GAST-D GROUND SYSTEM PROTOTYPE DEVELOPMENT

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SUMMARY

This paper provides an overview of the work completed under an FAA contract with Honeywell International to develop a GAST-D GBAS ground station prototype. The primary goal of this contract was to produce materials to aid in the validation of the draft GAST-D ICAO SARPS. Contract milestones and data of interest are included.

1. INTRODUCTION

The FAA entered into a contract with Honeywell International (HI) in May 2010 to develop a prototype GAST-D GBAS ground system. The baseline for this prototype is the FAA approved GAST-C HI SLS-4000 GBAS. Required hardware and software updates were made on the FAA-owned SLS-4000 located at the Wm. J. Hughes Technical Center at Atlantic City International Airport (ACY). The primary FAA goal for this contract was to support validation of the draft GAST-D ICAO SARPS.

Hardware updates including new GPS receiver cards at the reference stations, fiber optic cable runs from the references to the main processing unit, and the addition of two additional 'spare' reference stations were completed. Software updates included the development and implementation of GAST-D monitors and logic to handle more than four ground reference stations. A significant amount of effort was dedicated to validation of the GAST-D Ionospheric Gradient Monitoring requirement. Honeywell's initial development work showed that the requirement as originally written in the draft SARPS was infeasible. HI presented a proposed change at the May 2014 ICAO CSG meeting and began work with the help of other parties to validate the updated requirement. This work is being done by an ad-hoc CSG group and is being presented through other working papers at this meeting.

The FAA's GAST-D prototype development contract with HI is proceeding on schedule, and will run thru May 2015 to allow time for final documentation of the work completed, including a final report from Honeywell. This end date will also allow time to continue work on additional validation material that may be determined necessary at the end of this meeting.

2. DOCUMENTATION

Documentation including algorithm description documents (ADDs) and Hazardously Misleading Information (HMI) reports for all monitors implemented in the GAST-D prototype station, Preliminary System Safety Assessment (PSSA), and Functional Hazard Analysis (FHA) were submitted by HI to the FAA. These documents have been reviewed by the FAA and its key technical advisors (KTAs).

ADDs and HMI documentation was completed for the following GAST-D monitors and processes:

- 30-second smoothed corrections
- Excessive Acceleration (EA)
- Code-Carrier Divergence (CCD)
- Signal Deformation (SDM)
- Low Power (Single Satellite)

- Excessive RFI
- Cycle Slip
- Ephemeris
- Ionospheric Gradient Monitoring (IGM)

3. SOFTWARE UPDATES

Table 1**Error! Reference source not found.** describes the software builds delivered by Honeywell International (HI) over the term of GAST-D development contract. Each of these builds was loaded on the GAST-D prototype station at ACY, with performance continually monitored by the FAA's Ground-Based Performance Monitor (GBPM). The results of flight testing against software Builds 2 thru 4 was presented in a May 2014 (WP 19), with results of more recent tests against Build 7 presented in another WP at this meeting.

Build #	Description	Completion Date	Installation Date at ACY
1	Display Type 11 Message	12/2010	1/2011
2	Addition of 30 second smoothing, population of Type 11 messages, updates to message Types 2 & 3, updates to event logging	6/2011	6/2011
3	Incorporation of GAST-D EA monitor, initial incorporation of Iono Gradient Monitor, compliance with VDB Authentication Protocols	7/2012	7/2012
4	Initial GAST-D updates to Cycle Slip, Ephemeris, CCD, Low Power, Signal Deformation, Cross-Correlation, and RFI monitors	9/2012	10/2012
5	Final updates to GAST-D monitors	12/2012	1/2013
6	Measured Site Data (MSD) file updates for 6 RRs	9/2013	10/2013
7	Addition of RR selection logic, RFI monitoring updates, 6 RR updates for SDM, CCD, IGM, and carrier rate monitors	10/2013	1/2014

Table 1: Schedule of Software Updates

4. HARDWARE UPATES

Table 2 provides a summary of the hardware changes that were made to the FAA-owned SLS-4000 at ACY over the course of the prototype development contract.

