This resulted in one missing Type 1 and Type 11 message, one delayed Type 2 message, and one missing expected Type 4 message. Type 2 and Type 4 data were still broadcast within the required rates; only one frame of Type 1 and Type 11 data was missing, which is not enough to cause an issue due to the GAST-C message time out rate. The missing half-second of broadcast data was confirmed by viewing the signal-no-noise values from the airborne MMR. As expected, no loss of guidance or flags was observed.

3.2 Honeywell INR (GAST-D Prototype)

3.2.1 Tracking Issues

During these flight tests, data from the INRs repeatedly showed uncommonly high protection levels, which were linked to periods where the receiver was using far fewer satellites than what were in view. Further data analysis eventually revealed that this was caused by body masking by the aircraft combined with the faulty behavior of the code-carrier divergence (CCD) filter as implemented in the GAST-D airborne prototype. As explained in the INR GAST-D Validation report (available at http://laas.tc.faa.gov/documents/Docs/INR_FINAL_REPORT.pdf), the CCD filter as implemented has a bug which results in the filter taking longer than it should to settle below the 0.0125m threshold after a satellite loss of lock. Instead of taking seconds to re-admit an SV, the prototype receiver can take on the order of minutes. As this bug was not discovered until the very end of the GAST-D prototype development contract, a fix was not able to be completed.

Data analysis indicates that periods of low C/No on SVs below roughly 25 degrees elevation angle corresponds to times where the roll angle of the aircraft was high. The GPS antenna(s) on N47 and N49 are located on the top centers of the aircrafts, making them vulnerable to satellite blocking on turns. Though the Rockwell Collins receiver suffers from similar periods of low C/No and losses of lock, its performance remains good since it does not have a CCD filter to further aggravate the issue. The receiver may lose an SV for a moment, but will re-include it very quickly after it begins to track it again. Thus, it's rare to lose more than one satellite from the solution at a time. The Honeywell INR GAST-D prototype on the other hand, with the delayed re-admittance due to the faulty CCD filter, will end up excluding multiple SVs at the same time, resulting in poor geometries and high protection levels. It should be stressed that this affects only the GAST-D prototype INR. Production GAST-C models will not be subject to the delayed acquisition issue, and behave similarly to the Rockwell MMR. This was demonstrated during the testing on 8/19 and 8/20/2014, in which one of the airborne INRs was rolled back to the GAST-C approved software version for testing.

3.2.2 Baseline Data Collection

As indicated in the flight schedule in Section 2.3, flights were conducted on 4/28, 4/29, and 5/1/2014 with the system in its current nominal configuration (all primary RSMUs active). Approaches were flown to all runway ends at ACY—five 10-nmi approaches to each of the four and one 20-nmi approach to three. One 20-nmi orbit was also flown to verify VDB coverage. During this baseline testing, both INRs were loaded with their final available software build, v. 302 and tuned to the GAST-D version of the approaches broadcast by the HI SLS GAST-D prototype ground station.

Figure 10 thru Figure 13 show ensemble navigational system error (NSE) results for 21 approaches on both of the INRs flown. Two approaches were removed from the data set considered due to excessive pilot error. (These are the same two approaches that were removed from the Rockwell Collins GNLU-930 data—the pilots turned into the approach too late causing excessive apparent error in the NSE by deviations data.) The plots include data from both INRs. Figure 10 and Figure 12 show horizontal and vertical NSE as calculated using deviation values. These values are impacted by the effects of latency, leading to increased apparent error when the plane is not straight-on to the approach. As well, each deviation is repeated five times due to the update rate, causing the error to grow with each update. Figure 11 and Figure 13 show the NSE as calculated using the output PVT values; these outputs are not affected by latency and as such exhibit a much tighter error profile. Mean and standard deviation of the errors are indicated on the right-hand axes.

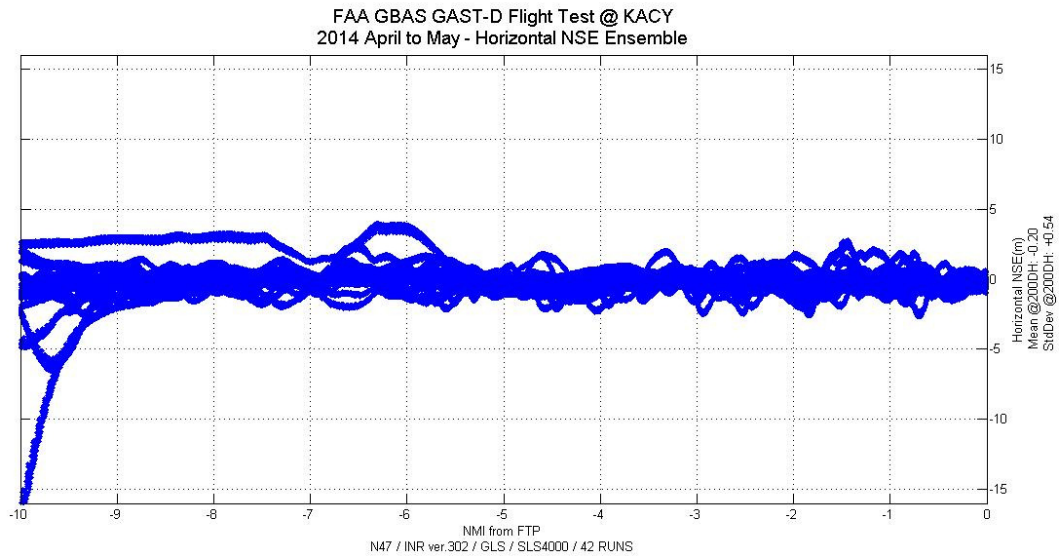

Figure 10: INR Baseline Approach Data-Horizontal NSE (Deviations)

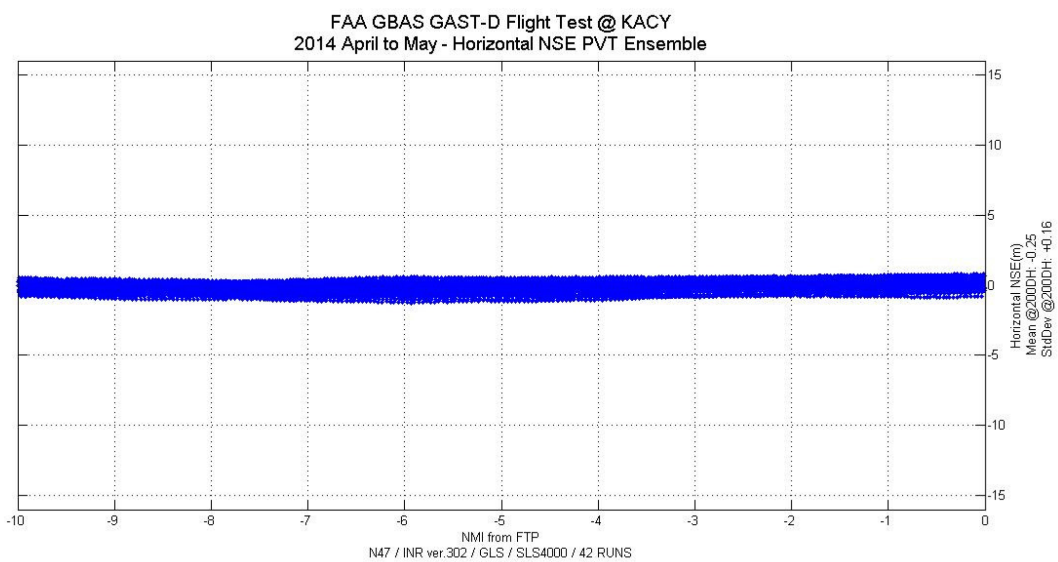

Figure 11: INR Baseline Approach Data-Horizontal NSE (PVT)

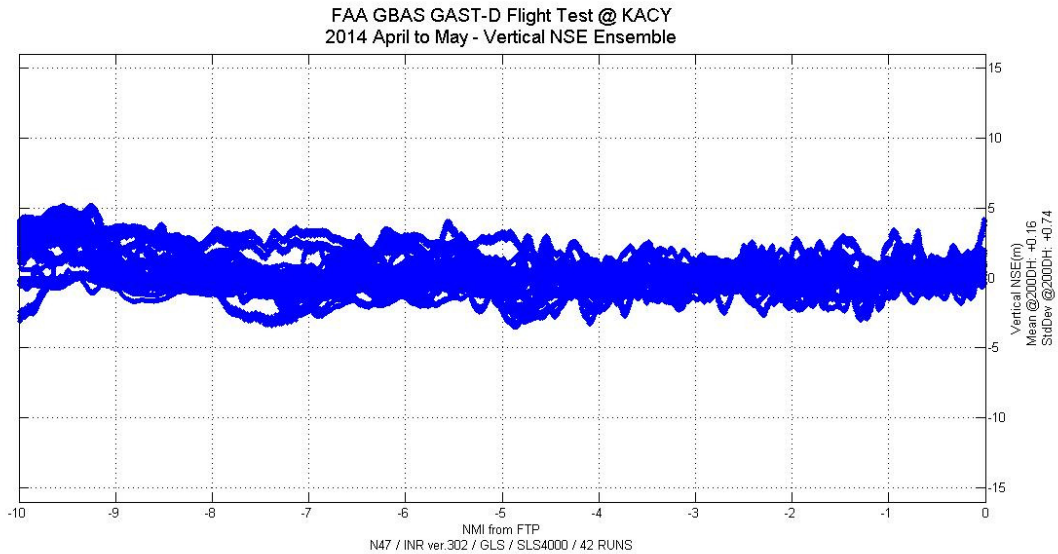

Figure 12: INR Baseline Approach Data-Vertical NSE (Deviations)

