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MarRINav
MARITIME RESILIENCE AND INTEGRITY OF NAVIGATION

D2 EGNOS/Beacons Initial Report

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MarRINav
MARITIME RESILIENCE AND INTEGRITY OF NAVIGATION

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Executive Summary

Satellite navigation systems such as GPS or Galileo are unable on their own to provide the reliability required for safety-of-life use. For this reason, augmentation systems, such as maritime radio beacon differential GPS (DGPS), have supported GNSS positioning; here ground stations monitor the satellite transmissions and send warning messages to users should the GNSS signals become unreliable.

The civil aviation sector has chosen to adopt Space-Based Augmentation Systems (SBAS) such as WAAS (the Wide Area Augmentation System) and its European counterpart EGNOS (the European Geostationary Navigation Overlay Service). SBAS systems monitor navigation satellites' signals on a continental scale with a network of ground stations. Any malfunction detected causes a warning to be communicated to users' receivers via geostationary satellites. The messages generated at the SBAS ground stations also include continuous corrections for smaller position errors, enabling the receivers on-board the aircraft to deliver more accurate position fixes.

In Europe, the EC is planning a maritime service, based on the existing evolution of EGNOS known as Version 2 (EGNOS V2), which could possibly be introduced as early as the end of 2021. The proposed service would provide warnings to mariners of GPS system faults. It would protect the vessel against errors in position caused by malfunction of GPS satellites or ground processing. This capability is termed "position integrity at system level".

WP2 aims to examine the future role of UK maritime critical national infrastructure (CNI) as a complement to EGNOS for the provision of position, navigation and timing (PNT) integrity. This includes both the EGNOS system level (currently EGNOS V2) and its user level (the future EGNOS V3) in a timeframe extending beyond 2030.

EGNOS was developed for the civil aviation sector, to ensure that airborne users would enjoy extremely high levels of "integrity"; that is, confidence that the aircraft's position was correct and with prompt warnings issued should there be a failure. Another vital goal was that "continuity" be protected: that is, an aircraft embarking on a certified airport approach procedure would have a very high probability of completing it successfully without system failure.

This initial report begins the analysis of the complementary use of EGNOS and existing Maritime beacons. As discussed, the EGNOS system and operations exist for aviation parameters and are not ideally suited for maritime requirements. It is therefore not possible to compare EGNOS and DGPS results directly (maritime vs aviation). This document describes a methodology to allow for an indirect but quantifiable comparison. It provides background information and describes the methodology behind the desk-based study to provide an initial assessment as to whether EGNOS and marine radio beacon DGPS offer complementary or redundant services.

The study uses a mix of Service Volume Simulations (which can also simulate as single point) and historic data to assess the performance of EGNOS and DGPS under both nominal and extreme conditions. For any meaningful conclusions to be drawn from the simulations it is essential that the outputs are not only comparable between tools but that they relate, in a way that is fully understood, to the expected performance of real receivers.

The work to date is not as advanced as it should be. To ensure that it produces meaningful results, the initial effort has concentrated on investigating the various ways that the very powerful and flexible simulation tools should be configured and operated. The work to date has highlighted issues related to the configuration of the error budget , which needs careful consideration before attempting to combine and compare DGPS and EGNOS performance.

This document is organised as follows:

- Section 1 introduces the study.
- Section 2 describes the tools and data used in the study
- Section 3 describes the tools configuration and validation, the series of steps taken to ensure that the tools output is realistic and comparable.
- Section 4 presents the results of the desk-based study as well as identifying limitations of this initial work.

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Glossary

3G	Third-Generation Cell-Phone Technology
A-RAIM	Advanced Receiver Autonomous Integrity Monitoring
C/N0	Carrier-To-Noise (Spectral Density) Ratio
C1	GPS Code L1 observation
CDF	Cumulative Distribution Function
DGNSS	Differential GNSS
DGPS	Differential GPS
DOP	Dilution Of Precision
EDAS	EGNOS Data Access Service
EGNOS	European Geostationary Navigation Overlay Service
EMRF	European Maritime Radionavigation Forum
EPFS	Electronic Position Fixing Systems
ESA	European Space Agency
ESSP	European Satellite Services Provider
GAGT	GLA Augmented-GNSS Toolset
GLA	General Lighthouse Authority
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Services, Second-Generation Cell-Phone Technology
GPS	Global Positioning System
GSA	European Global Satellite System Agency
HAL	Horizonal Alert Limit
HDOP	Horizontal Dilution of Precision
HMI	Hazardously Misleading Information
HNSE	Horizontal Navigation Standard Error
HNSP	Horizontal Navigation Standard Precision
HPL	Horizontal Protection Level
IALA	International Association of Aids to Navigation and Lighthouse Authorities
IBPL	Isotropy-Based Protection Level
ICD	Interface Control Document
IGS	International GNSS Service
IMO	International Maritime Organisation
IONEX	real world ionospheric measurements
L1	GPS upper l-band transmission frequency (1575.42 MHz)
LoS	Line of Sight
MHSS	Multiple-Hypothesis Solution-Separation
MOPS	Minimum Operational Performance Standards
MP	Multipath
M-RAIM	Maritime – Receiver Autonomous Integrity Monitoring
MSR	Multi-System Receiver
NGI	Nottingham Geospatial Institute
NLoS	Non Line-Of-Sight

NOAA	National Oceanic and Atmospheric Administration, United States Department of Commerce
PDF	Probability Distribution Function
PPM	Parts per million
PVT	Position Navigation Time
RAIM	Receiver Autonomous Integrity Monitoring
RIMS	Receiver Integrity Monitor Stations
RINEX	Receiver Independent Exchange Format
RTCM	Radio Technical Commission Maritime
SBAS	Satellite-based Augmentation System
SOLAS	Safety of Life at Sea
SSv2	SBAS Simulator v2
TSO-RAIM	Technical Standard Order – Receiver Autonomous Integrity Monitoring
UERE	User Equivalent Range Error
UK	United Kingdom
WAAS	Wide Area Augmentation System
WP	Work Package
ZTD	Zenith Tropospheric Delay

1. Introduction

1.1 Goal of the Work Package

To compare accuracy, system level integrity, continuity and availability performance of the EGNOS maritime A.1046 service with Beacon DGPS. Comparisons will address:

1. Geographical coverage over the UK and Irish waters under nominal ionospheric conditions, especially over northern and western extremities of the EEZ (200nm limit).
2. Specific instances of more extreme ionospheric conditions most likely to be encountered at higher latitudes of the British Isles.

The prior ESSP analysis [as presented at the European Maritime Radionavigation Forum] of continuity performance indicated marginal performance to the north and west of the British Isles. There is also no conclusive evidence of accuracy performance during a solar storm; if there are gaps in EGNOS performance under such conditions, does DGPS react differently and therefore offer the possibility of acting as a complimentary system?

This work will focus on:

1. Simulations to quantify performance of Beacon DGPS and EGNOS, in nominal conditions, but in UK and Irish waters at the periphery of EGNOS coverage.
2. Simulations with combinations of Beacon DGPS and EGNOS with the aim of recommending a simple logic in the receiver (e.g. geographic area and range from Beacon DGPS) to use one rather than the other. The overall aim of the study is to cover all the parameters. This initial report considers accuracy only at this stage.
3. Real data studies to compare actual performance of DGPS and EGNOS positioning under extreme ionospheric conditions.

1.2 Brief background to EU proposed EGNOS V2 ‘maritime ‘A.1046 service’

The development and provision of augmentation services (such as EGNOS and IALA DGPS beacons) are required as satellite navigation suffers from various faults including man-made faults, clock errors, signal deformation and space weather events, which can introduce location errors that may be potentially hazardous to safety of life (SOLAS) critical operations. To date, development of EGNOS services was primarily driven by the aviation community, to augment GPS with systems that detect and remove errors and therefore to achieve the required navigation performance parameters for safe aircraft operations.

This work is maritime-focused, as a number of important differences between the aviation requirements for EGNOS exist, and require consideration for the full utilisation of augmented services.

The general concept of differential GNSS (DGNSS) positioning is based on the assumption that errors experienced by users sufficiently close to each other can be considered common. The main error sources are satellite orbits and clocks, and atmospheric effects, and these are highly correlated for nearby users. These errors can be measured at a known location (termed a Reference Station, RS), by subtracting the known geometrical range to a satellite from the measured range. They can then be transmitted to nearby users to be applied as corrections. As the distance between a user and the reference station increases, the sources of error, particularly the atmospheric effects, become less correlated, so DGNSS becomes less effective. Table 1 lists the main contributors to the spatial decorrelation of the corrections.

Error Source	**Absolute**	**Relative**
Satellite Orbit	2 ... 50 m	0.1 ... 2 ppm
Satellite Clock	2 ... 100 m	0.0 ppm
Ionosphere	0.5 ... >100 m	1 ... 50 ppm
Troposphere	0.01 ... 0.5 m	0 ... 3 ppm
Multipath Code	Metre level	Metre Level
Multipath Phase	mm-cm level	mm-cm
Antenna	mm-cm level	mm-cm

Table 1 Error budget for absolute (SPP) and relative (differential) DGPS/DGNSS positioning (adopted after RTCM 10403.2, Differential GNSS (Global Navigation Satellite Systems) Services - Version 3 with Amendments 1 and 2*, November 7, 2013)*

EGNOS is one of a few satellite-based augmentation systems (SBAS) providing GNSS error corrections covering various regions across the world. SBAS utilises accurately coordinated ground stations that compute differential corrections, integrity messages and error bounding data. Some also provide ranging. Geostationary satellites then broadcast the correction messages over very large regions. Unlike DGNSS, SBAS attempts to split the total range error into separate components; Ephemeris, ionosphere and clocks. The accuracy of EGNOS meets the requirement that reported position should be within three metres in the horizontal plane and 4 meters in the vertical direction (with a probability of 0.95).

However, global augmentation systems cannot correct other error sources (e.g. tropospheric effects (partially mitigated by built-in models), multipath and user receiver contributions and local effects. Reception of the corrections is dependent on line-of-sight communications with an SBAS satellite, which will be at a low elevation when the user is near the edge of the SBAS footprint (e.g. in high latitude locations), leading to signal disruptions. While EGNOS can be accessed via the internet through the EGNOS Data Access Service (EDAS service), this option is not considered for maritime operations because wireless internet access via GPRS/3G, for example is limited.

DGNSS is most effective when the distance between the user and the reference station is short, and errors increase as this distance grows. In contrast, by splitting the error sources into their component parts, EGNOS performance does not vary significantly with distance from a single reference station - performance is generally uniform across the area covered by the network of ground stations. Performance is limited by the ability of the system to accurately model the component errors. For either system, errors will remain that create uncertainty in positioning accuracy. For these reasons the aviation community introduced the concept of required navigation performance (RNP) that strictly defines the safety and performance of flight navigation according to the following four mutually dependent parameters: continuity, integrity, availability and accuracy. These are defined in more detail as follows:

- Accuracy – this is the degree of conformance between the estimated or measured position and/or velocity of a platform and its true position or velocity.

