Proceeding Paper

UKSBAS Testbed Performance Assessment of Two Years of Operations

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† Presented at the European Navigation Conference 2024, Amsterdam, May 2024.

Abstract Current Satellite-Based Augmentation Systems (SBASs) improve the positioning accuracy and integrity of GPS satellites and provide safe civil aviation navigation services for procedures from en-route to LPV-200 precision approach over specific regions. SBAS systems already operate, such as WAAS, EGNOS, GAGAN and MSAS. The development of operational SBAS systems is in transition due to the extension of L1 SBAS services to new regions and the improvements expected by the introduction of Dual Frequency Multi-constellation (DFMC) services, which allow the use of more core constellations such as Galileo and the use of ionosphere-free L1/L5 signal combination. The UKSBAS testbed is a demonstration and feasibility project in the framework of ESA's Navigation Innovation Support Programme (NAVISP) sponsored by the UK's HMG with the participation of the Department for Transport and the UK Space Agency. UKSBAS testbed main objective is to deliver a new L1 SBAS signal in space (SIS) from May 2022 in the UK region using Viasat's Inmarsat-3F5 geostationary (GEO) satellite and Goonhilly Earth Station as signal uplink over PRN 158, as well as L1 SBAS and DFMC SBAS services through the Internet. SBAS messages are generated by GMV's magicSBAS software fed with data from Ordnance Survey's stations network. This paper provides an assessment of the performance achieved by UKSBAS testbed during the last two years of operations at SIS and user level, including a number of experimentation campaigns performed in the aviation and maritime domains, comprising ground tests at airports, flight tests on aircraft and sea trials on a vessel. This assessment includes, among others, service availability (e.g.: APV-I, LPV-200), Protection Levels (PL), and Position Errors (PE) statistics over the service area and in a network of receivers.

Keywords: UKSBAS; SBAS; Performance; Integrity; Accuracy; Availability; Testbed

Citation: Merino, J.G.; Llano, F.B.; Pattinson, M.; Easom, M.; Hernández, J.R.C.; Palomar, I.S.; Llapa, M.R.; Ilamparithi, S.P.; Hill, D.; Newton, G. UKSBAS Testbed Performance Assessment of Two Years of Operations.

Academic Editor: Terry Moore

1. Introduction

UKSBAS Testbed is a European Space Agency NAVISP Element 3 sponsored by UK Department for Transport and the UK Space Agency that aims to demonstrate a new UK national SBAS service to aid in assessing the options for future operational SBAS capabilities. The project is led by Viasat, while GMV collaborates by offering a technical solution to produce GPS augmentation SBAS L1 messages using real-time measurements from Continuously Operating Reference Stations (CORS) and generating a signal that is uplinked from Goonhilly Earth Station. The signal is being disseminated since 2022 through Viasat in-orbit geostationary (GEO) navigation transponder. In 2023, the infrastructure was updated with next-generation SBAS DFMC provision that augments GPS and Galileo dual-frequency measurements.

UKSBAS Testbed comprises the assessment of two different augmentation aids. On one hand, a SBAS legacy GPS L1 open service is broadcast through Viasat 3F5 geostationary satellite, usable (in test mode) by SBAS-enabled COTS receivers. Secondly, a SBAS DFMC open service that provides corrections for both GPS (L1 and L5) and Galileo (E1 and E5a) satellites is delivered over the Internet using SISNeT technology.