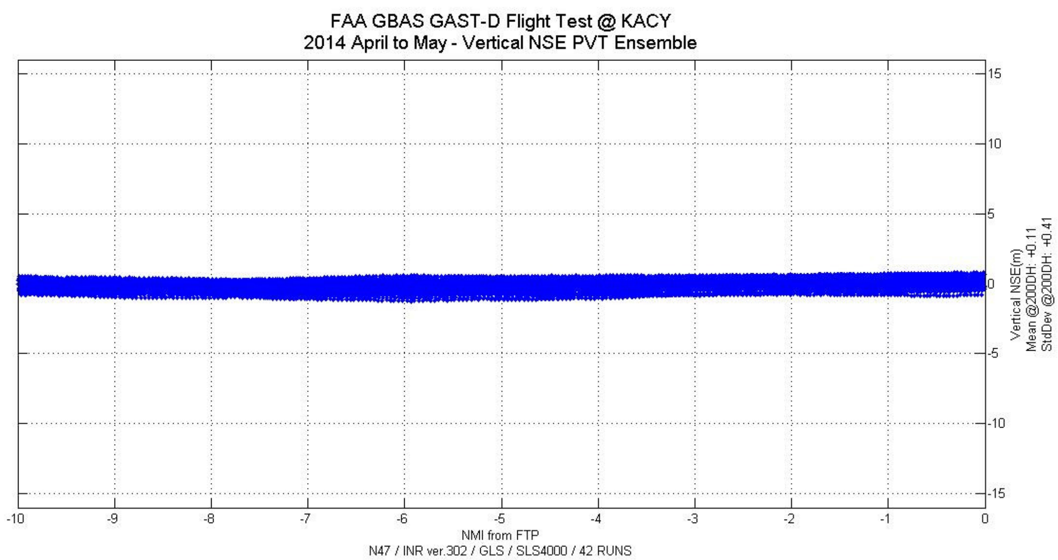

Figure 13: INR Baseline Approach Data-Vertical NSE (PVT)

3.2.3 Reference Switching Data Collection

Although nearly all of the RSMU switches on the ground station occurred outside of the PAR, the data collected on flights between 5/20 and 8/7/2014 do represent scenarios in which the SLS-4000 was using various combinations of either three or four RSMUs. Ensemble plots of NSE data from these approaches to ACY RWY 04 are shown in Figure 14 thru Figure 17, below.

Values from 73 approaches on INR #2 and 65 approaches on INR #1 are shown. INR #1 data from eight approaches during the 7/30/2014 flight test were discarded due to the INR indicating that it was in a fault mode for the entire period. The cause of this fault mode has not been determined but was not repeatable and did not appear to affect the data collected.

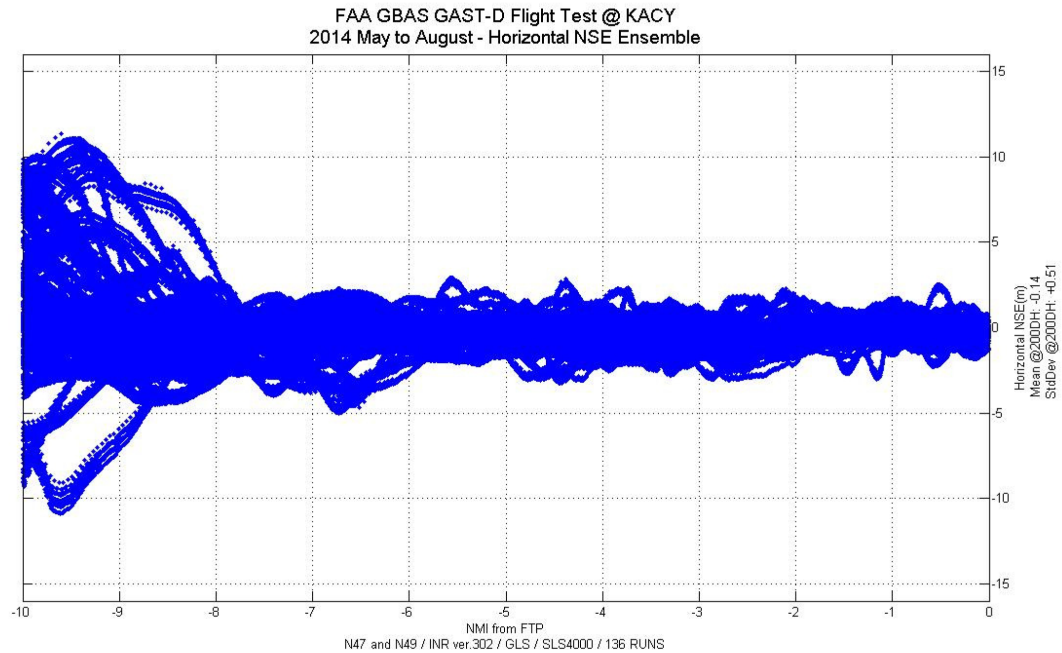

Figure 14: INR Reference-Switching Approach Data-Horizontal NSE (Deviations)

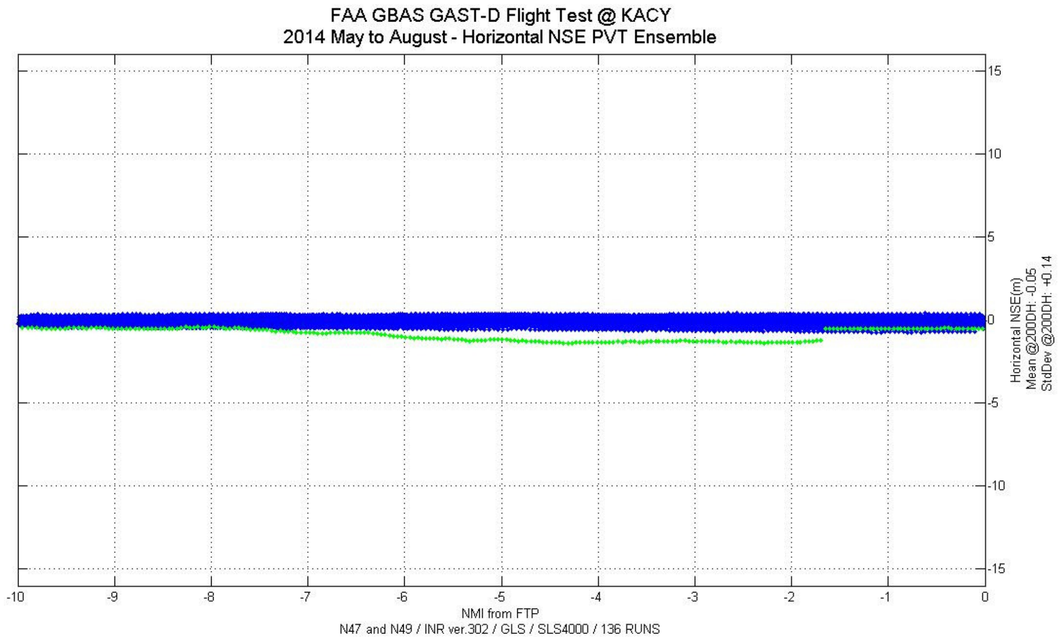

Figure 15: INR Reference-Switching Approach Data-Horizontal NSE (PVT)

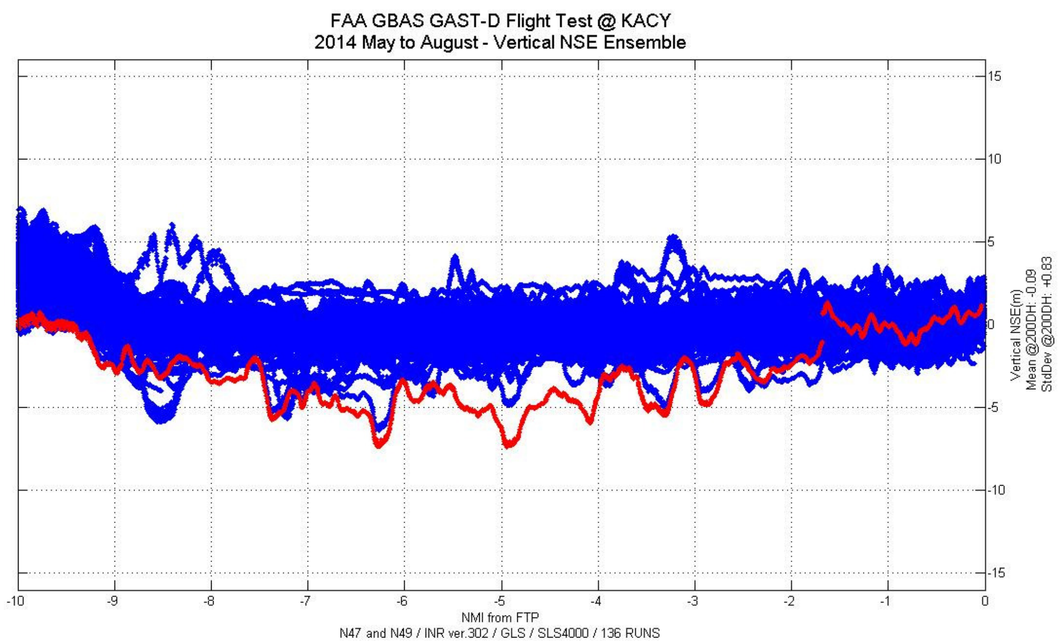

Figure 16: INR Reference-Switching Approach Data-Vertical NSE (Deviations)