- Integrity - this is the measure of the trust that can be placed in the correctness of the information supplied by a navigation system, including the ability of the system to provide timely warnings to users when the system should not be used for navigation. Although integrity is a complex framework, its ultimate goal is to associate a confidence level to any position estimate. The confidence level and the probability inherently associated to it are typically mapped to the concepts of “protection level” and “integrity risk”. Therefore, integrity is characterised by:

  - Protection level (PL): An estimated upper bound on the true position error (PE) provided by the localisation system. It is the maximum position error that could be caused by an undetected measurement error. In aviation, there are PLs for the horizontal and vertical directions. For ground vehicles it is more useful to distinguish between longitudinal and lateral PLs. The PL is the interval (radius of a circle in a plane), with its centre being at the true position, which describes the region which is assured to contain the estimated quantity.
  - Alert limit: The maximum allowable size of the PL not to be surpassed without raising an alert. Similar to the PL, the Alert Limit (AL) is the interval (radius of a circle in a plane), with its centre being at the true position, which describes the region which is required to contain the indicated position within a specified probability. Theoretically, if the error exceeds the AL, then an alarm should be raised, because an “out-of-bound” error is currently measured.
  - Time-to-alert: The Time To Alarm (TTA) is the maximum allowable time elapsed from the onset of the estimation system being out of tolerance until the equipment enunciates the alarm
  - Integrity risk: Probability, typically on a per-hour basis, that the true position error surpasses the alert limit without an alert being issued.

- Availability - The availability of a navigation system is the percentage of time that the services of the system are usable. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. Signal

availability is the percentage of time that navigation signals transmitted from external sources are available for use. Service availability is the percentage of time that the service provides the required integrity for the given accuracy level. Availability is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.

- Continuity – the ability of the total system (comprising all elements necessary to maintain an asset's position within the defined navigation space) to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.

Within the maritime sector, as in the aviation sector, safety-critical systems must be continuously available as vessels cannot be placed into a safe-state, i.e. stopped, in a relatively short time interval. Therefore, integrity and continuity risks in the maritime sector are defined over the duration of an operation, i.e. a specific manoeuvre, such as port entry, anchoring or docking. IMO A.1046 assumes a 15 minute duration of such manoeuvres as the basis of continuity specifications. The continuity and other requirements for the maritime sector are summarised in Table 2.

Maritime operational requirements on IMO A.1046 (27)						
	Horizontal Accuracy 95%	**Signal availability**	**Service continuity (over 15min)**	**Position update rate**	**Integrity warnings[1]**	**System coverage**
Ocean waters	100m	99.8%	-	2s	MSI as soon as practicable	Adequate[2]
Harbour entrances, harbour approaches and coastal waters	10m	99.8%	99.97%	2s	10s	Adequate[2]
[1]Generation of integrity warnings in cases of system malfunctions, non-availability or discontinuities.						
[2]Taking into account the radio frequency environment, the coverage of the system should be adequate to provide position-fixing throughout this phase of navigation.						

Table 2 EGNOS V2 maritime requirements (IMO Resolution A.1046, ESSP)

2 Tools Description

This section describes the tools and real-world historic data used to conduct the investigation of EGNOS/Beacon interoperability. Two principal modelling tools are selected for this analysis:

- SBAS Simulator V2 (SSv2) which is an EGNOS Service Volume Simulator.
- GAGT (GLA Augmented-GNSS Toolset) which provides marine beacon DGPS simulation.

2.1 SBAS Simulator v2 (SSv2)

SBAS Simulator v2 is a GNSS Service Volume Simulator (SVS), developed for ESA by Iguassu Software Systems. SSv2 was validated against the PEGASUS toolset, the core component of the EGNOS Data Collection Network, and went through the official ESA acceptance process. SSv2 is intended as a primary simulation tool for EGNOS.

The simulator is based on defined macro models. The error bounds definitions follow Minimum Operational Performance Standards (MOPS) for airborne navigation equipment (2D and 3D) using the Global Positioning System (GPS) augmented by the Wide Area Augmentation System (WAAS). This tool can act both as a global SVS but also as a local point simulator, allowing it to provide simulation of precision equivalent to the historical measurement accuracy.

To set up the tool for simulation, following configuration options are used :

- The historical GPS constellation is specified by TLE files. CORS stations locations are pre-defined within the software to match the existing CORS network.
- Ionospheric macro-models giving options to simulate residual ionospheric error (including geometric GIVE, constant user UIVE, historic IONEX file) were compared.
- User mask was set to 15 degrees.
- The option to simulate the probability of data loss (from satellite and CORS station) and fault tree was not used.
- The simulator utilises the aviation SBAS multipath model, that assumes exponential growth of multipath for low-elevation satellites. This model cannot be changed.

The simulator can also work with real data historic EGNOS messages (EMS), that include corrections as well as UDRE and GIVE, statistical estimates of the satellite and ionospheric errors remaining after applying the corrections. This overrides any macromodel settings within the software.

2.2 GLA Augmented-GNSS Toolset (GAGT)

GAGT is a Matlab-based toolset developed and maintained by GLA with the primary purpose of simulating DGPS and maritime EGNOS performance. GAGT is a verified marine beacon DGPS simulation tool. It also contains a model of SBAS which, although not formally validated, can be used to cross-check against SSv2. GLA believes that it thoroughly represents the EGNOS V2 maritime 1046 service.

In the current work the DGPS functions of GAGT are used. This mode simulates a user applying corrections from the nearest beacon.

- Only common-view satellites (visible simultaneously to both the user and the beacon) are included in the user's navigation solution.
- A nominal user differential range error (UDRE) is computed, as published in DO-229, after DGPS corrections are applied.
- A nominal local code-noise and multipath (CNMP) model, as published in DO-229, is applied for residual noise at the user's receiver.
- An estimate of parallax due to un-corrected orbital errors is calculated.
- Spatial de-correlation, as the user and the beacon reference station observe different amounts of atmospheric delay, so a bias error is incurred which depends on the distance from the user to the station (baseline length).
- Bias errors due to orbit, clock, troposphere and ionosphere are assumed to be eliminated by the DGPS differential corrections. This can be kept constant. In the current task vertical ionosphere delay was calculated from historic IONEX data to match the day.

2.3 RTKLIB

RTKLIB is an open source software package, created by T. Takasu from Tokyo University of Marine Science and Technology, for standard and precise positioning using GNSS. It is used to process historical data.

To obtain results representative of the marine DGPS beacon, RTKLIB was used as follows:

- Single difference processing using only GPS L1 code observations and broadcast ephemerides.
- Each of 114 Ordinance Survey CORS stations was processed against the NGB2 (Nottingham Geospatial Building) permanent station, located at the University of Nottingham, generating baselines between 30km and 800km in length.
- Data was processed using a 30s epoch (interval), without the use of any ionospheric or tropospheric correction models. The CORS coordinates were obtained from the OS website, with an accuracy of 2cm planar.
- Cut-off angle was set at 15 degrees

To obtain results representative of EGNOS, RTKLIB was used as follows:

- Standalone positioning using only GPS L1 code observations, EGNOS corrections and broadcast ephemerides
- Data was processed using 30s epoch (interval), using the EGNOS Broadcast ephemeris with fast and long-term (flt) correction messages clock corrections and ionospheric grid corrections.
- The EGNOS MOPS correction model was used for the troposphere.
- Cut-off angle was set at 15 degrees.

2.4 gLab

gLab is an ESA-approved GNSS processing software (capable of producing SPS, DGPS, EGNOS and PPP solutions). It was developed by the gAGE research group at the Technical University of Catalonia (UPC) and it has more advanced atmospheric settings. It will be not used as a main processing tool but, when severe weather is considered, it will be an alternative post-processing tool if RTKLIB validation will be needed. The aim is to provide the research with confidence that the processing software does not affect the results.

2.5 Historical Data

Aims of using historic data are:

1. Post-processing CORS RINEX data in RTKLIB to determine the accuracy that is expected from DGPS beacon (and GAGT) on ‘nominal days’.
2. Post-processing CORS RINEX data + EMS messages in RTKLIB to determine the accuracy that is expected from EGNOS (and SSv2) on ‘nominal days’.
3. Post-processing CORS RINEX data +EMS messages in RTKLIB under ‘extreme’ ionosphere conditions, to assess how well EGNOS positioning works under extreme conditions.
4. Post-processing CORS RINEX data in RTKLIB under ‘extreme’ ionosphere conditions, to assess how well DGPS positioning works under extreme conditions.

Compare 2 and 3 to determine relative performance Beacon DGPS and EGNOS under extreme conditions.

The following data formats will be used:

- ESA EGNOS Message Server (EMS), is a data interchange format for the SBAS messages, as broadcast by the EGNOS system through GEO satellite. This allows to post-process EGNOS corrections (for RTKLIB) and to use UDRE and GIVE, statistical estimates of the satellite and ionospheric errors remaining after applying the corrections (for SSv2).

- IONospheric map EXchange format (IONEX) is a data interchange format for 2- and 3-dimensional TEC maps given on a geographic grid. In the scope of the project IONEX is being used by SSv2 for ionosphere simulation.
- Receiver Independent Exchange Format (RINEX) is a data interchange format for raw satellite observation data. This allows the user to post-process data (in RTKLIB). A RINEX file and an EMS file is required for EGNOS post-processing. Two RINEX files (base and rover) are required for DGPS post-processing.

The following historical data will be used:

- For initial normal operational scenarios (in WP2.1.1) – Historical CORS station data and EGNOS messages;
- For dedicated Space Weather events (Scenarios in WP2.1.2) – Historical CORS station data and EGNOS messages; – Historical ionospheric maps from space weather event periods; – Potential use of historical RIMS data.

Only historical data will be used, and no dynamic data collection is required for the completion of the study. Processing of historical data will be conducted using open source RTKLIB. A set of supporting tools (in Matlab and python) will be used and developed to provide full analysis.

3 Tools configuration and validation

The study aims to compare the performance of marine beacon DGNSS and a maritime EGNOS v2 'A.1046' service to determine their levels of performance under both nominal and unusual conditions. This section describes the method of determining and comparing the performance of the two systems. It offers a description of how models of beacon DGPS and EGNOS are used in the study, together with the use that is made of historical recorded data.