Date of Change at ACY	Description
07/2012	Delivery and Installation of CAT-III Reference Station boxes with CAT-III GPS cards
7/2012	Running of fiber optic cable to the 4 RRs utilized in CAT-I configuration
7/2012	Inclusion of Power/Data Jumper Boxes for handling of COM over fiber optic cable, while using copper 422 infrastructure for power
7/2012	MIB Connection I/O configuration change to handle inputs for 2 additional RRs
12/2013-1/2014	Installation of two additional RSMUs (Reference Station Monitoring Units), including running of fiber optic cable and necessary power and communication infrastructure
7/2014	Data Recorder SW update for backward compatibility between CAT-I and CAT-III operation

Table 2: Schedule of Hardware Updates

5. CURRENT SYSTEM CONFIGURATION

The prototype GAST-D SLS station at Atlantic City International Airport (ACY) is currently operating with six total reference receivers, updated GPS receiver cards, and fiber connectivity. Figure 1 below shows the current configuration of the system at ACY. The four reference stations acting in a ‘primary’ mode are circled in green; the two reference stations that are used as ‘secondary’ references are circled in red. The locations of the VDB antenna and the ground reference point broadcast in the Type 2 message (marked as ‘centroid’) are also shown.

The station is currently running on Software Build 7, which as indicated in Table 1 includes GAST-D updates to monitoring algorithms as well as code to handle switching between primary and secondary reference stations.

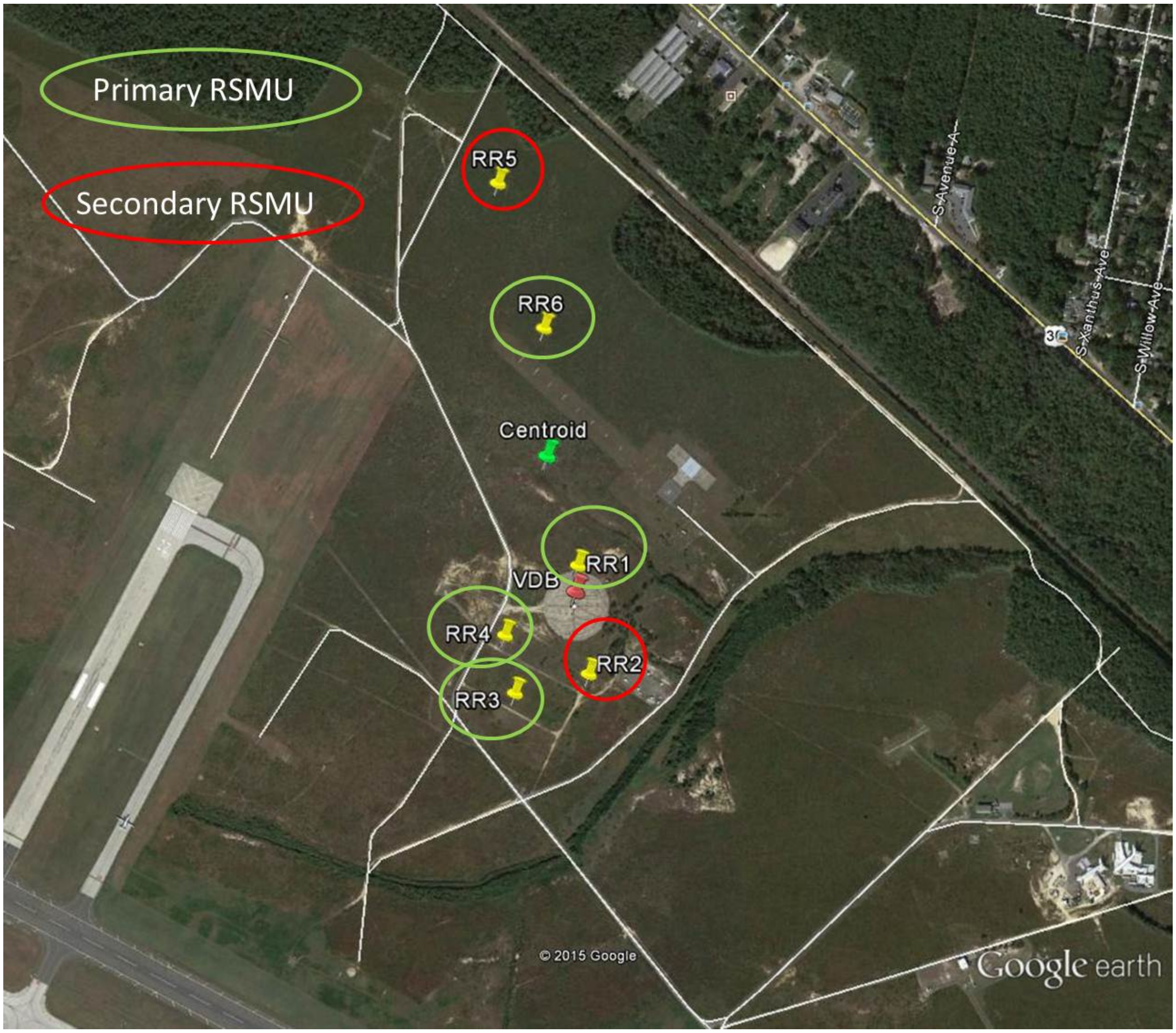

Figure 1: Current GAST-D Prototype Configuration at ACY

6. SARPS ISSUES ENCOUNTERED

Ionospheric Gradient Monitoring (Draft GAST-D SARPS Section 3.6.7.3.4)