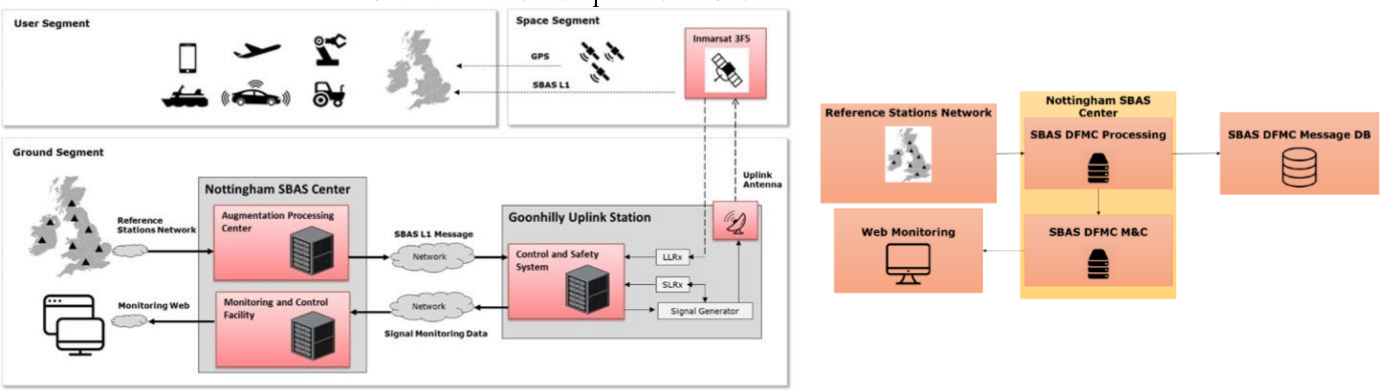
The objective of this paper is to provide an update of the Testbed definition and performances achieved during two years of operations, including user trials in the aviation and maritime domain.

2. UKSBAS Testbed Overview

This section provides an overview of the Testbed architecture and infrastructure deployed for provision of SBAS L1 SIS and SBAS L1 and SBAS DFMC SISNeT. SBAS L1 SIS broadcast has been live from May 2022 on, while SBAS DFMC provision over SISNeT was introduced in June 2023. The Testbed has been implemented in two different phases: Phase 1 between October 2021 and December 2022, and Phase 2A comprising between April 2023 and March 2024.

2.1. UKSBAS Architecture Overview

The following figure summarizes the architecture of UKSBAS L1 and UKSBAS DFMC SISNeT provision in the Testbed. Each of the different segments are described in more detail in subsequent sections.



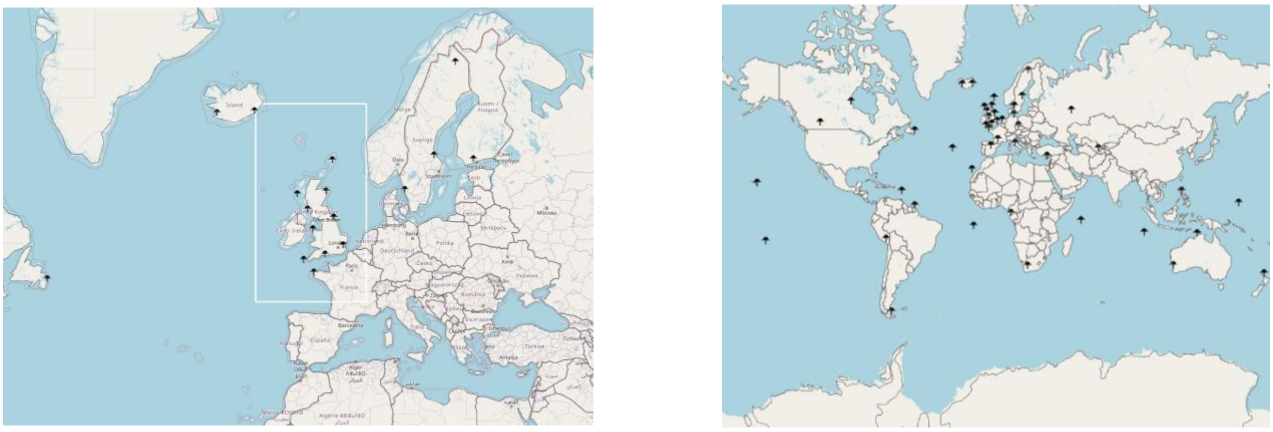
(a) **(b)**

Figure 1. UKSBAS Testbed architecture for UKSBAS L1 (a) and UKSBAS DFMC (b) processing chains.

2.2. Ground segment

The ground segment consists of all elements that are necessary to generate SBAS messages and send them to the satellite for broadcast. The main elements are the reference station network (for the acquisition of GNSS reference data), the Augmentation Processing Centre (APC) for generating the SBAS messages, and the Uplink Infrastructure, for sending the SBAS messages to the space segment for broadcast.

