EDAS for a DGPS maritime service: EGNOS-based VRS performance with pre-broadcast integrity monitoring

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BIOGRAPHIES

Jorge Morán has an MSc. in Telecommunication Engineering from the University of Oviedo. He has a background on SBAS, GNSS performances and software engineering. In 2008 he joined GMV AD, where he worked in several EGNOS related projects. Also in GMV, he acted as the project manager of EDAS v2 evolution. Since beginning of 2014, he is responsible for the EGNOS NOTAM Proposals Provision at ESSP SAS.

Elisabet Lacarra received her master degree in Telecommunication Engineering in 2005. Later she was collaborating in different projects related to GNSS systems in GMV AD. Since 2009 she has been working inside the ESSP, firstly as performance expert for the analysis and assessment of EGNOS performance and later as EDAS Service expert for the supervision of all activities related to the EGNOS Data Access Service.

Juan Vázquez has an MSc. in Telecommunication Engineering from the University of Oviedo. He has worked in the GNSS industry since 2008, when he joined GMV AD. There, he participated in several R&D projects related to GNSS system architecture, applications and integrity concepts. In 2010, he started working within the Service Provision Unit of ESSP SAS, as a consultant from GMV. He joined the Service Provision Unit of ESSP by beginning of 2012, where he is in charge of the team responsible amongst others for the EDAS service and EGNOS NOTAM Proposals provision.

Miguel A. Sánchez holds an MSc. in Telecommunication Engineering from the Technical University of Madrid (UPM). During 10 years in GMV AD he was deeply involved in GNSS projects related to EGNOS and GBAS development and operational implementation, and worked also as consultant for AENA and Eurocontrol. He joined ESSP SAS from its early stages as Service Development Manager and recently appointed as Service Adoption and Support manager responsible for user support, user data services activities and any activity aimed at facilitating the adoption of EGNOS services in all domains of application.

Francisco Cantos received the MSc. degree in Aerospace Engineering from the Higher Technical School of Engineering, University of Seville. He held a scholarship in the aerospace department to analyse airplanes trajectory near Seville airport. In 2014, he joined Sogeti HTC, and has been working in the EGNOS project as an external consultant in ESSP, focusing on the EGNOS NOTAM Proposals Provision.

Tamás Horváth is Sales and Marketing Manager at Alberding GmbH, where he is responsible for the development, marketing and sales of GNSS positioning software products and services. He received his M.Sc. degree in Surveying and Geoinformatics from the Budapest University of Technology and Economics in 2002. From 2002 to 2004 he worked at Thales GeoSolutions, UK, as GNSS Specialist and from 2004 to 2012 at the FÖMI Satellite Geodetic Observatory in Hungary, where he was head of the national GNSS Service Centre.

ABSTRACT

EDAS (EGNOS Data Access Service) is the EGNOS service providing free of charge Internet access to all the data generated and collected by the EGNOS infrastructure in real time and also through a historical archive. EDAS gathers the GNSS raw data collected by all the receivers located at the EGNOS Ranging and Integrity Monitoring Stations (RIMS), which are mainly distributed over Europe and North Africa. After processing the raw data collected by the RIMS, EDAS disseminates this GNSS information (GPS/GLONASS satellite navigation and observation data, EGNOS messages) to the EDAS users in different formats and protocols. Depending on the information provided, and also on the format and protocol used to transmit the GNSS data, the following services are distinguished: Main Data Streams, Data Filtering, SISNeT, Ntrip (real-time) and FTP (archive). In addition to the observation and navigation data broadcast by the GPS, GLONASS and EGNOS GEO satellites, EDAS, through its Ntrip service, computes and disseminates differential corrections and the required phase measurements and station data in RTCM format to support DGNSS and RTK positioning techniques.

EDAS service provision is performed by ESSP, as EGNOS Services Provider, under contract with the European GNSS Agency (GSA), the EGNOS program manager. The European Commission (EC) is the owner of

EGNOS system (including EDAS) and has delegated the exploitation of EGNOS to GSA.