The current draft GAST-D ICAO SARPS ionospheric monitoring requirement is copied below for reference. HI's first attempts at implementing a ground monitor to fulfil this requirement resulted in an excessive number of false alerts due to the presence of small gradients caused by transient tropospheric effects. After exploring a number of possible solutions it was decided that replacing the requirement entirely was the most promising solution. Ongoing work to validate the proposed new requirement by a CSG ad-hoc group is ongoing and is the subject of several working papers at this meeting.

> Annex 10, Appendix B, 3.6.7.3.4 Ionospheric Gradient Monitoring.
>
> A ground subsystem classified as FAST D shall within 1.5 seconds mark the differential corrections for affected satellites as invalid in MT11 ($\sigma_{pr\_gnd\_D}$ bit pattern "1111 1111"), if the probability that there is an undetected spatial ionospheric delay gradient with a magnitude greater than 1.5m/D in the direction of any approach supporting GAST D is greater than $1x10^{-9}$. D is the distance between the reference point of the FAST D ground subsystem and the threshold. The direction of the approach is defined by the runway heading.
>
> *Note - The total probability of an undetected delay gradient includes the prior probability of the gradient and the monitor probability of missed detection. For example, if the distance to the threshold is 5 km then the magnitude of the gradient that needs to be detected is 1.5 m/5 km = 300 mm/km. The magnitude of the undetected ionospheric spatial delay gradient as observed over a baseline parallel to runway being served must not exceed 300 mm/km with a total probability of greater than* $1x10^{-9}$

Use of More Than Four Ground Reference Stations (Draft GAST-D SARPS Section 3.6.4.2.4)

The GAST-D system design proposed by HI and implemented at ACY uses a total of six RSMUs (reference station monitoring units). Four of these RSMUs are designated as 'primaries' and are actively used in regular operation, with one RSMU assigned to each B-value slot in the Type 1 message. The additional two RSMUs are 'secondaries', and are intended to be swapped into B-value slots in incidents where a primary RSMU has experienced a failure or has been exposed to an event such as RFI which leaves it temporarily unusable. This design affords the system greater robustness and redundancy, and potentially allows for even higher levels of continuity and availability than with the current four-reference system.

However, 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 used in a way that allows for the use of secondary receivers in the B-value slots, this requirement would need to be changed or removed. Without a requirement update, the system would only be able to use the additional references for monitoring purposes, such as providing additional baselines for ionospheric gradient monitoring.

> 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 (WP 15) and RTCA SC-159 WG-4 in October 2014. Their recommendations and rationale for allowing reference switching given certain conditions are currently under discussion within these groups. This SARPS change will not be pursued as part of the GAST-D validation, but will be revisited as a maintenance change in the future. Flight testing during which reference switching was performed during approaches was conducted by the FAA at ACY and will be presented at a future meeting.

7. ANALYSIS OF GAST-D PROTOTYPE GROUND SYSTEM DATA

Monitor Event Rates

System event logs recorded by the GAST-D prototype station at ACY were downloaded and examined to observe the alarm rates of the GAST-D monitors implemented. The period of data used was 1/23/2014 thru 9/15/2014. During this time span the system was operating in GAST-D mode nearly continually and running Software Build 7. An attempt was made to validate the events logged by the station by means of comparison with data from the FAA's Ground-Based Performance Monitor (GBPM) installed at ACY, as well as with data available from the WAAS system and NANU information. However, determining whether or not a monitor trip constituted a false alert is not straight-forward and is not always possible. Details of logged monitor events follow.

Cycle Slips:

Table 3 provides a summary of the cycle slip events logged by the GAST-D prototype system in the period being examined. A large number of cycle slips were detected; however a majority of these were on PRN 1 and appeared to be alleviated by maintenance NANU several days after they began. One event in which cycle slips were logged on all SVs caused a loss of service. This event was concurrent with logged low power events and was likely due to an unknown interference source near the prototype site.

