GBAS Differentially Corrected Positioning Service Ionospheric Anomaly Errors Evaluated in an Operational Context

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BIOGRAPHIES

Tim Murphy is Technical Fellow with Boeing Commercial Airplanes where he is a member of the Electronic Systems organization. Tim has 25 years of experience in radio navigation communications and surveillance systems for civil aviation. The current focus of his work is avionics for new airplane product development, and next generation CNS technologies to support Air Traffic Management including satellite navigation. Tim is very active in the development of international standards for use of satellite navigation by commercial aviation. He received a BSEE and MSEE from Ohio University.

Matt Harris is a Systems Engineer at The Boeing Company. He is involved in various aspects of communication, navigation, and surveillance research as a member of the Air Traffic Management Group within Boeing Commercial Airplanes. Matt received his Bachelor of Science and Master of Science in Electrical Engineering from Ohio University.

Young Shin Park is a Ph.D. Candidate in Aeronautics and Astronautics in the Global Positioning System (GPS) Research Laboratory at Stanford University. Her current research interests are enabling LAAS DCPS and Airport Surface Movement, ionospheric anomaly threat model enhancement, and mitigation of the ionospheric anomaly threat to LAAS. She received a MS from Stanford University and a BS from Seoul National University.

Dr. Sam Pullen is a Senior Research Engineer at Stanford University, where he is the manager of the Local Area Augmentation System (LAAS) research effort. He received two S.B degrees in Aeronautics and Astronautics and History from MIT and M.S. and Ph.D degrees in Aeronautics and Astronautics from Stanford University. His current work includes the development of revised system architectures and algorithms for the next phase of LAAS to support Category II and III precision landings.

ABSTRACT

GBAS is a short-baseline differential GNSS system based on carrier-smoothed code phase measurements. One source of error in the system is the possible decorrelation of ionospheric delay between the ground system and the airborne equipment as the baseline increases. Typically, the ionosphere is well behaved over short distances, and the residual error after application of differential corrections is small. However, during solar storms and in geomagnetic equatorial regions, anomalies in the ionosphere can, on rare occasions, result in significant changes in observed ionospheric delays over relatively short distances. The impact of these anomalous ionospheric conditions has been studied extensively for the precision approach applications of GBAS.

The standards for GBAS include two types of service: the precision approach service, which provides deviation information relative to a defined final approach segment path, and the Differentially Corrected Positioning Service (DCPS), which provides differentially corrected latitude and longitude for use by flight management systems for a range of applications, including flying RNAV or RNP operations. Significant work has been done to mitigate the potential impact of errors induced by ionospheric anomalies on the precision approach service. For the DCPS, the potential baseline between the ground station and the user is much longer; consequently the potential errors that could be induced by an ionospheric anomaly are larger. Furthermore, because the DCPS must support many different flight operations, the ground-system geometry screening that is targeted to protect precision approach is insufficient to protect the DCPS. Initial studies of ionospheric anomaly errors and the DCPS led the FAA to withhold approval of the DCPS for the first GBAS ground station to be granted System Design Approval.

This study re-evaluates the problem of DCPS errors induced by ionospheric anomalies by examining these errors in the context of how DCPS is anticipated to be

used in the terminal area in support of specific RNAV/RNP operations. The study also considers the maximum undetected errors in the context of ADS-B applications given the current proposed separation standards to be supported.

BACKGROUND

The Differentially Corrected Positioning Service (DCPS) is one of two separate navigation utilities provided by Ground Based Augmentation Systems (GBAS) such as the U.S. Local Area Augmentation System (LAAS). The precision-approach LAAS utility, which provides ILS-look-alike angular deviations from the transmitted approach path, has already been approved for conditions up to and including CAT I weather minima [1]. However, the DCPS utility, which provides position, velocity, and time (PVT) in WGS-84 coordinates, has not been approved and is disabled by the current LAAS Ground Facility (LGF).

DCPS is intended to provide Differential GPS (DGPS) accuracy and integrity to GBAS-equipped aircraft for applications outside of precision approach, such as enroute and terminal-area flight operations and (potentially) airport surface movement. The most fundamental limitation on DCPS is the range at which the GBAS VHF Data Broadcast (VDB) can be reliably received. VDB coverage is required to extend at least 23 nmi. (about 45 km) within the precision approach coverage volume [2] and can be received at longer distances at higher altitudes [3]. However, while DCPS accuracy within 200 km of the LGF is at least as good as that from Wide-Area DGPS, integrity is difficult to guarantee far from the LGF. To address this, a parameter "D_{max}" is broadcast by the LGF that indicates the maximum range from the LGF at which integrity is supported [2].

The primary difficulty for DCPS integrity is error bounding under worst-case ionospheric anomalies. This problem has been studied extensively to date [4, 5]. Two aspects of these requirements pose the greatest difficulty. The first is that DCPS is required to meet integrity for any current or hypothetical aircraft application within D_{max}. The second is that the DCPS horizontal protection level (HPL) is required to bound rare-event errors (to a probability of 10^{-7} per hour) at any level of error. In other words, there is no error level small enough for which bounding by HPL is not required. This second requirement is a consequence of the first one: since potential DCPS applications are unlimited, all error magnitudes are potentially hazardous to some segment of the DCPS user population.

Taken together, these DCPS requirements are much harder to meet than those applied to GBAS CAT I precision approach. CAT I approach represents a single operation that occurs relatively close to the LGF (e.g., within 5 – 6 km) and has a known vertical alert limit of 10 meters. These constraints allow ground stations to perform position-domain geometry screening, inflating one or more broadcast parameters that affect user vertical protection levels (VPLs) so that potentially unsafe user satellite geometries are made unavailable [6,10]. However, because of the unlimited nature of DCPS applications and the need for protection-level bounding, this technique is not sufficient for DCPS as it is currently defined. Airborne geometry screening for DCPS is one approach that has been explored in [5], but it would require both requirements changes and changes to airborne equipment that has already been approved to RTCA DO-253 LAAS standards [7].

This paper examines additional means by which the GBAS DCPS integrity requirements can be met. It begins by summarizing how worst-case ionospheric anomaly impacts on DCPS users are modeled and simulated. Then previously-obtained results for maximum 2-D horizontal position errors as a function of DCPS HPL [5] are presented. It then examines the benefits of restricting DCPS applications to specific flight operations such as Area Navigation (RNAV) or Required Navigation Performance (RNP). More generally, this paper searches for practical means to achieve HPL bounding for all error values. The paper also considers operational means that could be used to protect against ionospheric anomalies. Finally, the paper considers potential changes in DCPS requirements or the way that they are interpreted in support of specific flight operations.

SIMULATION OF HPE AND HPL FOR DCPS

The simulation procedure used to obtain Horizontal Position Errors (HPE) and corresponding HPLs for DCPS has been expanded from the methodology in [4, 5] and is shown in Figure 1. One day of geometries with five-minute time updates and a 5-degree visibility mask angle at Memphis International Airport (MEM) is used to generate all-in-view, all 1-satellite-out (N–1), all 2-satellite-out (N–2), etc., down to all 4-satellite subset geometries. The variable N represents the number of visible satellites in the geometry (which are all assumed to be approved for use by the GBAS ground facility). The maximum supported distance from GBAS ground facility to user, defined as D_{max} and included in the information broadcast by the VDB [7,8], is set by the service provider. A typical value for D_{max} is 45 km, although shorter separations have also been evaluated.

Worst-case GPS range errors from the ionospheric anomaly threat model for the Conterminous U.S. (CONUS) [9] are applied to all individual satellites in all allowed subset geometries, one satellite at a time.

Anomalous ionospheric range errors applied to individual satellites are proportional to the distance from GBAS ground facility to user with the addition of a bias due to an assumed aircraft velocity in the direction of the ground facility. In this example, a velocity of 250 knots (128.61 m/s) is used because it is a typical aircraft velocity at a distance of 45 km from an airport, although the actual velocity could be different because DCPS can support many different kinds of operations. The nominal ionospheric gradient parameter, σ_{vig}, may vary due to the GBAS ground facility geometry screening needed to protect CAT I precision approach, which is briefly described in the next section. Here, a nominal (uninflated) σ_{vig} of 6.4 millimeters per kilometer is used to compute both HPE and the uninflated HPL, and a specific value of inflated σ_{vig} for each epoch obtained by a real-time sigma-inflation algorithm is used to compute the inflated HPL. A broadcast multiplier (unitless) for computation of the ephemeris error position bound for the GBAS positioning service, $K_{md\_e\_POS\_hrz}$ of 5.085 and a ephemeris decorrelation parameter, or "P-value," (P_k) of 0.00018 meters per meter are used [6,7,8]. HPE, HPL, and inflated HPL are computed as described in [7,8], and the largest HPE and corresponding HPL and inflated HPL are stored for each subset geometry generated by the satellite geometry simulation described above.

