

Applying Space Weather Information to GBAS: A Concept for Improved Availability

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BIOGRAPHIES

Leonardo Marini-Pereira received a Master's degree in Remote Sensing and Geoprocessing from the National Institute for Space Research (INPE), Brazil in 2008, and a PhD in Space Science and Technology from the Aeronautics Institute of Technology (ITA), Brazil, in 2021. He served 18 years in the Brazilian Air Force, researching CNS/ATM technologies for civil aviation with focus on GNSS navigation and low-latitude ionospheric effects on GBAS. He joined the German Aerospace Center (DLR) in 2026, where he continues working on dual-frequency multi-constellation GBAS.

Maria Caamano received a Master's degree in Telecommunications engineering from the University of Oviedo, Spain, in March 2015, and a PhD in Aerospace Science and Technology from the Polytechnic University of Catalonia (UPC), Spain, in July 2022. Since May 2015, she has been working as a research associate at the Institute of Communications and Navigation at the German Aerospace Center (DLR). Her work focuses on the development of dual-frequency multi-constellation Ground Based Augmentation Systems (GBAS).

Daniel Gerbeth received his Master's degree in Electrical Engineering and Information Technology from the Karlsruhe Institute of Technology, Germany in 2014, specializing in aerospace navigation. After working in sensor fusion at Fraunhofer IOSB, he joined the German Aerospace Center (DLR) in 2015. His research focuses on Ground-Based Augmentation Systems, reliable navigation for urban air mobility, and navigation resilience and cybersecurity in aviation.

Volker Wilken is a research scientist at the German Aerospace Center (DLR) Institute for Solar-Terrestrial Physics in Neustrelitz, Germany. He holds a PhD in Solar Physics and has over 23 years of experience in ionospheric research, including TEC derivation, scintillation measurement, and GNSS-based detection of TIDs. He developed real-time algorithms for Space Weather products and GBAS. As Group Leader for Effects on Technical Systems, he has participated in various national and international projects.

Paul David received his Bachelor's and Master's degrees in Geomatics from Neubrandenburg University of Applied Sciences and has contributed to projects such as WeGA and the development of Swarm products NeGIX and TEGIX for monitoring ionospheric gradients. He is a research associate at the DLR Institute for Solar-Terrestrial Physics in Neustrelitz, specializing in Space Weather impacts and ionospheric physics. His work focuses on developing near-real-time performance indicators and prediction models to mitigate GNSS disruptions caused by Space Weather.

Sebastian Bernhardt received a M.Sc. in computer science at the University of Augsburg, Germany in 2019. He joined the German Aerospace Center (DLR) Galileo Competence Center in 2020 to build the foundations of the System and Service Volume Simulation Environment S²VSE with his background in simulation and software design. In 2023 he became the Team Leader of the Performance Analysis and Simulation group. The group focuses on the analysis, simulation, optimisation and evolution of current and future navigation systems.

ABSTRACT

This paper proposes a novel concept to improve Ground-Based Augmentation System (GBAS) availability by integrating near-real-time Space Weather information from the Ionosphere Monitoring and Prediction Center (IMPC) into the GBAS Approach Service Types (GAST) C and E (GAST-C and GAST-E) as part of the In2Action project from the German Aerospace Center (DLR). The methodology uses IMPC products, including the Rate of TEC Index (ROTI), the Disturbance Ionospheric Index Spatial Gradients (DIXSG), a Wave Front Detector (WFD), and a near-real-time σ_{vig} estimate to classify the ionospheric state. For GAST-C, the concept replaces static, worst-case σ_{vig} inflation with near-real-time estimates when quiet conditions are verified. For GAST-E, external information is used to adaptively adjust the prior probability of anomalous gradients in the

airborne dual-frequency monitor. The concept was tested using flight data from a DLR campaign in Germany. Results for GAST-C show that near-real-time σ_{vig} integration avoids the excessive protection level inflation required by regional ionospheric threat models like CONUS or Brazil, while exhibiting smaller differences for the German threat model. For GAST-E, the approach achieved a 20% reduction in the ionospheric monitor test statistic under nominal conditions, directly increasing the margin against false alerts. While issues such as non-ionospheric data contamination and certification remain, this work demonstrates that a synergy between Space Weather monitoring and GBAS can significantly reduce operational conservatism without compromising civil aviation integrity requirements.

1 INTRODUCTION

The Ground-Based Augmentation System (GBAS) enables precision approach and landing operations using GNSS differential corrections while preserving integrity. However, the ionosphere remains one of the dominant error sources affecting system integrity and availability. Severe ionospheric gradients and scintillation phenomena can generate differential errors and signal degradation that challenge compliance with the stringent integrity, availability and continuity requirements of civil aviation.

To ensure safety, current GBAS architectures adopt conservative mitigation strategies. The GBAS Approach Service Type (GAST) C is the single-frequency (L1) and single-constellation (GPS) service to provide Category I approach and for the time being is the only service both standardized and in operation in the world. Operational GAST-C relies on inflated ionospheric uncertainty models to bound undetected residual errors, being the Position Domain Geometry Screening - PDGS (Lee et al., 2011), the most widely used basis for certifying a GAST-C ground facility. While effective in guaranteeing integrity, this static worst-case approach frequently reduces availability, even during nominal and quiet ionospheric conditions (Yoon et al., 2019; Yoon et al., 2020a; Yoon et al., 2020b).

The emerging dual-frequency multi-constellation (DFMC) architecture, GAST-E, introduces smoothed divergence-free processing (Murphy et al., 2021) and a dual-frequency airborne gradient monitor (Gerbeth et al., 2022; Murphy et al., 2022; Caamano et al., 2023). Although this improves nominal performance and mitigates divergence accumulation, ionospheric gradient threats and scintillation effects are not fundamentally eliminated. Conservative monitor multipliers and fallback single-frequency modes still limit availability.

These architectures share a common limitation: integrity protection is achieved through bounding assumptions that are independent of the actual ionospheric state. To address such an issue, this paper presents a concept for integrating near-real-time Space Weather information into GBAS to improve availability without compromising integrity. The approach leverages products from the Ionosphere Monitoring and Prediction Center (IMPC), operated by the German Aerospace Center – DLR (Kriegel et al., 2026), to provide an external, independent assessment of the current ionospheric state.

1.1 Motivation and scope

The work described in this paper is conducted within the framework of the DLR internal project In2Action (Insight, Information, Action), one of whose core objectives is the transformation of physical understanding of Space Weather into highly reliable short-term forecasts (nowcasting) to prevent operational disruptions in system-critical aerospace applications (DLR, 2025). One of the goals of In2Action is to integrate expertise that has thus far been distributed and, in some cases, isolated within DLR. In the scope of In2Action, the development of methods for the targeted use of customized nowcasting products for specific applications is based on existing, established DLR products, and the necessary adjustments, further developments, and extensions to the forecasting portfolio are determined by pre-defined requirements.

In the context of that project, this research aims to propose and demonstrate a concept to improve GBAS availability by integrating external ionospheric information. It should be emphasized that the present work is a preliminary proof-of-concept: it is ongoing research aiming to publish the first preliminary results from a limited dataset. The proposed concept is expected to culminate in a demonstration within the scope of the In2Action project, showcasing the integration of Space Weather nowcasting products with GBAS integrity monitors to predict the system's availability for different service levels.

The use of external information sources to assist GBAS, for enhanced monitoring under GAST-D, is supported by ICAO Annex 10, Volume I, Attachment D, Section 7.5.6.1.7 (ICAO, 2023), and motivated experiments with external networks to assist GBAS, e.g., Caamano et al. (2021, 2025, 2026) and Marini-Pereira et al. (2022, 2023, 2024). This provision motivates the systematic investigation of how Space Weather information can support GAST-C (operational) and GAST-E (in standardization) services. It should be noted that the Space Weather information required by GBAS is considerably more stringent than the Space Weather indicators and thresholds proposed in ICAO Doc 10100, *Manual on Space Weather Information in Support of International Air*

Navigation (ICAO, 2019). In that document, ICAO recommends thresholds for well-established Space Weather indices that can affect GNSS signals, such as vertical Total Electron Content (vTEC) and amplitude and phase scintillation (S_4 and σ_ϕ), for dissemination through Space Weather Advisories over broad latitude–longitude bands. While this approach may be useful for warning of potential disruptions, it remains too coarse for GBAS operations. Accordingly, this paper proposes the use of more refined Space Weather information tailored specifically to the GBAS architecture.

The Ionosphere Monitoring and Prediction Center (IMPC), provides a highly scalable framework generating near-real-time ionospheric-related indicators with variable temporal resolution and minimal latency (Kriegel et al., 2026). These products describe the current ionospheric state with significantly higher spatial and temporal resolution than global advisory systems, like the ones proposed by ICAO (2019). However, they are not aviation-certified and do not inherently satisfy GBAS integrity requirements. It should be noted that the proposed concept is designed to operate within the existing, certified GBAS integrity framework: external products are used only to relax parameters within predefined safe bounds, while integrity allocation remains internal to the GBAS architecture. Any future operational implementation would require the certification of the Space Weather service and its products for aviation use, which is beyond the scope of this paper.