UTC Date/Time	PRN	Description/Notes	Loss of Service/VPL>10m?
1/31/14 21:54:54-2/3/14 09:19:48	1	Between 1/31 and 2/3/14 the GAST-D prototype system logged a large number of brief cycle slip exclusions on PRN 1. The GBPM GPS receiver also lost lock intermittently during this time period. Soon after, at 1600 UTC on 2/3/14, a maintenance NANU was posted. Once the satellite was returned to service, these events ceased.	NO
3/5/14 20:07:57	32	Type 1 corrections for PRN 32 lost from 20:09 to 20:16 FAA GBPM GPS rx lost lock from 20:09 to 20:17	NO
3/7/2014 09:25:16	25	Type 1 corrections for PRN 25 lost from 09:26 to 09:32 FAA GBPM GPS rx lost lock from 09:26 to 09:29	NO
3/14/2014 07:49:15	4	Type 1 corrections for PRN 4 lost from 07:50 to 08:03 FAA GBPM GPS rx lost lock from 07:50 to 08:00	NO
4/1/2014 04:36:45	32	Type 1 corrections for PRN 32 lost from 04:38 to 04:49 FAA GBPM GPS rx lost lock from 04:38 to 04:42	NO
4/12/2014 23:51:45	26	Type 1 corrections for PRN 26 lost from 23:53 to 00:02 FAA GBPM GPS rx not yet tracking (low elevation SV)	NO

7/4/2014 18:16:57	3	Type 1 corrections for PRN 3 lost from 18:18 to 18:28 FAA GBPM GPS rx lost lock from 18:18 to 18:26	NO
7/21/14 18:51:31	32	Type 1 corrections for PRN 32 lost from 18:52 to 19:01 FAA GBPM GPS rx begins tracking at 19:02 (low elevation SV)	NO
8/28/2014 20:45:00	All	All Type 1 corrections lost from 20:47 to 20:49. No loss of lock on FAA GBPM GPS rx. Concurrent with logged low power events. Under investigation.	YES
Total # of Events: 9+ # of Events Leading to Loss of Continuity: 1			

Table 3: Summary of Logged Cycle Slip Events

Excessive Acceleration:

Thirty-four excessive acceleration events were logged by the HI GAST-D prototype at ACY during the period examined. In general, these events caused a loss of the affected correction in the Type 1 message for between one and three minutes. These events are summarized in Table 4. One of these events, a PRN 21 exclusion on 1/31/2014, led to a VPL greater than 10m at DH on all ACY runways for approximately one minute.

PRN	# of Events Logged	Notes
21	25	At least 12 of these events also affected the tracking of the GBPM GPS rx. PRN 21 has a history of issues that lead to EA trips. One of these events led to a loss of service (VPL>10m at DH) lasting 1 minute on all 4 ACY runway ends.
1	5	Events not observed in tracking of GBPM GPS rx. No loss of continuity due to monitor trips.
4	10	Not all event times have observed tracking issues on GBPM GPS rx. No loss of continuity due to these monitor trips.
6	2	Not all event times have observed tracking issues on GBPM GPS rx. No loss of continuity due to these monitor trips.
Total # of Events: 22 # of Events Leading to Loss of Continuity: 1		

Table 4: Summary of Logged Excessive Acceleration Events

Code-Carrier Divergence (CCD):

During the period examined, the HI GAST-D prototype system logged 15 CCD events. A majority of these events occurred on very low elevation satellites. The FAA GBPM GPS does not track reliably at these low elevations, making it difficult to determine if the receiver was impacted by an event as well. With one exception, all CCD exclusions lasted 1 minute or less and none of these events led to a loss of service. Further details of the CCD events logged are provided in Table 5.

UTC Date/Time	PRN	Notes	Loss of Service/VPL>10m?
2/19/2014 18:09:58	31	SV rising. Type 1 corrections for PRN 31 lost for less than 1 minute.	NO
2/27/2014 23:03:00	25	SV setting. Type 1 corrections for PRN 25 lost for less than 1 minute.	NO
2/27/2014 22:27:44	13	SV rising, excluded by CR monitor as well.	NO
2/28/2014 00:05:28	7	SV elevation ~10 degrees. Type 1 corrections for PRN 7 lost for less than 1 minute.	NO
2/28/2014 21:01:8610	7	SV elevation ~15 degrees. Type 1 corrections for PRN 7 lost for less than 1 minute.	NO
2/28/2014 27:31:86	10	SV setting. Type 1 corrections for PRN 10 lost for less than 1 minute.	NO
3/28/2014 18:40:11	16	SV rising. Type 1 corrections lost for PRN 16 lost for less than 1 minute.	NO
4/18/2014 19:33:58	3	SV elevation ~14 degrees. Type 1 corrections lost for PRN 3 lost for less than 1 minute.	NO
4/18/2014 20:09:21	19	SV elevation ~11 degrees. Type 1 corrections lost for PRN 19 lost for less than 1 minute.	NO
4/24/2014 19:33:17	19	SV rising. Type 1 corrections lost for PRN 19 lost for less than 1 minute.	NO
4/27/2014 15:51:19	18	SV setting. Type 1 corrections for PRN 18 lost for less than 1 minute.	NO
5/17/2014 00:10:50	20	SV elevation ~25 degrees. Type 1 corrections for PRN 20 lost for less than 1 minute.	NO