Firstly, the paper will introduce the EDAS system and its architecture, providing information about the data available through its real-time and FTP services. After introducing the EDAS services, this paper will focus on the potential use of EDAS as a source for the generation of differential GPS corrections based on Virtual Reference Stations (VRS), including the required integrity checks. The principle behind this solution would be to use the EGNOS augmentation message (RTCA format) delivered through EDAS as an input, to be then converted into RTCM SC-104 corrections (EGNOS-VRS) referenced to the locations of interest for maritime users (e.g. beacon locations). Transmission to final users could be done through IALA MF beacons or through AIS (Automatic Identification System) base stations (via AIS #17 message), hence ensuring compatibility with the deployed user equipment.

It is worth highlighting that the main advantage of the DGPS solution based on VRS (taking the EGNOS messages from EDAS as input) with respect to standard DGPS is that corrections can be remotely generated for any location within the EGNOS coverage area. Hence, a physical reference station at or close to the transmission site would not be required for the delivery of DGPS corrections for maritime navigation. In this context, EDAS could be used as part of a cost-effective solution fully compatible with the user equipment already deployed, and even providing some room for the rationalization of the infrastructure, in the current context where some European countries are or will be facing obsolescence issues in the short term.

In order to assess the potential benefits of the EGNOS-VRS concept for maritime navigation, the results of a performance analysis campaign conducted at different European locations were presented last year in the ION GNSS+ 2015 [19].This analysis showed that the accuracy and availability performance provided by an EDAS based VRS solution could be comparable to the results obtained with traditional DGNSS stations, indicating that the VRS corrections could meet the accuracy and availability requirements for general maritime navigation.

However, it is important to remark that apart from the availability and continuity requirements, the radio-navigation system shall provide "*integrity warning of system malfunction, non-availability or discontinuity*" to users [20]. The IALA DGNSS Integrity concept is based on an Integrity Monitoring (IM) station that retrieves the corrections broadcast (or to be broadcast) by the Reference Station (RS) and verifies that the information is within tolerance (both at pseudorange and position domain levels) based on the fact that the position of the IM is known. On the other hand, two different integrity approaches are possible, depending on whether the integrity check is done before or after broadcasting the corrections to the users: Pre-Broadcast Integrity or Post-Broadcast Integrity. The present study will be based on the Pre-Broadcast Integrity concept, which is the recommended option for DGNSS service providers implementing the Virtual Reference Station concept (for more information, refer to [17]).

Taking into account that integrity is an essential requirement for maritime radio-navigation systems, this paper will go one step further compared to the study presented last year, analysing the provision of integrity warnings in the EDAS-based VRS corrections and assessing the impact of the integrity check on the accuracy and availability performance. In order to do that, GPS measurements from multiple public reference stations in different European areas will be combined with EDAS-based VRS corrections generated for specific locations of interest and resulting in a diverse set of scenarios (different locations and baseline lengths have been considered).

The main tool for the performance assessment to be presented in this paper will be the Alberding EuroNet application, a real-time DGNSS software with flexible and scalable design that is able to process the EGNOS corrections in RTCA format from an SBAS-enabled GNSS receiver or from the EDAS service and derive EGNOS-VRS corrections in RTCM 2.3 or AIS #17 messages ready to be broadcast via IALA radio beacons or AIS base stations. The integrity solution implemented is based on the pre-broadcast monitoring concept, checking the computed differential corrections before being broadcast to the users. Correction data availability and age, positioning accuracy, satellite specific PRC (Pseudorange Correction) and RRC (Range Rate Correction) values and residuals, data rate, etc. are monitored in real time. In case any of the monitored parameters exceed pre-defined threshold values for a given period of time (taking as reference the DGNSS Broadcast Site Settings proposed in [17]) the Pre-Broadcast Integrity Monitoring module automatically generates a warning message and the software sets the health status of the given satellite or the reference station to "unhealthy".

EDAS OVERVIEW

EGNOS, the European Satellite Based Augmentation System (SBAS), provides corrections and integrity information to GPS signals over a broad area over Europe and is fully interoperable with other existing SBAS systems (e.g. WAAS, the North American SBAS).