Much of the study relies on using simulation tools to predict system performance. The objectives of the work package, which are to assess the performance of beacon DGPS and EGNOS in UK and Irish waters under both nominal and extreme conditions, rely on the outputs of these simulation tools being both comparable with each other (so they can be compared and combined), and representative of true positioning performance, so it is essential that the simulation outputs are shown to be realistic. This occupies all of the work presented here.

It is useful to define what is meant by 'performance'. Fundamentally the simulation tools will attempt to predict positioning *accuracy*, which is an input to the derivation of availability and continuity statistics. Accuracy is defined as the difference between a position solution and the true coordinates of the user.

Least-squares simulators assume a zero-mean normal distribution of measurement errors. Such measurement errors are represented by measurement *standard errors*. The standard error of a (pseudorange) measurement is often computed as the root-sum-square of several components of an error budget (ephemeris, multipath, ionosphere, thermal noise etc), each of which is expressed as an error in the direction of the range measurement. Measurement standard errors are then propagated through the least squares positioning solution, via measurement weights, to yield a *positioning standard error*. The least squares positioning solution is also where the impact of measurement geometry, i.e. which satellites are used and where they are relative to the user receiver, is accounted for. This approach is directly analogous to the concept of Dilution Of Precision, or DOP. DOP is used, as the name suggests, to express the amount by which the geometry of the satellites relative to the user location will 'dilute the precision' of the measurements:

Measurement precision x Dilution of Precision = positioning precision.

For example, if all the measurements are assumed to have a precision (standard error) of, say, 35cm, and the constellation geometry yields a DOP value of 1.5, then this will indicate that the position solution will have a precision (represented its 'standard error') of 35 x 1.5 = 52.5cm. The use of DOP in this way assumes that all measurements share a common standard error. The key difference between this simplified approach and a full least squares service volume simulator is that the latter allows for a different measurement standard error for each measurement. For example, low elevation satellites may have a larger standard error to represent larger uncertainties in the atmospheric models, and GNSS satellites that are

monitored by fewer RIMS may have a larger uncertainty associated with some error components, such as ephemeris and clock corrections.

Calculating the standard errors of each error component is a large part of what a service volume simulator does, and ensuring that those values are realistic is an important step in configuring such software.

Positioning standard error is hence one of the key outputs of a least squares service volume simulator. Fundamentally it is a quantity that is computed at a single location and a single instant in time. By allowing the constellation to evolve as the satellites move within their orbits, it is possible to produce a time series of positioning standard errors at a single point in space. To produce maps of performance over a 'service volume' a simulator will divide the surface into a series of grid points and compute such a time series at each grid point. The data obtained at each grid point can then be processed to generate representative statistics at each grid point (e.g. worst case positioning standard error), and the gridded statistics can then be plotted, e.g. as a contour map, over the entire service volume.

Positioning standard error is often referred to as '*precision*', and is an indication of the potential scatter of points that would be obtained if multiple position solutions were derived from multiple observations that all share the same distribution of measurement errors. It can be used as an indicator of the accuracy that a real receiver would achieve, using real measurements whose errors share the modelled distribution. This work package relies on this fact. But care must be taken when interpreting measurement standard errors as 'accuracy'. One of the principal factors to consider is the issue of biases in the measurements.

Least squares simulators assume that measurement errors are unbiased. In practice this means that either the positioning solution has models to correct or terms to solve for (estimate) possible biases (e.g. atmospheric delay effects), or the measurements are corrected externally (as in the case of EGNOS and DGPS). To account for the possibility that those terms/models/corrections are not perfect, leaving a residual systematic bias in the measurements, a least squares simulator can accommodate this by increasing the error budget such that it 'over bounds' the expected amount of the bias, but this does not then result in a true reflection of the bias or the scatter.

To illustrate this with arbitrary values, if all measurements have a noise of +/- 35cm but are biased by 1m, least squares simulation can only accommodate this bias by specifying a noise that is big enough to over bound 35cm + 1m. This will result in a position standard error that is big enough to include the biased position error, but which no longer properly reflects the scatter of the position solutions. The impact of biases, if of interest, must be studied using a different approach. The GAGT tool, for instance, explicitly models the impact of the decorrelation of some error components with increasing distance to estimate a bias vector at the user location, which is a separate step from the estimation of the standard error. Nevertheless, this over bounding approach will be encountered several times in this study.

3.1 Methodology Approach

Our overall approach can be defined as:

1. Verification of the GLA Augmented GNSS Tool (GAGT) to confirm the GAGT model's representation of real DGPS performance derived for a wide spread of differential baseline distances in typical atmospheric conditions.
2. Calibration and verification of the SBAS Simulator 2 (SSv2) model to confirm the SSv2 model's representation of expected maritime EGNOS V2 maritime 'A1046 service' performance.

Once the models are correctly configured:

1. Use the GAGT model to produce maritime beacon DGPS performance and maritime coverage plots across UK and Irish waters.
2. Use the SSv2 model to produce EGNOS maritime equivalent coverage plots across UK and Irish waters.
3. Comparison of EGNOS and DGPS from the coverage plots, identifying any possible shortfalls in the coverage of each, and any geographic areas that may benefit from a complementary use of the two systems.

In the further work, under WP2.1.2, not yet covered in this report, the analysis will be extended to consider the comparison of maritime EGNOS and marine beacon DGPS for the following:

1. Further analysis for vessel locations towards the westerly and northerly limits of EGNOS coverage within the 200nm EEZ of the UK and Ireland.
2. Effects of severe space weather conditions on the comparisons of the two systems, for scenarios identified by analysis of recorded historical data.
3. Assessment of interoperability options, e.g. EGNOS with a reduced number of IALA Beacons.

3.1.1 Stage 1: Determine the DGPS accuracy, expected from IALA DGPS beacons on a 'nominal day'

The aim is to demonstrate that the standard errors predicted by GAGT (scaled to represent the 95th percentile) are realistic estimates of the 95th percentile of real DGPS positioning. The challenge is to ensure that the error budget, configured through external files (e.g. IONEX) or representative variances, is realistic and representative of prevailing conditions and receiver performance.

We will compare estimates of Horizontal Navigation System Precision (HNSP) generated by GAGT with the accuracy (Horizontal Navigation System Error, HNSE) obtained by post-processing historical DGPS data.

We will use historical data from the UK CORS network to create 114 DGPS baselines of increasing lengths, demonstrating the effect of error de-correlation. The expected range of IALA DGPS beacons, due to radio range and normal ionospheric conditions, is up to 350km. In this study, we test extended baselines (up to 800km) to demonstrate that, in normal ionospheric conditions, the DGPS error de-correlation can be defined as linear. This assumption will be compared with other atmospheric scenarios, including the severe space weather conditions, in the later stage of the study.

Historical data was processed as follows:

- RTKLIB was used for single difference processing of 114 historical baselines (between NGB2 and each of the 114 stations in the CORS network) to simulate performance representative of the marine DGPS beacons under normal atmospheric conditions. For each baseline, the Horizontal Navigation System Error (HNSE) (DGPS horizontal position solution minus the truth) , resulting in a time series of 2880 data points (24hrs at 30s interval) for each baseline;
- For each baseline length, the 95th percentile of HNSE was determined, i.e. the value below which 95% of the HNSE values may be found. Figure 1 shows the cumulative distribution functions for all of the 114 processed baselines.

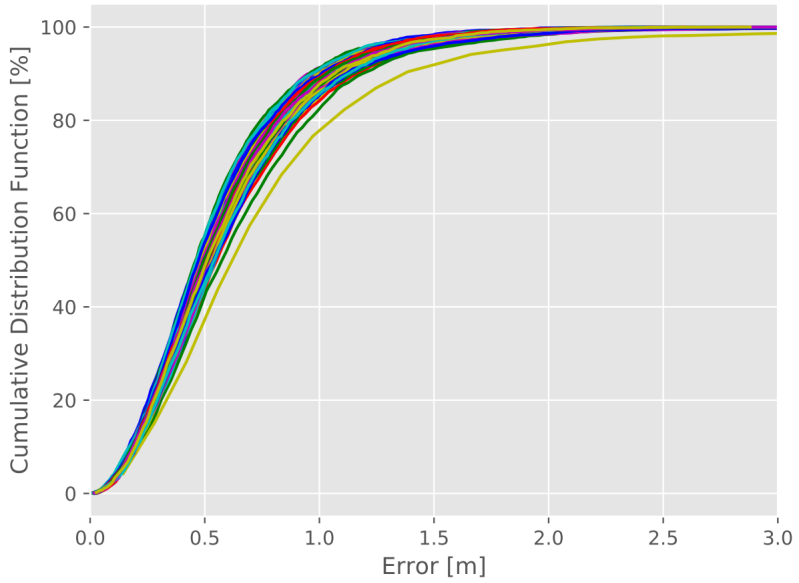

Figure 1 Cumulative Distribution Function (CDF) representation of 95th percentile for 114 DGPS baselines

- The baselines were by length and, assuming linear decorrelation of DGPS corrections with distance, the best fit straight line for the 95th percentile of HNSE was determined. The best fit lines are shown in Figure 2 and Figure 3;

DGPS performance was modelled using GAGT as follows:

- With a contemporary IONEX file to represent ionospheric conditions, and a Code Noise and Multipath (CNMP) error tuned to represent CORS measurements, DGPS performance (95th percentile of HNSP) was simulated for the same day and the same 114 baselines, to obtain the modelled Horizontal Navigation System Precision (HNSP).
- Assuming linear decorrelation of DGPS corrections with distance from the beacon, the best fit line through these simulated results was determined.

The GAGT simulations and historical data results were compared:

- The bestfit lines (HNSE and HNSP) were compared. Since the GAGT models have been previously validated, the expectation is that, with appropriate model settings, those will be similar, meaning that GAGT HNSP predictions will be indicative of real data HNSE.

Figure 2 shows the simulation and historical data comparison for day 75 of 2019. Although the best fit lines show differences in the intercept and the slope, the difference is at the sub-decimetre level. For comparison, a second day (day 107 of 2019) was processed the same way. The GAGT model remained the same as for day 75, but the IONEX file used to simulate the ionosphere was updated to a contemporary file for day 107. The results from this day are shown in Figure 3. The comparison is similar to that shown for day 75l the slopes are more similar on this day, but the intercept is again different, with the resulting difference being at the sub-decimetre level.