6/5/2014 04:48:55	15	SV rising. Type 1 corrections lost for PRN 15 lost for less than 1 minute.	NO
7/9/2014 19:30:05	4	SV rising. Type 1 corrections for PRN 4 lost for ~30 minutes.	NO
7/9/2014 20:22:46	6	SV rising. Type 1 corrections lost for PRN 6 lost for less than 1 minute.	NO
Total # of Events Logged: 15 Total # of Events Leading to a Loss of Continuity: 0			

Table 5: Summary of Logged CCD Events

Low Power:

Eleven low power monitor events were logged during the time period examined. Many of these events affected only one RSMU, and thus did not cause an interruption in Type 1 message corrections for the effected SVs. Only one event caused a loss of service; during this event (8/28/14) corrections for all SVs in view were lost. This incident was concurrent with logged cycle slip events and is likely due to an unknown interference source near the prototype site. Table 6 provides further details of the low power events observed.

UTC Date/Time	PRN	Description/Notes	Loss of Service/VPL>10m?
5/12/14 14:06:20-14:07:50	24	Only RSMU 6 affected, no loss of corrections	NO
7/21/14 18:51:39	32	Type 1 corrections for PRN 32 lost from 18:52 to 19:02 FAA GBPM begins tracking at 19:02 (low elevation SV)	NO
8/14/2014 01:28:31	7	Only RSMU 6 affected, low elevation setting SV, no loss of corrections	NO
8/14/2014 01:51:21	8	Only RSMU 6 affected, low elevation setting SV, no loss of corrections	NO
8/14/2014 02:44:00	30	Only RSMU 6 affected, low elevation setting SV, no loss of corrections	NO
8/22/2014 11:31:44	29	Low elevation setting SV, no loss of corrections (Affected RSMUs not recorded in log)	NO
8/22/2014 19:30:22	32	Low elevation setting SV, no loss of corrections	NO

		(Affected RSMUs not recorded in log)	
8/22/2014 23:26:35	13	Low elevation setting SV, no loss of corrections (Affected RSMUs not recorded in log)	NO
8/23/2014 13:16:34- 13:30:24 (Intermittent)	21	Low elevation setting SV, no loss of corrections (Affected RSMUs not recorded in log)	NO
8/28/2014 20:45:57	All	Type 1 Corrections for all SVs lost from 20:47 to 20:49 Follows logged cycle slip events/exclusions	YES
8/23/2014 23:02:36	13	Low elevation setting SV, no loss of corrections (Affected RSMUs not recorded in log)	NO
Total # of Events: 11 # of Events Leading to Loss of Continuity: 1 (Double-counted with loss of continuity event caused by cycle slip events.)			

Table 6: Summary of Logged Low Power Events

Signal Deformation (SDM):

During the period examined, the HI GAST-D prototype made two permanent satellite exclusions due to SDM. These exclusions required manual intervention to return the SV to use in the system and occurred on PRNs 23 and 25.

In addition, two non-permanent exclusions were made by the SDM over this period. These events occurred on PRNs 11 (excluded for one satellite pass) and PRN 18 (excluded for two days). These events occurred one day apart in May 2014 and no apparent interruption in tracking was observed by the GPBM GPS receiver. The exclusion of PRN 11 led to a VPL greater than 10m at DH at three of the four ACY runway ends.

In addition to the four SDM events summarized in Table 7, several incidents were also observed during which the SDM excluded all satellites for a period of 10 to 20 minutes. This began to occur after the introduction of the two additional RSMUs in the current ACY configuration and is likely to be a defect in how the SDM filter is implemented for more than four references. It is not believed to be indicative of an issue with the feasibility of a GAST-D capable SDM. This problem is currently under investigation by Honeywell.

UTC Date/Time	PRN	Description/Notes	Loss of Service/VPL>10m?
4/17/2014 19:35:06	23	PRN 23 permanently excluded. Manually readmitted on 5/10/2014.	NO
5/22/2014 19:17:53	11	PRN 11 excluded for entire SV pass. Readmitted on next SV rise.	YES
5/23/2014 06:56:47	18	PRN 18 excluded for two days. Readmitted on third day.	NO
5/23/2014 13:37:41	25	PRN 25 permanently excluded. Manually readmitted on 6/5/2014.	NO
Total # of Events: 4 # of Events Leading to a Loss of Continuity: 1			

Table 7: Summary of Logged SDM Events

Excessive RFI:

Twenty-two excessive RFI events were logged by the HI GAST-D prototype system during this period. Though the exact cause of these events is not known, all were concurrent with losses of lock on the GBPM GPS receiver, indicating that the alerts are valid. None of these events led to the exclusion of an RSMU, and none caused a loss of service and/or a VPL at DH of greater than 10m.