The purpose of this work is not to replace internal GBAS integrity monitors with external Space Weather data. Instead, the goal is to conceptually demonstrate how IMPC products or similar high resolution ionospheric monitoring systems can be incorporated in a bounded, conservative, and integrity-preserving manner to support adaptive tuning of ionospheric parameters within GAST-C and GAST-E. Therefore, the scope of this paper is intentionally limited to demonstrating the integration concept, evaluating potential availability benefits under nominal ionospheric conditions, and establishing integrity-preserving constraints. The treatment of extreme anomalous events is explicitly left for future work.

1.2 Ionosphere Monitoring and Prediction Center (IMPC) Products

The IMPC, operated by DLR, provides a suite of near-real-time ionospheric products derived from a network of ground-based GNSS receivers. A complete description and overview of the IMPC products can be found in Kriegel et al. (2026). Among the available products, those of particular relevance to the GBAS application are:

- **Vertical TEC Gradients from Global TEC Maps:** the IMPC generates global vTEC maps at regular intervals, from which horizontal gradients in vertical TEC are derived (Jakowski et al., 2011; Schmölter et al., 2025). These gradients provide a large-scale characterization of the ionospheric state over the region of interest, allowing for the identification of broad disturbances that may impact differential GNSS performance.
- **ROTI and DIXSG Indices:** for the detection of small-scale ionospheric irregularities, the IMPC provides the Rate of TEC Index (ROTI) and the Disturbance Ionospheric Index Spatial Gradients - DIXSG (Wilken et al, 2018), updated every minute. These indices serve as fast-response indicators of ionospheric activity and are the lowest-latency Space Weather products available in the IMPC suite, essential for triggering rapid alerts.
- **σ_{vig} Estimator:** the σ_{vig} estimator computes the standard deviation of the ionospheric gradient using a 24-hour sliding window of data from the IMPC station network. The result is provided as grid with cells of size $1^\circ \times 1^\circ$ of latitude-longitude, where each cell contains the σ_{vig} value in mm/km based on the data from the past 24 hours within each cell limits. The estimate is updated every 5 minutes and provides a statistical characterization of nominal ionospheric variability at the location of interest.
- **Wave Front Detector (WFD) and Parameter Estimation:** this is a dedicated tool within the IMPC suite, designed specifically for detecting and estimating parameters of ionospheric wave-like disturbances. It provides the most critical information upon which this work relies. It operates on a 5-minute update cycle and provides critical output parameters for each detected front, including gradient magnitude, propagation speed, front width, direction of propagation, and estimated time of arrival (ETA) at a reference location. The detection and estimation pipeline of this feature consists of five sequential stages. Raw GNSS measurements are first filtered by geometric and amplitude thresholds. Surviving observations are then screened for spatial-temporal coherence using a pairwise proximity criterion. Next, the velocity vector and propagation direction are estimated using one of four interchangeable methods. For each detected front, the distance and bearing to the target are computed, and an alignment check verifies reachability before estimating the time of arrival. Finally, individual results are aggregated into a consolidated output with a heuristic quality score (0–100).

Since the products of the IMPC must be used, as part of the In2Action project requirement for the respective demonstration, the latency and resolution of the products are constrained by what the IMPC can generate with its current infrastructure and data availability. GBAS requires low-latency information, with messages from the ground station being broadcast at every 0.5 s or 3 s, depending on the message type. Space weather information, in contrast, requires time to be collected, processed, and distributed. The network used by the IMPC was not built exclusively for this type of streaming and not certified for aviation

(unlike, e.g., SBAS). In its current processing pipeline, it would be extremely challenging to provide products with a latency better than 1 minute, which is the case for ROTI and DIXSG. In summary, ROTI and DIXSG at 1-minute intervals, and the TEC maps, the Wave Front Detector, and the σ_{vig} estimate at 5-minute intervals, represent the best the IMPC can currently deliver. Moreover, changes in the ionosphere capable of impacting GBAS performance (integrity and availability) are not expected to occur over short time periods when a large area of the ionosphere is monitored.

2 METHODOLOGY

The proposed concept introduces IMPC-derived indicators as an external validation layer for nominal ionospheric behavior. Within this framework, external Space Weather products are not used to compute protection levels directly. Instead, they serve solely as an independent check on whether the ionosphere is behaving as expected under nominal conditions. In this approach, integrity allocation remains internal to the GBAS architecture, and any relaxation of parameters is permitted only within predefined safe bounds. Consequently, during disturbed or uncertain conditions, worst-case parameters remain unchanged, ensuring that conservatism is maintained whenever the validation layer cannot confidently confirm quiet behavior. Under verified quiet conditions, however, this approach can reduce unnecessary overbounding, thereby improving availability while preserving integrity margins.

The proposed methodology integrates IMPC products into a two-stage classification framework that characterizes the prevailing ionospheric state in order to adaptively adjust GBAS integrity parameters. The classification operates on two distinct timescales. Fast-response indices (ROTI, DIXSG) are evaluated every minute against predefined thresholds, while the Wave Front Detector (WFD) operates on a 5-minute cycle. If the gradient magnitude estimated by the WFD falls below 100 mm/km, with a possible refinement to 50 mm/km, the ionospheric state is classified as nominal. Conversely, if anomalous ionospheric conditions are detected, either through the fast indices or the WFD detector, different procedures are applied for GAST-C and GAST-E.

2.1 Concept for GAST-C

The most widely accepted method for ensuring integrity in GAST-C is the Position Domain Geometry Screening (PDGS), developed by Lee et al. (2011). This approach safeguards against ionospheric gradients primarily through conservative geometry screening and inflated ionospheric uncertainty parameters. These parameters are derived under worst-case decorrelation assumptions and do not reflect actual ionospheric conditions. The Vertical Protection Level in fault-free conditions (VPL_{H0}) is computed by the airborne receiver as follows (RTCA, 2019):

$$VPL_{H0} = k_{ffmd} \cdot \sqrt{\sum_{i=1}^N s_{vert,i}^2 \cdot \sigma_{PR,i}^2} \quad (1)$$

where i indicates the i^{th} satellite of the N satellites used for the VPL computation, k_{ffmd} is a multiplier to bound the distribution for fault-free and missed-detection cases, $s_{vert,i}$ is the vertical projection factor onto the approach plane in the position solution and $\sigma_{PR,i}$ is the error contribution from each satellite whose corrections were broadcast by the ground station. The $\sigma_{PR,i}$ is a function of the standard deviations of the individual error sources, namely σ_{air} (airborne noise and multipath), σ_{tropo} (tropospheric delay), and σ_{iono} , which is itself derived from the parameter to be inflated in the PDGS algorithm (σ_{vig}). Hence, $\sigma_{PR,i}$ is given by (RTCA, 2019):

$$\sigma_{PR,i}^2 = \sigma_{gnd,i}^2 + \sigma_{tropo,i}^2 + \sigma_{air,i}^2 + \sigma_{iono,i}^2 \quad (2)$$

with $\sigma_{iono,i}$, which is the nominal residual errors in the corrections due to spatial decorrelation caused by the ionosphere, as a function of σ_{vig} ; the 2D horizontal distance between the aircraft and the GBAS reference point (X_{air}); the time constant of the code smoothing filter (τ , typically 100 s); and the ground speed of the aircraft (v_{air}). Then, σ_{iono} is calculated in the slant range using the vertical-to-slant obliquity factor, Fpp , by (RTCA, 2019):

$$\sigma_{iono} = Fpp \cdot \sigma_{vig} (X_{air} + 2 \tau v_{air}) \quad (3)$$

The PDGS algorithm identifies potentially hazardous satellite geometries by simulating worst-case scenarios based on a pre-established regional ionospheric threat model derived from historical data. As an example, the threat models used in this

work are for Germany (Mayer et al., 2009), the Conterminous United States – CONUS (Datta-Barua et al., 2010) and Brazil (Yoon et al., 2017; Chang et al., 2021). The maximum slope and respective σ_{vig} for each one are shown in Table 1.

TABLE 1 Parameters of the threat models for the PDGS for the σ_{vig} inflation

Regional Threat Model	Maximum slope	Nominal σ_{vig}
Germany	140 mm/km	2.07 mm/km
CONUS	425 mm/km	4.00 mm/km
Brazil	860 mm/km	14.00 mm/km

The regional threat model parameterizes anomalous ionospheric fronts in terms of their spatial gradient, width, and propagation speed, and identifies conditions under which gradients become unobservable to standard range-domain ground monitors, namely, when the front velocity matches the velocity of a satellite's ionospheric pierce point (IPP). The ground facility evaluates all credible satellite subsets that an aircraft might use, computing the Maximum Ionosphere-Induced Error in Vertical (MIEV) for each subset. A geometry is flagged as hazardous if its MIEV exceeds the Tolerable Error Limit (TEL), as established for CONUS by Shively and Niles (2008), while its standard Vertical Protection Level (VPL) remains below the Vertical Alert Limit (VAL). In such cases, the aircraft would rely on an unsafe geometry without receiving a timely alert.

