[EN-030] Using SBAS to Enhance GBAS User Availability: Results and Extensions to Enhance Air Traffic Management

(EIWAC 2010)

+Sam Pullen*, Ming Luo*, Todd Walter*, and Per Enge*

* Dept. of Aeronautics and Astronautics
Stanford University
Stanford, CA. 94305-4035 USA
[spullen | twalter | penge]@stanford.edu; ming94305@yahoo.com

Abstract: This paper describes the application of Space Based Augmentation System (SBAS) corrections and error bounds to improve the availability of Ground Based Augmentation Systems (GBAS). GBAS installations within good SBAS coverage can use the SBAS UDRE and GIVE error bounds to mitigate the most severe integrity threats to GBAS. GBAS systems are limited by their inability to detect severe ionospheric gradients with the required missed-detection probability. A method for using GIVE values to insure the absence of these gradients is described here, and the use of UDRE to mitigate ephemeris and signal-deformation failures is also discussed. Because the techniques used in SBAS monitoring are well known, GBAS installations outside of SBAS coverage can apply the same techniques based upon data from other GNSS reference networks that may already exist or can be built or expanded to serve GBAS. An expansion of an existing network in Australia is proposed here to demonstrate the potential of this approach. Concerns regarding the cost, safety, and certifiability of systems that use external networks that are not themselves certified are addressed.

Keywords: GNSS, GBAS, SBAS, integrity, ionosphere, ephemeris, anomaly, network

1. INTRODUCTION

SBAS and GBAS are augmentations of Global Navigation Satellite Systems (GNSS) that improve GNSS navigation so that it can meet the requirements of civil aviation precision approach and landing. SBAS is based upon widely-spread networks of ground reference stations and fixed locations that provide ranging corrections and error bounds via geostationary satellites over large regions of Earth. GBAS also uses reference receivers to derive corrections and integrity information, but each GBAS is limited to the property of a single airport, operates independently, and broadcasts local corrections and error bounds (valid within approximately 60 km) over a VHF data link. The limited observability of individual GBAS installations makes it difficult to tightly bound worst-case ionospheric and ephemeris errors, resulting in restricted GBAS user availability [1]. Previous work has shown that GBAS can achieve an availability of 99.9% or better for CAT I precision approach if availability is not limited by worst-case ionospheric and ephemeris errors. Once these errors are included, GBAS CAT I availability drops to 95 – 99% depending on the location of the GBAS site [2].

To improve availability for GBAS installations within SBAS coverage, simple but effective methods for using SBAS GIVE (Grid Ionospheric Vertical Error) and UDRE (User Differential Range Error) parameters have been developed. GIVE and UDRE provide bounds on satellite ionospheric and clock-ephemeris errors, respectively. When converted to the GBAS application, real-time SBAS GIVE and UDRE translate into much smaller bounds on ionospheric and ephemeris errors than GBAS can support on its own. As a result, GBAS CAT I availability when SBAS corrections are available (and show nominal behavior) returns to the 99.9% level, meaning that it is almost unconstrained by potential anomalies. This technique also allows the Differentially Corrected Positioning Service (DCPS) aspect of GBAS, which is currently disabled, to be enabled and used when SBAS indicates nominal ionospheric behavior [2]. In the rare cases where SBAS corrections are not available or show potential hazards, GBAS resorts to its internal monitoring and more-conservative error bounds (and disables DCPS). Note that this approach relies upon detailed knowledge of how SBAS derives UDRE and GIVE values. The method presented here has been verified to work with Raytheon-derived SBAS systems, such as the U.S. WAAS and Japanese MSAS, but additional work is needed to adapt this approach for other systems.

The technique developed here uses SBAS corrections that already exist, but the same method could utilize a smaller not support SBAS itself. For example, a region of the

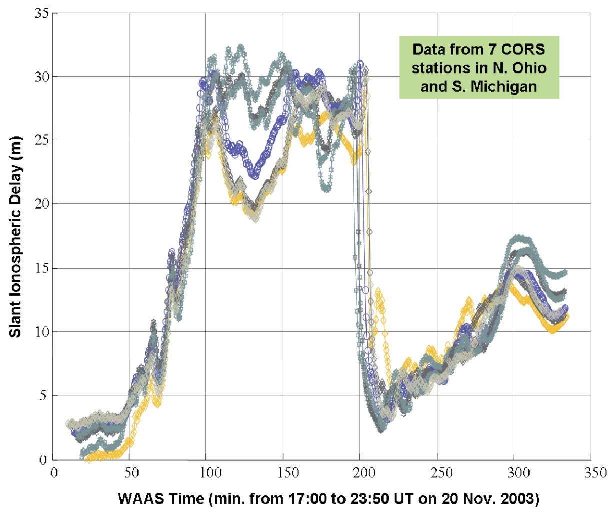

Figure 1: Ionospheric Delay on SVN 38 During 20/11/2003 Anomaly

world that is not currently covered by SBAS but intends to install GBAS at many airports could gain the "GBAS benefits" of SBAS by fielding a relatively small and inexpensive network of as few as 8 – 12 reference receiver sites surrounding the region. This concept is developed further using the example of Australia in this paper. Networks that do not use certified systems like SBAS to generate and relay safety-critical information present unique certification issues for the future. These issues are outlined for future consideration.

2. GBAS MITIGATION OF IONOSPHERIC SPATIAL ANOMALIES

GBAS users are potentially vulnerable to satellite system failures, atmospheric anomalies along the path that GNSS signals travel, and ground-system failures. GBAS systems that support CAT I aircraft precision approaches can mitigate almost all identified off-nominal conditions by detecting and excluding the affected measurements within the 6-second CAT-I time to alert. The one exception is a very large gradient in measured pseudorange between reference and user receivers that can occur when the ionosphere is extremely disturbed. Nominal ionospheric spatial gradients are about 1 – 4 mm/km (1σ). While these are not negligible for GBAS, they fit easily within the overall user error budget [4].