Total # of Events: 22
Events Causing a Loss of Continuity: 0

Carrier Rate:

In this period the GAST-D prototype's Carrier Rate monitor logged four events. Details of these events are shown in Table 8.

UTC Date/Time	PRN	Notes	Loss of Service/VPL>10m?
2/27/2014 06:31:11	8	Concurrent with DELTAV NANU on PRN 8.	NO
2/27/2014 22:28:05	13	54-hr exclusion of SV. FAA GBPM lost lock momentarily at start of event.	NO
3/7/2014 09:46:11	17	Concurrent with DELTAV NANU on PRN 17.	NO
4/18/2014	27	54-hr exclusion of SV. No loss of lock on	NO

19:34:22		ACY GBPM. Nearby EWR GBPM lost lock momentarily at start of event.	
Total # of Events: 4 # of Events Leading to Loss of Continuity: 0			

Table 8: Summary of Logged Carrier Rate Events

Summary of Monitor Event Logging:

There were over 87 logged monitor events from 1/23 to 9/15/2014, resulting in three instances of loss of continuity. Of these three events, two were caused by a computed VPL of greater than 10m at the decision height of one or more runways, and one was caused by a complete loss of corrections from the ground system for approximately two minutes. This event is under further investigation and is likely due to the presence of an unknown interference source near the prototype site.

Calculated maxSvert and maxSvert2 Values

Data collected from the GAST-D prototype station at ACY was used to compute the values of maxSvert and maxSvert2 that would be calculated by an airborne user in order to complete geometry screening. LAAS MOPS DO 253-C Section 2.3.9.4 defines these values; if these user-defined limits are exceeded the airborne receiver must downgrade to GAST-C mode. A need to set these thresholds too low in an aircraft would have a negative impact on availability and potentially GAST-D continuity.

For this simplified analysis, one day of data was chosen from each month from October 2013 thru September 2014. These 12 days of recorded SLS data were replayed thru the FAA's Ground-Based Performance Monitor code to obtain the values of interest. In this exercise, all satellites in view are considered, making results somewhat optimistic. The plots in Figure 2 and Figure 3 show maxSvert and maxSvert2 values for all 12 days, where data is sampled at a 5 Hz rate. This data sample has a maximum maxSvert value of less than 2.5, with a mean of 0.92. The maximum maxSvert2 value is less than 3.5, with a mean value of 1.53. Figure 4 and Figure 5 show the distribution of samples for maxSvert and maxSvert2, illustrating values near these maximums are relatively rare.