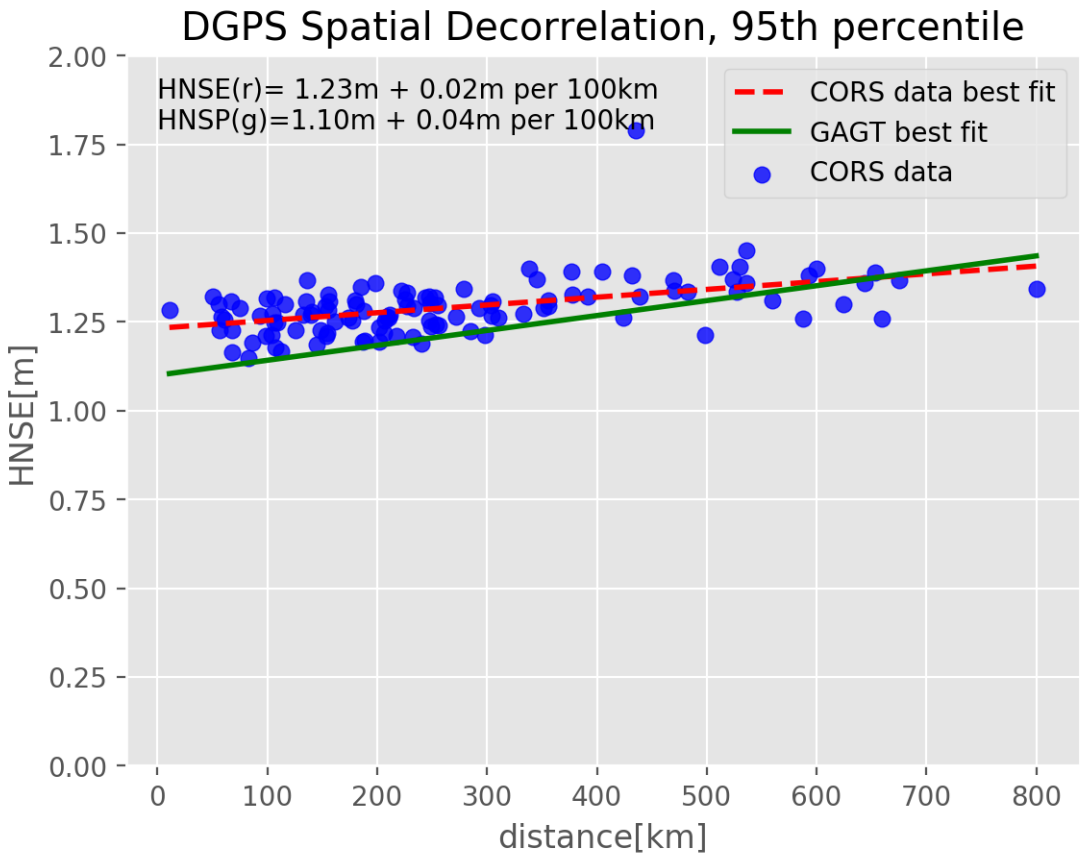

Figure 2 DGPS de-correlation effect showing difference between model (HNSP, green) and historical data (HNSE) for 075/19

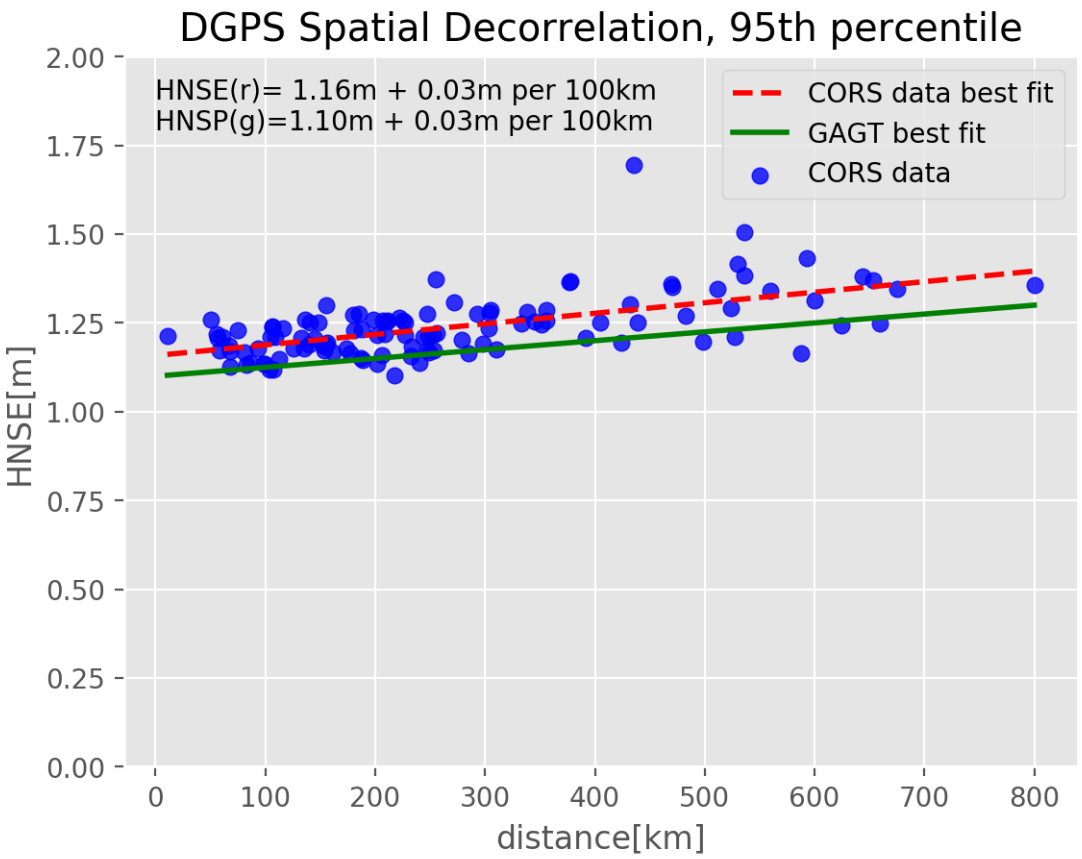

Figure 3 DGPS de-correlation effect showing difference between model (HNSP, green) and historical data (HNSE) for 107/19

3.1.1.1 Conclusion

Historic GPS observations from 114 stations in the CORS network were processed to simulate DGPS positioning performance across multiple baselines. The results were plotted as 95% error vs baseline length. GAGT was used to simulate the same day's data with realistic atmospheric and measurement errors, and a similar plot was produced.

There are small differences in the model (HNSP) and historical data (HNSE) which can be largely explained by the fact that the simulation attempts to match the overall behaviour of the atmosphere on the chosen day, but variations in that overall behaviour over the area covered by the 114 CORS stations will lead to differences. Although the two best-fit straight lines appear slightly different as a result, the magnitude of the differences is at the sub-decimetre level, so it can be concluded that GAGT is able to simulate the performance of real DGPS adequately.

3.1.2 Stage 2: Determine the EGNOS accuracy on a 'nominal day'

To understand whether SSv2's output of positioning standard errors represents the expected distribution of positioning errors that will be encountered by a real receiver making real measurements, it is necessary to compare the statistical outputs of the simulator with a range of results from real measurement data, and to configure SSv2 using sensible model parameters to achieve the best fit with real data.

To achieve this, the RTKLIB post-processing tool has been used to compute epoch-by-epoch position solutions from raw measurements (in the form of RINEX files) that were recorded at fixed CORS sites, together with contemporary measurement corrections that were broadcast by EGNOS, and which are introduced into the post-processing via EMS files. Each position solution was then compared with the known 'truth' coordinates of the CORS site, to generate a time series of measured position '*errors*'.

In parallel, SSv2 was used to generate a time series of positioning *standard errors* at the same location(s), using contemporary satellite ephemeris files. Several different time series have been produced, using different configurations of the software, to demonstrate the options available and the importance of the correct configuration.

A statistical comparison has then been made between the measured position errors (from real data) and the position standard errors from SSv2. Since the simulator generates only *standard errors*, a comparison with a series of measured position errors can only be made at an overall statistical level. The standard errors have an associated probability – they represent the position error that is expected to bound a given percentage of measured position errors. For horizontal standard errors, this expected percentage ranges from 63% (if the distribution of position errors is circular) to 68% in the limit if the distribution is skewed, tending towards a one-dimensional distribution.

The approach presented below is therefore to compare each measured position error to the corresponding simulated standard error, and to derive statistics for the 24-hour comparison. If the simulator is correctly set up, we would expect 63% to 68% of the measured position errors to fall below the corresponding simulated standard error. If the percentage is significantly lower, this implies that the simulated standard errors are too low, i.e. 'optimistic', and the error budget has underestimated the real measurement errors.

Conversely, a larger percentage implies that the simulator has overestimated the measurement errors. In addition, to assess the distribution of the real position errors compared to the simulated standard errors, in order to give confidence that the simulator is modelling the geometry correctly, we also introduce the concept of a 'normalised' position error.

To account for the variation in simulated standard errors due to changing satellite geometry, we divide the real position error by the corresponding simulated standard error, and then

assess the distribution of these normalised position errors. By definition, the proportion of normalised position errors which are below unity will be the same as the proportion of raw position errors which are below the corresponding position standard errors, so the expectation is that the proportion below unity will be between 63% and 68%. Furthermore, if the normalised position errors follow an ideal Rayleigh distribution, then the expectation is that the 50th percentile of the normalised position errors (which corresponds to the CEP, or circular error probable, radius) will be 0.83.

The above analysis approach will therefore yield two analysis plots for each tested data set:

- The first will be a time series of measured position errors, overlaid with the simulated standard errors, and a statement of the percentage of measured position errors that fall below the simulated standard errors.
- The second will be a histogram plot of the normalised position errors, with a statement of the 50th percentile, and the proportion below unity.

This part of the work aims to determine and demonstrate the most appropriate way to configure SSv2 to simulate realistic EGNOS performance on a 'typical' day. SSv2 offers four methods of modelling residual ionospheric measurement errors:

i. A user-specified constant IURE. This is a simplistic approach which is not expected to match actual ionospheric conditions except at a superficial level. It is used here only to demonstrate the impact on the simulations when the IURE is set to zero.
ii. A GIVE model (a built-in model of Grid Ionospheric Vertical Error). This model is highly configurable, but is based on the RIMS network's ability to monitor the ionosphere, rather than the actual state of the ionosphere.
iii. The use of an external IONEX file. This model uses 'post-event' grid representations of the actual state of the ionosphere to estimate the error in the ionospheric correction at each pierce point.
iv. The use of historic EGNOS messages (EMS). The EGNOS messages include UDRE and GIVE, statistical estimates of the satellite and ionospheric errors remaining after applying the corrections. These are used to compute an aviation certified error bound for the position solution in an integrity assessment. This information from EGNOS is over-estimated for the reason of aviation integrity (to ensure that the estimates overbound any biased error populations), so this method is expected to give the most pessimistic values of positioning standard error.

Results from all four of these methods are compared with results from post-processing historical data, as follows:

1. Use SSv2 to model EGNOS precision using a constant IURE of zero, to simulate perfect ionospheric corrections.
2. Use SSv2 to model EGNOS precision using the built-in GIVE model with default settings.