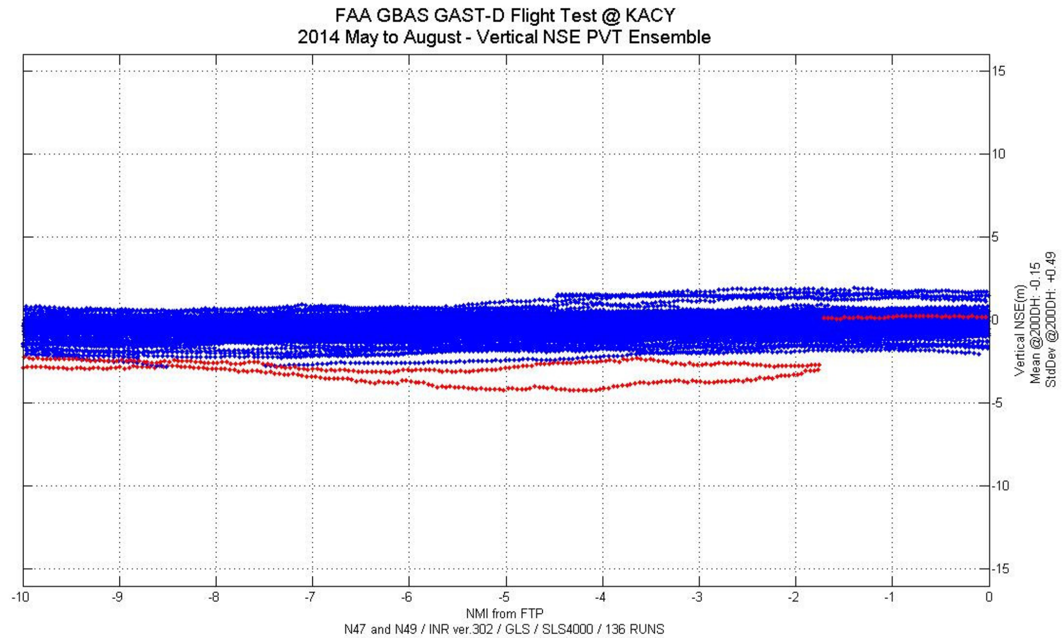

Figure 17: INR Reference-Switching Approach Data-Vertical NSE (PVT)

One approach in Figure 16 and Figure 17 of vertical NSE appears as an obvious outlier (marked in red). This is Approach #11 conducted on 5/20/2014, when the station was in Configuration Scenario #11, with only three RSMUs active—RSMUs 2, 5, and 6 in B-value slots 1, 2, and 4, respectively. RSMU 5 at ACY has substantially more masking that the other five RSMUs, with some masks at elevation angles as high as 70 degrees. During this approach PRN 31 was briefly masked from use on RSMU 5, causing it to also be removed from the Type 1 and Type 11 corrections messages as only two other RSMUs were in use at this time. NSE vs. Distance to threshold for this approach is shown in Figure 18 (NSE based on deviations) and Figure 19 (NSE based on PVT). The sudden improvement in error at approximately 1.75nmi out from threshold is coincident with the re-inclusion of PRN 31 by the ground station. As PRN 31 was a relatively high-elevation satellite, at approximately 64 degrees, its presence had a large impact on the accuracy of the solution. This poor NSE performance is not observed on the Rockwell Collins receiver during this approach because it had all other visible satellites in solution, while the HI INR was unable to use several other satellites in addition to PRN 31 due to the error in the CCD filter implementation. Note that although the VPLs, seen in Figure 18, are higher than what we generally see, the avionics never flagged, as the VPLs stayed just below the VAL at all times during the approach. The point at which the horizontal NSE exceeds the LPL in this figure, at approximately a half-mile from threshold, may cause concern. This is only due to the latency in the deviations outputs and the latency-free NSE would be well below LPL. This is verified by the NSE by PVT data shown in Figure 19; the PVT outputs are latency-free.

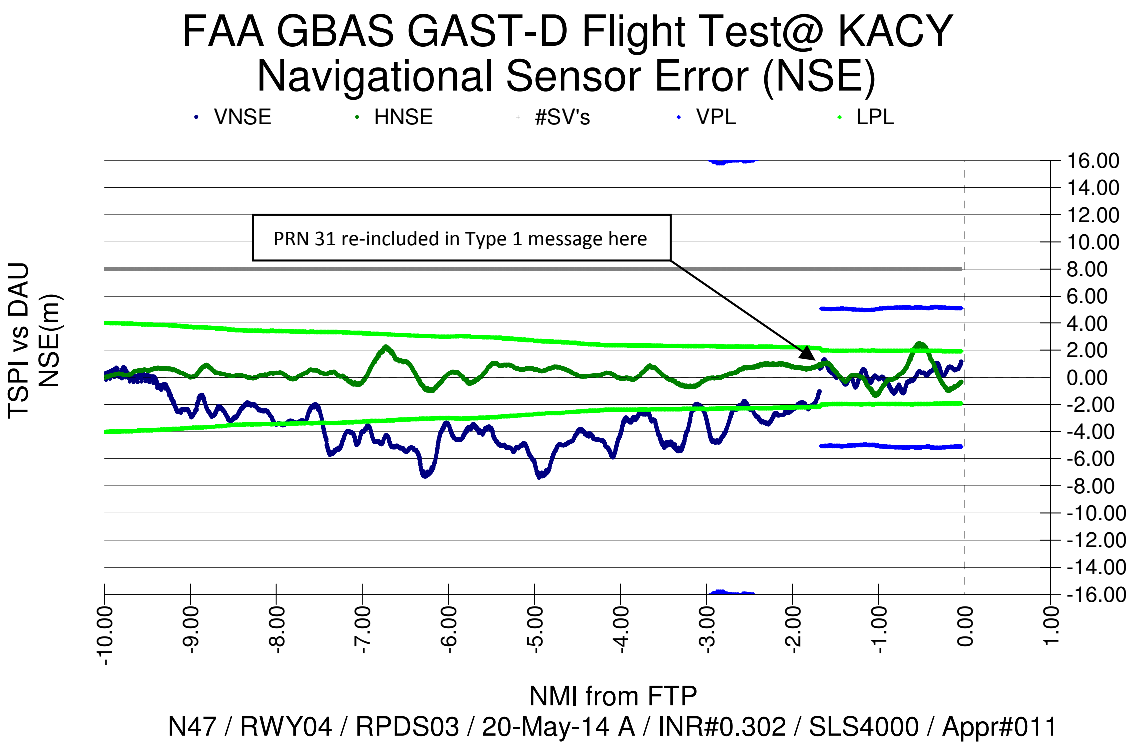

Figure 18: 5/20/2014 Approach #11 NSE (Deviations)

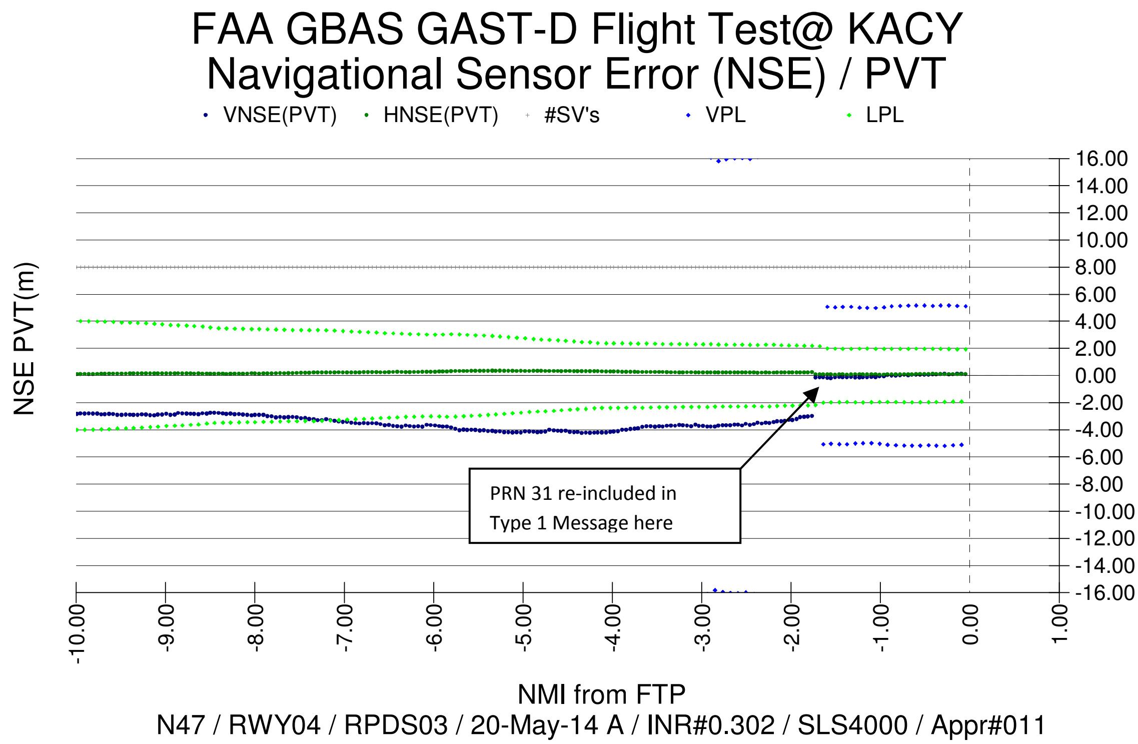

Figure 19: 5/20/2014 Approach #11 NSE (PVT)

Similarly, there is one obvious outlier (marked in green) shown in Figure 15, depicting horizontal NSE. This is Approach #5 conducted on 7/30/2014, when the station was again in Configuration Scenario #11. Here the affected satellite was PRN 28, again behind a mask on RSMU 5 and removed from the Type 1 corrections. NSE vs. Distance to Threshold calculated from deviations and from PVT for this individual approach on INR #1 is shown in Figure 20 and Figure 21, respectively. The time where PRN 28 is re-included in the Type 1 message and NSE errors improve is indicated on the plots.