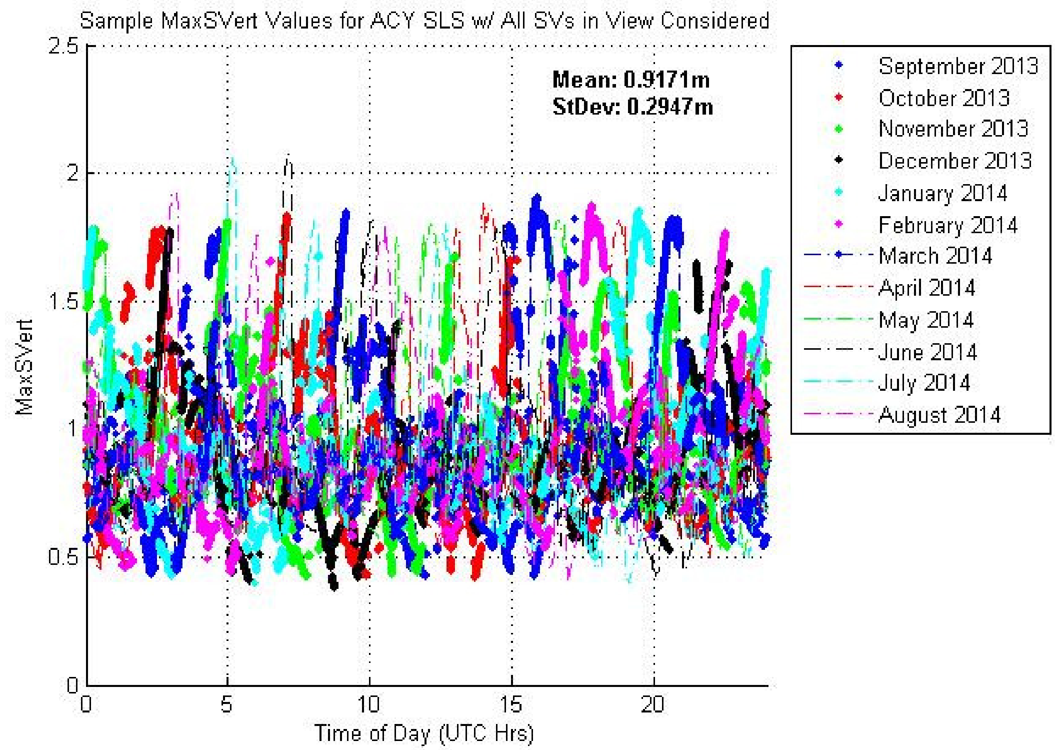

Figure 2: maxSvert Values for 12 Days at ACY

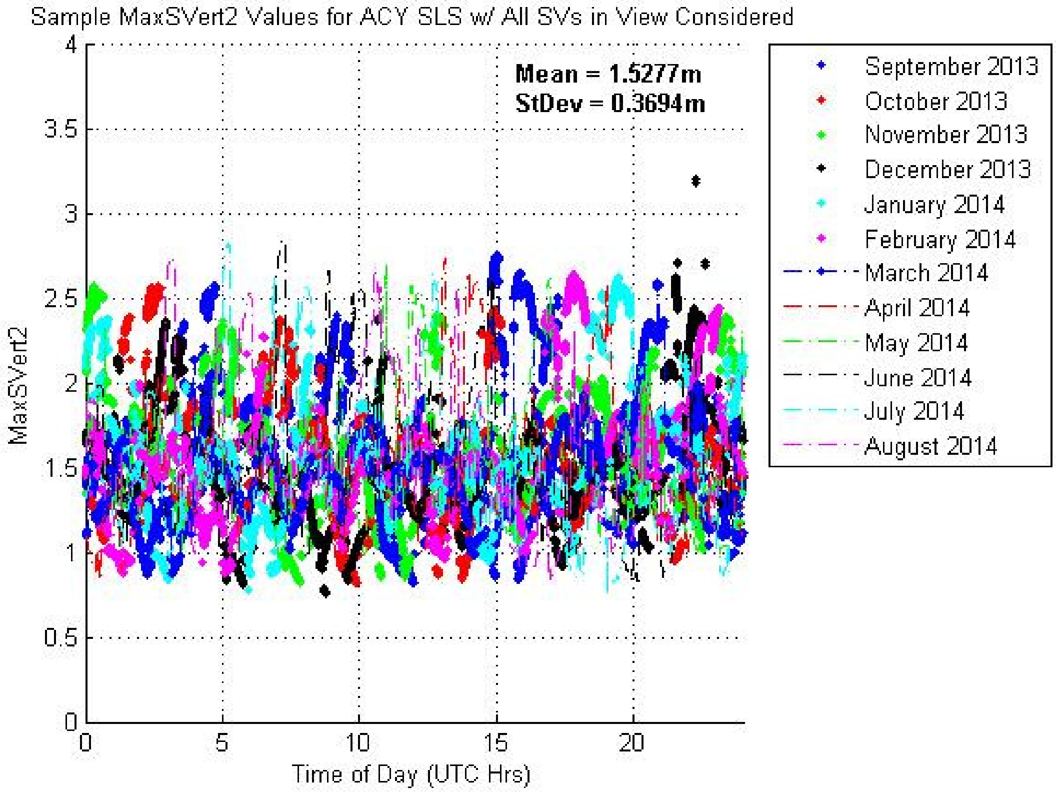

Figure 3: MaxSvert2 Values for 12 Days at ACY

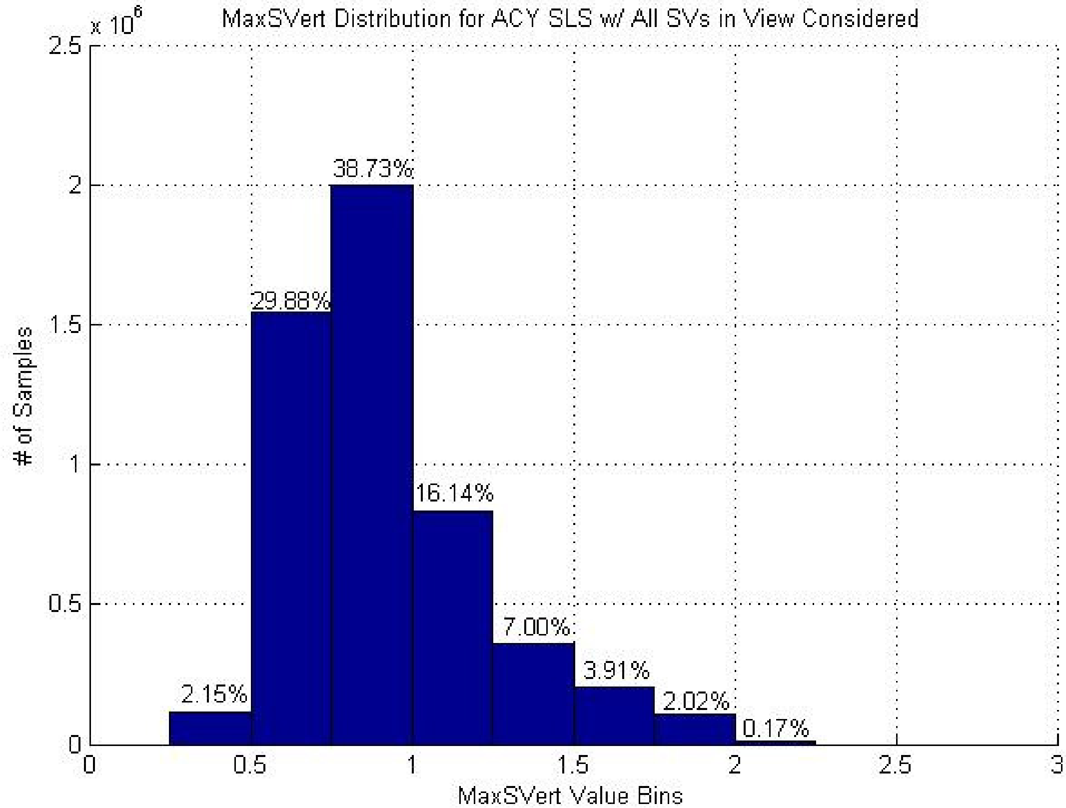