In summary, to mitigate these risks, the ground facility selectively inflates the broadcast parameter σ_{vig} . Since σ_{vig} is a key component in the calculation of the range-error variance, increasing it directly raises the VPL computed by the airborne receiver. The algorithm iteratively increases the σ_{vig} inflation factor until the VPL for every hazardous geometry is pushed above the VAL, effectively screening those geometries out and rendering them unusable for precision approaches. Although this methodology guarantees system integrity during severe ionospheric storms without requiring modifications to aircraft avionics, it inevitably reduces overall system availability, as some safe geometries are also screened out in the process.

For this reason, in the presented classification scheme proposed in this paper, the strategy for GAST-C basically consists whether to inflate the σ_{vig} through the PDGS or to use the one estimated by the IMPC. Therefore, in nominal conditions, i.e., when no alerts are issued by any Space Weather products (ROTI, DIX-SG, or the WFD), the broadcast σ_{vig} is computed using a 24-hour sliding window of nominal data preceding each epoch. In this case, the conservatism of the PDGS inflation is not required, allowing lower protection levels to be used.

The methodology to use the IMPC Space Weather information for GAST-C is depicted in the flowchart in Figure 1. During anomalous conditions, front parameters (gradient, speed, width, direction, and ETA) are computed by the WFD along with its quality score. If the estimated front characteristics remain below the regional threat model, uncertainty indicators meet predefined criteria, and IMPC is able to provide the required level of integrity (same as the original threat model), these parameters are inserted into the PDGS algorithm to inflate σ_{vig} in near real time. However, if the uncertainty indicator given by the quality score does not meet predefined criteria or the IMPC products are not able to guarantee the required levels of integrity, the conservative threat model parameters are used for σ_{vig} inflation instead. The basis for σ_{vig} inflation is in this case the nominal value obtained from historical data (e.g. 4 mm/km for CONUS). The updated value is then broadcast to the user. In the event that the gradient of the ionospheric front exceeds the limits of the regional ionospheric threat model, the system is declared unavailable, since there is no means to validate the detected gradient and conclude whether it is a real threat or a false alert.

This approach preserves the existing GAST-C integrity framework while enabling refined, case specific inflation rather than always applying regionally worst-case values, based on historical data. It is important to highlight that the fast indices are currently the lowest-latency space-weather indicators provided by the IMPC. If other reliable Space Weather products become available, the concept proposed in this project remains fully applicable. Moreover, if only fast indices trigger an alert during the 5-minute interval between WFD cycles, then standard/conservative threat model gradients are used to inflate σ_{vig} , consistent with current GAST-C architecture to preserve integrity.

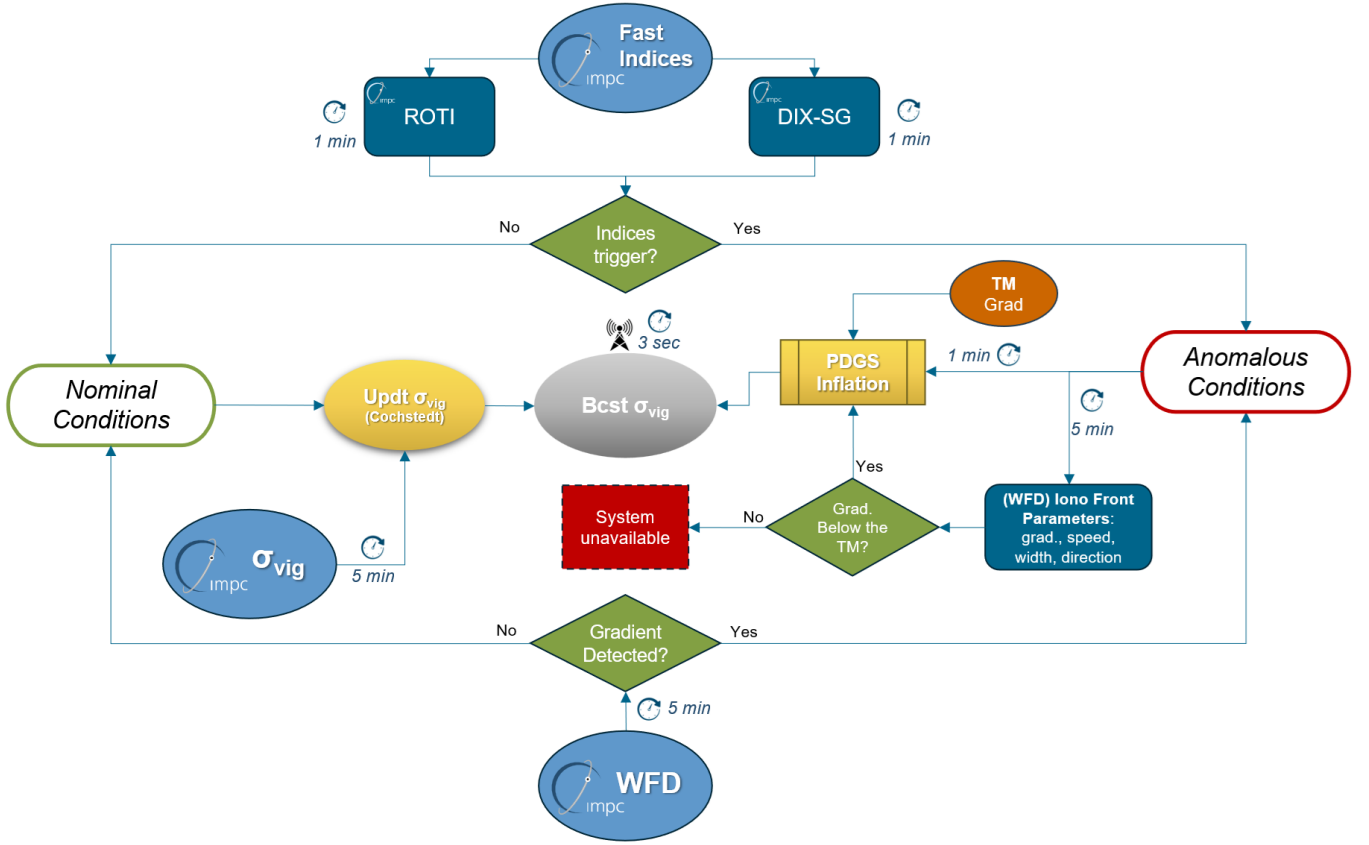


FIGURE 1 Methodology flow for the use of external IMPC products for GAST-C.

2.2 Concept for GAST-E

One of the most relevant mechanisms to ensure integrity and protect against ionospheric threats in GAST-E is the airborne dual-frequency monitor, as presented in Gerbeth et al. (2022); Murphy et al. (2022) and Caamano et al. (2023). The monitoring condition against the threshold $E_{v,iono}$ is given by:

$$VPL_{iono} = \left| \sum_{i=1}^N (I_{test,i} \cdot s_{vert,i}) \right| + k_{md,iono} \cdot \sqrt{\sum_{i=1}^N \sigma_{m,i}^2 \cdot s_{vert,i}^2} \leq E_{v,iono} \quad (4)$$

where, $I_{test,i}$ is the test statistic for satellite i ; $s_{vert,i}$ is the vertical projection factor onto the approach plane in the position solution; $\sigma_{m,i}^2$ describes the residual noise and multipath in the pseudorange corrections and the pseudorange measurements after smoothing for each frequency; and $k_{md,iono}$ is the integrity multiplier based on the residual integrity risk for missed detections. Here, the multiplier $k_{md,iono}$ is sized by the inverse Q-function according to a probability of missed detection (P_{md}) of 10^{-9} . The integrity multiplier is then given by:

$$k_{md,iono} = Q^{-1} \left(\frac{P_{md}}{2} \right) \quad (5)$$

When using the airborne monitor of equation 4, Gerbeth & Caamano (2023) reported a significant number of cases in which the ionospheric protection levels exceeded the corresponding alert limit under nominal ionospheric conditions, that is, in the absence of any gradient or anomaly. According to the authors, the nominal noise alone, combined with a weak satellite geometry and the stringent missed-detection requirements, resulted in considerably high ionospheric protection levels.