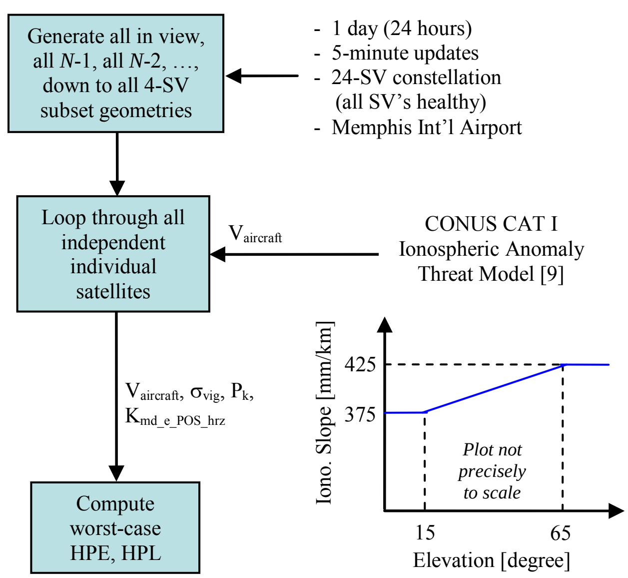

Figure 1 DCPS Simulation Procedure to Generate Worst-Case Errors under Ionospheric Anomalies

REAL-TIME SIGMA-INFLATION SIMULATION

The simulation used to establish real-time inflation factors for σ_{vig} to protect CAT I precision approach is based on the methodology in [6,10] and is modified to fit current GBAS operational design. Subset geometries are generated for CAT I in the same manner as for DCPS except that valid airborne geometries are limited to no more than two satellites fewer than the *N* satellites approved by the GBAS ground facility (*N*–2). In addition, geometries whose inflated Vertical Protection Levels (VPLs) are above the CAT I Vertical Alert Limit (VAL) of 10 meters are "screened out" (i.e., made unavailable for use). The assumed distance from GBAS ground facility to user at the 200-ft CAT I decision height is set to be 6 kilometers [6].

Unlike DCPS in this paper, the worst-case ionosphere impact for precision approach must be evaluated over all independent pairs of satellites in each subset geometry. Ionosphere-induced range errors for CAT I are determined by closed-form equations based upon the parameters from the ionospheric anomaly threat model for CONUS. These expressions, whose key parameter is the ionosphere front velocity, are modified from [6]. The GBAS ground facility uses a Code-Carrier Divergence (CCD) Monitor to detect anomalous ionospheric activity [11]. However, for this monitor to detect hazardous spatial gradients, the relative velocity (Δv [km/s]) between two GBAS ground facility Ionosphere Pierce Point (IPP) velocities projected onto the direction of the ionosphere front velocity must have sufficient magnitude. For smaller relative velocities, the CCD monitor does not alert, and the undetected user errors can be large.

The resulting closed-form range errors can be summarized as follows:

(1) Slow Ionosphere Front Speed:

$$\Delta v < \frac{0.0229\,[\mathrm{m/s}]}{\min\left[\frac{50\,[\mathrm{m}]}{W}, G\right]}, \quad \Delta v < 0.11\,[\mathrm{km/s}] \qquad [1]$$

There is no CCD detection in these cases. The error (ε [m]) induced by the ionosphere is proportional to the separation between the GBAS ground facility and the approaching aircraft. This relationship is expressed as:

$$\varepsilon = \min\left[\frac{50\,[\mathrm{m}]}{W}, G\right] \times \left(x + 2\,\tau\, v_{aircraft}\right) \qquad [2]$$

where,

W: Width of the ionosphere front [km];
G: Gradient or "slope" of the ionosphere front through which the IPP passes through [m/km];
τ: 100-second smoothing time of the Carrier-Smoothing filter used by GBAS [s];
$v_{aircraft}$: Velocity of the user aircraft during its final approach segment (assumed to be a constant 0.070 km/s in this paper) [km/s];

x : Distance between the GBAS ground facility and the user (assumed to be 6 km in this paper) [km].

(2) *Moderate Ionosphere Front Speed*:

$$\frac{0.0229\,[\text{m/s}]}{\min\left[\dfrac{50\,[\text{m}]}{W}, G\right]} < \Delta v < 0.11\,[\text{km/s}] \qquad [3]$$

In these cases, the CCD monitor alerts for some conditions within this range of relative speeds. Consequently, the errors that users could suffer begin to drop. Under the CONUS threat model, the maximum range error the user would suffer is no greater than 4 meters.

(3) *Fast Front Ionosphere Speed*:

$$\Delta v > 0.11\,[\text{km/s}] \qquad [4]$$

In these cases, The CCD monitor alerts with a very small missed-detection probability. Under the CONUS threat model, the maximum range error that users could potentially suffer is no greater than 2.5 meters.

The multiplier (unitless) which determines the probability of missed detection, K_{md} of zero, the broadcast multiplier (unitless) for computation of the ephemeris error position bound for Category I precision approach, $K_{md\_e\_CAT1}$ of 5.085, and the P_k of 0.00018 m/m, are used to get Ionosphere-induced-Error-in-Vertical (IEV), VPL, and required inflation factors for σ_{vig} [6,10].

In order to ensure that VAL bounds the Maximum-Ionosphere-induced-Error-in-Vertical (MIEV) for all usable "subset" geometries, real-time-sigma-inflation beyond the nominal sigma value of 6.4 mm/km is performed using computed and stored values of VPE and VPL for CAT I precision approach. This simulation procedure is based on Figures 10 and 11 in [10]. A single epoch is considered as an example to briefly explain the concept of σ_{vig} inflation. If IEV for a particular subset geometry is above the tolerable error limit (28.78 m) derived from the Obstacle Clearance Surface (OCS) at the CAT I decision height [12], σ_{vig} is increased until the VPL for that geometry (based upon the inflated σ_{vig}) is above VAL; thus that problematic geometry will be screened out (made unavailable) by the VPL check. This sigma-inflation procedure is repeated until all subset geometries with IEV exceeding 28.78 m are made unusable, meaning that the MIEV of the remaining "usable" geometries is no greater than 28.78 m. The resulting value of σ_{vig} per each epoch is fed into the DCPS simulation to compute inflated HPL for users not limited to the CAT I approach phase of flight.

PREVIOUS ANALYSIS RESULTS

DCPS simulation results for HPE and HPL with a fixed, uninflated value for σ_{vig} of 6.4 mm/km and a user located at separations of 45 km, 30 km, 20 km, and 10 km from a GBAS ground station at Memphis are shown in Figure 2, Figure 3, Figure 4, and Figure 5 respectively. These plots are in the form of HPE versus HPE-to-HPL ratio. The maximum HPE is about 419 km for a distance of 45 km, 330 km for a distance of 30 km, 271 km for a distance of 20 km, and 212 km for a distance of 10 km.

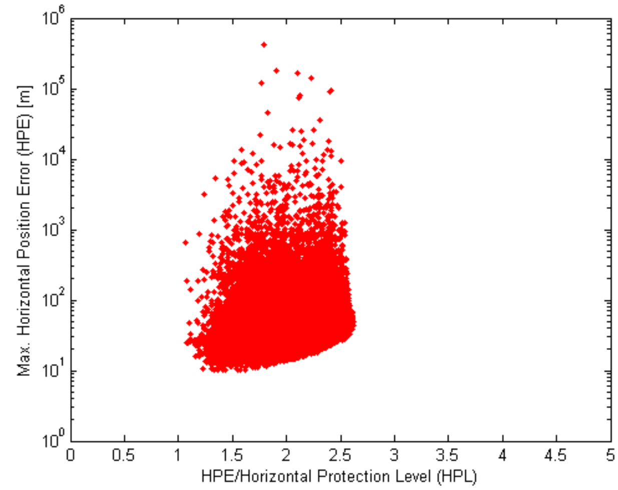

Figure 2 Worst-Case DCPS Errors at Memphis (45-km separation, σ_{vig} = 6.4 mm/km),

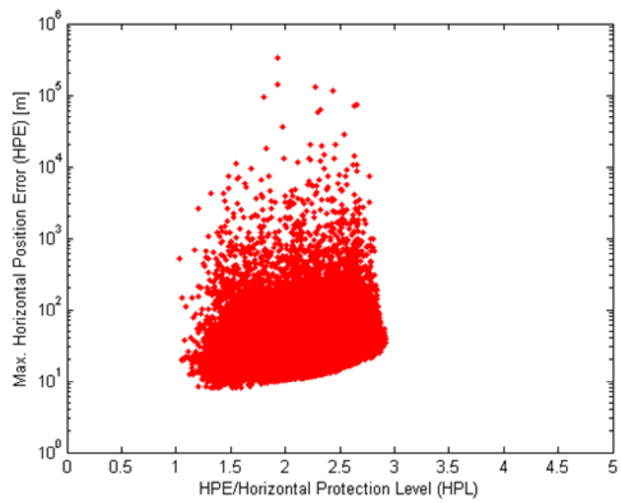

Figure 3 Worst-Case DCPS Errors at Memphis (30-km separation, σ_{vig} = 6.4 mm/km)

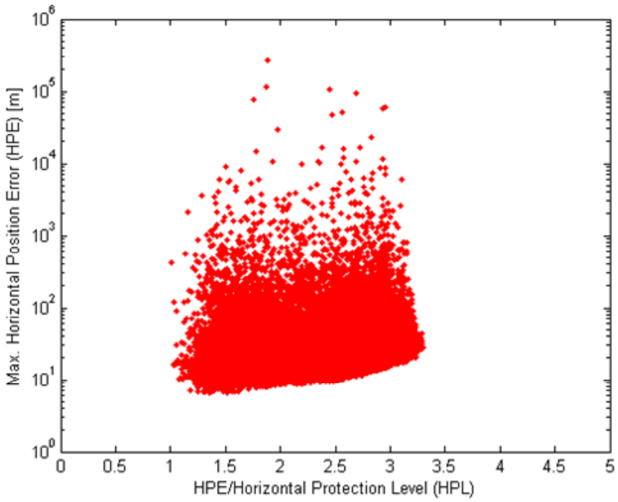

Figure 4 Worst-Case DCPS Errors at Memphis (20-km separation, σ_{vig} = 6.4 mm/km)