The Testbed approach for acquisition of reference data is to use existing CORS station already deployed. Two networks have been used, Ordnance Survey stations within the UK and IGS stations outside UK landmass. A regional station network has been chosen for SBAS L1 provision to ensure ionospheric monitoring, and a worldwide network for the iono/free SBAS DFMC provision.



(a) **(b)**

Figure 2. Reference station networks chosen to compute SBAS L1 (*a*) and SBAS DFMC (*b*) messages.

The Testbed elements that generate the SBAS messages are located at Nottingham. The Augmentation Processing Centre (APC) is responsible for processing the measurements received from the reference stations in order to compute the SBAS corrections and integrity information (UDRE/DFRE and GIVE) and formulate the SBAS messages to be transmitted according to RTCA standards [2]. This processing is carried out using GMV's product magicSBAS. SBAS L1 and SBAS DFMC messages can be provided in real-time over the Internet using SISNeT Protocol [4].

Finally, the SBAS L1 messages are transmitted to the Uplink Infrastructure located at Goonhilly, South West UK. Among other elements, the Uplink Infrastructure utlises a signal generator controller (SIGGEN) that generates the electromagnetic signal, GMV Signal Generator Controller (SGC) that allows command, control and monitoring of SIGGEN and a Full Motion Antenna (FMA) operated by Goonhilly Earth Station that transmits the signal to the Viasat/Inmarsat-3F5 satellite transponder for dissemination. Another important safety-related component is GMV's Uplink Safety Monitor (USM), which checks the intended transmission to align with the applicable safety standards (i.e.: ensuring MT0 broadcast at least once every 6 seconds).

2.3. Space segment

UKSBAS Testbed space segment consists of the Viasat/Inmarsat-3F5 geostationary satellite and its transponder payload that is used to broadcast the UKSBAS L1 Testbed signal over its footprint. Viasat operates this spacecraft, as well as supporting the signal uplink with TLE navigation parameters that support the uplink antenna orientation and the signal control.

2.4. Support segment

Lastly, UKSBAS Testbed includes a subsystem to operate, maintain and monitor the health of the whole system. The real-time performances are continuously monitored using magicMonitor**,** a browser front-end under uksbas.org domain that displays information such as the real-time SIS broadcast and reference receiver status and instantaneous service availability maps.

3. UKSBAS Performance Assessment

3.1. Signal-in-Space Availability

The Signal-in-Space availability has been calculated as the ratio of PRN 158 SBAS messages logged by the Long Loop Receiver in Goonhilly Uplink Station, one of the control receivers involved in the Signal Controller subsystem, over the total broadcast timeframe.

Testbed signal outages have been experienced due to a variety of causes which are now well-characterized and relate to the uplink antenna tracking capability in combination with the orbital inclination of the 3F5 vehicle located at 54º W (it is currently in an inclined orbit of more than 6 degrees due to its operational age). The spacecraft elevation as seen at Goonhilly varies between 12 and 22 degrees. As a consequence, the Long Loop Receiver periodically losses track of the SBAS signal over time. Other outage occurrences are related with planned maintenances at the APC, at Goonhilly and from the Internet network provider. Nevertheless, the high broadcast availability proves the capacity of the spacecraft to support SBAS provision over the UK.

Table 1. UKSBAS L1 Testbed SIS Availability at Goonhilly Uplink Station.

UKSBAS Phase	Start-End	Number of analyzed days	SIS Availability
Phase 1	07/05/2022 – 20/12/2022	228	99.43%
Phase 2A	04/04/2023 – 31/03/2024	363	99.01%