3. Use SSv2 to model EGNOS precision using historical IONEX data, to closely match the ionospheric conditions on the chosen day.
4. Use SSv2 to model EGNOS precision using historical EGNOS data, to demonstrate the pessimistic performance of EGNOS when the user range errors overbound the true errors for reasons of aviation integrity.
5. Estimation of EGNOS accuracy using historical data – Use RTKLIB to process historical data with historical EGNOS corrections to obtain a time series of 2880 data points (24hrs at 30s interval) of EGNOS position solutions. Calculate Horizontal Navigation System Error (HNSE) at each data point (EGNOS corrected horizontal position minus true position).
6. Compare all SSv2 model outputs with measured HNSE as described above.

For the initial tests, the station NGB2 was selected (Nottingham Geospatial Building), using data collected on day 107 of 2019.

The first step is therefore to compare the position standard errors produced by SSv2 under different settings. As described previously, these settings are:

i. A user-specified constant IURE. A value of zero was selected for this test to highlight the impact of the other models.
ii. The built-in GIVE model with default settings.
iii. The use of an external IONEX file from the same day as the measurement data.
iv. The use of historic EGNOS messages (EMS) from the same day as the measurement data.

The following figure illustrates the effects of these models over the complete 24-hour period.

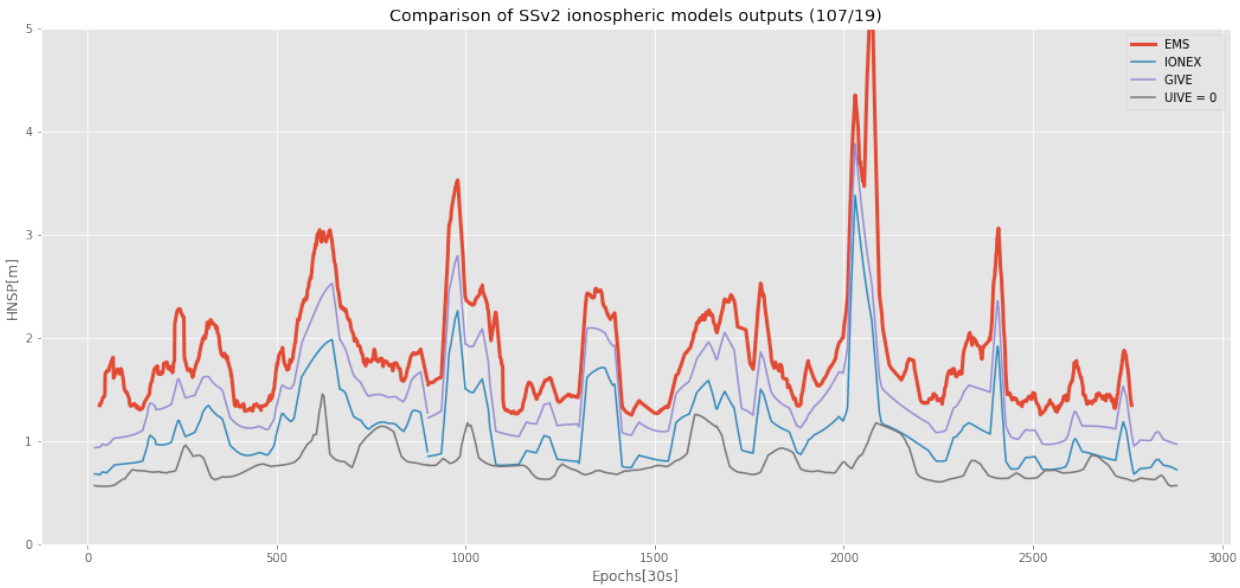

Figure 4 Comparison of SSv2 positioning standard errors with different ionospheric models

Each separate line in the above figure shows peaks and troughs that are dictated by the time-varying geometry of the available satellites. The figure demonstrates that the lowest standard errors are achieved when the IURE is set to zero, simulating perfect correction of the ionospheric effect. The line above that is the case when an IONEX file is used to represent the real state of the ionosphere on the chosen day. Above that is the case when the built-in GIVE model is used with default settings. The top line, indicating the most pessimistic estimates of positioning standard error, is the case where EMS messages are used, in place of modelled error budgets, to represent the measurement errors as broadcast on the chosen day. The pessimistic estimates of position standard error are caused by the inflated URE values broadcast by EGNOS, which ensure that the URE will always overbound a biased error distribution for the purpose of aviation integrity.

The next step is to generate measured position errors, by processing historic RINEX data and contemporary EGNOS corrections using RTKLIB.

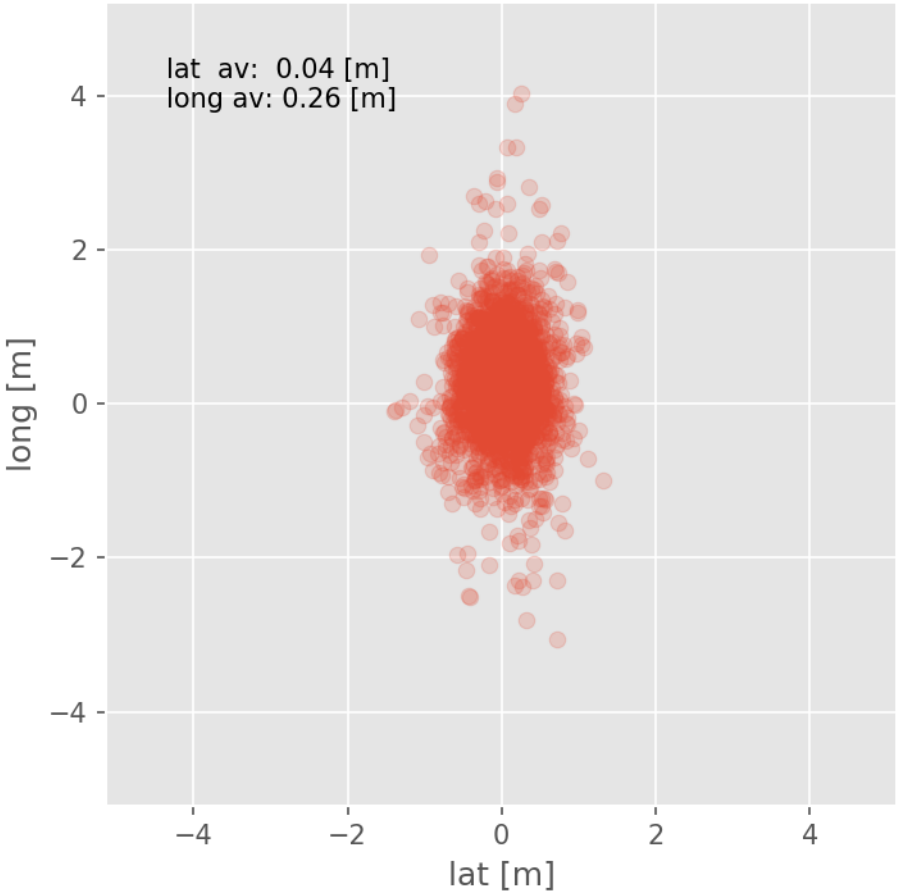

Figure 5 below is a scatter plot of horizontal positioning errors. A couple of points should be noted:

- The centre of the scatter plot appears to be close to (0,0), indicating that the mean position error is small. In fact, the mean position error is close to 26cm. This amount

of 'bias' in the mean has very little effect on the computation of scatter statistics, and can be considered negligible.

- The distribution is not circular. The spread in latitude error is greater than the spread in longitude error; a common feature with higher latitude stations, due to the 'hole' in the sky, centred over the North (and South) pole(s) where no satellites can appear. This non-circular distribution suggests that the percentage of points with an error below the corresponding standard error will be greater than 63%.

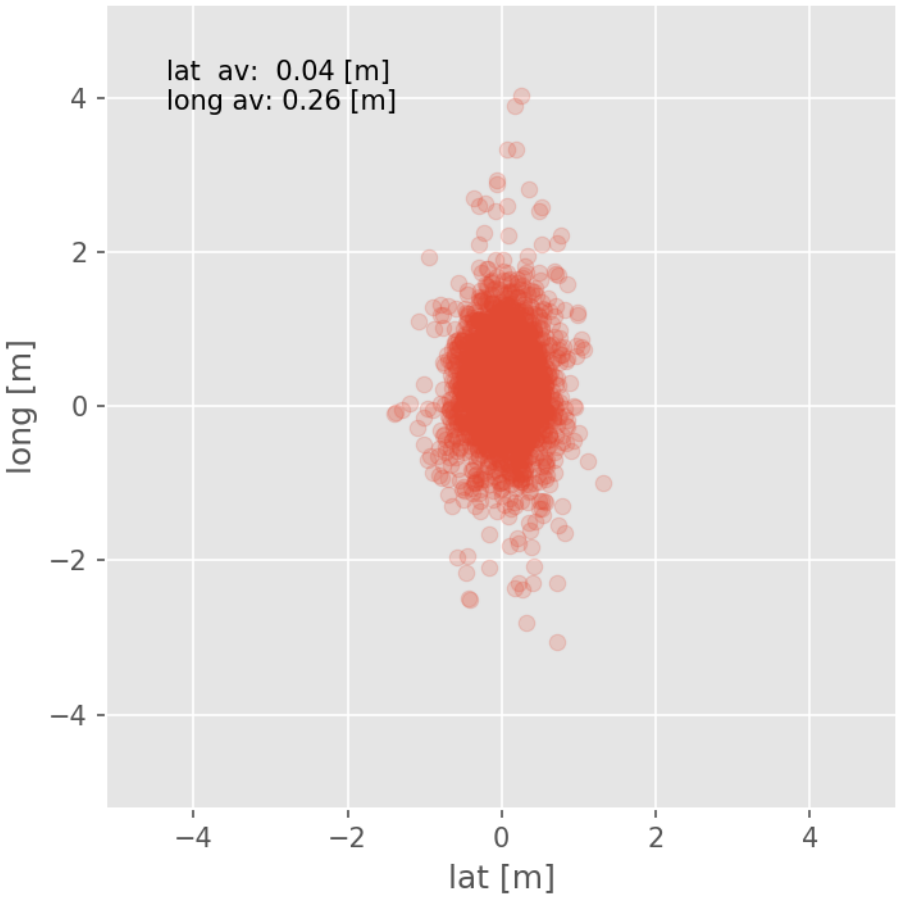

Figure 5 Scatter plot of position errors as computed from 24 hours of historic RINEX data at NGB2 station on day 107 of 2019.