However, the largest gradient observed under anomalous conditions in CONUS was about 412 mm/km in Northern Ohio shortly after 2100 UT on 20 November 2003. A gradient this large could cause differential user errors as large as 8.5 meters if not detected and excluded in time, and errors this large can easily generate vertical position errors exceeding the 10-meter Vertical Alert Limit for CAT I precision approach [5,6]. Figure 1 shows the impact of this event on slant ionospheric delays measured by a "cluster" of 7 nearby CORS stations in Northern Ohio and Southern Michigan tracking GPS SVN-38 as it passed overhead [5,7]. This illustrates the "bubble" or "filament" of enhanced delay that formed over this region of CONUS and moved roughly westward at an average velocity of 100 – 150 m/s. The spatial ionospheric delay gradients shown here exceed 25 mm/km (and are thus anomalous) from about 18:00 to 23:30 UT, but the ones of greatest concern occur just after 21:00 UT, when the extremely sharp downward step in delay occurs. Gradients among the stations included in this plot reach as high as 330 mm/km, while the 412 mm/km gradient was observed between two other stations just to the east of this cluster at about the same time [5,6].

GBAS ground stations will detect most potentially-threatening ionospheric gradients by observing the impact of the related temporal gradient on the code-carrier divergence monitor. However, the unusual ionospheric features that create anomalous gradients can move with a velocity that nearly matches the apparent IPP velocity of the affected GNSS satellite relative to the ground station, making detection and exclusion improbable. As a result, the anomalous ionospheric threat model for CAT I GBAS applies a front with the maximum gradient ever observed and validated (plus margin for measurement error) to the worst (most-sensitive) one or two satellites in any credible airborne geometry that would otherwise be available (e.g., its Vertical Protection Level, or VPL, is below the 10-meter CAT I Vertical Alert Limit, or VAL, at the decision height, or DH). This resulting "worst-case" result is called the "Maximum Ionospheric Error in Vertical (Position)," or MIEV [2,5]. The blue line and points in Figure 2 (from [2]) show an example of the resulting MIEV for an aircraft approaching a CAT I GBAS installation at Memphis (TN) airport and reaching the 200-ft DH 6 km from the centroid of the GBAS reference station antennas, based on the standard 24-satellite constellation given in [8]. For some epochs, MIEV exceeds 35 or even 40 meters, which is much larger than the 10-meter CAT I VAL.

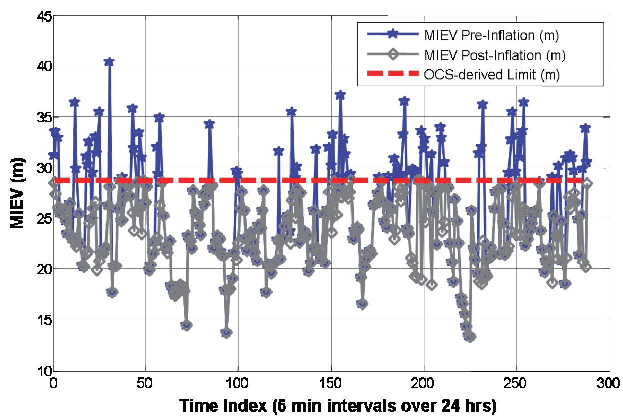

Figure 2: Maximum Ionosphere-Induced Vertical Errors at Memphis

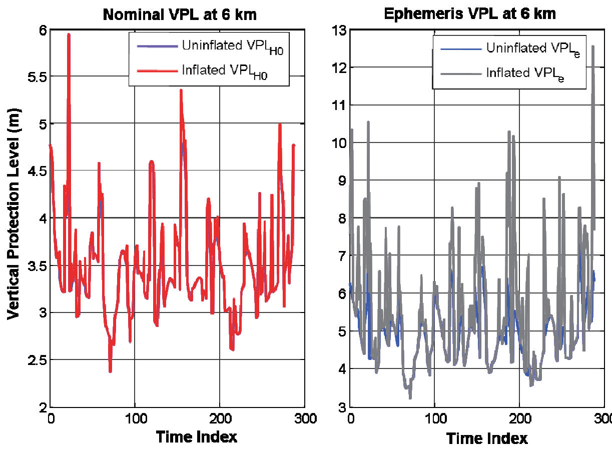

Figure 3: VPL Inflation Required to Remove Unsafe Geometries

Since the MIEV for a particular geometry cannot be significantly reduced without major changes to the design of GBAS, the analysis done to estimate safety zones for SBAS LPV operations down to 200 ft ("LPV-200") was extended to CAT I GBAS [9]. The resulting "tolerable error limit" (TEL) for GBAS of 28.8 meters at a 200-ft DH (compared to 35 meters for SBAS LPV-200 with the same DH) is based on the based on the underlying Obstacle Clearance Surface (OCS) for precision approach and is shown by the dashed red line in Figure 2. Even with this revised safety definition, the maximum MIEV exceeds TEL at the DH over 70% of the time.

Geometry screening was introduced into the CAT I GBAS ground system in order to remove all satellite geometries with MIEV exceeding TEL. While MIEV itself cannot be changed, the set of available geometries (those with VPL ≤ VAL as computed by the user) can be restricted by increasing or "inflating" integrity-related parameters broadcast by the ground station (σ_{pr_gnd}, σ_{vig}, and ephemeris P-values [10]) such that all potentially usable geometries with MIEV > TEL also have VPL > VAL and are thus unavailable. This requires a "brute force" set of position-domain calculations within the ground station that must be repeated every 30 – 60 seconds or so to adjust to changing satellite geometry [2,5]:

(1) identify all credible airborne geometries (for precision approach, typically all combinations of N, N–1, and N–2 satellites, where N is the number of satellites for which ground-station corrections are broadcast);

(2) compute MIEV for each credible and identify those (if any) that exceed TEL;

(3) compute the smallest possible airborne VPL for this potentially-hazardous subset of geometries;

(4) If any geometries in this subset have VPL ≤ VAL, begin a search process to find the smallest inflation factors that increase VPL above VAL for all geometries in this subset.

The parameter-inflation method detailed in [2] combines per-satellite σ_{pr_gnd} and P-value inflation, giving as many as 2N tunable parameters. Other methods only modify the single σ_{vig} parameter in real time, which simplifies the search procedure but gives slightly inferior results [5,11].

Figure 3 (from [2]) shows the degree of VPL inflation needed to make all potentially-unsafe geometries unavailable for the Memphis scenario shown in Figure 2. These two plots show VPL for the all-in-view geometry at Memphis, using all N satellites in view. The left-hand plot shows that very little inflation of the "nominal VPL" (VPL_{H0}) is used in this case because inflating σ_{pr_gnd} is much less effective than inflating P-values at 6 km. Because P-values are inflated instead, the inflated ephemeris VPL (VPL_e) is often much higher than the uninflated VPL_e in the right-hand plot. The benefit is shown by the gray line in Figure 2, which no longer exceeds the 28.8-meter TEL at the DH for any epoch.