In these cases, it must be noted that equation 5 assumes no external knowledge of ionospheric conditions, and hence, the prior probability of anomalous ionospheric gradients is assumed to be 1, resulting in an integrity multiplier equals 6.1. This leads to conservative bounds regardless of actual environment. Incorporating external Space Weather information makes it possible to assign a lower prior probability to the occurrence of anomalous ionospheric gradients ($P_{prior,iono}$), as done by Gerbeth & Caamano (2023), following the proposition of Yoon et al. (2020b). This approach reduces the inflation factor and makes the ionospheric monitor less sensitive. Hence, the inflation factor becomes:

$$k_{md,iono} = Q^{-1} \left(\frac{P_{md}}{2 \cdot P_{prior,iono}} \right) \quad (6)$$

Under nominal ionospheric conditions, such as during extended quiet geomagnetic periods, these conservative assumptions reduce the achievable availability for both GAST-C and GAST-E. External Space Weather information may offer a means to relax ionospheric inflation parameters during verified quiet conditions, while maintaining current integrity levels during disturbed periods.

Therefore, for GAST-E, the proposed approach modifies the prior probability for the presence of an anomalous ionospheric gradient used in the gradient monitor, using equation 6. Consequently, the strategy, depends on whether conditions are nominal or anomalous. In nominal conditions the prior probability is reduced to a minimum value, which can be conservatively adopted as 10^{-3} , as used by Gerbeth & Caamano (2023), yielding a smaller multiplier around 4.9, and therefore reduced monitoring values. In anomalous conditions, the prior probability is set to 1, reinstating the conservative multiplier.

The full analysis proposed by Caamano et al. (2023) then applies, including threshold evaluation and potential switching to the ionospheric free combination (Murphy et al., 2021). In summary, the airborne monitor continues to operate as defined in Caamano et al. (2023). Only the prior-probability input to the multiplier is modified according to the environmental classification. The full proposed methodology for GAST-E is depicted in the flowchart in Figure 2.

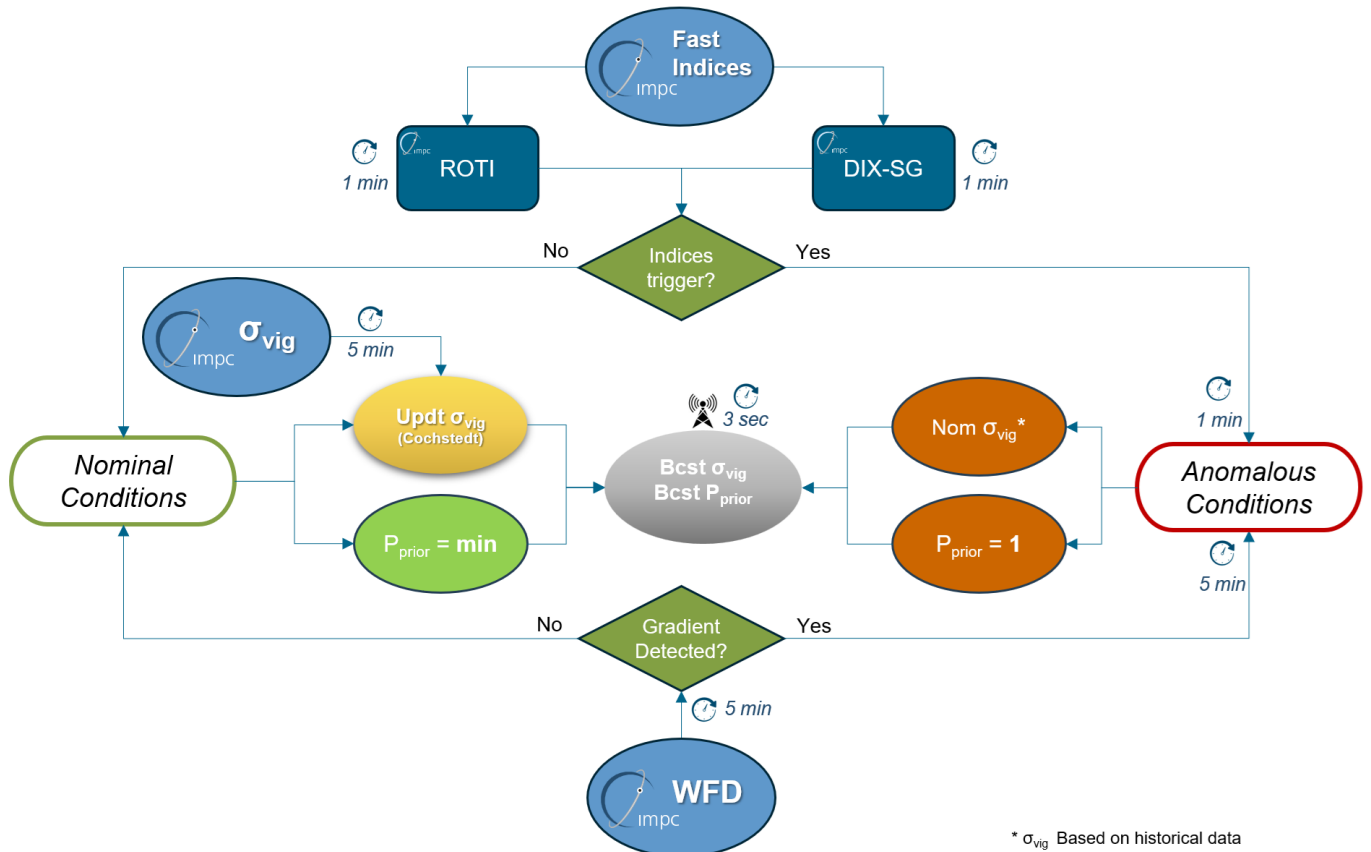


FIGURE 2 Methodology flow for the use of external IMPC products for GAST-E.

3 EXPERIMENTAL SETUP AND IMPC DATA

3.1 Experimental Setup

The geographic scope of the present work is limited. Cochstedt Airport, in Germany, was chosen as the test area for this work because it is owned by the German Aerospace Center (DLR) and serves as a sandbox for multiple tests in cross-disciplinary areas, including resilient navigation, drones, and eVTOL testing. To fulfill the criteria of the internal DLR project, the preliminary proof-of-concept must be demonstrated at Cochstedt using DLR's products, i.e., the IMPC.

To that end, a dataset from a flight campaign was selected. The campaign was conducted by DLR at the Cochstedt airfield, within the framework of the CySNAB project (Cybersecure Satellite Navigation for Aviation and Beyond) (DLR, 2024), and took place between the 6th and 8th of August 2025. One of the project's goals is to demonstrate a concept for a cyber-secure GBAS, and for this reason, the aircraft was subjected to intentional jamming during most of the campaign. Accordingly, the flight periods used in the present work were selected to exclude jamming windows and include only nominal flight segments. During the campaign, the aircraft was based in Braunschweig, Germany, approximately 80 km from the experimental airfield, and flew daily to Cochstedt to perform approaches, most of which were intentionally jammed. As a result, the clean (non-jammed) data is concentrated primarily in the flights from Braunschweig to Cochstedt. After filtering the airborne data, two periods from two different days were selected, yielding approximately 47 minutes of flight per day. Figure 3 shows the trajectory of the flights along with the flight profile on both days, highlighting the location of the GBAS station in Cochstedt.