Figure 6 below shows a simple time series of the raw measured position errors. The noise in these position errors obscures any underlying structure (such as the expected correlation with SSv2 standard errors), so Figure 7 shows the same data with a mild smoothing filter applied (20-epoch sliding window average). This is purely to aid visualisation; all statistics in all of the following figures are always generated from the raw unsmoothed data.

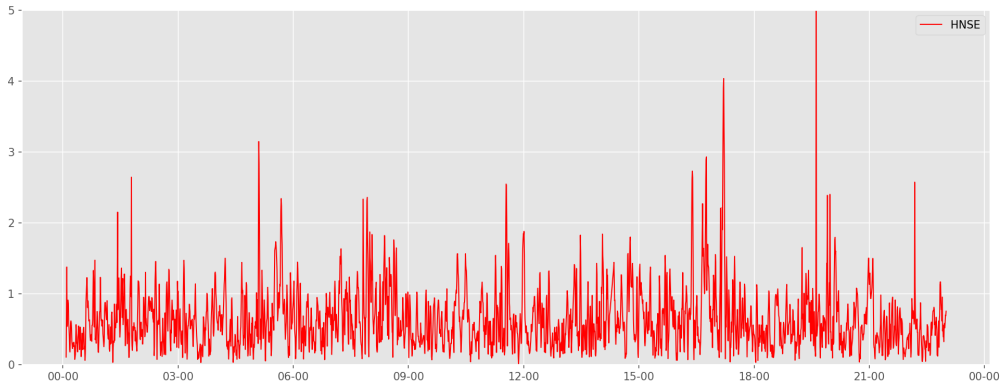

Figure 6 Raw position error (HNSE) determined from RTKLIB processing of historic RINEX data from NGB2 on day 107.

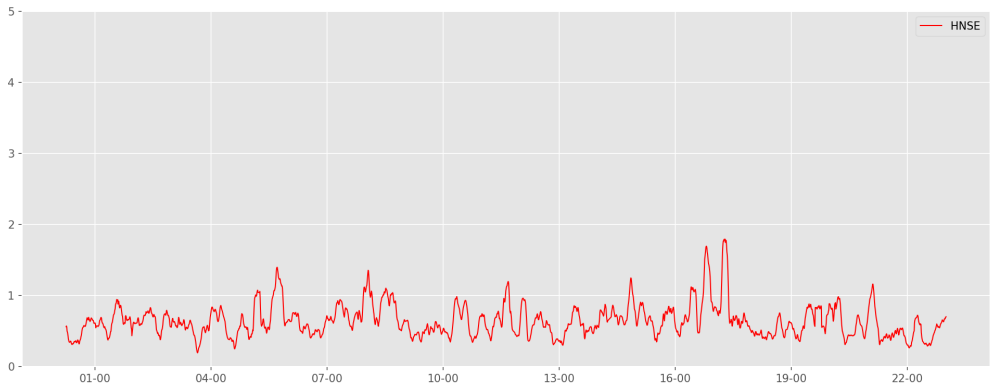

Figure 7 Smoothed position error (HNSE) determined from RTKLIB processing of historic RINEX data from NGB2 on day 107.

The above figures show that the position errors are not entirely random – there is some structure, especially in the smoothed plot, which indicates some time correlation between epochs. The spikes at approximately 17:00, are particularly notable.

We next show the smoothed plot of position errors overlaid with the position standard errors computed by SSv2 using the IONEX model. From the four SSv2 outputs shown in *Figure 4*, this is the configuration that best matches measured position errors.

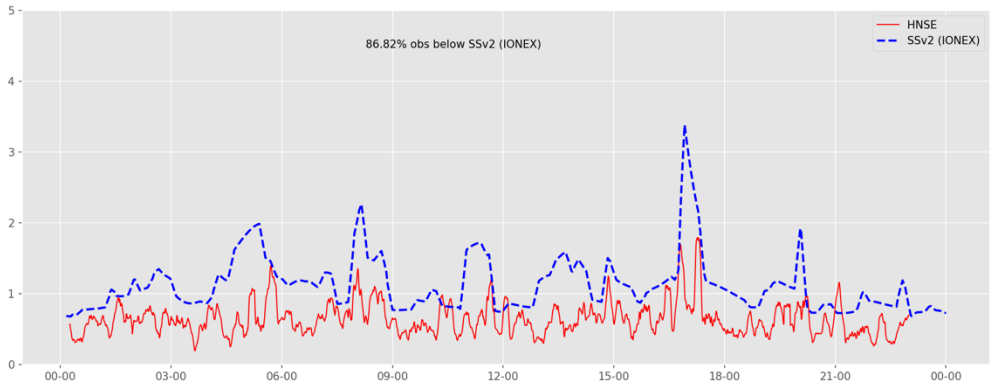

Figure 8 Smoothed position error overlaid with SSv2 standard errors, from NGB2 on day 107

It is notable that the spikes at approximately 17:00 correspond to a spike in the simulated standard error. It is also clear that several other 'features' in the measured position are correlated with similar features in the simulated position standard errors, such as the peaks between 08:00 and 09:00, and between 19:00 and 20:00. This is an expected result; in general, large position errors should only occur when the satellite geometry is poor and/or when the measurement errors are large, so this observed correlation confirms that the simulation is generally matching at least the geometrical properties of the real measurements.

Recalling that the expected percentage of measured position errors that should fall below the corresponding simulated standard errors is between 63% and 68%, it is clear that the actual calculated percentage, 84%, is too high, indicating that the simulated standard errors are too high on average. This indicates that the SSv2 error budget is not yet configured to match the errors present in the real data.

Figure 9 shows the SSv2 configuration panel corresponding to the above simulations. It shows how the various components of the overall error budget are configured. There are three greyed-out options:

- σ_{UDRE} is greyed out because, in the default configuration, SSv2 computes this value as a function of the number of RIMS that are currently observing the satellite (see *Figure 10*).
- σ_{DFRE} is greyed out because it only applies to dual frequency simulations
- σ_{UIVE} is greyed out because the ionospheric error is computed from the supplied IONEX file, rather than from the built-in model.

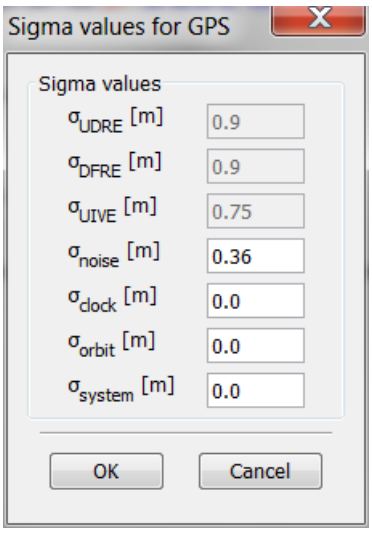

Figure 9 Configuration of measurement error budget within SSv2.

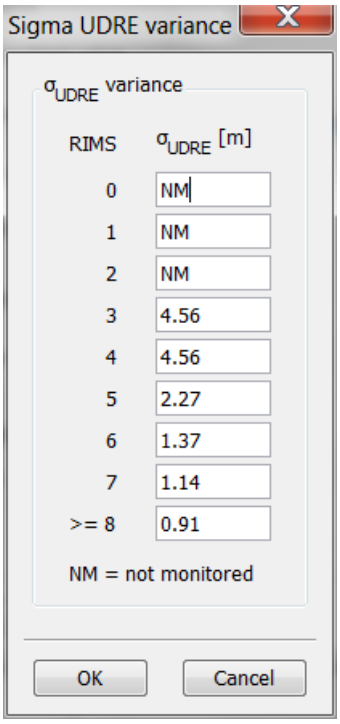

Figure 10 Configuration of σ_{UDRE} within SSv2.

It can be seen from *Figure 10* that σ_{UDRE} decreases as the number of RIMS tracking the satellite increases, reflecting the fact that ephemeris and clock errors are better observed (with a smaller uncertainty) when the satellite is tracked from more receivers on the ground. It can also be seen that σ_{UDRE} is never less than 0.91m, even when tracked by many more RIMS.

It is possible to disable the RIMS-based σ_{UDRE} model and simply supply a fixed value that should be used for all satellites at all times. As an illustration, *Figure 11* shows that the use of a fixed value of 0.90m produces virtually identical results to the use of the σ_{UDRE} model

(shown in *Figure 8*), suggesting that most satellites are observed by 8 or more RIMS continuously, so the model always yields a σ_{UDRE} value of 0.91m.

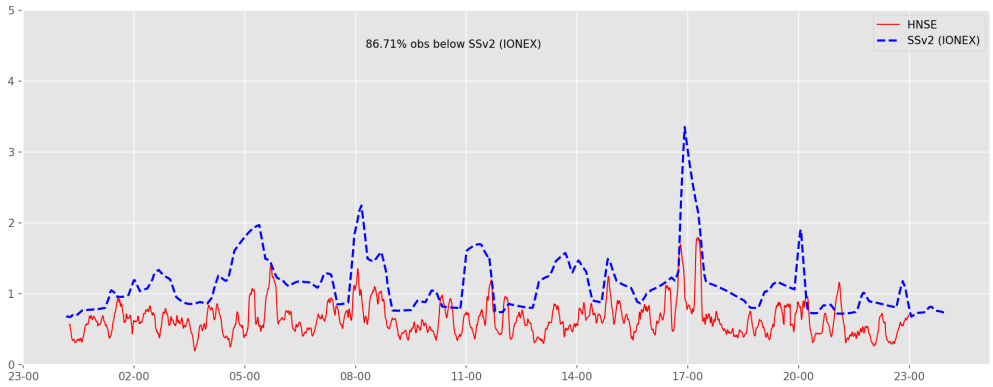

Figure 11 Smoothed position error overlaid with SSv2 standard errors from constant σ_{UDRE} value of 0.90m, from NGB2 on day 107.

The overall measurement standard error in SSv2 is computed as the root-sum-square of all the model components. From the above conclusion that the default SSv2 standard errors are too high, it is clear that one or more of the model components needs to be reduced. From an analysis of the measurement residuals in the real data processing it was concluded that the measurement noise from the receiver at NGB2 was not significantly different from the σ_{noise} value of 0.36m used as the default value in *Figure 9*, and anyway, with a σ_{UDRE} value that is never less than 0.91m, the RSS of all the measurement errors will be dominated by σ_{UDRE}, so small changes in σ_{noise} will have a negligible effect.