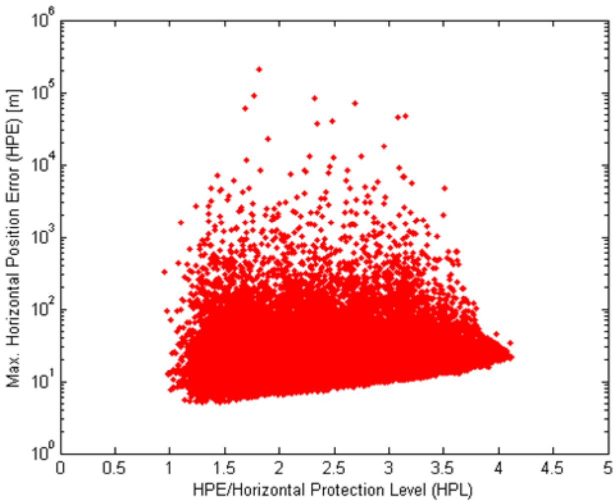

Figure 5 Worst-Case DCPS Errors at Memphis (10-km separation, σ_{vig} = 6.4 mm/km)

The result in Figure 2 for the 45-km separation mirrors that shown in [4] before mitigations to improve DCPS performance are applied. Note that this result is worse than the corresponding figure in [4] because we are assuming the minimum σ_{vig} here instead of the maximum one in [4]. The values of several parameters described in this paper are also different from those in [4].

Note that none of the HPE values in these plots are bounded by their corresponding HPLs. In other words, the HPE-to-HPL ratio always exceeds 1.0. This indicates that the existing DCPS integrity requirements cannot be met by CAT I GBAS without changes to the definition of DCPS integrity [13,14] and/or the airborne receiver requirements [7]. The current GBAS requirements for DCPS integrity are that position errors must be bounded by the corresponding protection levels to the 10^{-7}-per-hour probability level, regardless of the size of the error [13, 14]. However, the significance of the errors in these four figures depends greatly upon their operational context, as explained in the next section.

OPERATIONAL CONSIDERATIONS

GNSS outputs may be used for a variety of applications on the airplane, including:

- position determination in support of navigation and guidance, (e.g. Required Navigation Performance (RNP) applications);
- position determination in support of surveillance through Automatic Dependent Surveillance (e.g. ADS-C or ADS-B applications);
- time transfer (e.g., to set the pilot's clock);
- position determination in support of situational awareness and alerting systems (e.g. Enhanced Ground Proximity Warning Systems (EGPWS)).

The requirements for each of these applications vary. The real implications of errors exceeding the protection level will depend on the particular operation. Because the augmentation system has no way of knowing what operation the user is performing, the existing requirements have been written such that an integrity failure is defined as any Horizontal Position Error (HPE) that exceeds the Horizontal Protection Level (HPL). However, in many cases, errors that exceed the protection level (i.e., HPE > HPL) may actually be completely insignificant when viewed in the context of the operation being conducted.

Whenever GNSS is used for an application where horizontal performance is required and integrity is a consideration, HPL is used to determine if the system currently provides the required integrity. In other words, all aviation applications will involve some level of geometry screening to ensure that the horizontal position solution has the required level of integrity. This is invariably done by comparing the instantaneous HPL to some maximum allowable limit which defines acceptable performance for that operation. This limit is generally referred to as the Horizontal Alert Limit (HAL). The HAL defines the level of error that is considered to be significant from an integrity point of view for the operation. Note that it is possible for HPE to exceed HPL without exceeding HAL. Although such cases are technically defined as integrity failures, they are not operationally significant.

Figure 6 illustrates the difference between errors that are technically integrity failures and errors that are also potentially significant in an operational context. Figure 6 shows the maximum HPE that can be generated by all possible geometries vs. the ratio of HPE to HPL for each geometry. Each point in the plot represents a different geometry where all possible combinations of 4 or more satellites are considered over 24 hours with a 5-minute time interval. The simulation used to develop the results in Figure 6 assumed that the distance between the airborne user and the ground station was 45 km and that the ionospheric threat model is as described in [9]. Note that, since all points in the plot have HPE/HPL > 1, then HPE always exceeds HPL, and all the geometries have maximum potential errors that are technically integrity failures. However, for an operation with a requirement of HAL = 1.0 nm, relatively few geometries have errors that lie above the HAL = 1.0 nm line in the figure. Furthermore, the dashed green line in the figure indicates the condition where HPL = HAL = 1.0 nm. For all points above the green dashed line, the HPL for the geometry exceeds HAL; therefore the DCPS would not be used. In other words, a test of HPL ≤ HAL results in all the geometries indicated as green in the figure being rejected by the geometry filter.

Figure 6 illustrates that defining a HAL (as a function of an operation) separates the total space of possible geometries into three groups:

1) Geometries where HPE < HAL (shown as blue in the figure)
2) Geometries where HPL > HAL (shown as green in the figure), and
3) Geometries where HPL ≤ HAL and HPE > HAL (shown as red in the figure).

The geometries in group 1 above produce HPE < HAL, which by definition should be acceptable as long as the probability of a latent failure with an error somewhere near the HAL is improbable enough that the 95% accuracy requirements are not violated. For ionospheric anomalies, this should not be an issue since these are rare events to begin with.

The geometries in group 2 above are also not a concern from an operational standpoint because the HPL ≤ HAL geometry screen results in these cases being rejected. Hence, errors that could have been generated with those geometries are of no concern because those geometries simply will not be used.

The third group defined above represents the geometries which could produce errors that are potentially significant given the HAL applied to the operation. In this paper, we refer to these as "significant geometries".

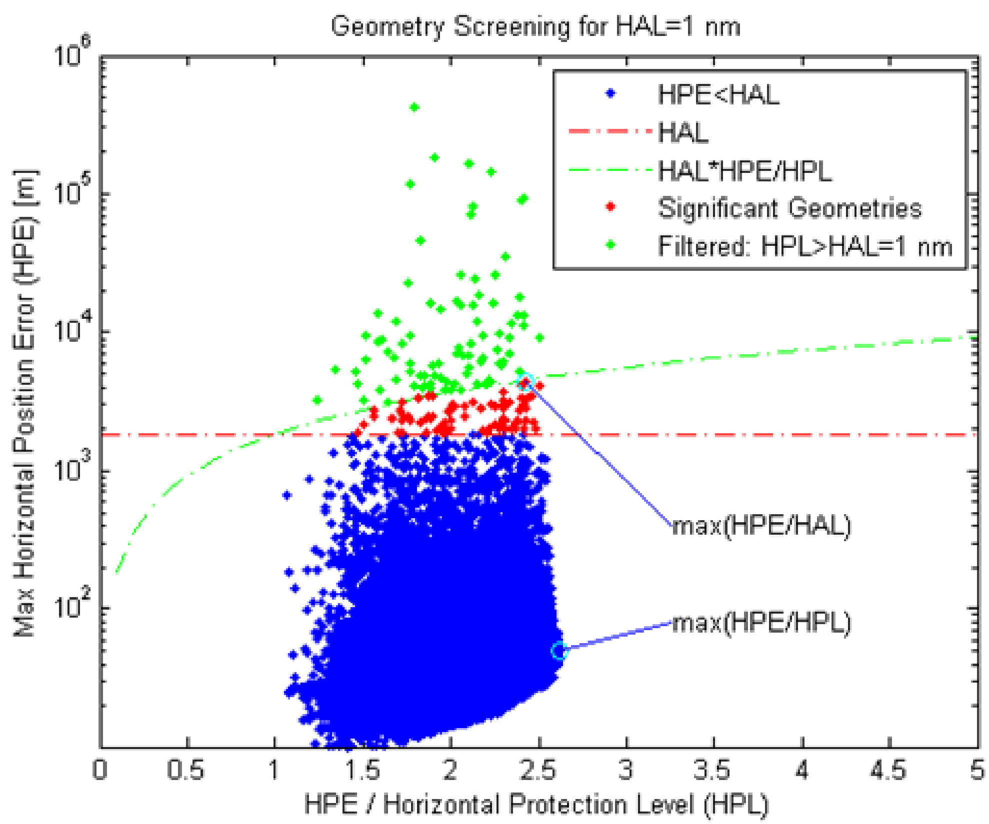

Figure 6 Implications of Geometry Screening on Maximum Horizontal Position Error

From Figure 6, it can be seen that relatively few geometries that could have been used over 24 hours could have produced errors that are “significant” given an operation with a requirement of HPL < HAL = 1 nm. In fact, there are 40,052 possible geometries shown in Figure 6, and for HAL = 1 nm, only 89 of those geometries have a maximum possible error (given the threat space assumed in [9]) that falls within the region of significance (i.e. HPE > HAL and HPL < HAL.). Since all geometries are not equally likely, one cannot infer any probability from the ratio of significant geometries to the total number of geometries (89/4052 = 0.0022). In fact, doing so would result in an overestimation of the likelihood of a receiver actually using one of these significant geometries.