While the uninflated VPL stays well below the 10-meter CAT I VAL, five (5) out of the 288 five-minute epochs making up a 24-hour day of repeatable GPS geometries have an inflated VPL_e slightly exceeding 10 m, causing loss of availability for CAT I precision approaches. While the degree of availability loss for recent constellations of 30 or more satellites is less common than for the standard 24-satellite constellation, it is still significant and is the limiting factor in current GBAS availability [2,5]. As noted in the Introduction, CAT I GBAS availability without this "geometry screening" is in the range of 99.5 – 99.9%, while it is an order of magnitude lower (95 – 99%) with geometry screening included.

3. SBAS IONOSPHERIC MITIGATION AND ITS POTENTIAL USE IN GBAS

Because the availability loss due to GBAS ground system geometry screening is severe enough to threaten the viability of GBAS for CAT I and DCPS, alternatives that use external information to remove the need for geometry screening are of great interest. Recall that the need for geometry screening is due to the inability of an individual GBAS ground station to observe and detect all ionospheric anomalies before users are threatened. SBAS, which is made up of a networks of reference receivers, does not have this problem within its primary coverage region. Therefore, allowing GBAS to use the SBAS corrections broadcast on L1 by SBAS GEO satellites is logical and straightforward, even though it would only aid the GBAS installations within good SBAS coverage.

3.1 SBAS Ionospheric Anomaly Mitigation

SBAS provides its assessment of ionospheric uncertainty via the GIVE integer (GIVEI) values for each Ionospheric Grid Point (IGP) included in Message Type 26 [12]. Each

Table 1: GIVEI and Corresponding Values (Table A-17 in [12])

$GIVEI_i$	$GIVE_i$ Meters	$\sigma^2_{i,GIVE}$ Meters^2
0	0.3	0.0084
1	0.6	0.0333
2	0.9	0.0749
3	1.20	0.1331
4	1.5	0.2079
5	1.8	0.2994
6	2.1	0.4075
7	2.4	0.5322
8	2.7	0.6735
9	3.0	0.8315
10	3.6	1.1974
11	4.5	1.8709
12	6.0	3.3260
13	15.0	20.7870
14	45.0	187.0826
15	Not Monitored	Not Monitored

GIVE integer translates into a 99.9% bound on the vertical (zenith) error in the ionospheric correction for that gridpoint (this correction is called the "IGP Vertical Delay Estimate"). GIVE can be divided by 3.29 to obtain the bound in one-sigma format. Table 1 (Table A-17 in [12]) shows these relationships, including the fact that GIVEI of 15 means "Not Monitored" and indicates no confidence at all in the broadcast correction for that grid point.

Because SBAS users apply ionospheric corrections over baselines of hundreds of kilometers, ionospheric gradients that could be hazardous to SBAS users are much smaller than those for GBAS. This is a key reason why SBAS GIVE information is valuable to GBAS. The algorithms developed for the Federal Aviation Administration (FAA) Wide Area Augmentation System (WAAS) version of SBAS that insure the integrity of each IGP correction and GIVE are described in [13,14]. These papers define consistency tests on the WAAS ionospheric delay measurements whose IPPs are within a certain radius of each IGP. The degree of consistency is used to help set the GIVE or, alternatively, raise the GIVE level to a GIVEI of 14 or 15 corresponding to a GIVE of 45.0 meters or "Not Monitored" if the measurements are sufficiently inconsistent. A GIVE of 45.0 m is sufficient to prevent the corresponding ionospheric correction from being useful for vertical guidance, while "Not Monitored" prevents use of the correction entirely (in both cases, horizontal-only users can use SBAS clock/ephemeris corrections without the ionospheric corrections).

The "most threatening" ionospheric anomaly for SBAS is the one that causes the most severe errors (i.e. largest gradients) but just escapes detection by the ionospheric-delay-consistency monitors defined in [13,14]. As noted above, these events are not hazardous to GBAS users. The significant gap between events hazardous to SBAS and

Table 2: GBAS Classification of WAAS GIVE Values

GIVE Value	GIVE Integer	GBAS Class.	*Notes*
≤ 6.0 m	0 – 12	Good	*WAAS verifies that no threat is present here.*
15.0 m	13	Not Observed	*WAAS observations are too limited to confirm that no threat exists.*
45.0 m	14	Bad	*WAAS detects a nearby ionosphere storm – possible threat.*
Not Monitored	15	Not Observed	*WAAS observations are too limited to provide any iono. assurance.*

those hazardous to GBAS insures that SBAS GIVE increases occur well before any GBAS hazard occurs, removing any GBAS time-to-alert concerns. In fact, all four ionospheric storm days in CONUS that generated gradients large enough to potentially threaten GBAS users (29-31 October 2003 and 20 November 2003) would have been detected with margin (prior to any significant GBAS impact) by the "Extreme Storm Detector" defined in [14]. Unlike the more-limited storm detector defined in [13], which increases GIVEs upon individual IGPs, the extreme version increases GIVEs upon all IGPs once a sufficiently-large storm is detected.

3.2 GBAS Use of SBAS GIVE Values

Given the reliability of SBAS GIVE values, a procedure for GBAS ground stations to use these values in real-time has been developed. However, two limitations should be noted. First, while SBAS GIVE values can be accessed by any GBAS installation from which one or more SBAS GEO satellites are visible, GBAS sites need to be inside the network of SBAS reference stations to obtain a significant benefit. Second, the specific use of GIVE values proposed here is based on the algorithms given in [13,14] for use in WAAS. The same method may be equally safe for other SBAS networks depending on the algorithms that they use to bound IGP correction errors.

Table 2 shows how each WAAS GIVE (for a given IGP) can be converted to a GBAS ionospheric alert. GIVE integers 0 – 12 represent normal "good" values that insure that no ionospheric anomaly (at least one potentially threatening to GBAS is present). GIVE integer 14, corresponding to a GIVE of 45.0 m, represents "bad," meaning an alert of a possible anomaly. GIVE integer 15, representing "Not Monitored," is treated as "not observed" or "neutral," meaning that WAAS provides no information regarding this IGP. The same is true of GIVE integer 13 (GIVE = 15.0 m), except that in this case, the IGP is observed by WAAS but relatively poorly. While such an IGP is almost certainly verified to be safe for GBAS use, an element of conservatism is applied in treating it as "neutral."