3.2. Service Volume Availability

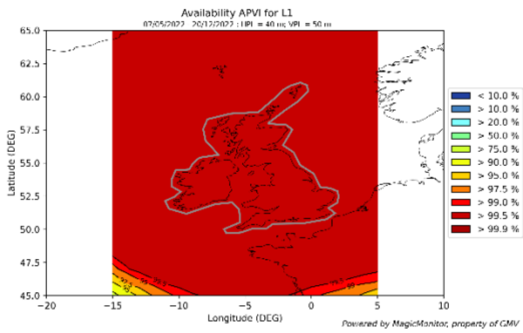
The service volume availability measures the percentage of time at each point in an area that the user level integrity (the Protection Levels) meets the service level requirements for Horizontal and Vertical Alert Limits (HAL,VAL). Figure 3 shows the cumulative measured availability for APV-I service level (HAL=40m and VAL=50m) and LPV-200 (HAL=40m and VAL=35m) in UKSBAS service area computed by GMV Eclayr tool at message generation level, without accounting for broadcast outages. The system succesfully meets operational performance levels (over 99.9%) in terms of availability during the Testbed duration.

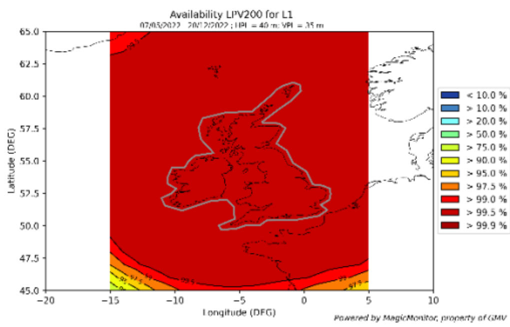
3.3. Accuracy

The accuracy of the service can be assessed at different levels of the solution: at satellite level (accuracy of the correction) and at user position level.

At satellite level, the correctness of the satellite orbit and clock corrections are evaluted by comparison with reference orbits and clocks products from IGS [6].

Figure 4 presents the satellite residual error statistics for all satellites evaluated at the Worst User Location of UKSBAS service area during Phase 2A. The data is presented in the shape of histograms, in logarithmic scale to account for the distribution tails, and Q-Q plots, to facilitate the comparison with a folded normal distribution with the estimated mean and standard deviation computed from the empirical data.





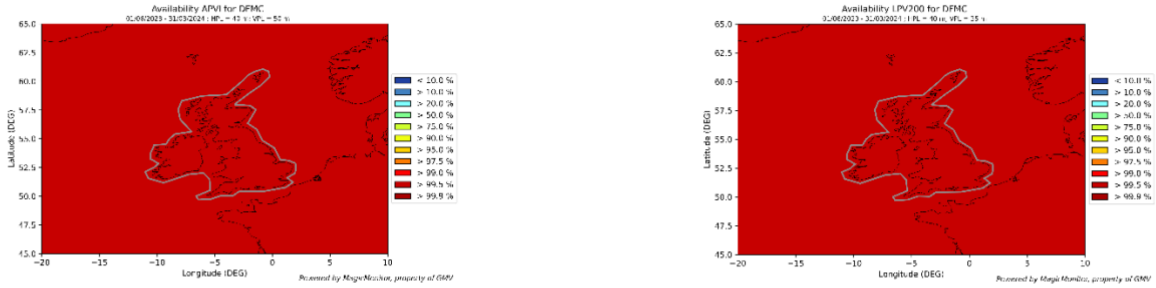
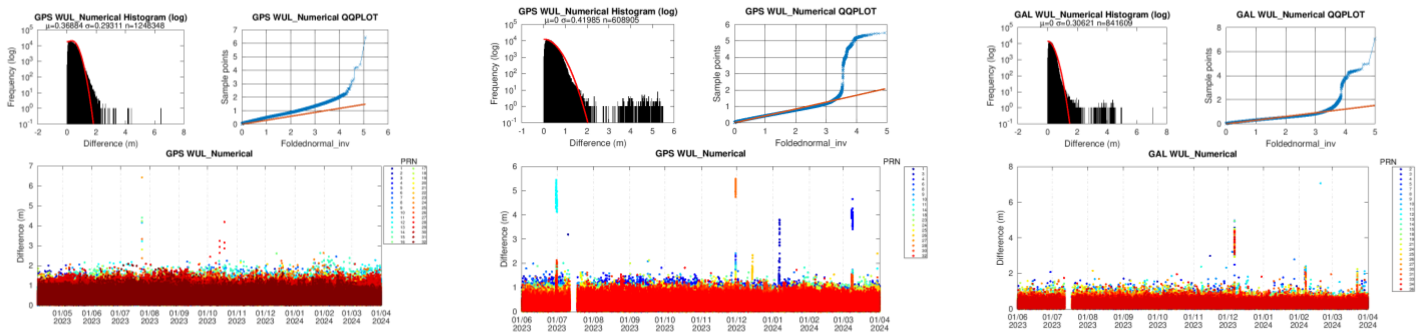