ESSP (European Satellite Services Provider) is the EGNOS system operator and EGNOS Service provider, under contract with the European GNSS Agency (GSA), for the following three services:

- **EGNOS Open Service (OS)**, freely available to any user [2].
- **EGNOS Safety of Life (SoL) Service**, that provides the most stringent level of signal-in-space performance for safety critical applications [3].

- **EGNOS Data Access Service (EDAS)**, which is the EGNOS terrestrial data service offering free of charge access to GNSS data to authorised users by GSA (under delegation of EC) [1].

As it can be observed in Figure 1, EDAS gathers all the raw data coming from the GPS, GLONASS and EGNOS GEO satellites collected by all the receivers located at the EGNOS stations. There are currently 39 ground stations (Ranging and Integrity Monitoring Station - RIMS) and 6 uplink stations (Navigation Land Earth Stations - NLES), mainly distributed over Europe and North Africa. EDAS disseminates this GNSS data in real time and through an archive (historical data access) to EDAS users and/or Service providers that distribute the data locally or to specific set of applications. In consequence, EDAS allows users to "plug in" to the EGNOS system by providing access to GPS/GLONASS satellite navigation and observation data, along with the EGNOS messages received by EGNOS ground stations.

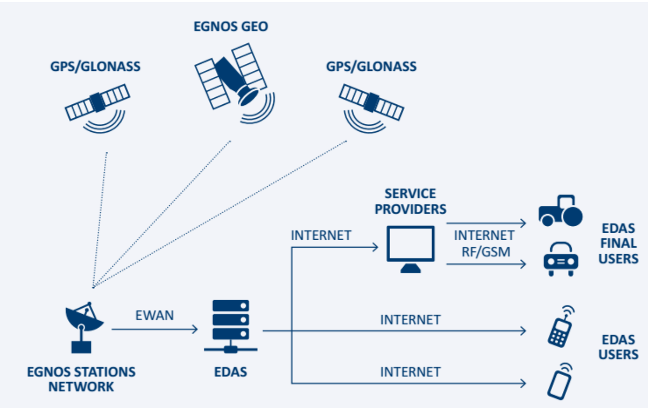

Figure 1: EDAS High-Level Architecture [1]

EDAS therefore provides an opportunity to deliver EGNOS data to users who cannot always view the EGNOS satellites (such as in urban canyons), or GNSS data to support a variety of other services, applications and research programs.

The European Commission officially declared an initial set of EDAS services available to EU users in July 2012. In April 2013, a new set of value-added services was subsequently declared available, to extend the initial EDAS portfolio and enable EDAS to support new application domains.

Currently, the services provided by EDAS are as follows (please refer to the EDAS Service Definition Document [1] - for a detailed description, https://egnos-user-support.essp-sas.eu/new_egnos_ops/content/egnos-sdds):

- **Main Data Streams** [4]: GNSS data is provided through the Internet in real time in ASN.1 format [8] (Service Level 0) and RTCM 3.1 [9] format (Service Level 2).
- **Data Filtering** [4]: Filtering capabilities to allow GNSS data to be received from only certain subsets of RIMS stations when connecting to EDAS Service Level 0 and/or 2. Currently 6 different groups of RIMS stations are defined according to geographical criteria.
- **SISNeT Service** [6]: EGNOS messages provided in real time using the SISNet protocol [10] defined by ESA.
- **FTP Service** [5]: Historical GNSS data available through an FTP site including:
  - EDAS SL0, SL2 raw data.
  - GPS/GLONASS navigation and observation data (RINEX format [12])
  - EGNOS messages (EMS [13] + RINEX-B formats)
  - Ionosphere information in IONEX [14] format.
- **Ntrip service** [7]: GNSS measurements and corrections in real time using Ntrip protocol [11], delivered in RTCM 3.1 [9], 2.3 [16] and 2.1 [15] formats. Within the data delivered by the Ntrip service, differential GNSS corrections and phase measurements as well as additional messages for RTK (Real-time kinematic) positioning are provided.

The following table summarizes the types of data that can be retrieved via the different EDAS services.