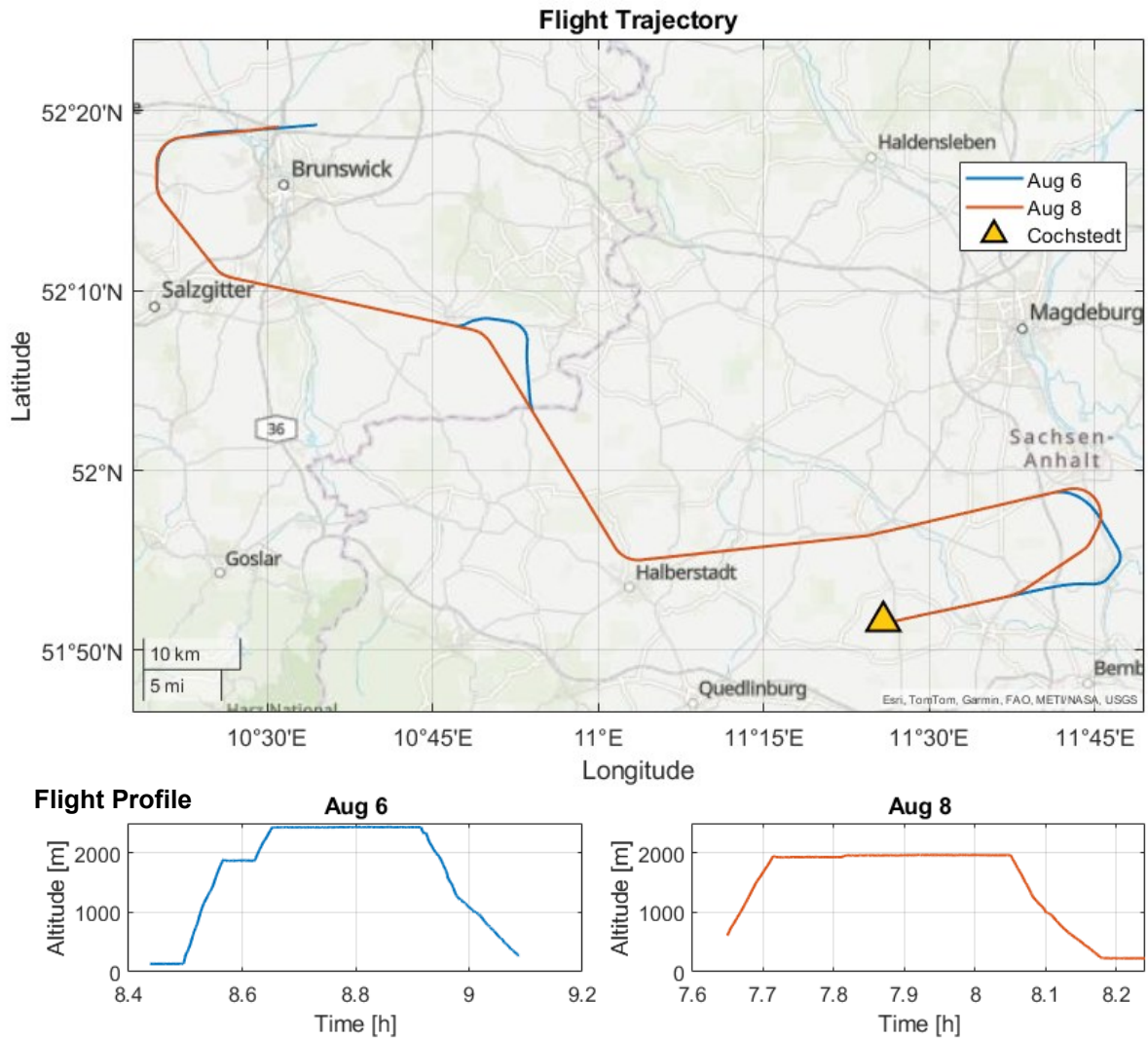


FIGURE 3 Trajectory of the flights (upper panel) and flight profiles (bottom panel) for both days analyzed in the experiment highlighting the Cochstedt experimental GBAS station.

Three geodetic reference receivers equipped with choke-ring antennas were used to process the data as a GBAS ground station. Accordingly, σ_{gnd} models were derived from ground-station data specific to those days. The resulting elevation-dependent models were all within the performance requirements of Ground Accuracy Designator C (GAD-C), as defined in ICAO (2023).

The ground-station data was then processed to generate corrections for multiple processing modes, two of which were selected for this work: single-frequency (L1), single-constellation (GPS), with a smoothing time constant of 100 s, used in the GAST-C experiment; and divergence-free (DF), dual-frequency (L1-E1/L5-E5), dual-constellation (GPS/Galileo), with a smoothing time constant of 200 s. This time constant, shorter than the 600 seconds usually applied when using the divergence-free observable, was chosen to maximize the amount of useful data, given the limited availability of the dataset. In addition, a variant version of the smoothing filter was adopted to accelerate convergence, make the measurements ready to be used sooner, and improve data availability. For the airborne segment, multipath models were derived from the airborne data for the observables corresponding to the selected processing modes, using the methodology and tool developed within the DUFMAN project (Circiu et al., 2020, 2021).

3.2 IMPC data

The IMPC data for the selected dates was obtained and filtered for the specific flight periods. It is worth noting that, although the main goal of the proposed concept is to leverage Space Weather information for real-time assistance, the experiment conducted in this work to validate the concept was performed as a post-processing analysis, given the current phase of the project.

Four main products were used in the experiment, as indicated in the diagrams in Figures 1 and 2. One of them, the WFD, is a routine designed to trigger under anomalous conditions. Since the present work is limited to assessing the benefits of reducing conservatism under nominal conditions, no triggers were reported from this detector. The remaining three Space Weather sources are operational IMPC products: ROTI, DIXSG, and the near-real-time σ_{vig} estimate. The first two, referred in this paper as ‘fast indices’ due to their lower latency, are detectors that are compared against predefined thresholds and act alongside the WFD, while the latter is intended for use under nominal conditions to replace the traditional σ_{vig} derived from historical data.

The analysis of the fast indices, as well as the real-time σ_{vig} , is performed along the path of each Ionospheric Pierce Point (IPP) as seen from the ground station, considering a buffer of 100 km to account for the displacement of the IPP along the line of sight between the aircraft receiver and the satellite. For each IPP position within the area covered by its path, including the 100 km buffer during the 5-minute latency period of the product, the σ_{vig} values are extracted from the grid and the maximum is determined. Since the ground station can broadcast only one σ_{vig} value, the maximum value among all IPPs during the period is selected and broadcast for use in the VPL computation. This selection procedure accounts for the impact of the chosen update rate and grid resolution on the performance of the methodology: the 5-minute update cycle of the σ_{vig} product is covered by the 100 km buffer, which also accounts for the displacement of the IPPs during the latency period, and the $1^\circ \times 1^\circ$ resolution of the σ_{vig} grid is handled by taking the maximum value over all grid cells crossed by the IPP paths. The analysis is therefore conservative with respect to both the temporal and spatial discretization of the IMPC products.

Figure 4 shows examples of σ_{vig} estimates from the IMPC for one 5-minute epoch on two different days of the experiment, corresponding to the selected flight periods, along with the IPPs seen by the GBAS ground station above a 5° elevation angle. The GBAS ground station is represented by a golden triangle and the IPPs by red dots with white contour. On both days, the southeastern and northeastern areas exhibit larger-than-expected values, which are likely uncorrelated with any ionospheric phenomena. While the causes of this behavior require further investigation, it could be speculated that the root cause may be related to electromagnetic interference from jamming, as these areas are well-known for being affected by this type of interference due to regional conflicts. Values slightly larger than the nominal historical value for Germany can also be observed on the western part of the map, which are unlikely related to jamming, but that also require further investigation.

Since the adopted σ_{vig} value was extracted only from the IPP paths, which in this case were relatively far from the affected zones, the maximum values obtained (approximately between 3.5 and 4.5 mm/km) were closer to the expected nominal σ_{vig} for Germany, i.e., 2.07 mm/km (Mayer et al., 2009). Nevertheless, this behavior highlights the need for improvements in the IMPC products to isolate metrics and indicators that are solely related to the ionosphere, removing other sources of interference that may contaminate indicators intended to represent nominal conditions, as is the case for σ_{vig} . Therefore, an additional monitoring layer for the IMPC products must be implemented to ensure the quality of the provided products. Such monitoring is out of the scope of this paper and is left for future work.

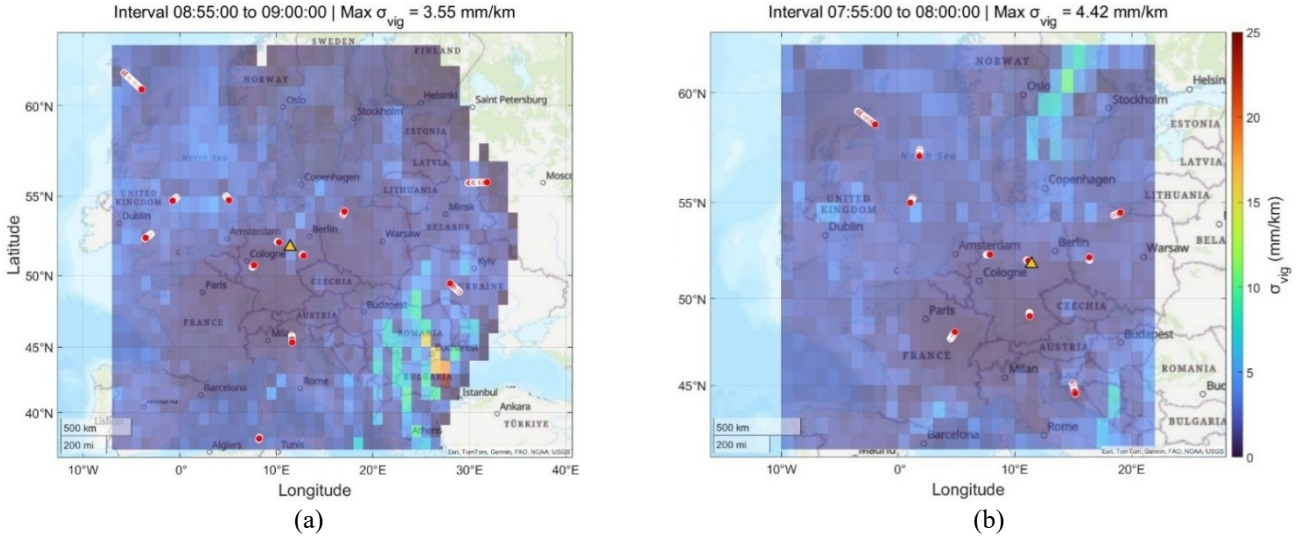


FIGURE 4 IMPC σ_{vig} grid with the IPPs seen from the Cochstedt GBAS station (golden triangle) during a 5-minute period on (a) 06-Aug-2025 and (b) 08-Aug-2025. The maximum σ_{vig} through all IPP paths during each period is 3.55 mm/km in (a) and 4.42 mm/km in (b).