Figure 3. Measured APV-I (left) and LPV-200 (right) cumulative availability of UKSBAS L1 solution (top) and UKSBAS DFMC solution (bottom) over the Service Area during Phase 2A.

Note that in the case of SBAS DFMC, Satellites E14 and E18 from Galileo constellation have been excluded from the satellite accuracy analysis of UKSBAS DFMC, as they are deployed in eccentric orbits and present significant differences to the core constellation. The 95% ranging accuracy values at WUL were 85 cm for UKSBAS L1 GPS corrections, and 76 cm and 54 cm for UKSBAS DFMC GPS and GAL corrections respectively.



(a) **(b)** **(v)**

Figure 4. Satellite Residual Error at Worst User Location for UKSBAS L1 (a) and UKSBAS DFMC for GPS (b) and GAL (c) constellations.

To assess user position level accuracy, GNSS data from HERS station (located at southern UK) has been processed using GMV's magicGEMINI tool to compute UKSBAS user level solutions.to compute SBAS solutions using the broadcast UKSBAS messages received at the Uplink Station and complete UKSBAS DFMC messages from the Augmentation Processing Center through magicGEMINI tool. Figure 5 shows the position error histograms in the horizontal plane and the vertical axis (in absolute value), respectively, for the whole applicable duration of Phase 2A. The improvement of SBAS DFMC solution in terms of more available satellites and removal of a high percentage of the ionospheric error translates into sub-meter accuracy levels (95% values 70 cm and 91 cm in horizontal and vertical projection respectively), which is a significant improvement compared to SBAS L1 values, at 95 cm and 1.55 m respectively.

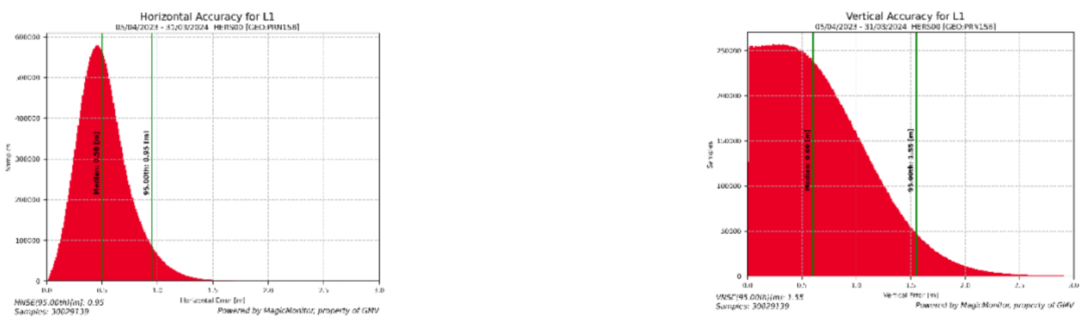


Figure 5. Satellite Residual Error at Worst User Location for UKSBAS L1 (left) and UKSBAS DFMC for GPS (middle) and GAL (right) constellations 4. UKSBAS Testbed Aviation Trials.

The aviation trials were aimed to assess UKSBAS user level performance in different aviation environments using standard RTCA algorithms [2] Data was collected from both static and dynamic aviation environments across various locations in the UK.

4.1. Static Aviation Trials: Airports study

Static data collections have been carried out at four different airports to showcase the performance of the SBAS signal at the geographic boundaries of UK, at North (Inverness, in the Scottish Highlands), South (Exeter, in the county of Devon), West (Londonderry, in Northern Ireland) and East (Norwich, in the county of Norfolk), for approximately 2 weeks per airport. Septentrio AsteRx SB receivers were employed, connected to Septentrio PolaNt-x antennas located in their respective local airports to assess the performances that surrounding landing aircraft would be able to achieve with augmentation, such as APV-I and LPV-200 services.