Mode	EDAS Service	Type of Data				Protocol	Formats
		Observation & navigation	EGNOS messages	RTK messages	DGNSS corrections		
Real Time	SL/DF 0	X	X			EDAS	ASN.1
Real Time	SL/DF 2	X	X			EDAS	RTCM 3.1
Real Time	SISNeT		X			SISNeT	RTCA DO-229D
Real Time	Ntrip	X		X	X	Ntrip v2.0	RTCM 2.1, 2.3, 3.1
Archive	FTP	X	X			FTP	RINEX 2.11, RINEX B 2.10, EMS, IONEX, SL0 and SL2

Table 1: EDAS Services

EGNOS data coming from the EDAS Services can be used for the development of applications based on GNSS data streams, or for the provision of added-value services based on EDAS. As examples, EDAS services are currently used for tracking dangerous goods, high precision positioning, management of airport fleets, engineering activities in the EGNOS programme, monitoring of GNSS performance, atmospheric investigation and R&D activities.

In particular, this paper will be focused on the use of the EGNOS message delivered by EDAS in real time (through the SL2 and SISNeT services) for the generation of EGNOS-based Virtual Reference Stations (VRS) on the locations of interest for maritime users (e.g. IALA beacons).

EDAS registration

In order to request an EDAS account, users should follow the steps detailed below:

1. Register in the EGNOS User Support Website: http://egnos-user-support.essp-sas.eu
2. Fill and submit the EDAS registration form (only accessible upon registration in the web)

After the verification of the provided data and access authorization from GSA, the EGNOS Helpdesk will provide the user with the credentials and configuration details necessary to connect to the requested EDAS Service. Additionally, the website credentials will allow the user to download user oriented documentation and SW, such as the EDAS Client SW User Manual [4] and the user information packages for each EDAS Service ([5], [6], [7]).

EDAS users are welcome to contact the EGNOS Helpdesk (egnos-helpdesk@essp-sas.eu or +34 911 236 555) for EDAS registration and for any request related to EDAS, including EDAS services status, connectivity issues, technical specifications, data streams structure, conditions of use, etc.

EDAS online information

The following means of information are made available by ESSP regarding EDAS through the EGNOS support website (http://egnos-user-support.essp-sas.eu):

- **EDAS Service Definition Document** [1]: The EDAS SDD provides information on the EDAS services and their conditions of use. In terms of content, the EDAS SDD describes the EDAS system architecture and provides an overview of the current EDAS services with regards to the information that is transmitted, the data formats, protocols and committed performance.
- **EDAS section in the EGNOS User Support Website**: Up-to-date information about the EDAS services, along with the interface with the EGNOS helpdesk and the form to register as EDAS user can be found in the EDAS section of the EGNOS User Support Website. Additionally, the real-time status of all EDAS services is also publicly available on this site (see Figure 2).
- **EGNOS Monthly performance report:** containing the EDAS performance of the last month, in terms of availability and latency for all services.

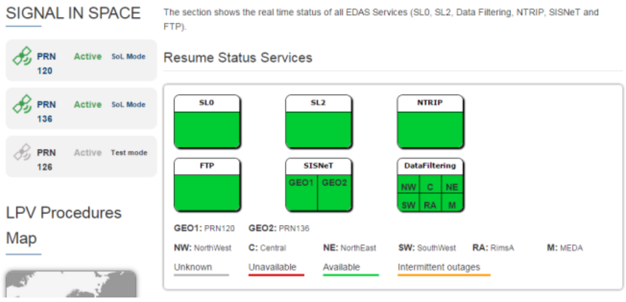

Figure 2: Real-time EDAS services status

EDAS Services Performance

The EDAS SDD [1] defines the committed performance levels for EDAS (levels that should always be met in a nominal situation) in terms of availability and latency:

- **Availability**: percentage of time in which EDAS is providing its services according to specifications. The availability is measured at the EDAS system output (excluding user access network performance).
- **Latency**: time elapsed since the transmission of the last bit of the navigation message from the space segment until the data leaves the EDAS system (formatted according to the corresponding service specification). EDAS latency is a one-way parameter defined for real-time services.