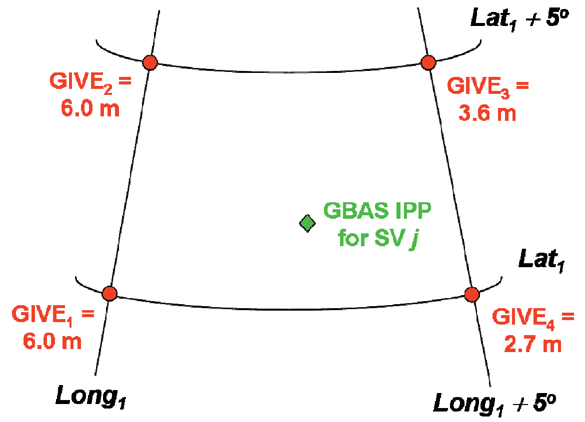

Figure 4: Nominal IPP Scenario – All Surrounding IGPs are "Good"

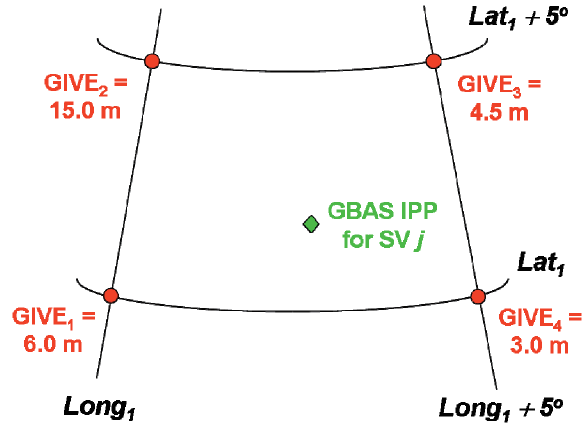

Figure 5: "Not Observed" Scenario 1 – At Least One Surrounding IGP is "Neutral" (GIVE = 15.0 m)

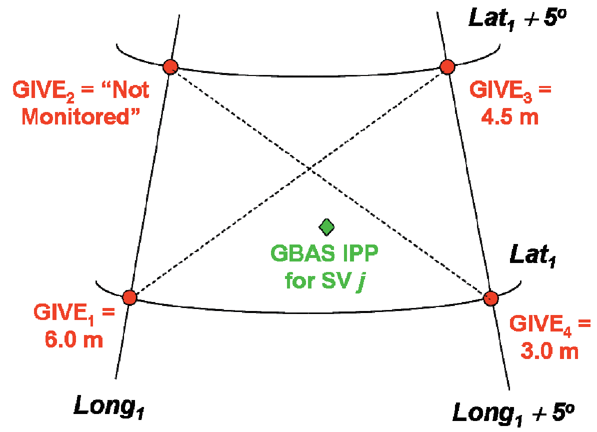

Figure 6: "Not Observed" Scenario 2 – One Surrounding IGP is "Not Monitored"

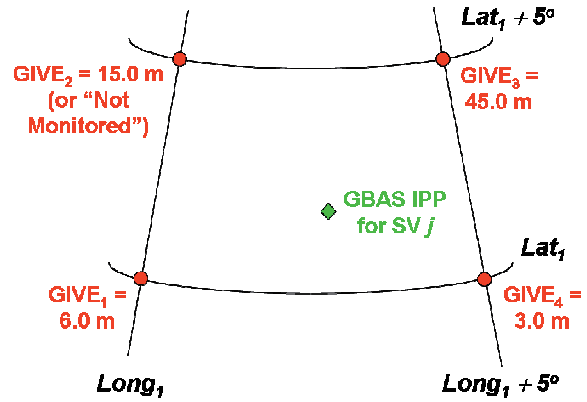

Figure 7: Alerted Scenario – At Least One Surrounding IGP is "Bad"

The IGP classifications in Table 2 are used on a satellite-by-satellite basis within the GBAS ground station, which would update the ionospheric status of each satellite it is tracking at the same frequency as geometry screening is implemented. Figures 4, 5, and 6 illustrate how these IGP states are used to make an ionospheric determination for each GBAS satellite. Figure 4 shows the most common case for a GBAS installation well within WAAS coverage. It shows the four WAAS IGPs surrounding the GBAS IPP for a particular satellite *j*. In Figure 4, the GIVE values for all four IGPs are classified as "Good" in Table 2. Since the GBAS IPP is surrounded by "good" IGPs on all sides, satellite *j* is assured of having nominal ionosphere (or at least no significant anomaly). Therefore, no geometry screening is needed to protect this satellite, and hypothetical anomalies affecting this satellite are not used to determine MIEV during geometry screening.

Figures 5 and 6 show two examples of scenarios where one or more of the four IGPs surrounding a GBAS IPP is classed as "not observed." Figure 5 shows the more common case where three of four IGPs are "good" but one is "not observed." In Figure 5, one IGP has GIVE = 15.0 meters, but the same result would apply if multiple IGPs had a combination of GIVE = 15.0 m or "Not Monitored." The most likely cause of this is near the edge of WAAS coverage, where insufficient measurements are present to establish a GIVE below 15.0 meters. Because one or more potential ionospheric anomaly approach directions cannot be precluded, GBAS should treat this case as "neutral" with respect to satellite *j*, meaning that WAAS currently provides no assurance that this satellite is free of potentially threatening anomalies.

Figure 6 shows an important variation in which a single "not observed" IGP is actually "Not Monitored." This is not uncommon near the edges of WAAS coverage and specifically indicates a lack of observability. In this situation, the Section A.4.4.10 of the WAAS MOPS [12] allows users to interpolate a valid correction and error bound from the other three IGPs if the IPP in question is within the triangle formed by connecting the three "good" IGPs. This is the case in Figure 6, where the GBAS IPP for satellite *j* lies within the triangle formed by the IGPs 1, 3, and 4, which all have "good" GIVEs. The same would be true if IGP 3 (upper right) were "Not Monitored" but IGP 2 had a GIVE below 15.0 meters, as the GBAS IPP lies within the triangle formed by IGPs 1, 2, and 4.

However, if either IGP 1 or IGP 4 were "Not Monitored," the "triangle test" would fail, and WAAS users would not be able to interpolate a valid GIVE for satellite *j*. GBAS should follow the WAAS precedent here and use the triangle test to define whether or not IPPs in the scenario shown by Figure 6 can be validated as "good."