The Signal-In-Space availability is calculated as the percentage of epochs the receiver logged PRN 158 SBAS messages over the scenario duration. The signal reception was successful from Exeter and Inverness trials, while building obstruction degraded the solution partially (Derry) or fully shadowed the GEO signal (Norwich).

Table 1. Signal-In-Space availability per airport.

Airport Location	Start-End	SIS Availability
Exeter	13/06/2023 – 23/06/2023	99.00%
Norwich	26/06/2023 – 06/07/2023	0%
Derry	25/07/2023 – 05/08/2023	74.56%
Inverness	01/08/2023 – 11/08/2023	98.55%

Due to the issues with the obstruction of the GEO SIS in some of the locations, non-representative of the actual airborne environment, the L1 SBAS messages were added during the postprocessing of the data. Natural Resources Canada (NRCAN) Precise Point Positioning (PPP) service [6] was used to obtain the receiver reference position for all the static trials and derive the Position Error. The performance analysis revealed that UKSBAS L1 solutions outperformed standalone GPS L1 solutions in most of the cases, by leveraging ionospheric and satellite corrections. It is noteworthy that the achieved accuracy improvement of UKSBAS L1 solution has shown similar accuracy levels compared to EGNOS PRN 136 augmentation, despite being a non-operational testbed.

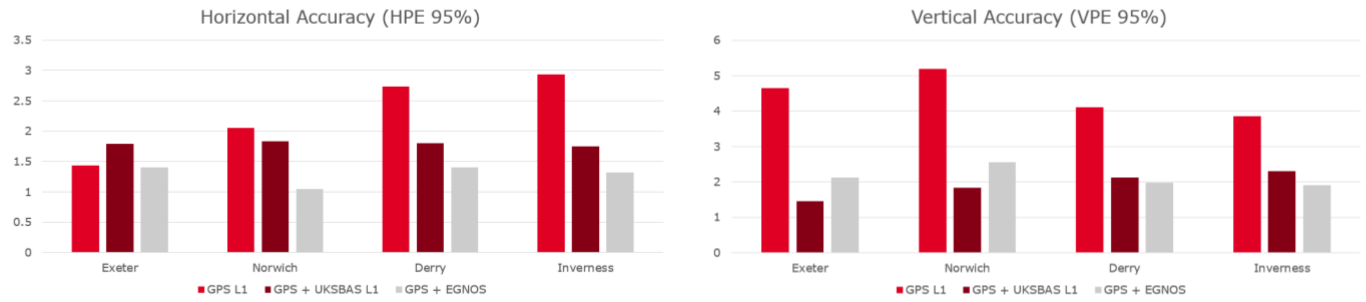


Figure 6. Comparison of 95% Horizontal and Vertical Position Error Statistics at airports.

The SBAS protection levels were studied for assessing the availability performance of the system at user level.

The processed solution was compared against LPV-200 operational requirements (HAL=40m, VAL=35m), In all the locations, the protection levels achieved in post-processing where compatible with APV-I and LPV-200 requirements.

4.2. Dynamic Trials

The dynamic aviation trials collected GNSS data from onboard an aircraft, processed it using different solutions and compared the results in order to show the performance improvement that can be achieved with UKSBAS.

The UKSBAS team has collaborated with Isles of Scilly Skybus to collect data from several flights between St. Mary's airport, Land's End, Newquay, using a handheld Garmin 66r GNSS receiver placed close to the cockpit windshield of a De Havilland Twin Otter aircraft. As this demonstration configuration is not appropriate for an operational airborne SBAS in terms of environment quality, the results achieved are not representative and are not further discussed in this paper.

Additionally, the UKSBAS team, supported by PildoLabs Ltd, undertook end-to-end flight trials/demonstrations using a Saab 340 aircraft at Cranfield, UK, with the engagement of aviation stakeholders. The following paragraphs show the performance achieved with data collected on the 24th October. In the flight under analysis, PRN 158 was tracked 93% of the time.