Based on the above definitions, the table below provides EDAS services' minimum availability and maximum latency:

Performance	SL0	SL2	SISNet	FTP	Ntrip	Data Filtering	
						SL0	SL2
Availability	98.5%	98.5%	98%	98%	98%	98%	98%
Latency (sec)	1.30	1.45	1.15	N/A	1.75	1.60	1.75

Table 2: EDAS services min availability and max latency

The availability and latency parameters achieved from August 2015 to July 2016 are shown in the figures below. EDAS availability has always been above 99% and the latency has been consistently below 1 second. Hence, it can be seen that the commitment values have been met for all the services throughout the whole period.

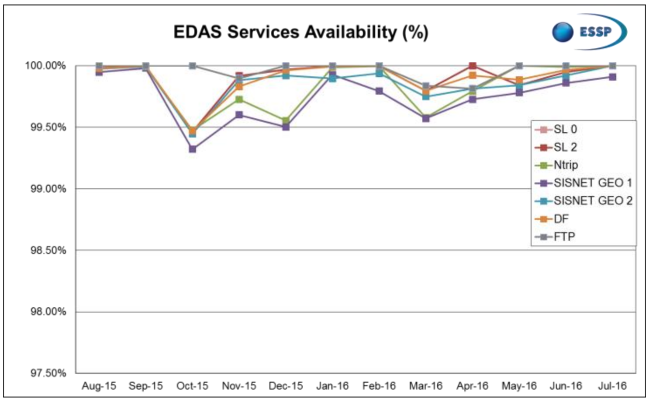

Figure 3: EDAS services availability (August 2015 – July 2016)

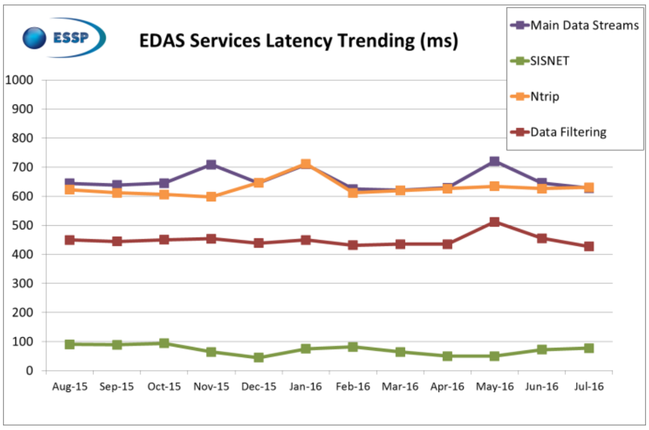

Figure 4: EDAS services latency (August 2015 – July 2016)

EDAS FOR EGNOS-BASED VIRTUAL REFERENCE STATIONS

DGNSS System for maritime navigation

IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) radiobeacon DGNSS is the internationally accepted method of providing differential GNSS corrections and integrity information to maritime users.

The IALA DGNSS employs the principle that the main sources of error in satellite navigation (i.e. satellite clock errors, satellite ephemeris errors, tropospheric and ionospheric delay estimation errors) are highly correlated for two users located relatively close to each other. Differential GNSS corrections are computed by placing a reference station with a GNSS receiver at a known location, determining corrections to the satellite ranging signals, and broadcasting these corrections to users. Then, since the satellite locations and reference antenna location are known, the ranges can be determined precisely. By comparing these ranges to those obtained from the satellite pseudorange measurements, the pseudorange errors can be accurately estimated, and corrections determined. These corrections can then be broadcast to nearby users, who use them to improve their position solutions, removing the bias errors common to the reference station and user receivers. The accuracy is then limited by user receiver noise, inter-channel biases, user local effects and differential station location uncertainty. The standard used for the dissemination of these DGNSS corrections is RTCM SC-104 2.x [16].

EGNOS, as any SBAS system, is also providing corrections to the same errors (i.e. satellite clock and ephemeris errors along with ionospheric delay estimation errors), with one exception: the troposphere. For this error source, SBAS systems do not provide corrections; users are expected to apply a model to reduce the error in the position due to this effect.
On the other hand, the IALA DGNSS Integrity concept is based on an Integrity Monitoring (IM) station that retrieves the corrections broadcast (or to be broadcast) by the Reference Station (RS) and verifies that they are within tolerance (both at pseudorange and position domain levels) based on the fact that the position of the IM is known.