The other major component of the error model is the ionospheric model, and since it is anticipated that the use of a contemporary IONEX file will match the prevailing ionospheric conditions for any given day, the only option for reducing the error budget is to use smaller values for σ_{UDRE}. Whilst the theoretical justification for this is unproven at this stage, it is possible that the σ_{UDRE} model is designed to be conservative, and that the large number of RIMS tracking each satellite did result in smaller σ_{UDRE} values on the day in question. Further investigation of this is required, but as an illustration of an approach that can lead to lower simulated position standard errors, the fixed value of 0.90m was reduced to 0.50m, and the resulting position standard errors are plotted in *Figure 12*

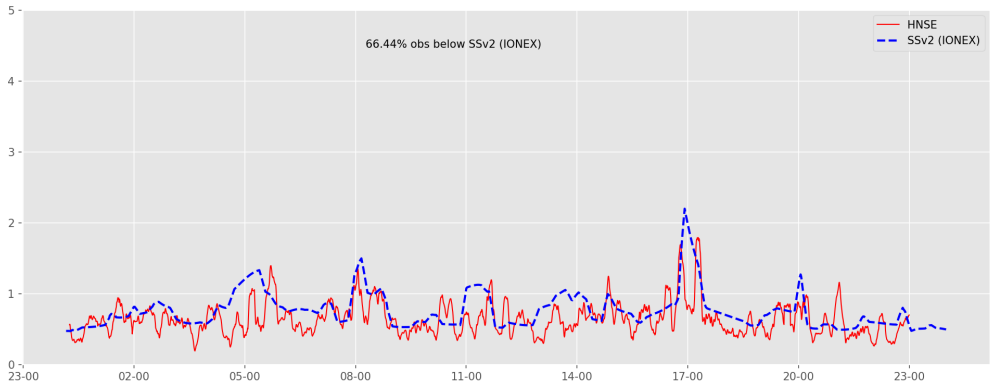

Figure 12 Smoothed position error overlaid with SSv2 standard errors from constant σ_{UDRE} value of 0.90m, from NGB2 on day 107

With the fixed value of 0.50m for σ_{UDRE}, the simulated standard errors are clearly now a better match to the measured position errors, and the percentage of measured position errors that are below the simulated standard errors is now 66.4%, which is within the expected range.

Furthermore, the distribution plot of the normalised position errors (
Figure 13 below) shows that CEP, the radius that encloses 50% of normalised position errors, is 0.76, rather than the expected 0.83. This indicates that the position errors are slightly smaller than the simulated standard errors might suggest. However, increasing σ_{UDRE} above 0.50m would also have the effect of increasing the 66.4% of points that are below the simulated standard error, such that they might exceed the maximum 68%. So it seems that either the distribution of measured standard errors does not match a perfect Rayleigh distribution or the simulation does not perfectly represent the measurement errors.

However, for a single station, with fewer than 3000 data points, it would be unlikely for the statistics to fit perfectly, so the similarity between the simulation and real measurement errors, as illustrated in *Figure 12*, is encouraging. If borne out by repeated tests with different data sets, then it is an indication that SSv2, as configured, can be used to predict real positioning accuracy.

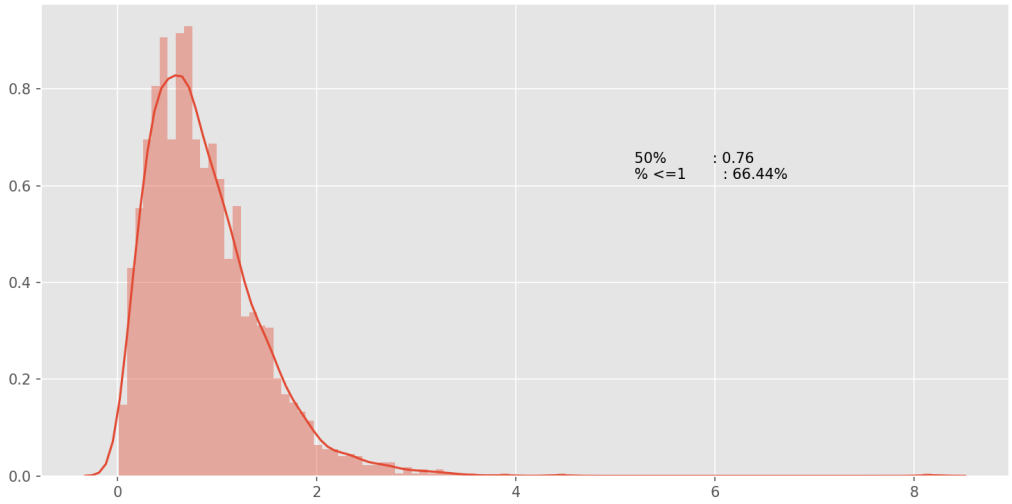

Figure 13 Distribution of normalised position errors from NGB2 on day 107

As a first attempt to determine whether the simulation model used in the above example can produce realistic results under different conditions, another day of data from the NGB2 receiver has been processed. Whilst day 107 of 2019 was classified as a 'quiet' ionospheric day, this additional day, 134 of 2019, was classified as a 'disturbed' ionospheric day. The processing approach applied above was repeated:

- Historic RINEX data from NGB2 on day 134 was processed in RTKLIB using contemporary EGNOS corrections.
- SSv2 was used to simulate the same day, using the same model configuration (σ_{UDRE} = 0.90m and 0.50m, σ_{noise} = 0.36m). The only difference was that the correct contemporary IONEX file for day 136 was used to represent the prevailing ionospheric conditions.
- In Figure 14, the scatter plot of measured position errors shows similar characteristics to the earlier day, as shown in Figure 5. The mean of the scatter plot is biased from the known value by 25cm.

The measured position errors appear to be similar to the earlier example. There is a notable spike at approx. 15:00, lasting approx. 20 minutes

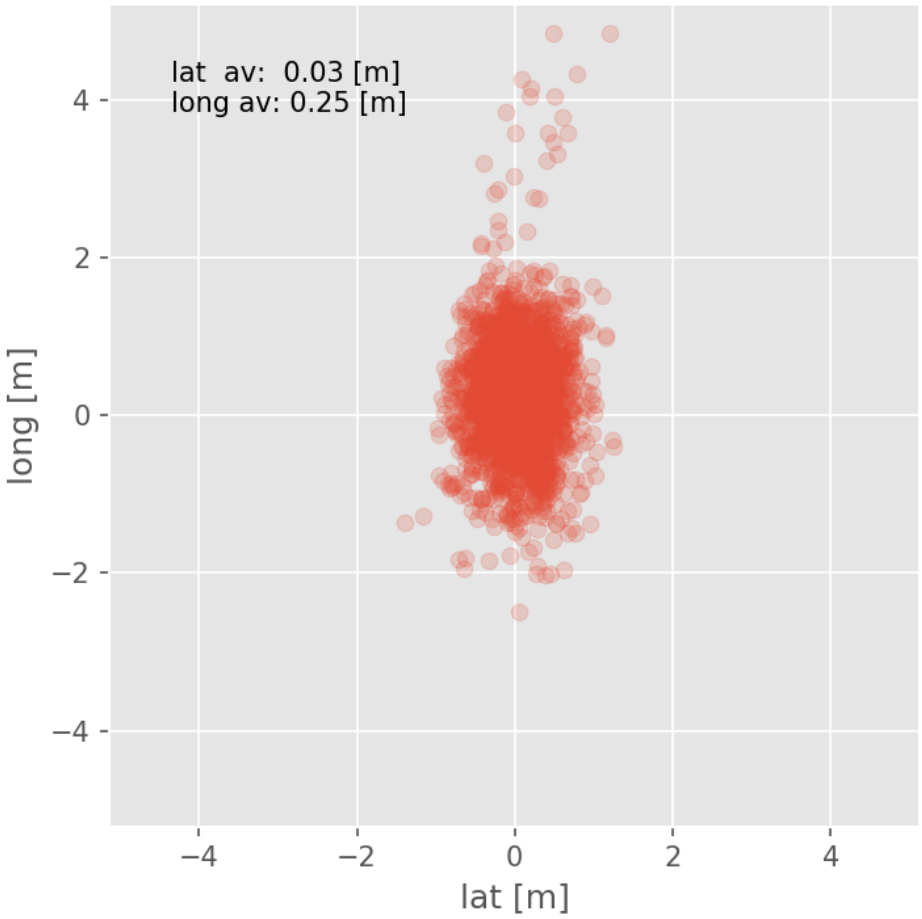

Figure 14 Scatter plot of position errors as computed from 24 hours of historic RINEX data at NGB2 station on day 134 of 2019.

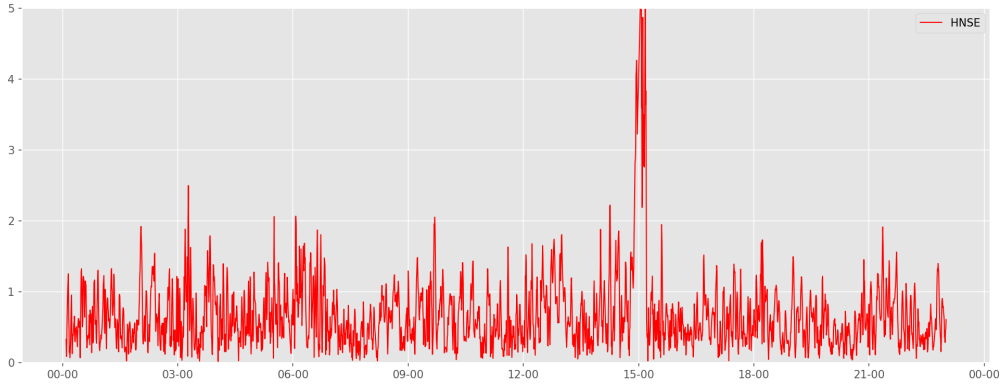

Figure 15 Raw position error (HNSE) determined from RTKLIB processing of historic RINEX data, from NGB2 on day 134.

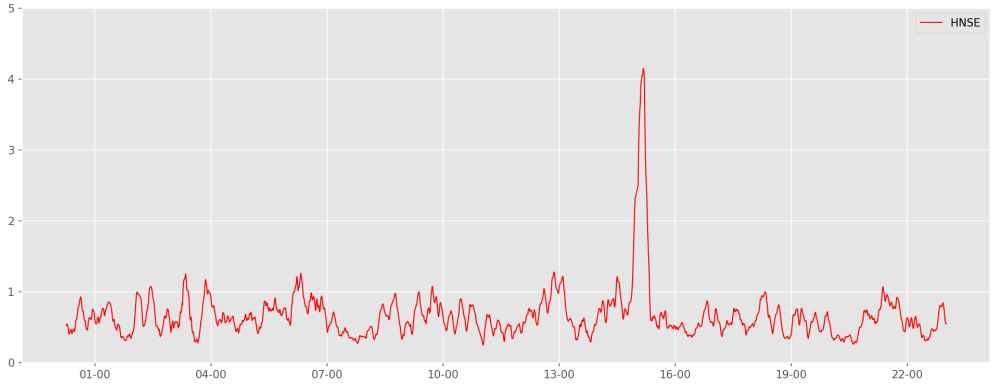

Figure 16 Smoothed position error (HNSE) determined from RTKLIB processing of historic RINEX data, from NGB2 on day 134.