Figure 7 shows the case where one or more surrounding IGPs has a "bad" GIVE of 45.0 m, representing a warning from WAAS of potentially-severe ionospheric spatial decorrelation. Another IGP is "not observed," but the result for GBAS satellite *j* would be "bad" even if the other three IGPs were all "good" because at least one approach direction has a potential anomaly. While the "bad" result for satellite *j* in Figure 7 is worse than the "neutral" result in Figure 5, the impact on GBAS CAT I precision approach is the same because the geometry screening implemented to support CAT I assumes the constant presence of a worst-case anomaly. In other words, it assumes a WAAS result of "bad" all the time on all satellites tracked by GBAS. A "neutral" result is of less concern, but the practical consequence is the same.

Therefore, both "bad" and "neutral" results for a given otherwise-usable satellite require the GBAS ground station to exclude that satellite from use or include it within the normal geometry-screening algorithm as a "vulnerable" satellite that contributes to MIEV. If only one or two satellites of the *N* approved for use are "bad" or "neutral," the resulting MIEV is likely to not require parameter inflation or availability loss, and this can be checked in real time by a trial execution of geometry screening. On the other hand, if DCPS is being supported based on the use of SBAS to validate ionospheric safety, exclusion of "neutral" or "bad" satellites may be required, as geometry screening protects CAT I but not DCPS [3].

Note that the CAT I GBAS geometry screening algorithm should be retained regardless of the benefits of SBAS so that it can be used when SBAS is not available at a given site or is temporarily unavailable due to, for example, a GEO satellite outage. As noted above, it also allows the partial use of SBAS to validate some satellites as "safe" while leaving others as "unsafe" and thus contributors to MIEV. The existing geometry screening algorithm should work well with SBAS information, although it could be tailored further to optimize the benefits of SBAS or external ionospheric monitoring.

3.3 Validation of SBAS GIVE Method

Validation testing of this method for use of SBAS GIVE values was conducted during our study of "Local Area Monitoring" or "LAM," which is a simplified version of GBAS that combines SBAS corrections and integrity parameters with local monitoring at the reference site [15]. The LAM implementation simplifies the GIVE method further by establishing a single threshold test on the User Ionospheric Vertical Error, or UIVE, for a given satellite

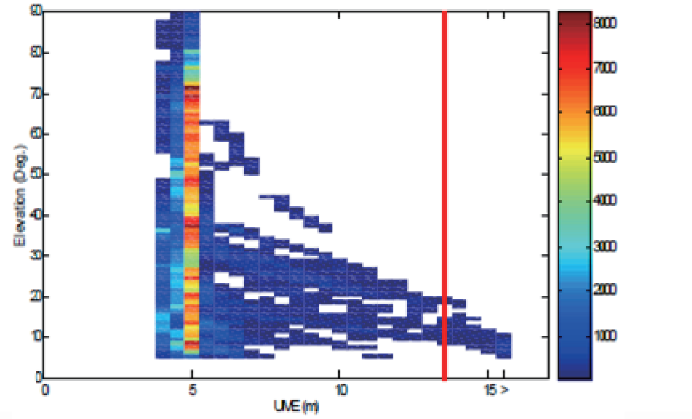

Figure 8: UIVE Under Nominal Ionospheric Conditions (from [15])

IPP, which is derived from the surrounding GIVE values by the algorithm given Section A.4.4.10 of the WAAS MOPS [12]. Setting UIVE ≤ 13.0 meters as the constraint for a valid "good" IPP is more conservative than the method given in Section 3.2 [15]. Note that this UIVE threshold takes the place of Table 2 and Figures 4 and 7 above, while the "not observed" cases shown in Figures 5 and 6 are handled by logic, although receivers compliant with the WAAS MOPS typically take care of this determination internally [15].

Validation testing done for the LAM method examined nine nominal days in 2004 – 2005 when no ionospheric alerts were expected. As shown in Figure 8 (from [15]), UIVE occasionally exceeded 13.0 meters at low elevation angles (below 20 deg.), when the obliquity factor that converts vertical or zenith delay to actual slant delay approaches its maximum value of just above 3.0. Over all epochs and satellite elevations, UIVE exceeded 13.0 meters 0.6% of the time (i.e., a probability of 0.006) [15]. These alerts usually disappeared quickly (within 10 minutes); thus the interruption of the WAAS guarantee of "good" ionosphere would have been brief. Nevertheless, these occasional outages highlight the value of retaining geometry screening and running it in the background to minimize unexpected service degradations.

As noted previously, there is no need to test either the simplified LAM method or the more-complete method given in Section 3.2 on days of potentially threatening ionospheric behavior. Even though the most threatening storms that have been observed in CONUS (in October and November 2003) occurred before the Extreme Storm Detector was implemented, the original storm detector present at WAAS commissioning in July 2003 made all affected IGPs unusable before any significant error could have impacted GBAS users. Studies of stored WAAS ionospheric delay measurements show that this would also have been the case for other severe storms that occurred prior to July 2003.

4. USE OF SBAS FOR SATELLITE MONITORING

As with ionospheric monitoring, the broad geographic scope of SBAS measurements makes SBAS much better at observing and monitoring satellite orbit states than individual GBAS installations. SBAS can independently estimate orbit locations for satellites within its coverage, unlike GBAS. As a result, SBAS provides independent δx, δy, δz orbit corrections in Message Type 25 along with "fast" pseudorange corrections and error bounds (User Differential Range Error, or UDRE) in Message Types 2 – 6 and 24 [12]. The maximum broadcast values of the δx, δy, δz orbit corrections are ±128 meters. These are much smaller than the ephemeris error magnitudes that would potentially threaten CAT I GBAS users (2000 meters or more). In addition, failures that cause the broadcast satellite orbits (ephemerides) to become hazardously wrong either would develop over minutes to hours ("Type A" faults) or would occur when a new and faulty navigation data message replaces an older one ("Type B" faults) [18]. Even in the latter case, several minutes are used to validate the new ephemeris, giving time for SBAS warnings to be received and heeded by GBAS. Therefore, if SBAS is to be used to aid GBAS against ionospheric anomalies, this additional information regarding ephemeris health should be used as well.