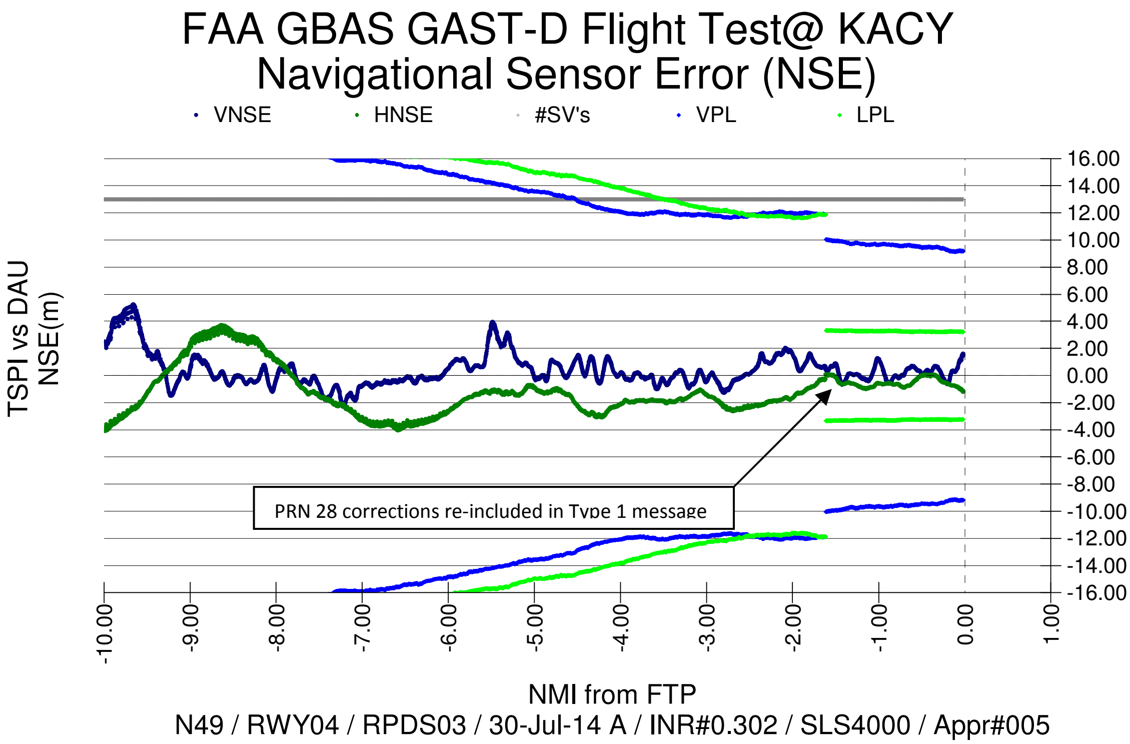

Figure 20: 7/30/2014 Approach #5 NSE (Deviations)

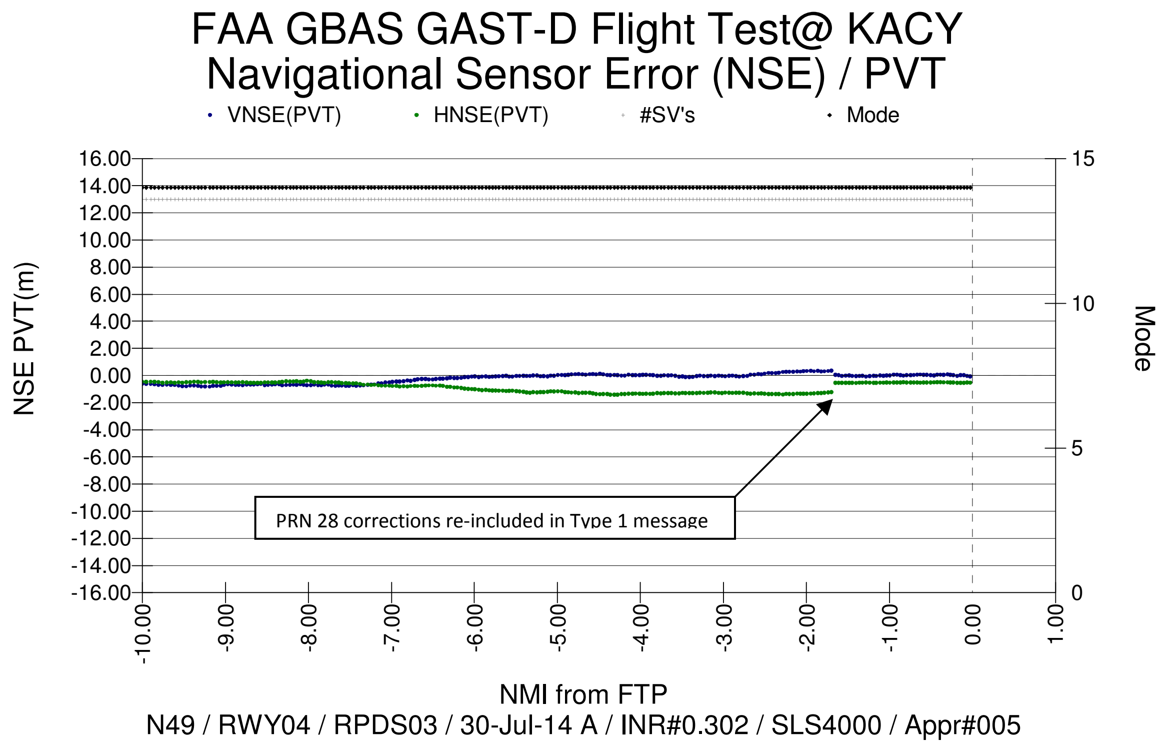

Figure 21: 7/30/2014 Approach #5 NSE (PVT)

One instance where the ground station switched from a configuration using a secondary RSMU to one using the primary RSMU was captured inside the PAR. Data from INR #1 for this approach is shown in Figure 22 thru Figure 24, showing NSE, VPL, and RRFM monitoring outputs. No apparent changes are seen in the airborne receiver data or performance when this switch takes place. Notably, ACY is a low-multipath environment where B-values on all RSMUs are generally in the -5 to 5 cm range—thus large swings in the RRFM or protection level values due to a reference switch would be unexpected.