4 RESULTS

The experiments for GAST-C and GAST-E were conducted as indicated in the flowchart of Figures 1 and 2. Both experiments have in common the use of the updated near real-time σ_{vig} provided by the IMPC and the detection strategy based on the fast indices (ROTI and DIXSG) and the WFD. Once the chosen periods exhibit nominal behavior of the ionosphere, despite what was observed in the σ_{vig} grid, neither the fast-index detectors nor the WFD indicated anomalous conditions. Under nominal conditions, the benefits of the proposed concept arise from reducing the conservatism of the GAST-C and GAST-E services, with the expectation of reducing the protection levels in GAST-C, or reducing the test statistic used as a monitor for GAST-E, and hence improving availability. For GAST-C, this is achieved by not applying the PDGS to inflate σ_{vig} . For GAST-E, this is achieved by considering a prior probability of anomalous ionospheric gradients lower than 1 in the calculation of the dual-frequency airborne ionospheric monitor. The results of both experiments serve to demonstrate the benefits of moving away from a conservative approach, once nominal conditions are confirmed. The results for each service type are detailed in the following sections.

4.1 Results for GAST-C

The results obtained for GAST-C compare the Vertical Protection Level (VPL) generated through the inflation of σ_{vig} by the Position Domain Geometry Screening (PDGS) using three well-known threat models (TM), as benchmarking cases. The VPLs generated for the periods of 6th of August 2025 and 8th of August 2025 are presented respectively in Figures 5 and 6. The curves labelled ‘VPL uninflated IMPC’ refer to the protection levels computed without σ_{vig} inflation via PDGS, meaning the σ_{vig} value used in the computation is the one extracted from the IMPC. In Figure 5, the data is interrupted in the final approach when the aircraft started to be jammed, close to the point where the Vertical Alert Limit is 10 m. As for the results shown in Figure 5, the reduction in the protection levels is significant when compared to the VPLs generated by the threat models for CONUS and Brazil. However, the protection levels by the IMPC σ_{vig} are slightly larger than those generated by the threat model for Germany. This is because the nominal σ_{vig} for Germany (2.07 mm/km) is smaller than the values extracted from the IMPC grid (between 3.5 and 4.5 mm/km). Additionally, the PDGS algorithm did not generate inflation factors for any epochs during the flight period when considering the German threat model, even when only the minimum 24 satellites were considered for the GPS constellation.

Considering the larger σ_{vig} values obtained with real-time IMPC monitoring (between 3.5 and 4.5 mm/km) relative to the nominal historical value for Germany (2.07 mm/km), no benefit was found in using real-time σ_{vig} for Germany. Real-time calculation of this parameter would prove beneficial when the estimated values can be smaller than large nominal values based on historical data. For example, in Brazil, where the nominal σ_{vig} was found to be 14 mm/km (Chang et al., 2021), real-time estimations would be beneficial if the estimated values were below 14 mm/km, assisting in reducing protection levels and improving availability.

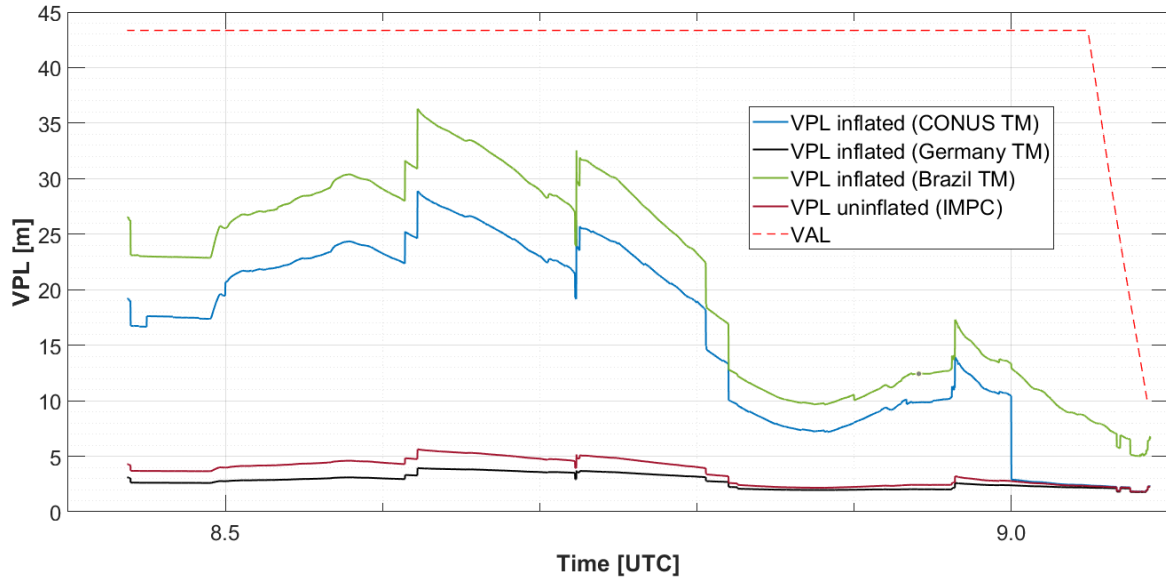


FIGURE 5 Vertical Protection Levels on 06-Aug-2025, generated with inflation for three benchmarking threat model and with no inflation using the near-real-time σ_{vig} provided by the IMPC.

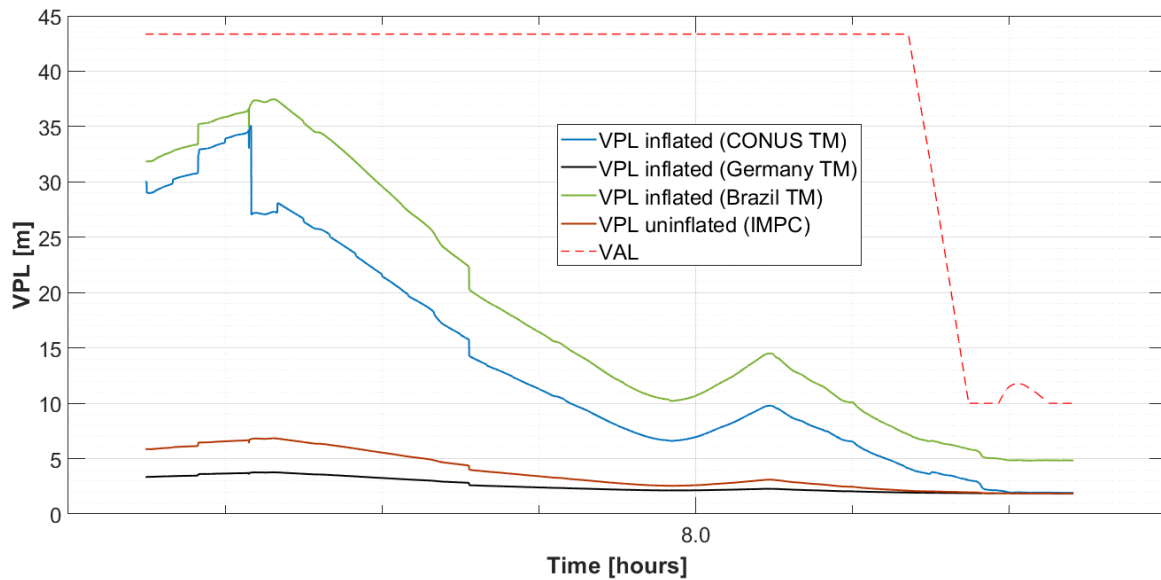


FIGURE 6 Vertical Protection Levels on 08-Aug-2025, generated with inflation for three benchmarking threat model and with no inflation using the near-real-time σ_{vig} provided by the IMPC.

A similar behavior is observed in the results for 8th of August 2025, shown in Figure 6. The VPLs from the IMPC are significantly lower than those from the CONUS and Brazil threat models, and only slightly larger than those generated by the German threat model. This difference is more prominent in the flight segments before the final approach, and the reasons are the same as for the first experiment day: larger σ_{vig} values and no inflation factor when using the German threat model. During the final approach, the PDGS resulted in no inflation factor either for the German or CONUS threat models. In this segment, an increase in VAL is observed due to the increasing distance between the aircraft and the GBAS station. Since VAL depends on aircraft altitude, which in turn depends on the distance from the GBAS station, an increase in this distance, as part of the approach procedure, results in a corresponding increase in VAL.

Although the proposed methodology yields lower performance compared to the nominal σ_{vig} value for Germany, the use of near-real-time σ_{vig} estimates from the IMPC still provides a clear benefit over inflating σ_{vig} via PDGS with other ionospheric threat models, even considering the need for improved monitoring and the current sub-optimal latency. Furthermore, despite the aforementioned areas for improvement, the IMPC-derived σ_{vig} values tend to reflect realistic ionospheric conditions. It is also worth noting that the nominal σ_{vig} for Germany was published 17 years ago and has not been revised since.