A simple algorithm for GBAS ephemeris assurance that is sufficient to achieve a large benefit is shown in Table 3. For each satellite approved for use by a given GBAS ground station, UDRE integers (or UDREIs) of 12 or below (corresponding to UDRE values of 50.0 meters or less) correspond to an assurance of "good" ephemeris, allowing GBAS to assign a conservative but low (for GBAS users) ephemeris minimum detectable error (MDE) of 500 meters in 3-D orbit space. A UDREI of 13 (UDRE = 150.0 m) provides a less-precise bound but still supports an MDE of 1500 meters. A UDREI of 14 ("Not Monitored") is "neutral" for GBAS, meaning that GBAS can make use of the satellite based on the ephemeris MDE supported by GBAS monitoring alone (about 2700 meters) [18]. However, a UDREI of 15 ("Do Not Use") represents a detected anomaly that should be treated as "Do Not Use" by GBAS as well. Unlike for ionospheric anomalies, where GBAS protects against the worst possible event, GBAS makes assumptions about the prior probability and nature of ephemeris faults that cannot be relied upon once SBAS indicates "Do Not Use."

In most cases, SBAS is also a better monitor of satellite signal deformation (SD) and code-carrier coherence (CCC) than is GBAS. The LAM concept detailed in [15] places conservative thresholds on the broadcast UDRE integers as a means to detect potential SD and CCD faults. For satellites at or above 38 deg. elevation, an SBAS UDREI > 8 (corresponding to UDRE > 5.25 m) gives an integrity alert. For satellites below 38 deg., UDREI > 11

Table 3: GBAS Ephemeris Classification of WAAS UDRE Values

UDRE Value	UDRE Integer	GBAS Class.	Ephemeris MDE (m)
≤ 50.0 m	0 – 12	Good	500
150.0 m	13	Adequate	1500
Not Monitored	14	Neutral	GBAS value
Do Not Use	15	Do Not Use	Exclude from Use

(corresponding to UDRE > 15.0 m) gives an alert. For LAM, an SBAS alert from this monitor would lead to satellite exclusion, whereas for GBAS, a more-flexible response would be preferable, as GBAS ground stations have their own SD and CCC monitors. For example, this SBAS UDREI check could be used to validate the lack of anomalous signal deformation on a new satellite that has just been flagged "healthy" for use by the GPS Operational Control Segment. Once this initial validation is completed, internal GBAS SD monitoring can confirm that signal deformation does not appear in the future.

5. EXTENSIONS OF THE SBAS IONOSPHERIC CONCEPT

The use of SBAS as an external source of ionospheric assurance for GBAS has three major advantages. One is the fact that SBAS corrections easily accessible on GPS L1 are already certified for aviation use to the integrity level required for CAT I and DCPS. Another advantage is that regions covered by SBAS continue to expand and are likely to eventually cover most of the developed world [16]. Finally, at least in the case of WAAS, sufficient information is known to ensure that WAAS GIVE values can be translated into assured guarantees of ionospheric safety for GBAS.

Unfortunately, even in the most optimistic future projections for SBAS, significant portions of the world will not have SBAS coverage that is good enough to support the approach laid out in Section 3.0. The fact that SBAS coverage is limited is a major deterrent to its use in GBAS. This is true even though SBAS would serve as an external augmentation that only improves performance – it is never required for GBAS because geometry screening will be retained.

Two alternatives to SBAS have been discussed. One is the use of short-term space weather forecasts or "nowcasts" based upon external observations of ionospheric behavior that include plasma-physics modeling. To some degree,

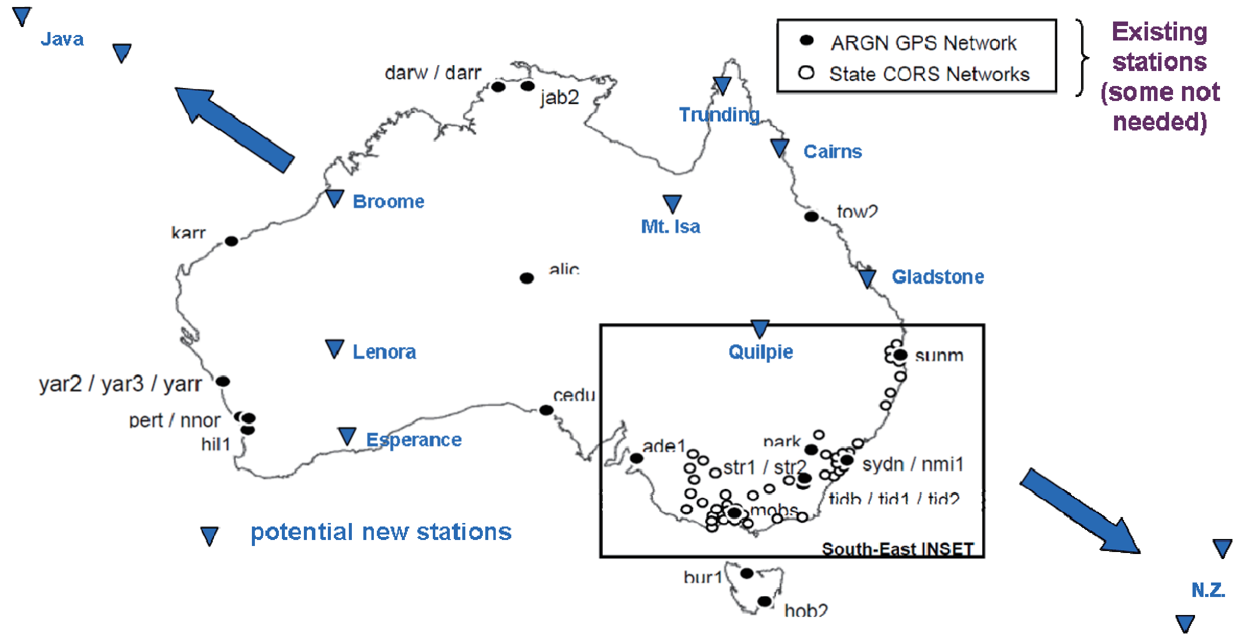

Figure 9: Example GBAS Integrity Support Network in Australian Region

ionospheric weather prediction should be feasible, and extensive research in this area is being conducted. However, decades of experience with atmospheric (i.e., tropospheric) weather forecasting suggests that it will be very difficult to make ionospheric forecasting reliable enough to meet aviation integrity requirements without being too conservative to be helpful.