Figure 4: Distribution of maxSvert Values for 12 Days at ACY

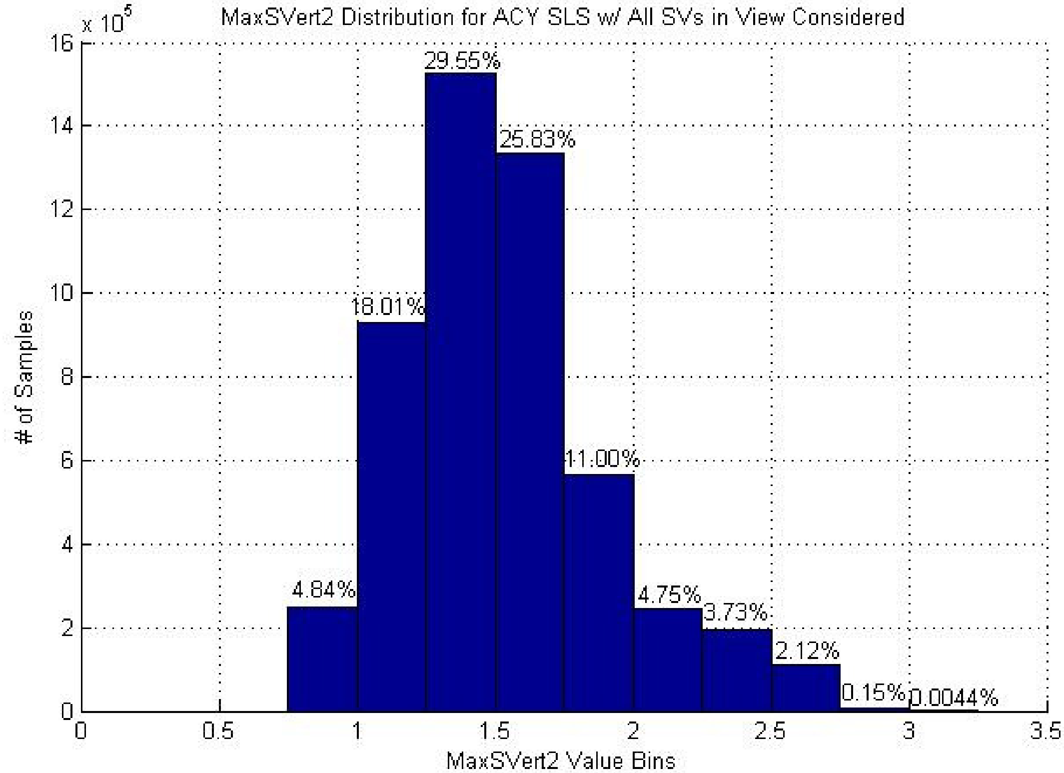

Figure 5: Distribution of maxSvert2 Values for 12 Days at ACY

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