4.2 Results for GAST-E

The experiment for GAST-E is focused on comparing the value of the airborne ionospheric monitor test statistic (VPL_{iono}) with the prior probability of anomalous ionospheric gradients ($P_{prior,iono}$) set to 1, as the standard model, or set to a minimum probability when nominal conditions are declared. In the case of this experiment, this minimum value was conservatively set to 10^{-3} without further analysis.

Figures 7 and 8 depict the results for the monitor values during the flight with both values for the prior probability, respectively for the 6th and 8th of August 2025. As expected, because they are both nominal days with respect to the ionosphere, the ionospheric detection features from the IMPC did not trip during the period of flight, and hence, the airborne monitor used $P_{prior,iono}$ as 10^{-3} all the time. As a consequence, there was no satellite exclusion and no switches to the ionospheric free mode. The resulting values for the airborne monitor were significantly below the vertical error threshold ($E_{v,iono}$), set to 8.4 m, as used by Caamano et al. (2023).

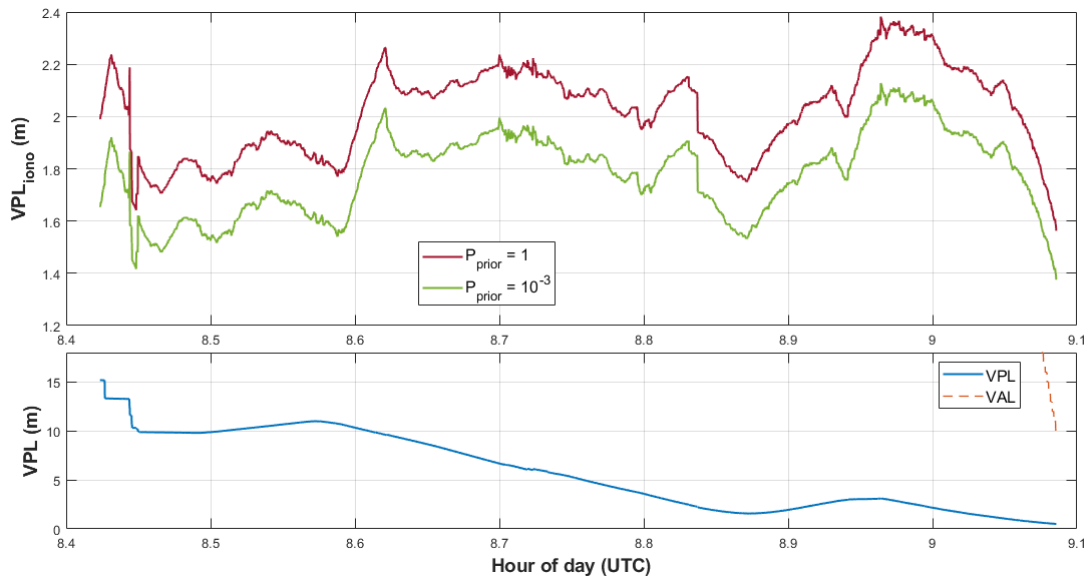


FIGURE 7 Airborne ionospheric monitor test statistic (upper panel) with $P_{prior,iono}$ set to 1 and 10^{-3} , along with the resulting Vertical Protection Level (bottom panel) for 06-Aug-2025.

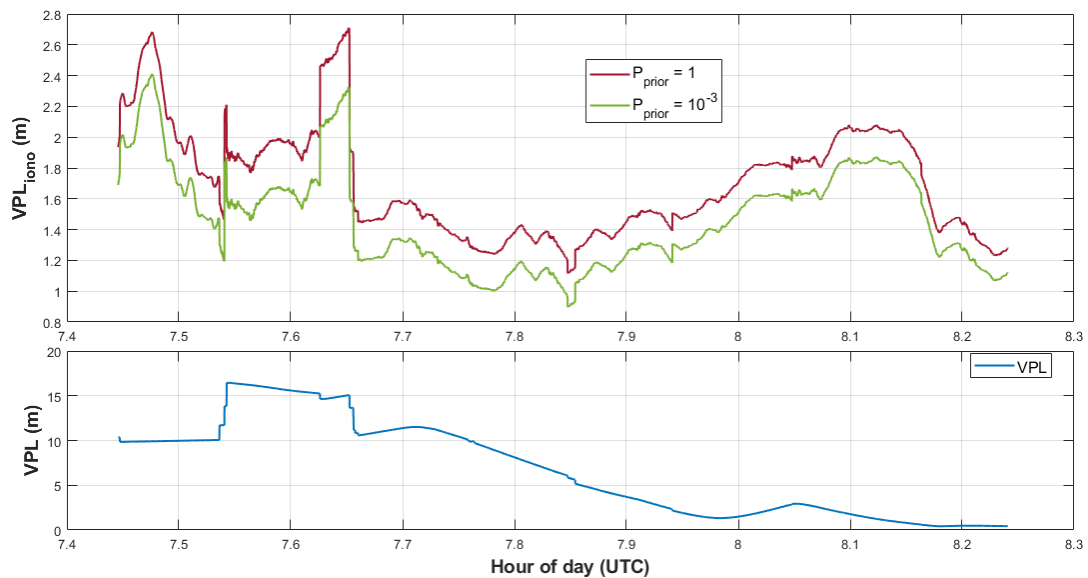


FIGURE 8 Airborne ionospheric monitor test statistic (upper panel) with $P_{prior,iono}$ set to 1 and 10^{-3} , along with the resulting Vertical Protection Level (bottom panel) for 08-Aug-2025.

In Figures 7 and 8, using $P_{prior,iono}$ as 10^{-3} resulted in a reduction of approximately 20% in the monitor values. While the conservative choice of 10^{-3} for the prior probability already yielded noteworthy results, further and more detailed analyses could identify even lower values, leading to a more pronounced reduction in the monitor values under nominal conditions. Although this difference is negligible for the data used in the present experiment, since both values remained well below the established threshold, such a reduction could prove beneficial when the monitor operates close to the threshold. In such cases, it may help prevent protection levels from exceeding alert limits (i.e., loss of availability) under nominal conditions. This could occur as a result of the airborne monitor exceeding the thresholds, excluding satellites, switching to ionospheric-free mode, and yielding larger protection levels that may exceed the alert limits, as reported by Gerbeth & Caamano (2023).

5 CONCLUSIONS

The results presented in this paper constitute a significant deliverable of the DLR In2Action project, aligning with its objective to bridge the gap between physical Space Weather understanding and operational aerospace applications. This work has demonstrated a concept for integrating external ionospheric information into the GBAS architecture to enhance system availability.

The proposed methodology indicates that near-real-time Space Weather products, such as those provided by the Ionosphere Monitoring and Prediction Center (IMPC), can be effectively utilized as an independent layer to classify the current state of the ionosphere and adapt the parameters for the GBAS service accordingly. For GAST-C, which remains the only currently certified GBAS service for precision operations, the integration of near-real-time σ_{vig} estimates allow for a reduction in the conservatism inherent in the PDGS algorithm. Experimental results showed that while current IMPC σ_{vig} values (3.5–4.5 mm/km) are slightly higher than the 17-year-old historical nominal value for Germany (2.07 mm/km), they remain significantly lower than the inflated values required by the CONUS and Brazil threat models, thus preventing unnecessary geometry screening under verified quiet conditions. These results showcase the potential benefit for regions with a more active ionosphere.

As GAST-E is still under international standardization, the use of external information to justify a lower prior probability of anomalous gradients ($P_{prior,iono} = 10^{-3}$) resulted in a 20% reduction in the airborne monitor test statistic. There was no impact on availability in this case, but the reduction could be beneficial when the original test statistic (with prior probability equal to 1) exceeds the threshold. Hence, this reduction can be critical for maintaining availability in geometries where nominal noise might otherwise trigger false alerts or satellite exclusions. These empirical findings provide valuable evidence that can directly contribute to ongoing standardization discussions, supporting the definition of more efficient integrity limits.

Despite these benefits, several challenges remain. The IMPC products are not currently aviation-certified, and ensuring their integrity for real-time safety-critical applications is a primary hurdle. The conducted analysis identified instances where non-ionospheric interferences, potentially related to regional jamming, contaminated the σ_{vig} grid. This underscores the urgent need for an additional monitoring layer within the Space Weather service provider to isolate pure ionospheric indicators.