The other approach takes advantage of the ionospheric monitoring algorithms developed for WAAS in [13,14] using measurements from existing or purpose-built dual-frequency GNSS networks. If these networks do not support SBAS users, they can be built far more simply and cheaply than SBAS because the reliability, redundancy, and time-critical demands of SBAS measurements and data transmission do not apply. This is true because, as mentioned above, external ionospheric augmentation of GBAS is not required for GBAS to operate. Thus, individual reference stations or communication lines can fail and degrade the performance of ionospheric augmentation, but GBAS availability will degrade gracefully. Even if the network or its communication link to GBAS fails completely, GBAS will still support 95 – 99% availability for CAT I based on geometry screening.

Figure 9 shows an example of a "GBAS Integrity Support Network" that could be developed for Australia, which is actively implementing GBAS but does not have good SBAS coverage. The black and white circles on the map show two networks of existing dual-frequency receivers that were used to study and estimate ionospheric spatial gradients over Australia [17]. A relatively small subset of these stations could be combined with a subset of the additional (new) stations shown in with blue triangles to create a permanent monitoring network that surrounds the intended GBAS installations. Again, this network does not need redundant receivers at each site, as the loss of measurements from one or two sites does not cripple the observability of the network. In addition, guaranteed second-by-second communications reliability is not needed because the WAAS GIVE algorithms provide alerts many minutes before GBAS users could be threatened. Some level of redundancy is likely optimal in this type of network, particularly at the "master station" that receives measurements and executes the monitoring algorithms, but this would be based on an overall cost-benefit analysis rather than being directly connected to user integrity. Once ionospheric anomaly monitoring is implemented, ephemeris monitoring as described in Section 4.0 could be added at little cost.

6. CONCERNS AND LIMITATIONS REGARDING UNCERTIFIED NETWORKS

While the "ionospheric assurance" network outlined in Section 5.0 provides a cost-effective means of augmenting GBAS in regions outside of good SBAS coverage, several problems must be addressed before GBAS can take credit for this external monitoring. The first limitation is that the software in a pre-existing network would not have been developed to the certification standards described in RTCA DO-178B [19]. Redeveloping existing code to DO-178B standards would be expensive and time consuming, but is probably not necessary. At most, only the new integrity monitor algorithms and output routines added to the master station would need to be developed to

DO-178B standards. This approach emulates the one taken by the WAAS Master Station, where corrections are generated by uncertified code but are monitored by "Level-B" certified code [20]. Corrections or other information generated by uncertified ("Level-E") code cannot be trusted – in the conservative aviation approach, they must be treated as always incorrect. However, the Level-B-certified monitor software can be assumed correct to the 10^{-7} integrity level required for CAT I precision approach. If the monitors also achieve a 10^{-7} missed-detection probability against errors in results output by uncertified code, the resulting monitor outputs can be treated as safe to the 10^{-7} level and used for GBAS CAT I precision approach and DCPS.

The second concern relates to the reliability and security of the communication links that provide integrity network outputs to individual GBAS ground stations. SBAS corrections are encoded on GPS-like L1 signals, which is convenient and is certified as part of SBAS. In contrast, the interface of the proposed networks will likely need to use existing infrastructure and adapt to local circumstances to be cost-effective. The safety concern here may not be limited to erroneous data that provides an invalid assurance of safety. It could theoretically also include deliberately corrupted data or dangerous executables (e.g., "viruses") that could shut down a GBAS station or "spoof" it into providing faulty data. Means to assure the safety of the connection link as well as the software certainly exist and can be tailored to the system that is implemented, but the approach used to insure safety must be acceptable to the aviation service provider and its certification authority.

The issues raised in this section are not limited to integrity support networks. They also apply to the use of ionospheric weather forecasts or any other information that is generated externally and fed into GBAS ground stations. While the safety concerns are definitely solvable technically, a larger barrier may be the resistance of aviation service providers to adapt to a model in which external information is used at all. GBAS, in particular, supports the precision approach applications that have been well-served by the Instrument Landing System (ILS) for decades, and ILS transmitters operate independently without any need for external information beyond occasional maintenance and flight inspections. The underlying expectation has been that GBAS will be "ILS lookalike" so that existing avionics, air-traffic controllers, managers, and maintainers can operate as they always have. Adding external information, while beneficial and straightforward from a technical standpoint, represents a major change from their point of view. This natural resistance will likely degrade over time as the benefits of real-time networking and information-sharing become both evident and necessary to meet future civil aviation requirements, such as those expressed by the FAA's "Next Generation" (NextGen) development effort [21].

7. SUMMARY

This paper describes the limitations on GBAS monitoring of ionospheric anomalies and ephemeris failures and proposes methods for using the more-comprehensive integrity information provided by SBAS correction messages or regional "integrity support networks" executing SBAS-like monitoring algorithms. Extremely large ionospheric spatial gradients that can go undetected by GBAS ground systems. This threat currently makes GBAS support of DCPS infeasible and requires VPL inflation via geometry screening, which protects CAT I user integrity at the cost of reducing availability by about a factor of 10. Application of SBAS GIVE values using the method explained in this paper removes almost all of this availability loss and allows DCPS to be enabled. A similar method for using SBAS UDRE values improves upon GBAS ephemeris monitoring, which reduces the ephemeris VPL and further improves availability. While achieving large benefits from SBAS requires GBAS installations to be within good SBAS reference station coverage, integrity support networks represent an option for providing similar capability to regions like Australia that are not well-covered by SBAS today.

This paper demonstrates the benefits of using external information to augment GBAS integrity, but significant operational and certification challenges must be overcome to insure safety while retaining cost-effectiveness. Further validation testing of the GIVE and UDRE algorithms developed here would provide additional confidence of the efficacy of these methods. Databases of WAAS GIVE and UDRE values over time would allow validation under both nominal and off-nominal conditions, although failure testing might require detailed simulations of WAAS monitoring algorithms. Finally, examination of the ionospheric and ephemeris monitoring algorithms for SBAS networks in Europe (EGNOS), Japan (MSAS), and elsewhere would help determine if the algorithms applicable to WAAS can be used for SBAS worldwide.

8. ACKNOWLEDGMENTS

The authors would like to thank the many researchers who have contributed greatly to the understanding of extreme ionospheric spatial gradients and potential mitigations, including Juan Blanch (Stanford), Jiyun Lee (KAIST), Seebany Datta-Barua (San Jose State), Attila Komjathy (JPL), Jason Rife (Tufts University), Tom Dehel and John Warburton (FAA Technical Center), Takeyasu Sakai, Susumu Saito, and Takayuki Yoshihara (ENRI), Tim Murphy and Matt Harris (Boeing), and Mats Brenner (Honeywell). We also thank the FAA LAAS Program Office for their support. However, the opinions expressed here are solely those of the authors.