Figure 7 shows the number of geometries that fall within the significant region as a function of HAL. Note that the "Drill down to 4" case includes all possible geometries of at least 4 satellites (and thus is the same set of geometries shown in Figure 6). Also shown in the figure are curves that consider all possible geometries if no more than 2 or 3 satellites at a time are removed from the constellation. Note that, for the case where no more than 2 satellites are removed, the number of significant geometries for HAL > 0.3 nm is small indeed (i.e., only one or two geometry samples per day fall within the significant region). Most significant geometries require 3 or more satellites to be removed from the constellation.

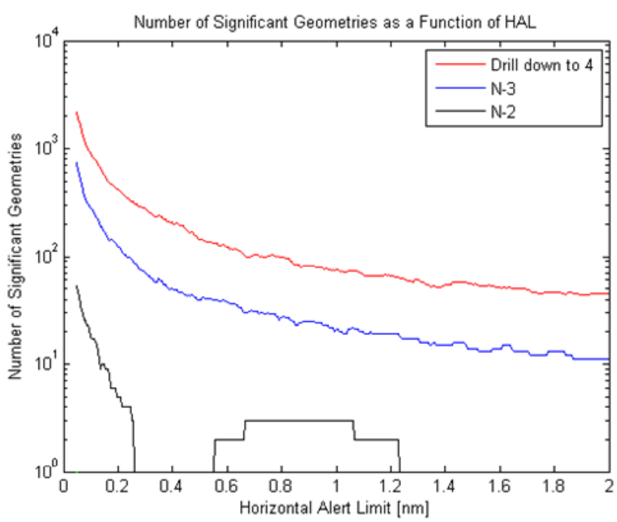

Figure 7 Number of Significant Geometries over 24 Hours as a Function of HAL

There are many reasons that satellites may not be tracked by user receivers. One or more satellites may in fact be out of service at a given time. Additionally, airborne receivers may stop tracking a satellite signal (temporarily) due to banking or maneuvering. If the GBAS ground station does not provide a correction for a given satellite, then the airborne receiver will not use that satellite in the position solution. Therefore, situations where one or two of the potentially available satellites are not used are not so uncommon. Situations where three or more satellites are unavailable are much rarer events. So, in reality, for a DCPS user to experience an error that is operationally significant, the relatively rare event of a poor satellite geometry must line up in time with the relatively rare event of a severe ionospheric gradient being in exactly the right place at the right time.

Figure 8 shows the maximum ratio of HPE to HAL as a function of HAL, considering only the geometries which could produce errors in the significant region (as illustrated in Figure 6). Note that the maximum ratio of HPE/HAL goes up and down as HAL increases because the driving point (illustrated as max(HPE/HAL) in Figure 6) changes as different geometries enter or leave the significant region. For the case illustrated, the maximum ratio of HPE to HAL varies between 2 and a peak value of about 2.5. This should be compared to the maximum ratio of HPE to HPL for this distance and aircraft speed of 2.62. In other words, the maximum HPE/HAL for any HAL will be somewhat less than the maximum HPE/HPL for that aircraft speed and distance.

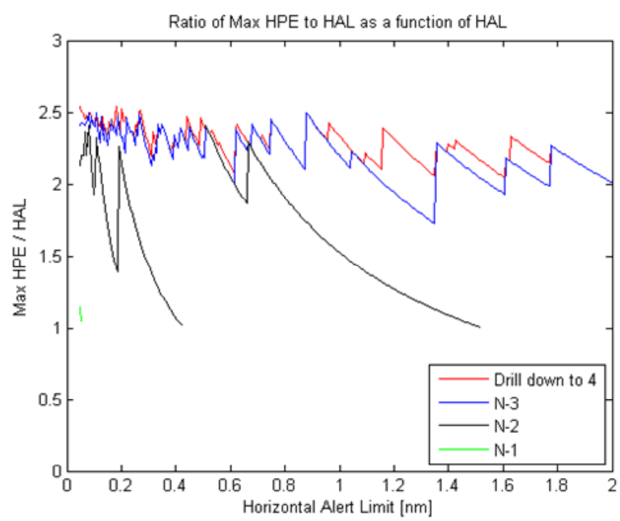

Figure 8 Maximum Ratio of HPE to HAL as a Function of HAL Considering only the Significant Geometries

The impact of ionospheric anomalies on DCPS depends on many factors, including the aircraft speed and the distance between the user and the ground subsystem. Thus far, we have only considered four scenarios; i.e., an aircraft traveling at a speed of 250 nmi/hr at four different distances from the ground station (i.e., 45 km, 30 km, 20 km and 10 km). Figure 9 shows the maximum HPE/HPL ratio over a range of aircraft speeds and distances between the aircraft and ground facility. Each point in this graph is generated by using the process described in Figure 1 and then finding the max(HPE/HPL) as illustrated in Figure 6. The aircraft speeds chosen are intended to represent different types of operations that could be supported by DCPS. Note that some combinations may not be relevant. For example, an airplane traveling at 10 m/s at a distance of 60 km from the ground station is an unrealistic situation, as DCPS is unlikely to even be used to support surface operations at an airport that far from a GBAS installation. Similarly, an airplane traveling at 230 m/s at a distance of 0 km from the ground station would imply an airplane at cruise speed very near the runway, which is somewhat nonsensical. An airplane at cruise speed will probably never be closer than a few kilometers from a ground station, even if it flies directly over the ground station. However, here the separation distance refers only to the horizontal separation of the respective pierce points; therefore an aircraft could fly thorough a point such that the distance between the ionospheric pierce points is zero.

Figure 9 clearly illustrates the trend in max(HPE/HPL) as a function of distance between the user and the airport. The HPL equations are a function of distance, but so is HPE. HPE grows as a function of baseline length at a faster rate than HPL until a point where the ephemeris error bounding equation (HPL_{eph}) becomes larger than HPL_{H0}. Thereafter, the HPL grows at a faster rate than the HPE; hence the maximum ratio gets smaller.

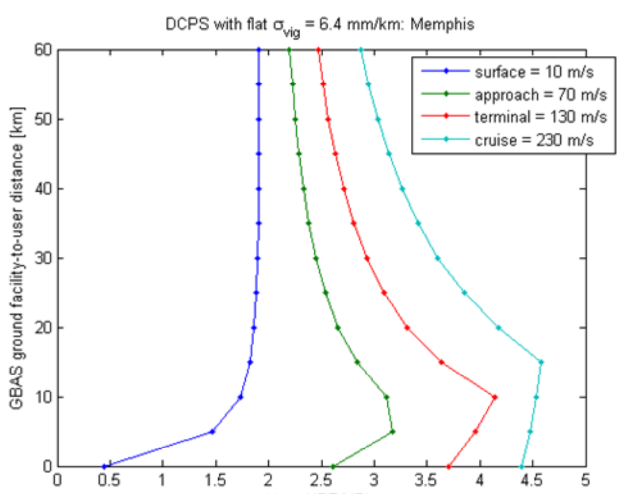

Figure 9 Maximum Ratio of HPE to HPL as a Function of Distance and Aircraft Speed – No Inflation of Uplink Parameters

Whether or not errors of a magnitude that fall within the significant region are actually significant given the context of a given operation is still debatable. To understand this better, we need to briefly discuss some real-world applications that may be supported by DCPS.

RNP OPERATIONS

Required Navigation Performance (RNP) operations refer to a class of operations where onboard monitoring of airplane performance is used to ensure that the airplane remains within a pre-specified containment region around the desired path. In practice, this means that the Total System Error (TSE) of the airplane must be kept within 2 times the specified RNP level with a probability of 0.99999. TSE is assumed to be the combination of Navigation System Error (NSE) and Flight Technical Error (FTE). NSE includes normal and non-normal errors from the navigation system (in our case of interest, the DCPS from GBAS). The FTE includes the ability of the pilot or autopilot to fly the indicated path. Figure 10 illustrates the relationship between RNP, TSE, NSE, FTE, and the required containment boundary.

The onboard navigation system provides two pieces of information to aid in real-time monitoring of airplane NSE. The Figure of Merit (FOM) is an estimate of the 95% accuracy of the navigation system. The Horizontal Protection Level (HPL) referred to previously is an estimate of a radius around the indicated position such that the probability of the true airplane position being outside the circle is less than or equal to 10^{-7}. Since TSE is the combination of NSE and FTE, there is an allocation between the contributions of NSE and FTE when determining what thresholds to use in order to ensure that TSE does not exceed the containment surface. Consequently, a threshold for HPL is set at somewhat lower than 2 times the RNP value in order to account for the contribution of FTE. On various airplanes, the ratio of the threshold (or effective HAL) and RNP is in the range of 1 to 1.7 times RNP. The value can vary from one airplane type to the next because the FTE performance may be different from one airplane model to the next. For RNP operations, GNSS use is filtered based on HPL ≤ HAL where HAL is between 1 and 1.7 times RNP.