In conclusion, while the experiments were limited to nominal days and specific flight data, they provide a preliminary proof-of-concept. Future work will focus on expanding the dataset to include disturbed ionospheric conditions, refining the quality indicators of the Wave Front Detector (WFD), and developing the necessary integrity-preserving framework required for operational application. In particular, the plans for assessing the performance of the methodology under anomalous conditions will be implemented by generating synthetic anomalous gradients in the network used by the IMPC. The IMPC products will be re-generated with these anomalous gradients, and the methodology will then be assessed regarding its capability of classifying the ionosphere as anomalous. A sensitivity test will also be performed to check the limits of the proposed methodology and determine specific thresholds for the parameters involved. The simulation through synthetic gradients will also allow expanding this analysis beyond Germany to assess the global applicability of the proposed concept.

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REFERENCES

- Caamano, M., Gerbeth, D., Sato, H., Circiu, M. S., & Felux, M. (2023). Performance evaluation of the ionospheric threat mitigation strategies in dual-frequency multi-constellation GBAS. *2023 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, 196–207. <http://doi.org/10.1109/PLANS53410.2023.10140062>
- Caamano, M., Juan, J. M., Sanz, J., & Pullen, S. (2025). Overbounding of near real-time estimated ionospheric gradient slope in low-latitude regions. *NAVIGATION*, 72(1). <https://doi.org/10.33012/navi.689>
- Caamano, M., Juan, J. M., Sanz, J., & Pullen, S. (2026). Real-time ionospheric threat adaptation to increase CAT-I GBAS availability in equatorial regions. *NAVIGATION*, 73. <https://doi.org/10.33012/navi.754>
- Caamano, M., Juan, J. M., Felux, M., Gerbeth, D., González-Casado, G., & Sanz, J. (2021). Network-based ionospheric gradient monitoring to support GBAS. *NAVIGATION*, 68(1), 135–156. <https://doi.org/10.1002/navi.411>
- Chang, H., Yoon, M., Pullen, S., Marini-Pereira, L., & Lee, J. (2021). Ionospheric spatial decorrelation assessment for GBAS daytime operations in Brazil. *NAVIGATION*, 68(2), 391–404. <https://doi.org/10.1002/navi.418>
- Circiu, M.-S., Caizzzone, S., Enneking, C., Fohlmeister, F., Rippl, M., Meurer, M., Felux, M., Gulie, I., Rüegg, D., Griggs, J., Lazzarini, R., Hagemann, F., Tranchet, F., Bouniol, P., & Sgammini, M. (2021). Final results on airborne multipath models for dual-constellation dual-frequency aviation applications. *Proceedings of the 2021 International Technical Meeting of The Institute of Navigation*, 714–727. <https://doi.org/10.33012/2021.17862>
- Circiu, M.-S., Caizzzone, S., Felux, M., Enneking, C., Rippl, M., & Meurer, M. (2020). Development of the dual-frequency dual-constellation airborne multipath models. *NAVIGATION*, 67(1), 61–81. <https://doi.org/10.1002/navi.344>
- Datta-Barua, S., Lee, J., Pullen, S., Luo, M., Ene, A., Qiu, D., Zhang, G., & Enge, P. (2010). Ionospheric threat parameterization for local area global-positioning-system-based aircraft landing system. *Journal of Aircraft*, 47(4), 1141–1151. <https://doi.org/10.2514/1.46719>
- DLR - German Aerospace Center. (2025, April 16). *IN2ACTION*. <https://www.dlr.de/en/so/research-transfer/projects-1/current-projects-1/in2action>
- DLR - German Aerospace Center. (2024, July). *Do not disturb*. <https://www.dlr.de/en/media/publications/magazines/all-digital-magazines/dlrmagazine-176/do-not-disturb>
- Gerbeth, D., & Caamano, M. (2023). Adaptive airborne ionospheric gradient monitoring for dual-frequency GBAS. *Proceedings of the 36th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2023)*, 1725–1733. <https://doi.org/10.33012/2023.19268>
- Gerbeth, D., Caamano, M., Circiu, M. S., & Felux, M. (2022). Airborne ionospheric gradient monitoring for dual-frequency GBAS. *Proceedings of the 2022 International Technical Meeting of The Institute of Navigation*, 1110–1122. <https://doi.org/10.33012/2022.18179>
- International Civil Aviation Organization. (2023). *Annex 10, aeronautical telecommunications: Volume I - Radio navigation aids* (8th ed., Amdt. 93).
- International Civil Aviation Organization. (2019). *Doc 10100, Manual on Space Weather Information in Support of International Air Navigation* (1st ed.).
- Jakowski, N., Mayer, C., Hoque, M. M., & Wilken, V. (2011). Total electron content models and their use in ionosphere monitoring. *Radio Science*, 46(6), 1–11. <https://doi.org/10.1029/2010RS004620>
- Kriegel, M., David, P., Tagargoust, Y., Vasylyev, D., Wenzel, D., Nistor, F., & Berdermann, J. (2026). Ionosphere Monitoring and Prediction Center (IMPC). In *United Nations Germany Workshop on the International Space Weather Initiative: Preparing for the Solar Maximum* (pp. 295–302). Springer Nature Singapore. https://doi.org/10.1007/978-981-95-1121-1_33

- Lee, J., Seo, J., Park, Y. S., Pullen, S., & Enge, P. (2011). Ionospheric threat mitigation by geometry screening in ground-based augmentation systems. *Journal of Aircraft*, 48(4), 1422–1433. <https://doi.org/10.2514/1.C031309>
- Marini-Pereira, L., Moraes, A. O., & Pullen, S. (2022). A simple and effective approach to real-time ionospheric monitoring for GBAS in low latitudes. *Proceedings of the 35th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2022)*, 2954–2969. <https://doi.org/10.33012/2022.18339>
- Marini-Pereira, L., Moraes, A. O., & Pullen, S. (2023). Advanced warning of threatening equatorial plasma bubbles to support GBAS in low latitudes. *IEEE Transactions on Aerospace and Electronic Systems*, 59(5), 4858–4869. <https://doi.org/10.1109/TAES.2023.3243581>
- Marini-Pereira, L., Moraes, A. O., & Pullen, S. (2024). A simple and effective approach to real-time ionospheric monitoring at low latitudes and its applicability to GBAS. *NAVIGATION*, 71(1). <https://doi.org/10.33012/navi.619>
- Mayer, C., Belabbas, B., Jakowski, N., Meurer, M., & Dunkel, W. (2009). Ionosphere threat space model assessment for GBAS. *Proceedings of the 22nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2009)*, 1088–1097.
- Murphy, T., Harris, M., Balvedi, G., McGraw, G., Wichgers, J., Lavik, L., Topland, M., Tuffaha, M., & Saito, S. (2022). Availability of iono gradient detection with alternative architectures for DFMC GBAS. *Proceedings of the 35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022)*, 12–33. <https://doi.org/10.33012/2022.18305>
- Murphy, T., Harris, M., McGraw, G., Wichgers, J., Lavik, L., Topland, M., Tuffaha, M., & Saito, S. (2021). Alternative architecture for dual frequency multi-constellation GBAS. *Proceedings of the 34th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2021)*, 1334–1374. <https://doi.org/10.33012/2021.18152>
- RTCA. (2019). *Minimum operational performance standards for GPS local area augmentation system airborne* (DO-253D).
- Schmölter, E., Tagargoust, Y., Wilken, V., Kriegel, M., & Berdermann, J. (2025). Improving the global Total Electron Content maps provided by the Ionosphere Monitoring and Prediction Center—preliminary results. *Journal of Space Weather and Space Climate*. <https://doi.org/10.1051/swsc/2025039>
- Shively, C. A., & Niles, R. (2008). Safety concepts for mitigation of ionospheric anomaly errors in GBAS. *Proceedings of the 2008 National Technical Meeting of The Institute of Navigation*, 523–534.
- Wilken, V., Kriegel, M., Jakowski, N., & Berdermann, J. (2018). An ionospheric index suitable for estimating the degree of ionospheric perturbations. *Journal of Space Weather and Space Climate*, 8, A19. <https://doi.org/10.1051/swsc/2018008>
- Yoon, M., Kim, D., & Lee, J. (2020a). Extreme ionospheric spatial decorrelation observed during the March 1, 2014, equatorial plasma bubble event. *GPS Solutions*, 24(2), 1–11. <https://doi.org/10.1007/s10291-020-0960-x>
- Yoon, M., Kim, D., Pullen, S., & Lee, J. (2019). Assessment and mitigation of equatorial plasma bubble impacts on category I GBAS operations in the Brazilian region. *NAVIGATION*, 66(3), 643–659. <https://doi.org/10.1002/navi.328>
- Yoon, M., Lee, J., & Pullen, S. (2020b). Integrity risk evaluation of impact of ionospheric anomalies on GAST D GBAS. *NAVIGATION*, 67(2), 223–234. <https://doi.org/10.1002/navi.339>
- Yoon, M., Lee, J., Pullen, S., Gillespie, J., Mathur, N., Cole, R., Souza, J. R., Doherty, P., & Pradipta, R. (2017). Equatorial plasma bubble threat parameterization to support GBAS operations in the Brazilian region. *NAVIGATION*, 64(3), 309–321. <https://doi.org/10.1002/navi.203>