When the simulated position standard error using a σ_{UDRE} value of 0.90m is overlaid on the measured position errors (Figure 17), it is again clear that the error budget is overestimating the simulated measurement errors, such that 84% of measured errors fall below the simulated standard errors. The spike at 15:00 is captured well by the simulation.

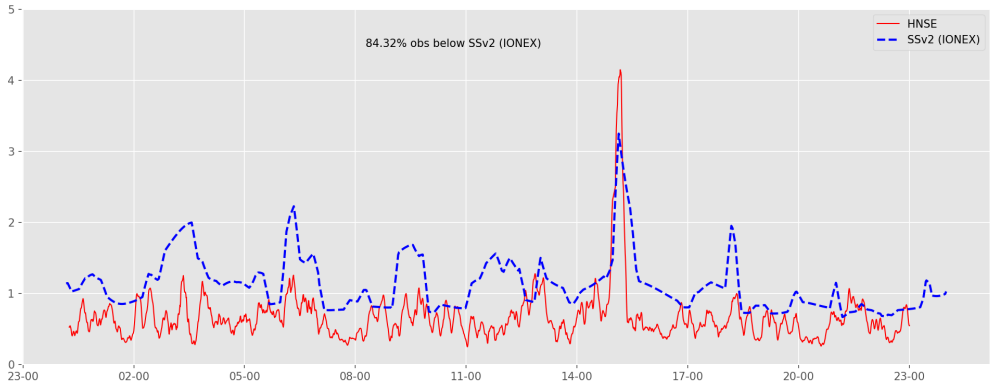

Figure 17 Smoothed position error overlaid with SSv2 standard errors from constant σ_{UDRE} value of 0.90m, from NGB2 on day 134.

However, with a σ_{UDRE} of 0.50m, the results are similar to the results with day 107, with 63.8% of measured position errors falling below the simulated standard errors, which is again within the expected range.

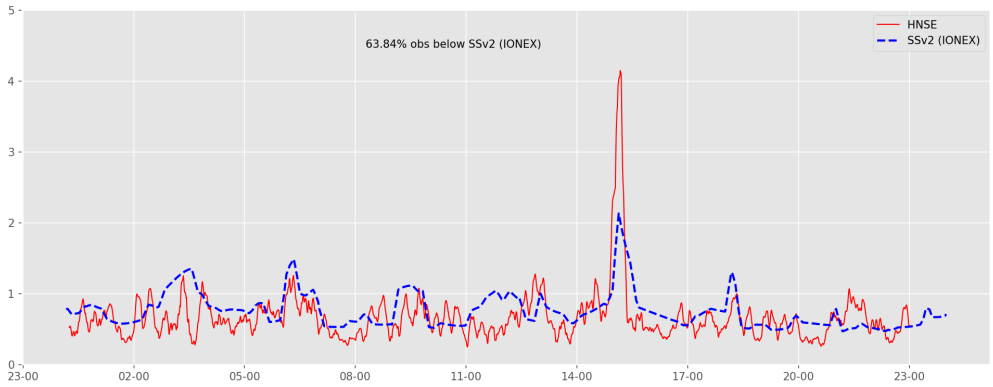

Figure 18 Smoothed position error overlaid with SSv2 standard errors from constant σ_{UDRE} value of 0.90m, from NGB2 on day 134.

Finally, when the distribution of the normalised position errors is shown, the CEP radius of 0.77 is again slightly smaller than the value expected from the idealised Rayleigh distribution, but is very close to the 0.76 obtained with the earlier data set.

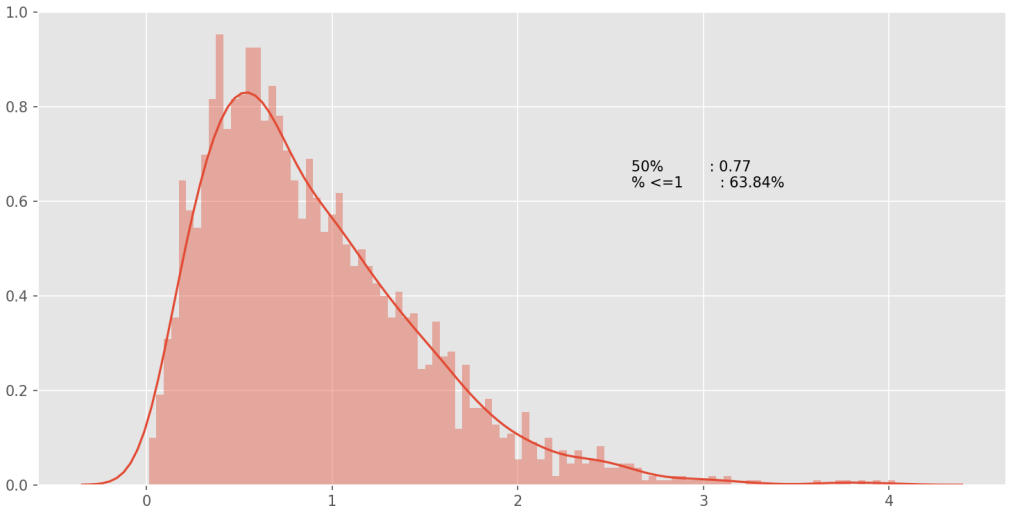

Figure 19 Distribution of normalised position errors for NGB2 on day 134.

This analysis of day 134 therefore demonstrates that the simulation model performs equally on a ‘quiet’ ionospheric day and on a ‘disturbed’ ionospheric day.

3.1.2.1 Conclusion

To summarise, the foregoing discussion has demonstrated:

1. That simulated position standard errors from SSv2 can be made to match measured position errors on a selected day by making an adjustment to the error budget models – specifically, the σ_{UDRE} model has been replaced with a fixed value of 0.50m to achieve a good match with measured position errors.
2. That the same adjustment performs equally well on a second day, with different ionospheric conditions, by supplying the correct contemporary IONEX file.
3. What has not yet been demonstrated is the theoretical justification for reducing σ_{UDRE} to 0.50m, although a much higher number of RIMS than the model's limit of 8 could have resulted in smaller model uncertainties. Additional analyses in SSv2 will be used to investigate this. It would be preferable to retain the model that bases the σ_{UDRE} value on the number of RIMS tracking the satellite, but to perhaps reduce the values used in that model to make the model less conservative (more realistic) and possibly to reflect the benefits of tracking with more than 8 RIMS.

4 Comparison of DGPS and EGNOS V2 accuracy

The above steps aim to prepare the simulation tool SSv2 to output HNSP values that are relevant to a maritime receiver using EGNOS corrections. The SSv2 IONEX ionosphere macro-model was identified as the most realistic model at this point, although further work is required to ensure that the overall error budgets are realistic. Once this is achieved, use of this model will produce realistic precision values that can be used to study the relationship between EGNOS and DGPS performance.

One aspect is the notional 'cross-over' point between DGPS and EGNOS, i.e. the distance from a beacon at which the DGPS and EGNOS corrected positions are of a similar accuracy (as depicted conceptually in Figure 20).

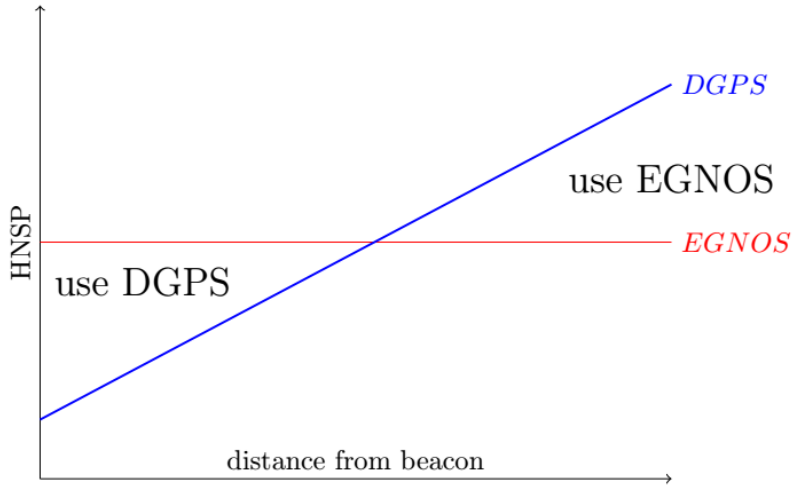

Figure 20 The conceptual overview of the cross-over point between DGPS and EGNOS position accuracy

This could lead to a simple rule to be applied in the receiver that would determine which service to use based on distance from the nearest DGPS beacon. The situation will be more complex at the edges of EGNOS coverage, so the analyses will focus specifically on the waters around the UK and Irish ports that are most affected by being within the peripheral coverage of EGNOS.

Another aspect is the relative performance under extreme conditions. It is conceivable that EGNOS and DGPS may cope with extreme ionospheric conditions to different degrees. For instance, it is conceivable that the resolution of the EGNOS ionospheric grid model, and the ability of the RIMS network to populate the model (e.g. through the distribution of ionospheric pierce points), may not be sufficient to capture the detail of a small-scale ionospheric disturbance, particularly at the edges of EGNOS coverage. Under such conditions,

a DGPS beacon may be able to better mitigate the ionospheric disturbance by virtue of its closer proximity to the user.

Studies so far have been based on a limited data set, which is sufficient for the initial stage, demonstrating the feasibility of the approach, but further datasets, and varied atmospheric conditions, will be used to verify the initial findings and to explore the above issues.

The aim is to integrate the outputs of GAGT and SSv2 to enable comparisons to be made under any conditions, and to demonstrate the performance that could be expected if the two systems are used in combination. Tools to evaluate combined performance, or the difference in performance, will be developed, to enable easy visualisation of the results, and models to compute availability and continuity statistics will be included.

For instance, it is feasible that any deficiencies in EGNOS performance could be mitigated with a subset of DGPS beacons, i.e. potential weaknesses at the periphery of EGNOS coverage may only affect the areas around a few of the DGPS beacons. The study could therefore identify those DGPS beacons whose role could be wholly met by EGNOS and could be decommissioned, as well as those which 'patch' the EGNOS performance and should be retained. It is also feasible that any weaknesses in EGNOS performance are solely due to the decline in performance at the periphery of EGNOS coverage, i.e. nominal performance within the core coverage area might be sufficient for maritime usage, in which case a limited expansion of the RIMS network, perhaps using existing beacon sites, might mitigate this peripheral decline. These possibilities will be explored by comparing and combining the outputs of the simulation tools, and by performing further analyses with historic data.

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