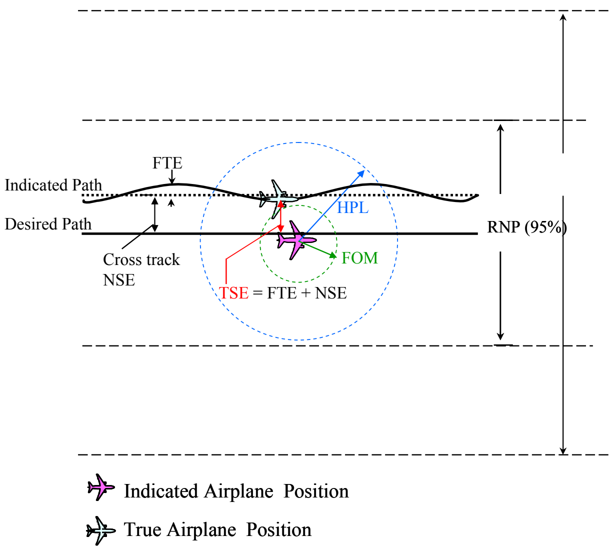

Figure 10 RNP Accuracy and Containment

National aviation authorities (e.g., the US Federal Aviation Administration) establish vertical and horizontal separation standards to facilitate the safe navigation of aircraft in controlled airspace. National separation standards are based on the provisions of ICAO Doc 4444 (Procedures for Air Traffic Management) [15], especially Chapter 5. Differences from these standards (if any) are published in national Aeronautical Information Publications (AIPs). The techniques used to ensure separation are numerous and complicated and depend upon the phase of flight and the relative trajectories of the multiple aircraft involved. In some cases, separation is maintained by specifying a minimum time window between two airplanes arriving at a proximate area. In other cases, separation is maintained by defining a minimum distance between defined tracks.

Figure 11 illustrates two tracks (at the same altitude) that could be employed in the terminal area with RNP = 0.3 nm. Current ICAO standards require a minimum of 3 nm separation between aircraft. A navigation error that would be large enough to move one aircraft into the track of the other aircraft would need to be 8 times the size of RNP. Since aircraft will perform geometry screening with a HAL of 1.7 × RNP or less, the ratio of HPE necessary to put one airplane in the other airplane's track (HPE ≥ 8 × RNP) to HAL (≤ 1.7 × RNP) would be 8/1.7 = 4.7. This of course assumes that only one of the two airplanes is affected by the error. In reality, under an ionospheric-anomaly scenario, both airplanes will likely be affected and, if tracking the same set of satellites, both will move in the same direction. If different subsets of satellites are tracked, theoretically the anomaly could move the airplanes in different directions, and potentially even towards each other. However, practically speaking, such a case would require both airplanes to use very different subsets of satellites with poor geometries.

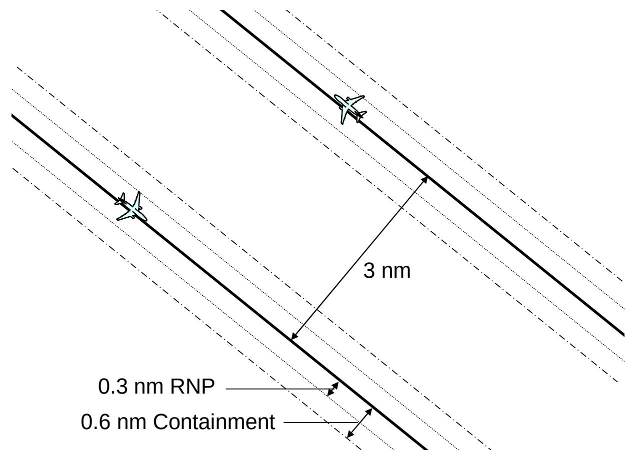

Figure 11 Airplane Separation Standards and 0.3 RNP Terminal Area Operations

The case of RNP and the separation of aircraft from terrain or obstacles is more complicated since buffers on the order of 10 × RNP are not required. Obstacles and terrain may be much closer to the defined path than 10 × RNP. Consequently, analysis of the significance of errors would need to be done on a case-by-case basis given the specific procedure design and airport environment. A full discussion of this case is beyond the scope of this paper. However, it is mentioned to underscore the fact that the effect of maximum unmitigated DCPS errors must be evaluated in the context of each operational use of DCPS.

AUTOMATIC DEPENDENT SURVEILLANCE (ADS-B) OPERATIONS

ADS-B is a cooperative surveillance system that operates using a data communication protocol with automatic broadcast of identification, position, velocity, and other parameters by participating users. Any equipment capable of receiving ADS-B data can use the data for various applications ranging from situational awareness to aircraft separation monitoring.

In the first phases of ADS-B implementation, ground facilities will receive data broadcast from aircraft for surveillance of those aircraft in various phases of flight. This operational concept is referred to as “ADS-B Out” and will be the focus of this paper. As the technology matures, aircraft may be equipped with the capability to receive ADS-B data and use it to enhance situational awareness or for self-separation using cockpit displays of information such as weather and aircraft traffic. This operational concept is known as “ADS-B In.”

Several countries have either commenced initial operations and/or have plans to mandate ADS-B equipage in the coming years. For example, the U.S. FAA has published a notice of proposed rule making (NPRM) for ADS-B that calls for a mandate of equipage and certain levels of performance by 2020 [16]. Nav Canada has mandated a basic level of ADS-B capability for some specific high-altitude airspace in the Hudson Bay area as of January 2009 [17]. Australia's ATLAS program and Europe's CASCADE program will result in ADS-B capability mandates as early as 2012 and 2015, respectively [18,19].

The position source performance categories defined for ADS-B are described briefly below. Several published and draft application requirements for performance of ADS-B position sources are also discussed.

In order to conserve the available data link bandwidth, a relatively small number of bits are allocated to the performance parameters describing the instantaneous status of the ADS-B position information. Consequently, the position accuracy and containment parameters were quantized into broad categories called NACp and NIC, respectively. The containment integrity level, SIL, is also limited to a few particular values.

Table 1 shows the ADS-B navigation accuracy and integrity categories, NACp and NIC, and their respective performance requirements. The estimated position uncertainty (EPU) represents 95% position accuracy, and the containment radius (R_C) is a bound on the position error associated with the integrity level represented by SIL. SIL levels range from zero to four representing unknown integrity, 10^{-3}, 10^{-5}, and 10^{-7}, respectively, per hour or operation.

Table 1 Summary of ADS-B Accuracy and Integrity Categories and Related Performance Requirements

NACp	*95% Horizontal and Vertical Accuracy Bounds (EPU and VEPU)*	*NIC*	*Horizontal and Vertical Containment Bounds*
0	EPU = 18.52km (10NM)	0	Rc = 37.04km (20NM)
1	EPU < 18.52km (10NM)	1	Rc < 37.04km (20NM)
2	EPU < 7.408km (4NM)	2	Rc < 14.816km (8NM)
3	EPU < 3.704km (2NM)	3	Rc < 7.408km (4NM)
4	EPU < 1852 m (1NM)	4	Rc < 3.704km (2NM)
5	EPU < 926 m (0.5NM)	5	Rc < 1852 m (1NM)
6	EPU < 555.6 m (0.3NM)	6a/b	6a: Rc < 1111.2 m (0.6NM) / 6b: Rc < 926 m (0.5NM)
7	EPU < 185.2 m (0.1NM)	7	Rc < 370.4 m (0.2NM)
8	EPU < 92.6 m (0.05NM)	8	Rc < 185.2 m (0.1NM)
9	EPU < 30 m	9	Rc < 75 m
10	EPU < 10 m	10	Rc < 25 m
11	EPU < 3 m	11	Rc < 7.5 m

Table 2 lists both published and draft positioning performance requirements in terms of ADS-B categories for various applications ranging from radar-like surveillance in non-radar airspace (NRA) to better than radar performance for radar airspace applications (RAD), including parallel approach, Final Approach and Runway Occupancy Awareness (FAROA), and surface applications such as Airport Surface Situational Awareness (ASSA). Note that most of the applications require a SIL level of 2, which corresponds to containment integrity of 10^{-5} per hour, while protection levels computed by existing certified RAIM algorithms and augmentation systems provide 10^{-7} per hour (which corresponds to a SIL of 3).

Table 2 Application Specific Requirements

Application	**NACp**	**NIC**	**SIL**
NRA (5 NM) *DO-303*	5	4	2
NRA (3 NM) *DO-303*	6	5	2
NRA CASCADE *DO-260 A*	5	4	3
NRA CASCADE *DO-260*	5	5	3
NRA ATLAS *Australia*	0	6a	2
NRA NPRM *FAA*	9	7	2
RAD En Route (5NM) *DO-318*	7	5	3
RAD Terminal (3NM) *DO-318*	7	6	3
RAD Dep. Par. Appr. (2.5NM) *DO-318*	7	7	3
RAD Ind. Par. Appr. *DO-318*	8	7	3
Enhanced Vis. Acq. *DO-317*	5	0	0
Enhanced Vis. Appr. *DO-317*	6	6	1
ASSA / FAROA Surface *DO-317*	9	0	0
In Trail Procedures *RFG DO-312*	5	5	2

Figure 12 illustrates the use of ADS-B for surveillance in support of separation assurance given two routes at the same altitude separated by some distance X nmi. As mentioned above, X will be 3 to 5 nmi in the terminal area. Given X and the required NIC level, it can be shown that the largest undetected error will not allow the airplanes to lose separation without detection. For example, if X = 5 nmi, then a NIC of 5 would correspond to a buffer of 5 × NIC between the routes. Given HPL < NIC, and the maximum HPE/HPL is 4.7 (as shown in Figure 9), then the largest undetected error would not be able to put one airplane in the other's path without detection.