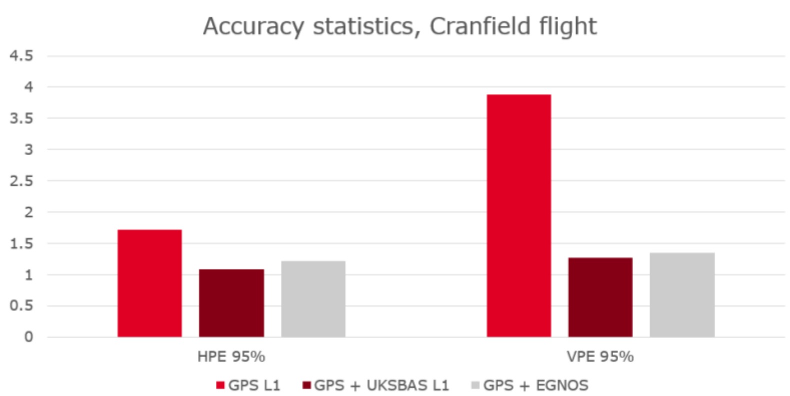


Figure 7. Comparison of 95% Horizontal and Vertical Position Error Statistics from Cranfield flight.

It is observed that the UKSBAS L1 solution improved the accuracy over standalone GPS L1, matching EGNOS 136 performances. On the other hand the results showed horizontal and vertical protection levels below the corresponding LPV-200 alert limits, ensuring the availability of the service.

5. UKSBAS Testbed Maritime Trials

5.1. Maritime Trials Overview

The objective of the maritime trials was to assess the user level performance of the UK SBAS testbed in a maritime environment through analysis of maritime-adapted solutions with legacy SBAS (UKSBAS L1 testbed and EGNOS) and DFMC SBAS (UKSBAS DFMC via post-processing). In the simplest case, the standard aviation equations are used, but with a modified multipath model to account for the fact that multipath errors are higher in the maritime domain. In the second case, a further change is made whereby maritime specific sigma UDRE and GIVE values are used instead of the nominal values broadcast in the SBAS messages. These maritime specific values are generated as part of the Maritime Integrity Support Facility (MISF), which was created as a dedicated maritime service as part of the testbed to provide maritime specific integrity information instead of the broadcast aviation values through Maritime Integrity Support Interface (MISI) messages.

The maritime trials involved the deployment and operation of SBAS enabled equipment on the Scillonian III, a vessel undertaking routine passenger services operated by Isles of Scilly travel, and travelling between Penzance, Cornwall and St Mary's, Isles of Scilly. The deployed equipment computed and logged real-time GPS L1 + SBAS solutions using the broadcast UK SBAS signals and recorded raw GNSS measurements and received SBAS messages for post-processing. The equipment was installed on the vessel for 3 days, covering 3 return trips from Penzance to St Mary's.

5.2. Maritime Trials Performance Assessment

For user level performance, the recorded data was post-processed in different modes and the estimated positions were compared with a reference solution (generated using RTKlib in PPK mode relative to CORS reference sites).

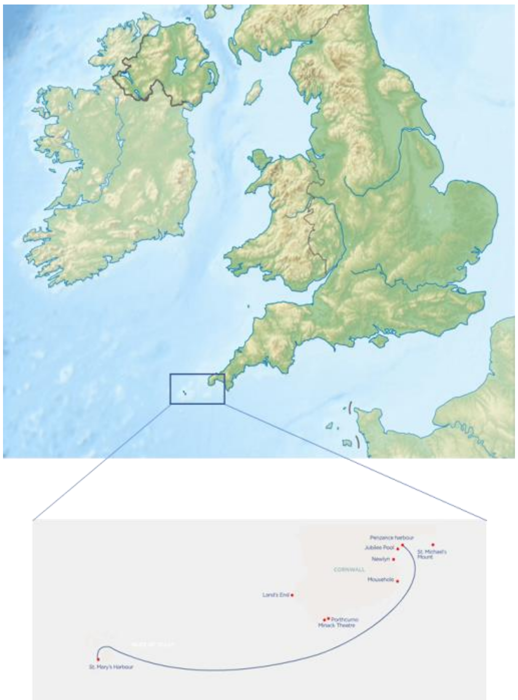


Figure 8. Overview of Vessel route on 27th June 2023.