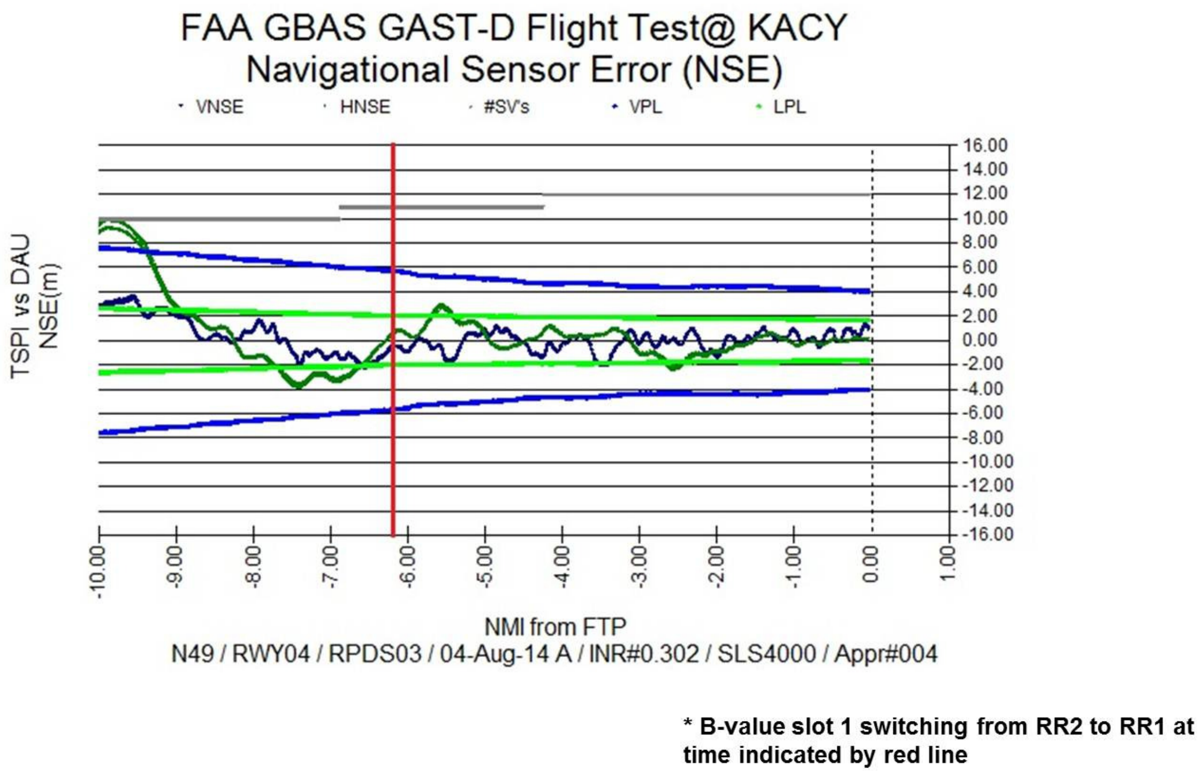

Figure 22: NSE at Time of RSMU Switch

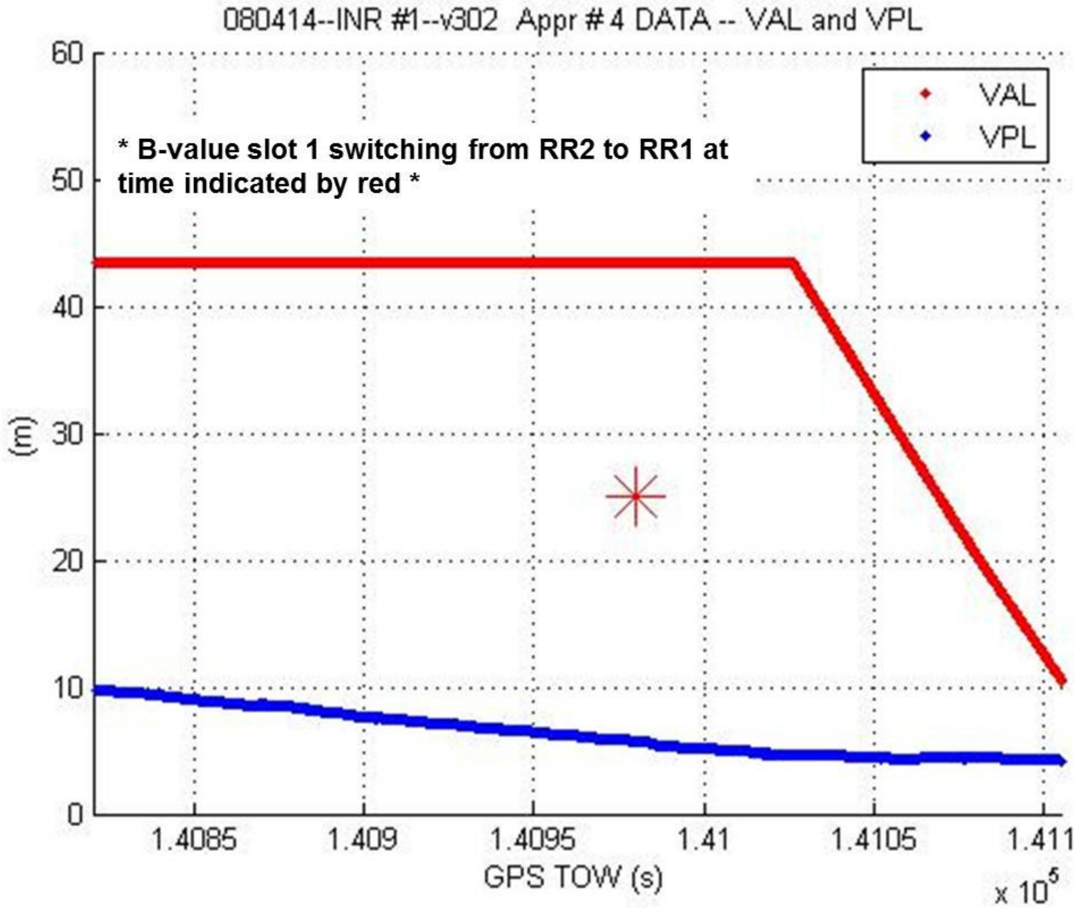

Figure 23: VPL and VAL at Time of RSMU Switch

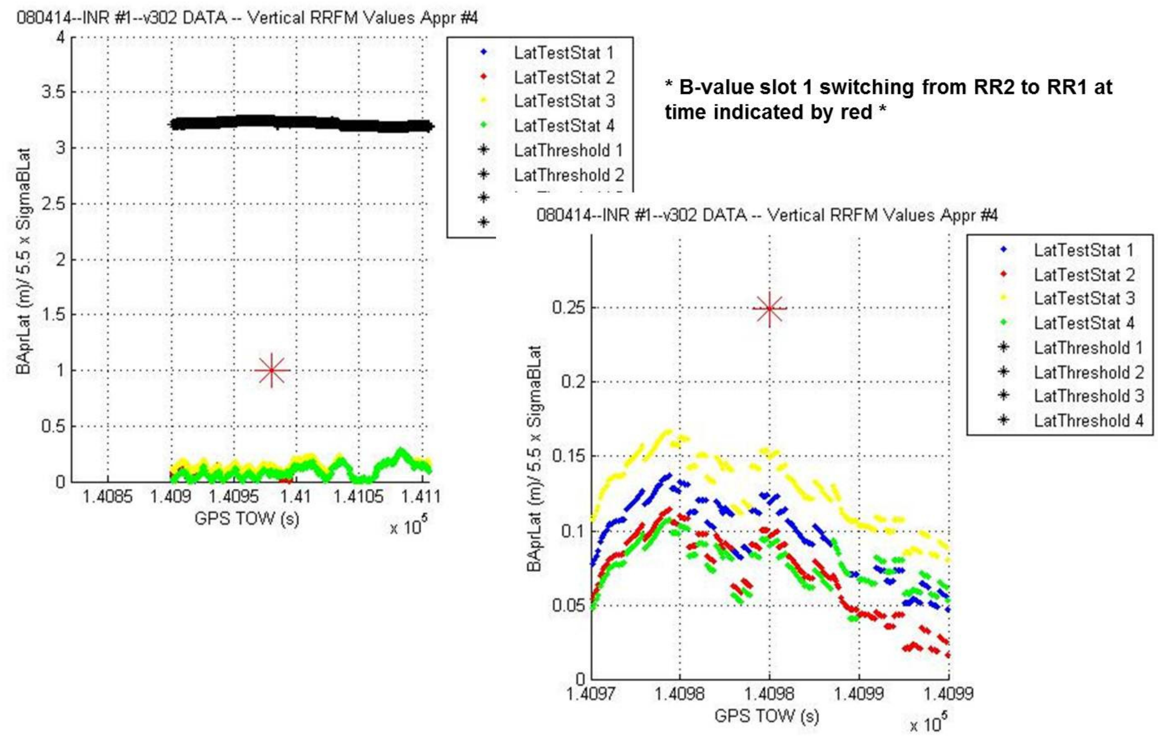

Figure 24: RRFM Test Statistics and Thresholds at Time of RSMU Switch

3.2.4 VDB Switching Scenarios

Approaches where switches between the two available VDB transmitters of the SLS-4000 took place were conducted on 5/21/2014 and 8/5/2014. On 5/21 the VDB was manually switched from VDB #1 to VDB #2. This test was intended to mirror what would happen during the routine switch between VDB transmitters that is scheduled every 12 hours. During the 8/5 approach VDB #1 was de-powered such that the system was responsible for switching to transmitting on VDB #2. This test was meant to mimic how the ground system might behave during an actual VDB failure.

Analysis of the data collected on the two airborne INRs indicated no gaps in guidance or other anomalous behavior as a result of the manual switch on 5/21/2014. VDB transmission data recorded by the SLS on the ground also showed that there were no gaps in Type 1, 2, 4, or 11 message transmission—messages were sent at their regular rates throughout the entire approach.

During the 8/5/2014 approach, where the VDB was de-powered forcing the SLS to swap to the secondary VDB transmitter automatically, the VDB transmission data indicated that one frame of data was lost. This resulted in one missing Type 1 and Type 11 message, one delayed Type 2 message, and one missing expected Type 4 message. Type 2 and Type 4 data were still broadcast within the required rates; only one frame of Type 1 and Type 11 data was missing, which is not enough to cause an issue due to either the GAST-C or GAST-D message time out rates. The missing half-second of broadcast data was confirmed by viewing the signal-to-noise values from the airborne INRs. As expected, no loss of guidance, flagging, or service downgrades were observed.

3.2.5 Overall GAST-D Monitor Performance

Data collected from the GAST-D prototype monitors was binned for analysis across all data sets (baseline, reference switching, and VDB switching scenarios). Results were generally consistent with what was collected during earlier flight tests conducted during the prototype development contract. The sections below cover this data on a monitor-by-monitor basis.