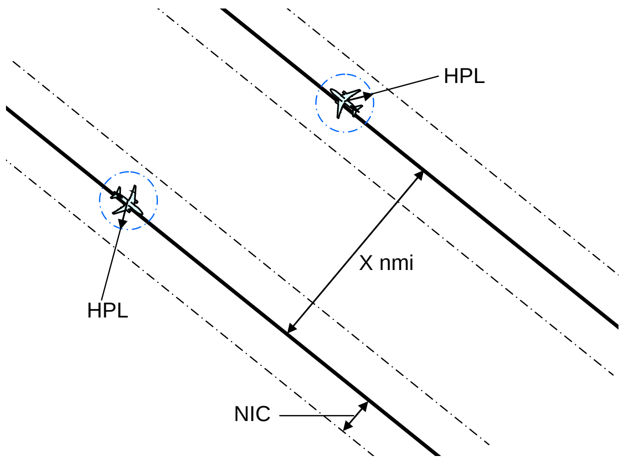

Figure 12 ADS-B Surveillance and Horizontal Separation

OVERVIEW OF POSSIBLE SOLUTIONS

Having described the challenges with safely implementing DCPS in the existing GBAS architecture, we can now begin to discuss the various degrees of freedom that could be exercised to solve the problem. The following general strategies for approving DCPS have been identified:

Strategy #1) Find a way to show compliance with the current high-level requirements. Enforce HPL error bounding using one or more of the following methods:

- Changes to the GBAS system: airborne, ground or both
- Operational mitigations

Strategy #2) Change the high-level requirements. For the worst-case ionosphere-induced error, accept HAL bounding instead of requiring HPL Bounding. Perform a worst-case analysis to show that the residual risk is acceptable in the context of the operation(s) supported.

Strategy #3) Change the interpretation of the high-level requirements. Accept that the prior joint probability of ionospheric anomaly and all other conditions necessary to cause HPE > HPL is $< 10^{-7}$/hour. Perform a worst-case analysis to show that the residual risk is acceptable in the context of the operation(s) supported.

In later sections, it will be shown that these strategies are somewhat interlinked and that, ultimately, the preferred solution will probably be a mixture of several of these elements.

STRATEGY #1) POSSIBLE METHODS TO ENFORCE HPL BOUNDING

In the following sections, several methods are considered that could enable the HPL to bound even the worst-case errors predicted by the ionospheric anomaly threat model. The methods include changes to either the airborne or ground station requirements, or both. Each of these approaches requires consideration of both system performance and financial costs. It may also be possible to enforce HPL bounding through operational mitigations. The use of operational mitigations to ensure HPL bounding is discussed in a later section.

CHANGES TO THE GROUND SYSTEM REQUIREMENTS TO ENFORCE HPL BOUNDING

Protection level bounding equations for DCPS are defined in ref [7] (section 2.3.10.2) and ref [8] (section 3.6.5.5.2.2). Several parameters in the HPL computation are broadcast by the ground reference system. If no changes are to be made to the airborne equipment and no parameters are added to the uplink, then the currently defined parameters are the only tools that could be used to enforce HPL bounding. The parameters of interest are σ_{vig}, and the ephemeris bounding parameters, P_k and $K_{md\_e\_POS\_hrz}$. Generally speaking, inflating any of these parameters will result in increasing the HPL computed by the airborne equipment. Theoretically, one could inflate one or more of these values to ensure that HPL bounds the maximum error.

The notion of inflating these uplink values is nothing new. In fact, inflation of uplink parameters has already been employed in the design of a GAST C GBAS as part of a strategy to mitigate the effects of ionospheric anomalies on the precision approach service [6,10]. However, inflating parameters comes at a significant cost to system availability.

Figure 13 shows the effect of inflating the uplinked value of σ_{vig} to the largest value that can be coded in the Type 2 uplink message (i.e., 25.5 mm/km). The scenario used to generate the data in Figure 13 is essentially the same as in Figure 6 except for the inflated σ_{vig}. Note that the maximum HPE/HPL has been reduced to about 1.25 (as opposed to 2.62 in Figure 2). Furthermore, the majority of the geometries have been shifted to the left of the HPE/HPL = 1 line. There are still a significant number of geometries with HPE/HPL > 1.

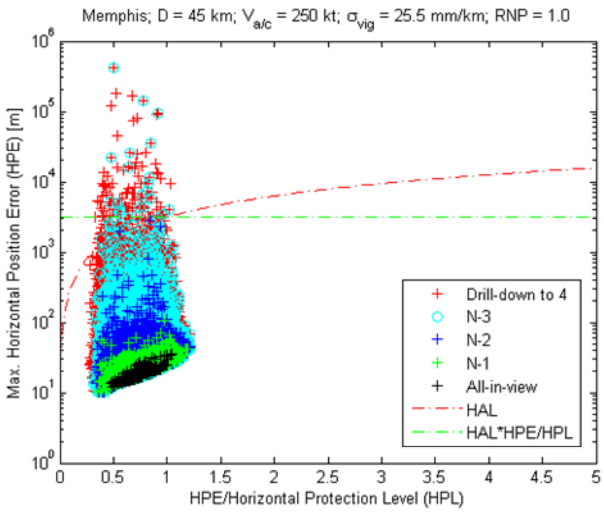

Figure 13 Constant inflation of σ_{vig} to 25.5 mm/km reduces horizontal errors to within 20 percent above HPL at 45 km

Figure 13 also shows the geometries differentiated by the number of satellites removed from the nominal constellation in order to produce that geometry. Also, the region of significance for RNP 1 operation is shown (assuming HPL < 1.7 × RNP is required). Note that this extreme inflation of σ_{vig} does result in a situation where no geometries fall in the region of significance (for RNP = 1 nmi and that particular airplane design).

The parameter σ_{vig} is used in the protection level computations for both the DCPS and the precision approach service. Inflation of σ_{vig} to 25.5 mm/km would greatly reduce the availability of VPL < 10 m required for GAST C GBAS to support CAT I approaches. Furthermore, Figure 13 illustrates that inflation of σ_{vig} alone would not move all the possible geometries to the HPE/HPL < 1 region. Consequently, inflation of σ_{vig} alone is not a practical solution to strictly enforce HPL bounding.

Figure 14 shows the effect of dynamic inflation of σ_{vig} (as described above) on the max(HPL/HPE). For this scenario, σ_{vig} is inflated when necessary to protect the GAST C service for CAT I against ionospheric anomalies. From the figure, it can be seen that this level of dynamic σ_{vig} inflation only modestly reduces the max(HPE/HPL) ratio over the range of aircraft speeds and separation distances. Dynamic σ_{vig} inflation is more effective at reducing max(HPE/HPL) at shorter baseline distances.

Figure 14 also shows the effect of inflation of the ephemeris error bound parameter P_k. For this case, P_k was set to the largest value that can be coded in the Type 1 uplink message, 0.001275 m/m. Hence the curves in the figure represent the maximum mitigation that could be achieved with P_k inflation, even though this level of P_k inflation is impractical due to the fact that the availability of CAT I approach service would be reduced to an unacceptable level. Aggressive P_k inflation can apparently enforce HPL bounding at farther distances. However, at higher speeds (i.e., approach speed and above), bounding at shorter baselines is still a problem. Consequently, Figure 14 confirms that inflation of P_k alone will not enforce HPL bounding for all relevant aircraft speeds and distances.

AIRBORNE CHANGES TO ENFORCE HPL BOUNDING

One possible strategy for enforcing HPL bounding for DCPS would be to impose new requirements on the airborne equipment. This is inherently problematic since airborne equipment has already been fielded based on the current standards. The first GLS capable airplane was delivered to Qantas in May of 2005. At the time of this writing, there are approximately 75 Boeing 737 airplanes with GLS capability in service. As GBAS is a basic function on the 787 and 747-8, this number of fielded receivers will grow substantially before a requirements change could be processed and a software update developed and implemented. Certifying a new part number and recalling, modifying and re-fielding equipment are expensive and time-consuming processes.

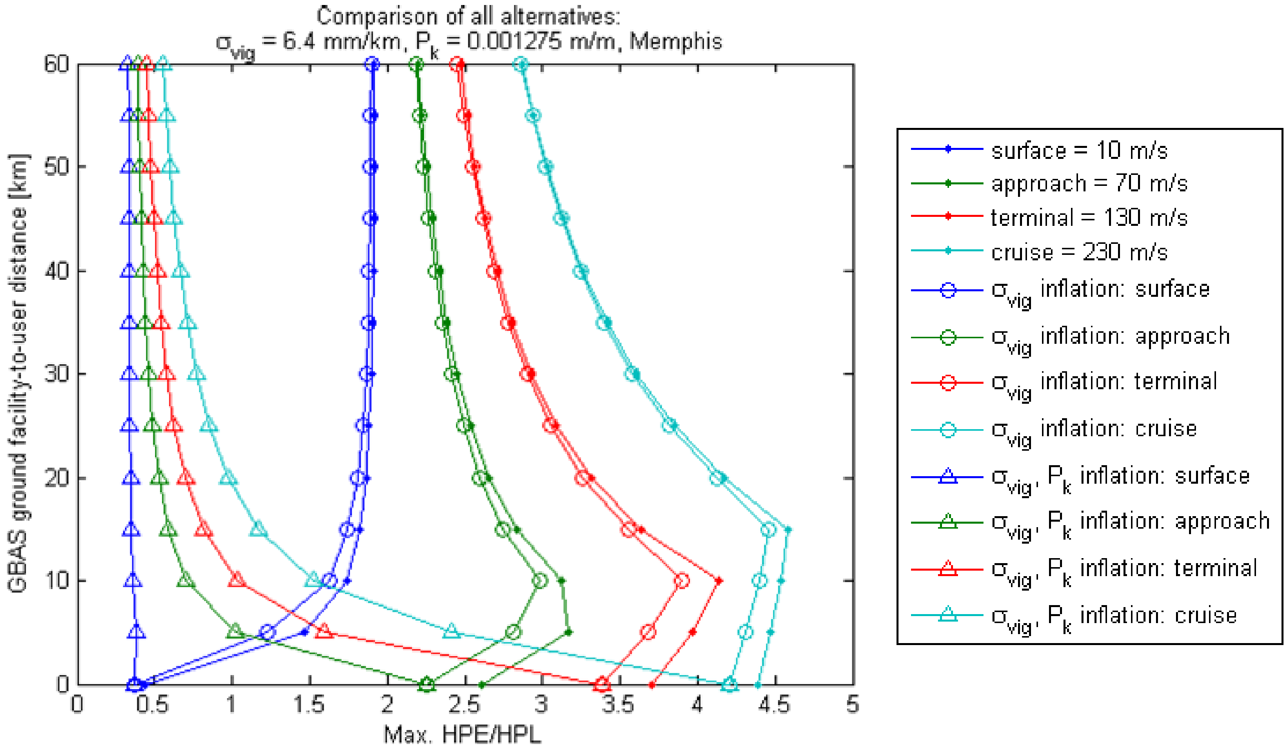

Figure 14 Effect of Dynamic Inflation of σ_{vig} and Inflation of P_k to the Maximum Possible Value