9. REFERENCES

[1] S. Pullen, T. Walter, P. Enge, "System Overview, Recent Developments, and Future Outlook for WAAS and LAAS," *Proc. GPS Symp. 2002*. Tokyo, Japan, GPS Soc./Japan Inst. of Nav., Nov. 11-13, 2002, pp. 45-56. http://waas.stanford.edu/~wwu/papers/gps/PDF/Pullen Tokyo02.pdf

[2] S. Ramakrishnan, J. Lee, S. Pullen, P. Enge, "Targeted Ephemeris Decorrelation Parameter Inflation for Improved LAAS Availability during Severe Ionosphere Anomalies," *Proc. ION NTM 2008*, San Diego, CA, Jan. 28-30, 2008, pp. 354-366. http://waas.stanford.edu/~wwu/papers/gps/PDF/RamakrishnanIONNTM08.pdf

[3] T. Murphy, M. Harris, Y.S. Park, S. Pullen, "GBAS Differentially Corrected Positioning Service Ionospheric Anomaly Errors Evaluated in an Operational Context," *Proc. ION ITM 2010*, San Diego, CA, Jan. 25-27, 2010, pp. 394-410. http://waas.stanford.edu/~wwu/papers/gps/PDF/MurphyIONITM10.pdf

[4] J. Lee, S. Pullen, S. Datta-Barua, P. Enge, "Assessment of Ionosphere Spatial Decorrelation for Global Positioning System-Based Aircraft Landing Systems", *AIAA J. of Aircraft*, Vol. 44, No. 5, Sept.-Oct. 2007, pp. 1662-1669. http://www.aiaa.org

[5] S. Pullen, Y.S. Park, P. Enge, "Impact and Mitigation of Ionospheric Anomalies on Ground Based Augmentation of GNSS," *Radio Science*, Vol. 44, Aug. 8, 2009. http://www.agu.org/journals/rs/rs0904/2008RS004084/2008RS004084.pdf

[6] S. Datta-Barua, J. Lee, *et al.*, "Ionospheric Threat Parameterization for Local Area Global-Positioning-System-Based Aircraft Landing Systems," *AIAA J. of Aircraft*, Vol. 47, No.4, July-Aug. 2010, pp. 1141-1151. http://www.aiaa.org

[7] Continuously Operating Reference Station (CORS) Network, U.S. National Geodetic Survey. http://www.ngs.noaa.gov/CORS/

[8] *Global Positioning System Standard Positioning Service Performance Standard*. Washington, D.C., U.S. Department of Defense, 4th Edition, Sept. 2008. http://www.navcen.uscg.gov/pdf/gps/geninfo/2008SPSPerformanceStandardFINAL.pdf

[9] C. Shively, R. Niles, "Safety Concepts for Mitigation of Ionospheric Anomaly Errors in GBAS", *Proc. ION NTM 2008*, San Diego, CA, Jan. 28-30, 2008, pp. 367-381. http://ion.org/search/view_abstract.cfm? jp=p&idno=7695

[10] *GNSS-Based Precision Approach Local Area Augmentation System (LAAS) Signal-in-Space Interface Control Document (ICD)*. Washington, DC, RTCA SC-159, WG-4, DO-246D, December 16, 2008. http://www.rtca.org

[11] J. Lee, J. Seo, *et al.*, "Ionospheric Gradient Threat Mitigation by Geometry Screening in GNSS Ground Based Augmentation Systems," submitted to *AIAA J. of Aircraft* (forthcoming). http://www.aiaa.org

[12] *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System User Equipment*. Washington, DC, RTCA SC-159, WG-2, DO-229D, December 13, 2006. http://www.rtca.org

[13] T. Walter, A. Hansen, *et al.*, "Robust Detection of Ionospheric Irregularities," *Proc. ION GPS 2000*, Salt Lake City, UT, Sept. 19-22, 2000, pp. 209-218. http://waas.stanford.edu/~wwu/papers/gps/PDF/toddion00.pdf

[14] L. Sparks, A. Komjathy, *et al.*, "Extreme Ionospheric Storms and Their Impact on WAAS," *Proc. Int'l. Beacon Satellite Symp. 2005*, Alexandria, VA, May 3-5, 2005. http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/37807/1/05-0934.pdf

[15] J. Rife, S. Pullen, *et al.*, "WAAS-Based Threat Monitoring for a Local Airport Monitor (LAM) that Supports Category I Precision Approach," *Proc. IEEE PLANS 2006*, San Diego, CA., April 25-27, 2006, pp. 468-482. http://waas.stanford.edu/~wwu/papers/gps/PDF/RifeIONPLANS06.pdf

[16] T. Walter, J. Blanch, P. Enge, "Coverage Improvement for Dual Frequency SBAS," *Proc. ION ITM 2010*, San Diego, CA, Jan. 25-27, 2010, pp. 344-353http://www.ion.org/search/view_abstract.cfm ?jp=p&idno=8815

[17] J. Bollard, "GBAS Ionospheric Threat Model Evaluation: Mid-latitude Australian Region," ICAO NSP Working Group of the Whole (WGW) Meeting, Montreal, Canada, WGW/IP 2, May 17-28, 2010. http://www.icao.int

[18] B. Pervan, L. Gratton, "Orbit Ephemeris Monitors for Local Area Differential GPS," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 41, No.2, April 2005, pp. 449-460. http://www.ieee.org

[19] *Software Considerations in Airborne Systems and Equipment Certification*, Washington, D.C.: RTCA SC-167, DO-178B, Dec. 1, 1992. http://www.rtca.org

[20] T. Schempp, S. Peck, R. Fries, "WAAS Algorithm Contribution to Hazardously Misleading Information (HMI)," *Proc. ION GPS 2001*, Salt Lake City, UT, Sept. 11-14, 2001, pp. 1831-1837. http://www.ion.org/search/view_abstract.cfm?jp=p&idno=1858

[21] *FAA's NextGen Implementation Plan 2010*, Washington, DC, U.S. Federal Aviation Administration, March 2010. http://www.faa.gov/about/initiatives/nextgen/media/NGIP_3-2010.pdf

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