Dual Solution Ionospheric Gradient Monitor (DSIGMA)

DO-253C LAAS MOPS Section 2.3.9.3

Figure 25 shows the vertical and lateral DSIGMA values for all epochs where data was marked as 'in-air' by the INR. There are two instances where the magnitude of $DSIGMA_{vert}$ is greater than 2m. These both occurred outside of the PAR but on the inbound portion of the flight, with one instance occurring on INR #1 and one on INR #2. These events happened four days apart at roughly the same time of day (10 minutes apart), which points to a dependency on satellite geometry and tracking issues. DSIGMA data for these times is shown in Figure 26, with corresponding VPL/VAL values shown beneath in Figure 27. As indicated, in addition to dropping out of GAST-D mode due to a flag on DSIGMA, GBAS guidance during the approaches occurring in this time span would have been lost entirely at some point due to VPL exceeding VAL. Figure 28 shows the number of satellites in view and marked valid or invalid on INR #1 on 8/1/2014 during the $DSIGMA_{vert}$ > 2m event. Note that the x-axis in this figure is in seconds of day and not seconds of week. The INR is routinely using between two and five less satellites than it has available (in view and with corrections provided) due to body masking and the effects of the erroneous implementation of the GAST-D prototype's CCD filter. Similar data on the number of satellites in use was observed during the $DSIGMA_{vert}$ > 2m event on 8/5/2014.

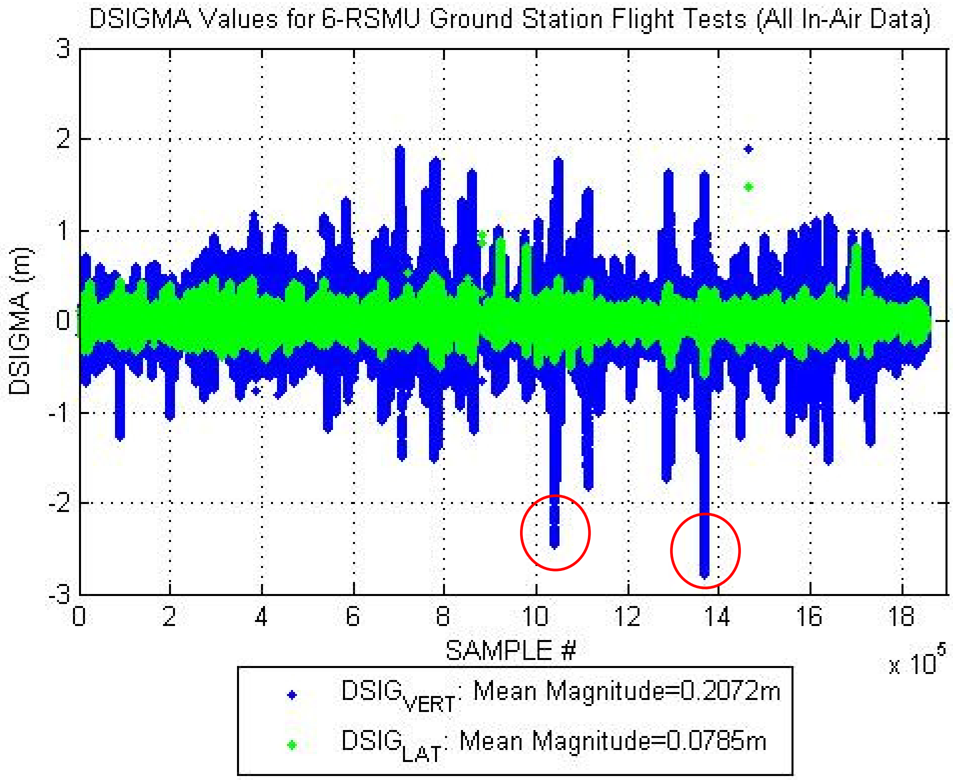

Figure 25: Composite DSIGMA Data (All flights)

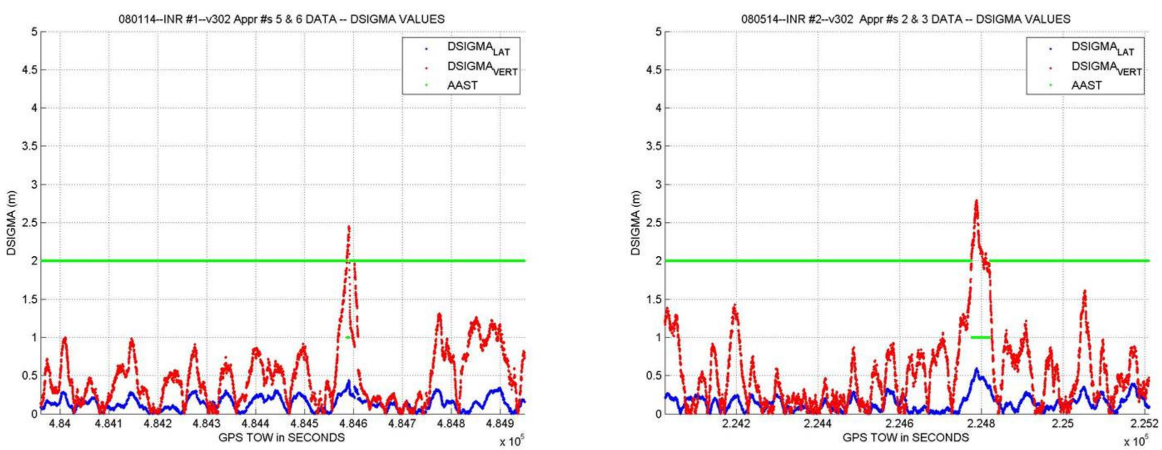

Figure 26: DSIGMA > 2m

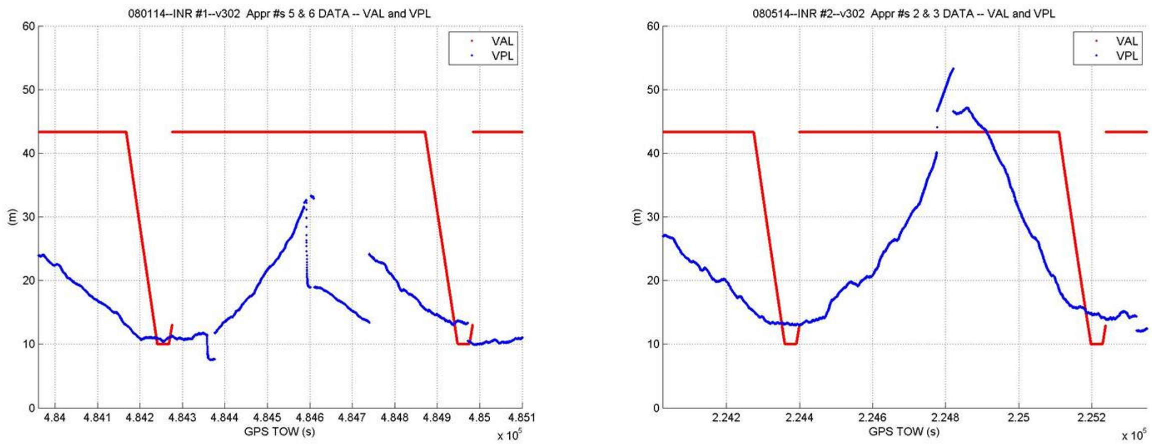

Figure 27: VPL & VAL where DSIGMA > 2m

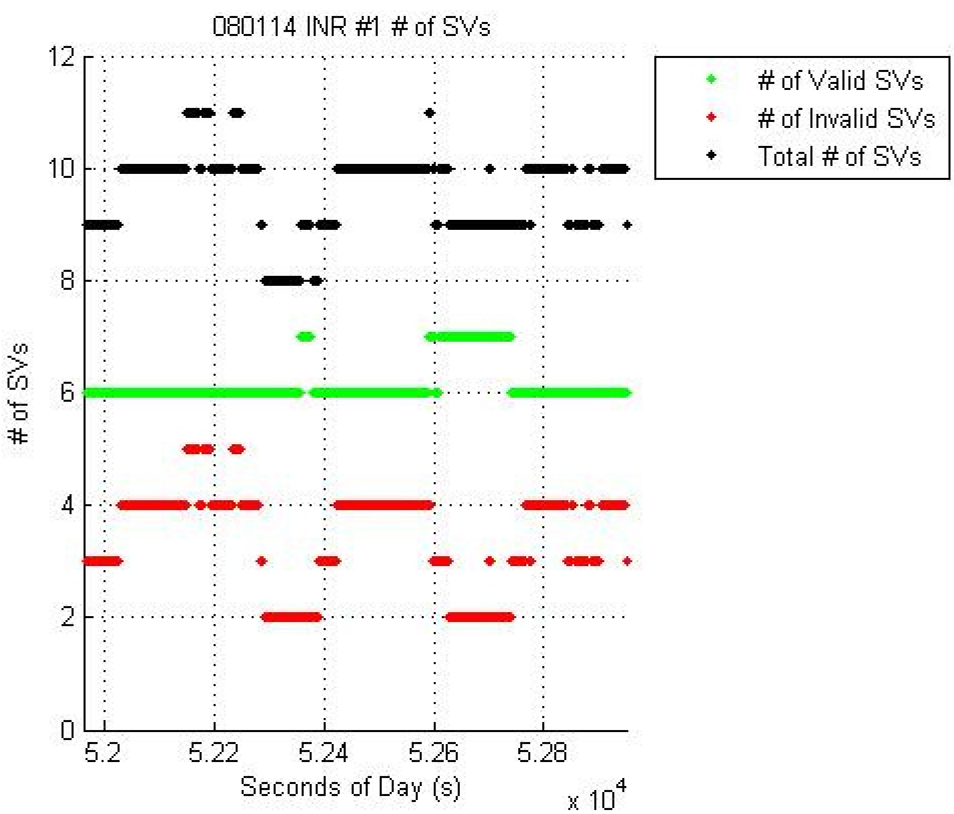

Figure 28: 080114 INR #1 # of SVs for Approach #s 5 & 6

Differential Correction Magnitude Check

DO-253C LAAS MOPS Section 2.3.9.5

Figure 29 and Figure 30 show the outputs for the 100-second and 30-second smoothed pseudorange horizontal projection differential correction magnitude (HPDCM) values. 30-second smoothed HPDCM values are output at 10 Hz when the INR is in GAST-D mode, while 100-second smoothed HPDCM values are output at 1 Hz when the INR is in either GAST-C or GAST-D mode. As seen in earlier flight testing, these values never near their 200m alert threshold. Mean values are 2.3334m for the 30-second and 2.6920m for the 100-second smoothed outputs.