If changes are made only to the airborne equipment, then a single standardized approach would have to cover all of the world's ionospheric environments. Different regions may have different threat spaces (e.g. equatorial regions, vs. mid-latitude regions). Changes to the ground segment (or operational limitations) could be tailored to the local environment. However, doing so for airborne changes only is impractical.

One brute-force means of enforcing HPL bounding is suggested by inspection of Figure 9, which reveals that HPL could bound in all cases if the computed HPL were simply inflated by a factor of 4.7. So, if the computations for HPL currently specified in [7] and [8] were modified to include multiplication by a factor of 4.7, the HPL would bound the absolute worst-case error at all speeds and distances. This would of course come at some cost to availability, particularly for tighter HAL requirements. For example, ADS-B with a NIC of 11 (i.e. 7.5 meters) may not be supported at all if the current HPL computation is inflated by 4.7. A variation on this strategy would be to make the inflation factor a function of the aircraft speed (with lower inflation factors for lower speeds). Doing so would prevent availability for surface operations (with low aircraft speeds) from being needlessly limited by a high inflation factor driven by protecting high-speed aircraft. Alternatively, the inflation function could be made a function of both aircraft speed and distance.

There are some fundamental difficulties with the strategy of inflating HPL directly. The derivation of the inflation factor (or function) will depend on the specific ionospheric threat space assumed. Furthermore, if the inflation factor (or function) is hard-coded into the airborne equipment, then the reduction in availability will be there all the time regardless of the state of the ionosphere.

Another potential strategy for enforcing HPL bounding through an airborne change would be to require geometry screening based on limiting the maximum allowable magnitude of the projection of the error on any satellite into the horizontal position domain: $|S_{horz}|_{max}$. This strategy was explored in the previous paper on this subject [5]. Figure 15 illustrates the impact of limiting $|S_{horz}|_{max}$ to be less than or equal to 4. The geometries indicated by green dots in Figure 15 would fail the $|S_{horz}|_{max} \leq 4$ check, and DCPS would not be used. Only the geometries with the red dots would remain. Note that this strategy limits the maximum HPE that can be produced, but it does not in fact strictly enforce HPL bounding. The points on the graph that pass the geometry screening are still technically integrity failures since HPE > HPL. This approach would still require some requirements changes (strategy #2) or changes in the interpretation of the requirements (strategy #3). This approach also will not work for arbitrarily small HAL requirements. For surface operations with very small alert limits, it may be possible to additionally rely on the reduced speeds to ensure that errors are limited to an acceptable level.

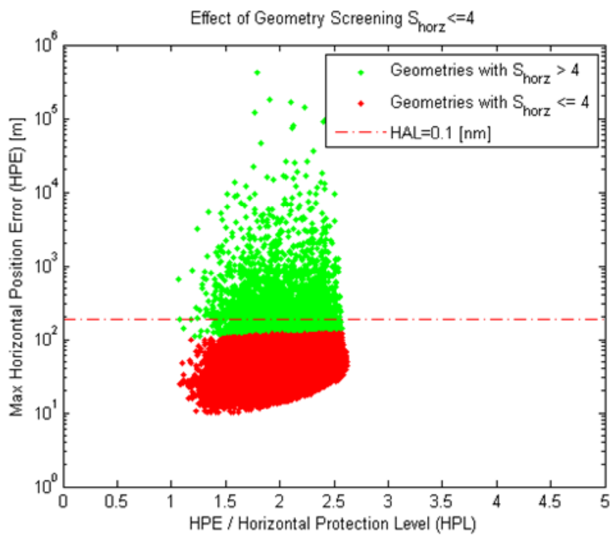

Figure 15 Effect of Geometry Screening by Limiting $|S_{horz}|$ to be Less than or Equal to 4

Another strategy that could be employed to enforce of HPL bounding by implementing changes only to airborne equipment is through the implementation of RAIM. This strategy was explored in previous work on the subject [5] and was shown to provide only slightly better performance than screening based on $|S_{horz}|_{max}$.

ENFORCING HPL BOUNDING BY CHANGING BOTH THE AIRBORNE AND GROUND REQUIREMENTS.

If changes could be made to both the airborne and ground system requirements, then an improved means to enforce HPL bounding could be developed. For example, an HPL inflation factor (or function) like that discussed above could be introduced where the specific value of the factor or parameters of the function are uplinked by the ground subsystem. This would allow the inflation function to be tailored to the specific environment and/or appropriate threat space. The inflation function could be dynamically changed as a function of space weather monitoring or other means of determining the status of the ionosphere (e.g., via SBAS). Alternatively, the uplink parameters could be set to static values that would cover the worst case ionospheric conditions. This "set-and-forget" approach would come at some cost to system availability.

STRATEGY #2) & STRATEGY #3) POSSIBLE SOLUTIONS BY HIGH-LEVEL REQUIREMENTS CHANGES OR BY ALTERNATE INTERPRETATION OF THE REQUIREMENTS

The results above suggest that the existing DCPS integrity requirements cannot be met without modifications to avionics that have already been approved for CAT I use. Before this conclusion is accepted, it makes sense to reconsider the safety interpretations that lie underneath the existing integrity requirements to see if they accurately represent the operational context of DCPS.

One possible change that has been addressed in detail above is removing the “HPL bounding” requirement such that HPL need not exceed the worst-case ionosphere-induced horizontal error if the worst-case error is not threatening to a given operation. In other words, HAL bounding would be accepted rather than insisting on HPL bounding. This change in the requirements philosophy is needed if the significance of errors in the operational context are to be leveraged as part of the overall mitigation scheme. It would also be required to gain any benefit from restricting DCPS to specific operations where the maximum errors are not operationally significant, and it may be needed to make airborne geometry-screening modifications practical as well. This represents an explicit change to the existing requirements and standards, and it is a change that would have to be made before any strategy that exploits HAL bounding criteria (rather than HPL bounding criteria) can be implemented.

The other change explored above, limiting possible airborne subset satellite geometries to 3 or fewer satellites missing from the set of *N* satellites broadcast by the LGF, would be a change in the interpretation of the existing requirements, which presume that all possible airborne subset geometries are protected. This approach was followed in the CAT I LAAS approval process in which an “*N*–2” constraint (2 or fewer satellites missing) was adopted [6], with the responsibility for this constraint being placed on the service provider. This limitation for CAT I was partially based on the extreme unlikelihood of aircraft losing more than 2 out of *N* usable satellites when on a stabilized, near-level precision approach. For DCPS, more varied flight dynamics (including tighter turns and more-severe banking) must be considered; thus *N*–3 appears to be a better choice. The results in this paper show that making use of the *N*–3 constraint greatly reduces the number of “significant geometries” of concern to DCPS as well as the duration over which individual aircraft may be exposed to such geometries.

Because the number of significant geometries can be reduced to a very low level, the question of how threatening the remaining significant geometries are should be re-assessed. From the results in Figure 7 for HAL = 1.0 nmi with the *N*–3 constraint, significant geometries (all of which are 4-satellite geometries, meaning $N \leq 7$) make up only 0.05% of all 4-satellite geometries and 0.1% of all subset geometries within the N–3 constraint. Since geometries using all or almost all of the N usable satellites are much more likely than N–3 geometries, the actual probability of an aircraft encountering a significant geometry is much smaller than these percentages imply.

Finally, the level of danger implied by encountering a significant geometry when a worst-case ionospheric anomaly is present should be re-examined. Even under anomalous ionospheric conditions, the likelihood of the worst-case gradient modeled in the simulations used in this work is quite low [20]. Combining this with the probability of encountering a significant geometry for DCPS should result in a probability in the neighborhood of the 10^{-7}-per-hour loss-of-integrity probability requirement for DCPS. Note that this loss-of-integrity probability requirement assumes that all violations of DCPS integrity are of "hazardous" consequence. For RNP 1.0 and above, this may not be the case, as aircraft using RNP 1.0 are spaced at intervals of at least 3 to 5 nmi (5.56 – 9.26 km) horizontally. For such operations, a consequence of "major" might be more appropriate, implying a revised loss-of-integrity probability requirement of 10^{-5} per hour [21].

POSSIBLE OPERATIONAL MITIGATIONS

Some of the solutions to the problem of how to deal with ionospheric anomalies for DCPS could be operational mitigations. This section will describe several possible operational mitigations. Operational mitigations could be part of a solution under any of the three strategies identified above.