The mean 95% Horizontal Position accuracy values from the different trials are shown at Figure 9. The results show the comparative benefits of UKSBAS integration into positioning systems, compared to relying on standalone GPS L1 signals. Furthermore, the GPS + Galileo Dual-Frequency Multi-Constellation configuration achieves a 95% horizontal accuracy of approximately 1 meter.

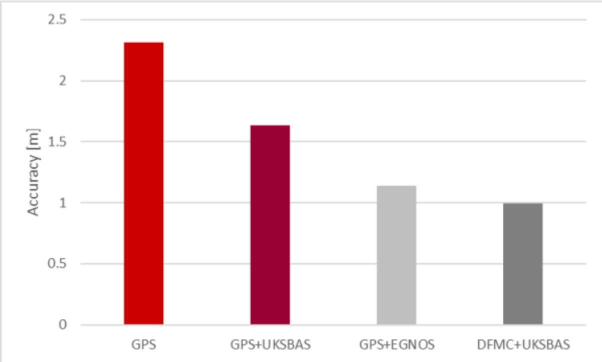


Figure 9. 95% values of Horizontal Position Error for different positioning solutions.

The effect of MISI messages in the accuracy performances is minimal, since the differential corrections are not changed through the MISI messages - only the sigma values. However, we do see some impact in the protection levels, since the MISI sigma values are smaller and so the weightings for all satellites (and hence total protection levels) are reduced, whilst still maintaining bounding of the position errors. As an example, the following figure shows the horizontal position errors vs HPL for 29th June am journey for GPS L1 + UKSBAS on the left and GPS L1 + UKSBAS + MISI on the right. Although there is not a large difference, it can clearly be seen that the protection levels for the MISI case are smaller.

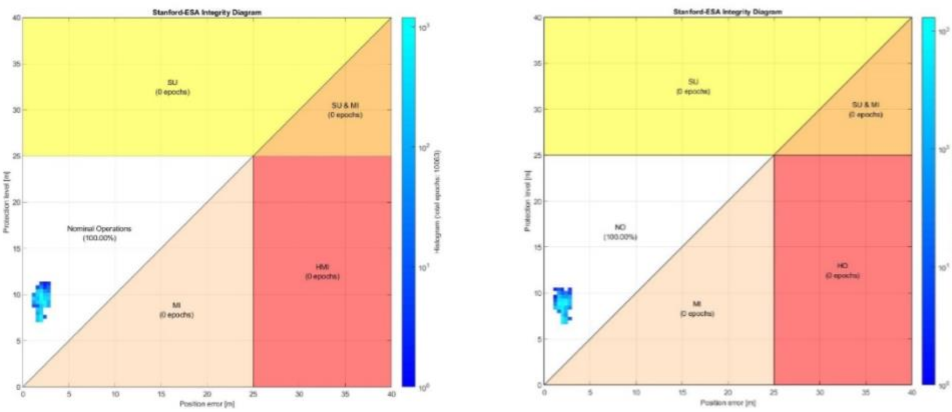


Figure 10. 95% Horizontal Error vs HPL for GPS L1 + UKSBAS (left) and GPS L1 + UKSBAS + MISI (right).

6. Conclusions

UKSBAS Testbed has been continuously broadcasting through the Viasat/Inmarsat 3F5 transponder for two years with outstanding performances. This paper reports the performances achieved during the Testbed operations, comprising the provision of SBAS L1 and SBAS DFMC augmentation aids. Additionally, the aviation and maritime trials showcase the effectivity of the system in providing a valuable solution to the transport sector in the UK.

Acknowledgments: The authors wish to acknowledge the support given by UK authorities, UKSA and Department for Transport, and ESA in the conduction of these activities, as well as Isles of Scilly Travel, Skybus, Isles of Scilly Steamship Group, Highlands Skybus, & Islands, Cranfield and RCA.

Conflicts of Interest: The authors declare no conflict of interest.

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