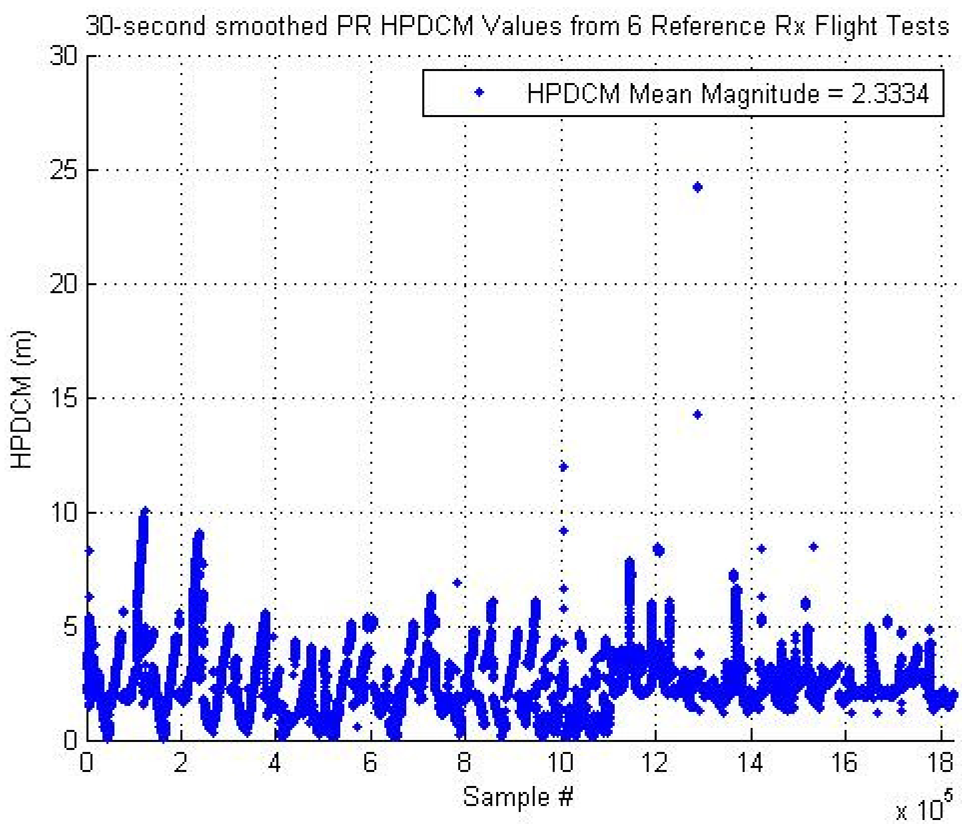

Figure 29: Composite 30-sec HPDCM Data

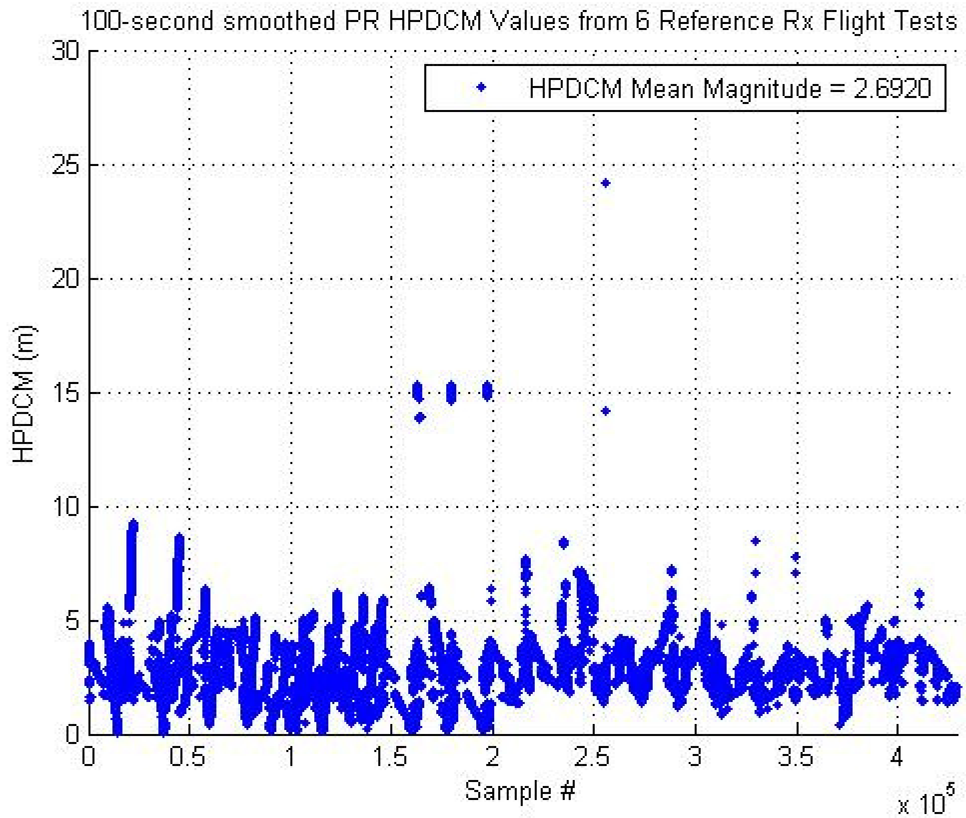

Figure 30: Composite 100-sec HPDCM Data

Reference Receiver Fault Monitoring (RRFM)

DO-253C LAAS MOPS Section2.3.11.5.2.3

Reference receiver fault monitoring (RRFM) is conducted by the GAST-D prototype INR when the aircraft is inside the PAR. The results shown in Figure 31 and Figure 32 contain the lateral and vertical RRFM test statistics and corresponding computed thresholds. Results are shown for data collected on ground and while airborne. Thresholds are inflated when the aircraft is on the ground to account for the potential for increased multipath—these times account for the periodic instances of higher values seen. As in earlier flight testing, no RRFM flags were observed during any flights in this set of tests. Since most ground RSMU switching was done when the aircraft was outside of the PAR, RRFM data at the time of the switches is not available, aside from the case shown in Section 3.2.3 of this report.