One potential operational mitigation is to limit the use of DCPS to certain operations. For example, DCPS use could be restricted to RNP operations with a required RNP larger than 0.1 or 0.3 nm. This operational mitigation could be used in conjunction with other mitigations in this paper that would limit the potential maximum error (HPE) to a value that is not operationally significant for the RNP level of interest given the characteristics of the procedure (e.g. aircraft separation, terrain, etc.) at the airport of interest. Similarly, the design of routes could be controlled such that the absolute maximum error ($4.7 \times$ HAL for the example in Figure 9) would not result in a hazardous situation.

Another perhaps more generally applicable operational mitigation would be to simply turn the DCPS off whenever the probability of an unacceptably large ionospheric anomaly is too high. This could be achieved in a variety of ways. For example, if an SBAS is available in the region of interest, the state of the ionosphere could be monitored via SBAS, and real-time SBAS information could be used to automatically turn off the DCPS service when a sufficiently severe ionospheric storm is detected. Alternatively, space weather could be monitored via a variety of sources and used to identify when the probability of an ionospheric anomaly is unacceptably large. The DCPS could then be turned off and then turned back on when the space weather condition has abated. By doing this, the maximum ionospheric anomaly that a user could be exposed to would be limited.

Use of DCPS could be restricted by several different kinds of operational procedures including:

a. The DCPS service could be literally turned off at the source. Parameters in the uplink Message Type 2 indicate the availability of DCPS. These could be modified dynamically to turn DCPS on and off.
b. A requirement could be introduced to check space weather conditions prior to dispatch when the flight plan includes an operation where worst-case DCPS errors could be operationally significant.
c. ATC could stop issuing clearances for specific operational procedures during an unacceptably risky space weather event.

Of these three options, option (a) is the most practical means to restrict DCPS usage. While some airlines already consider space weather conditions as part of dispatch procedure on polar routes, the situation is more complicated for DCPS, as DCPS is not always required for any given operation. In many cases, DCPS provides enhanced availability for operations that can be supported by GPS with RAIM-based integrity only. Therefore, a dispatch requirement based on space weather conditions would make operations unavailable when they would have been available otherwise. It would be a very difficult task for an airline to determine if DCPS really is required for the operation. Furthermore, there is no flight-deck means to turn off DCPS use in the event that space weather conditions indicate it should not be used. Similarly, it is not practical for ATC to determine which airplanes are or are not using DCPS. Therefore, denying clearances due to space weather conditions (option (c) above) would affect all users, whether they are using DCPS or not. Furthermore, the procedure may well have been viable without DCPS. For all of these reasons, it is best to turn DCPS off at the source.

Figure 16 illustrates the impact of limiting the maximum threat through space weather monitoring and operational procedures to restrict use of DCPS. The two clouds of points in the graph represent the worst case HPE that could occur for all possible geometries observed over one day at Memphis airport. The red points are the same scenario as shown in Figure 2. The blue points are the result of an analysis where the worst-case ionospheric gradient in the threat space was limited to 150 mm/km. Note that, at the user-to-ground separation of 45 km, the worst-case errors for all geometries are bounded by HPL.

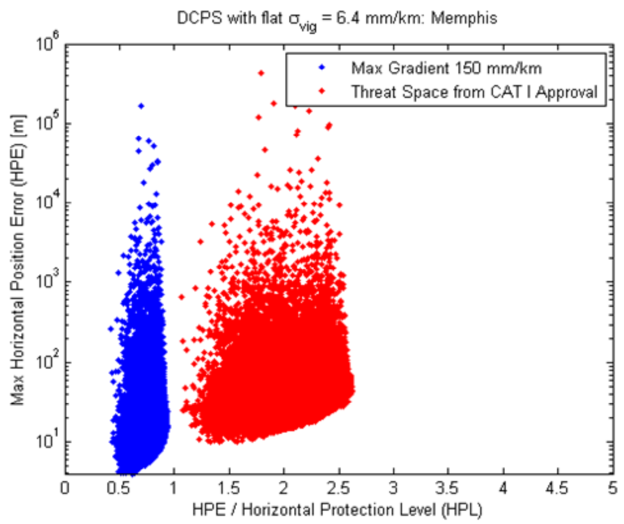

Figure 16 Example of Limiting the Maximum Threat to 150 mm/km

Figure 17 illustrates the effect of limiting the maximum threat to 150 mm/km for the entire range of aircraft speeds and distances. Although the situation is dramatically improved (compared with Figure 9), HPL still does not bound the worst-case HPE at higher aircraft speeds and shorter baseline lengths.

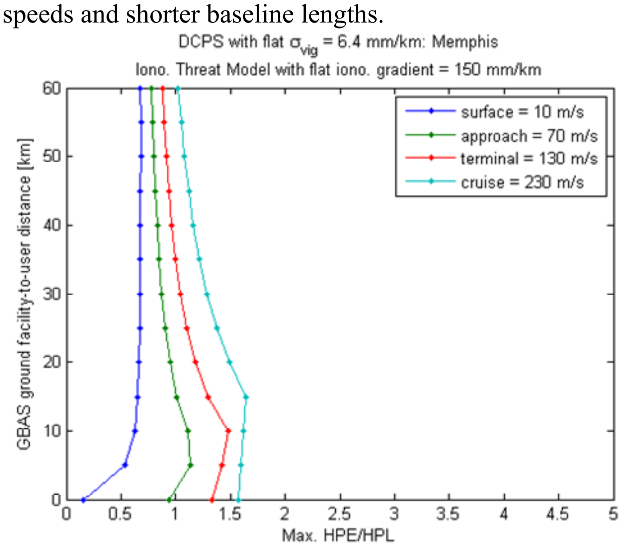

Figure 17 Effect of a Limited Threat Space (*G* = 150 mm/km) for Different Aircraft Speeds and User Distances

Figure 18 illustrates the effect of further limiting the maximum threat to 100 mm/km for the entire range of aircraft speeds and distances. Note that, in this case, HPL bounds HPE for all distances and speeds up to 130 m/s (252.7 nmi/hr). HPL bounding is exceeded only slightly for higher speeds. Consequently, if DCPS were limited to use in the terminal area only, where speeds will not significantly exceed 250 nmi/hr, then limiting the threats to which the user is exposed to no greater than 100 mm/km will allow HPL to bound the worst-case HPE at all distances from the airport. Since 100 mm/km represents 25 to 50 times the nominal ionospheric gradient (at mid-latitudes), it is a very large anomaly and should be relatively easy to detect using SBAS [22].

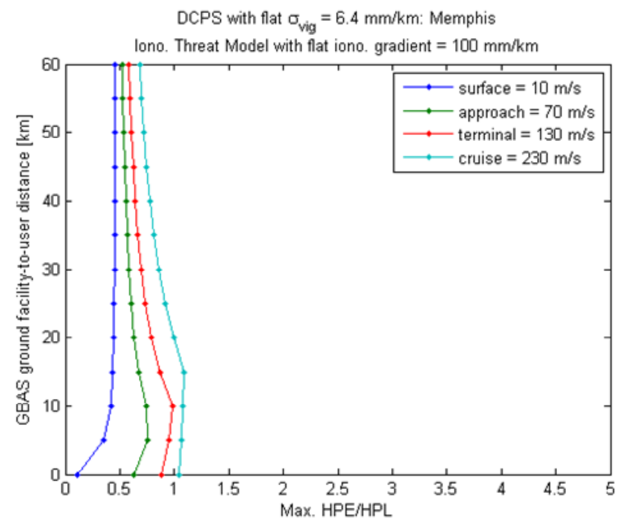

Figure 18 Effect of a Limited Threat Space (*G* = 100 mm/km) for Different Aircraft Speeds and User Distances

CONCLUSIONS

This paper has presented three general strategies for authorizing DCPS services in the presence of the ionospheric spatial anomaly threat. The preferred solution will likely be a combination of more than one strategy and will ultimately be up to the service providers and standards development bodies. For example, a service provider could decide to combine space weather monitoring and an operational procedure to 'turn off' the DCPS (strategy #1) with an analysis that shows that residual errors that could occur are not operationally significant (strategy #3). In this way, service providers can decide how to balance the operational risk.

This paper has identified multiple potentially viable approaches to solving this problem that require no changes to the existing GBAS system standards:

- Strategy #1: Operational mitigation: turn off DCPS during ionospheric storms (external ionosphere or space weather monitoring). HPL bounding can be enforced if the maximum gradient experienced by the user is less than or equal to 100 mm/km.
- Strategy #3: Analyze worst-case HPE in the operational context given the local ionospheric threat

space. Ensure that authorized operations are safe given the worst case undetected error.

The research shows that unilateral changes to either airborne or ground systems alone are generally ineffective or grossly inefficient in solving this problem. In most cases, changes to only one end of the system would need to be combined with a requirements change (i.e., HPL bounding would not be ensured). However, if changes were made to both the airborne and ground system requirements, an optimized method for HPL bounding could be implemented.

A change in the high-level requirements (Strategy #2) could be a potential part of the solution. A requirements change could enable some solutions that would require no changes to the system if used in combination with Strategy #3. However, to gain the full benefits of the requirements change, additional airborne geometry screening would be required to ensure HAL bounding. While this strategy may be attractive because no information external to the system (e.g., space weather monitoring) is required, this approach does not necessarily support all possible DCPS operations.

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