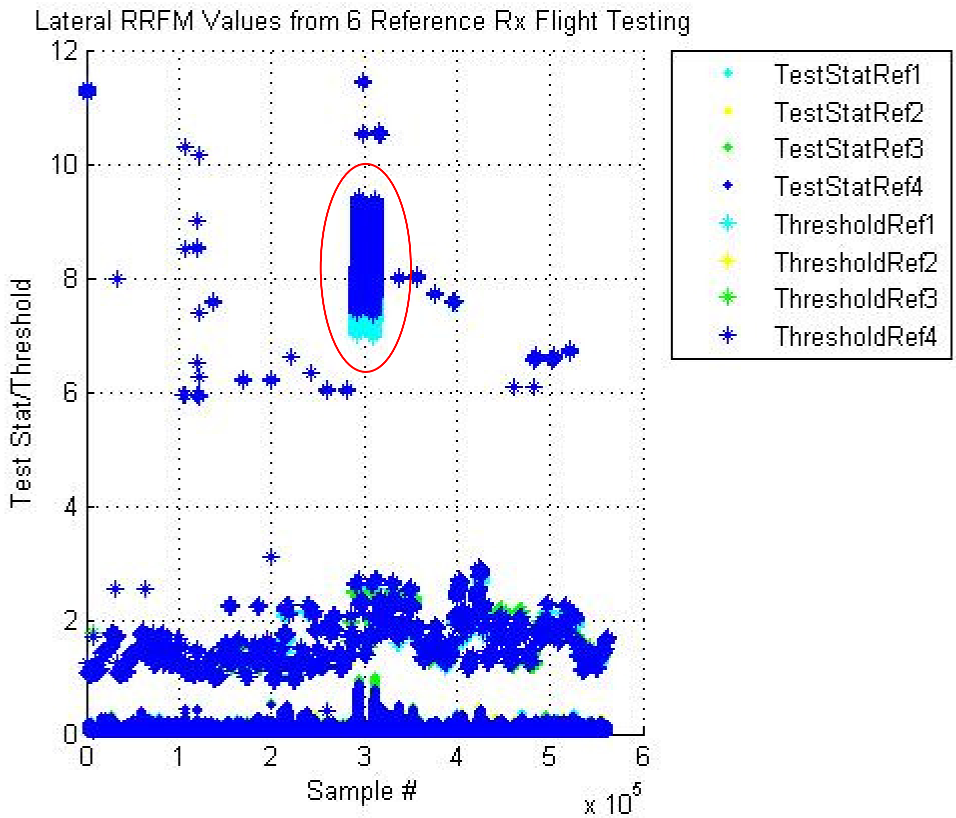

Figure 31: Composite Lateral RRFM Data

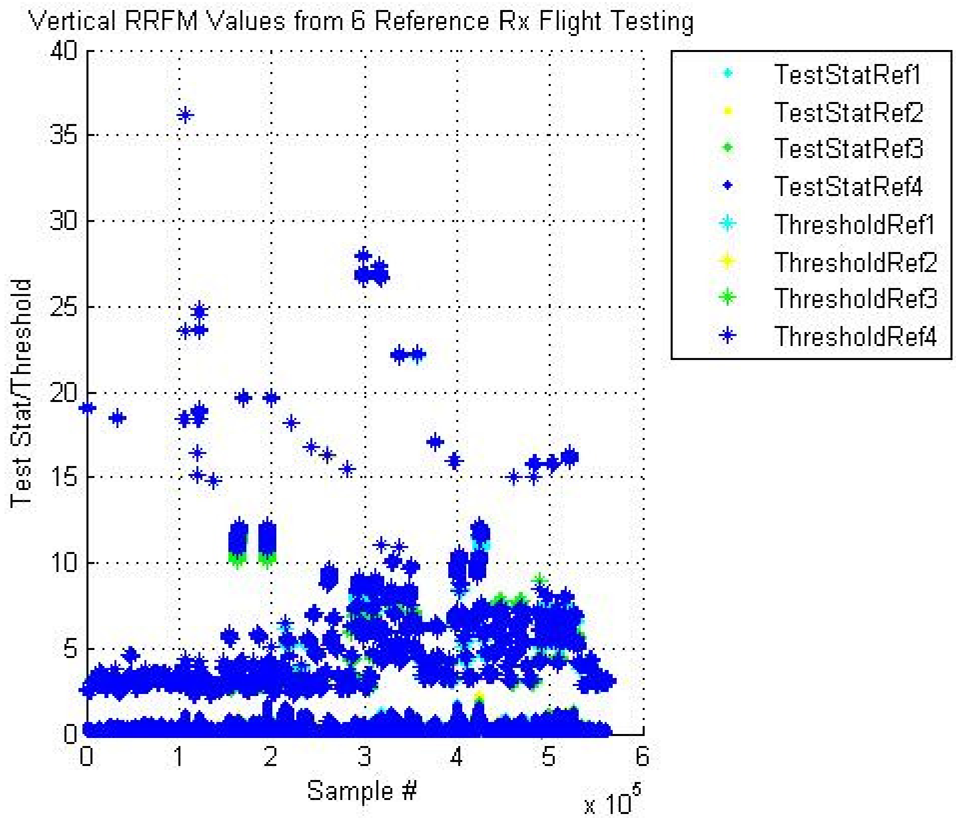

Figure 32: Composite Vertical RRFM Data

There is one period shown on the lateral RRFM values plot that appears to have both test statistics and thresholds elevated above average values for a somewhat prolonged period of time. These points are circled in red in Figure 31 and occurred during approach #5 on 7/30/2011. This is one of the approaches noted in Sections 3.1.2 and 3.2.4, during which RSMU switching scenario #11 was being tested, and appears to be tied to the poor satellite geometry available for use by the INRs at that time. This depletion in geometry was caused by a combination of satellites being withheld by the CCD filter in the INR GAST-D prototype and masking on RSMU #5 on the ground. Lateral RRFM values from only INR #1 during this flight are shown in Figure 33, with the data of interest marked by a red oval. (Note that this data appears twice in a row in the composite plot since they are a concatenation of all data available, where the similar results of INR #1 and INR #2 are shown one after another.)

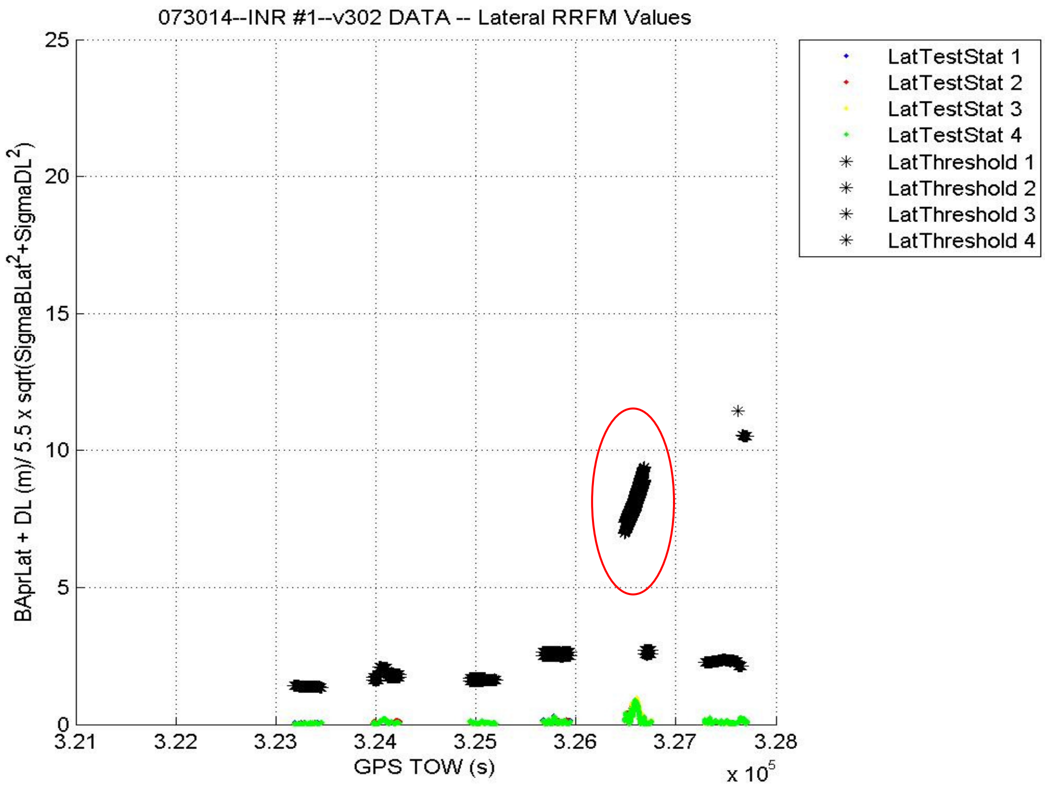

Figure 33: Lateral RRFM values - 07/30/2014 INR #1

Fault Detection (RAIM)

DO-253C LAAS MOPS Section 2.3.9.6

RAIM fault detection is implemented in INR v. 302. No faults were detected during this set of flight tests, whether the aircraft was on air or on the ground. This is consistent with what was observed during earlier flight testing.

Code Carrier Divergence Filtering

DO-253C LAAS MOPS Section 2.3.6.11

Due to the known bug in the implementation of the code carrier divergence (CCD) filter in INR v. 302, CCD data from this set of flight tests was not analyzed. See 'GAST-D Validation Report: Results from the HI INR Development Contract', available for download at http://laas.tc.faa.gov/documents/Docs/INR_FINAL_REPORT.pdf, for more information.

4. Summary & Conclusions

Flight testing of the current Build 7 version of the Honeywell SLS GAST-D prototype ground station at the FAA Wm. J. Hughes Technical Center at Atlantic City Int'l Airport (ACY) was conducted to verify performance during switching between primary and secondary reference receiver monitoring units (RSMUs) in the six reference receiver configuration, as well as to observe performance during VDB switchover periods. Avionics receivers tested were the Rockwell Collins GNLU-930 (approved for GAST-C use), and the Honeywell Integrated Navigation Receiver (INR) with GAST-D prototype software running. Issues with body masking by the aircraft caused some unexpected issues in the data collected, and trouble with the timing of the forced switches from primary to secondary RSMUs led to most switches occurring when the aircraft was outside of the PAR. However, based on the data that was available, switching from primary to secondary reference receivers and back, and thus changing the physical location correlating to a B-value transmitted in the Type 1 message while the transmitted ground survey point remained static, did not cause any anomalous behavior in the avionics under test. As well, no gaps in guidance, flags, or service level downgrades were observed during VDB switchovers conducted on two separate days.

5. Future Work

A final week of GAST-D flight testing has been scheduled during January 2015. Although the work completed during the flight tests described in this paper provide useful material for validation of both the GAST-D monitors and the use of six ground reference receivers, it is desirable to conduct a larger number of approaches during which switches between primary and secondary RSMUs take place while the aircraft is on final approach and inside the PAR. Additional testing of VDB switchover scenarios may also be conducted in order to verify the system behavior observed during the single approach in which a VDB transmitter was failed during this set of flight tests.