Currently, in July 2016, there are more than 300 IALA DGNSS stations in over 45 countries throughout the world including the majority of European Member States. However, some of the DGNSS networks existing in Europe are becoming obsolete. For this reason, several European Member States are starting to analyse the necessity of upgrading and modernizing their DGNSS networks. In this context, the EGNOS messages obtained from EDAS could be used for the generation of EGNOS-based VRS corrections, which could be part of a cost-effective solution fully compatible with the user equipment already deployed, and even providing some room for the rationalization of the infrastructure.

EDAS for EGNOS-based Virtual Reference Stations

As described in the IALA Guideline 1112 [17], marine beacon infrastructure can be considered to fall into two different architectures, with either equipment all sited at the broadcast locations (**classic approach),** or with some of the infrastructure in a central location and only the transmitting equipment at the broadcast site (**network approach**).

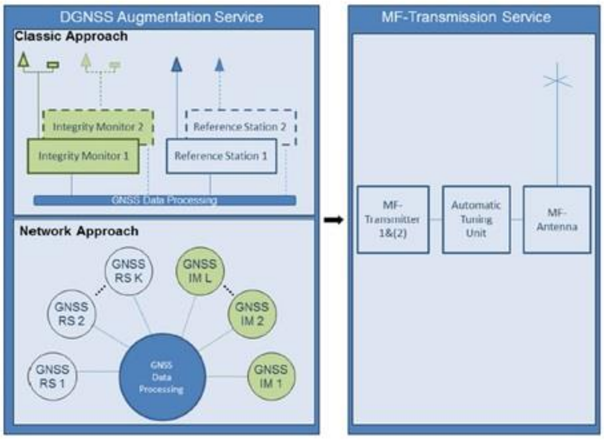

Figure 5: DGNSS Service Architecture: Classic and Network Approach [17]

ESSP, under the leadership of GSA, is working in this field considering different alternatives for the use of EGNOS/EDAS as an alternative source for the provision of a DGPS corrections service for maritime users also considering the system architecture of the resulting solution, its technical benefits and its potential cost saving impact.

In particular, the test setup for this paper is based on the network approach for the generation of EGNOS-based Virtual Reference Stations (VRS). The principle behind this solution is to use the EGNOS augmentation message (RTCA format [21]) delivered through EDAS as an input, to be then converted into RTCM SC-104 [16] corrections (EGNOS-VRS) referenced to the locations of interest for maritime users (e.g. beacon locations). At this point, it is important to remark that the EGNOS augmentation message delivered through EDAS is robust to local effects potentially affecting the receiver: jamming interference, receiver noise or user visibility conditions (as long as one EGNOS RIMS is tracking the GEO satellite, its messages will be output through EDAS).

The integrity of these corrections is checked before being broadcast to the users (Pre-Broadcast Monitoring) using the raw data collected by an independent network of monitoring receivers. Transmission to end users could be done through IALA MF beacons, AIS (Automatic Identification System) base stations (via AIS #17 message) or in the future through VDES (VHF Data Exchange System), hence ensuring compatibility with the deployed user equipment.

At high level, the architecture of a network EGNOS-based DGPS service comprises the following elements:

- **Central Facility** (CF), responsible for the generation and integrity monitoring of the PRC corrections. For each VRS station, the central facility computes the pseudorange correction as the sum of:
    - The fast range corrections broadcast by EGNOS (Message Type 2-5, MT24).
    - The contribution of the satellite position error (based on the EGNOS long-term corrections -MT24 and MT25) projected to each line of sight.
    - The satellite clock error based on the EGNOS long-term corrections.
    - The ionospheric range correction, based on the user's (IALA Beacon) ionosphere pierce point (IPP) and on the ionospheric delay corrections broadcast by EGNOS (MT26).
    - The tropospheric correction, depending on the relative user (IALA Beacon) to satellite position
- **Monitoring Network**, providing GNSS raw data to monitor the **integrity** of the EGNOS-based PRC corrections.
- **Beacon Transmitters Network**, responsible for the transmission of the corrections computed by the CF to the final users.

In order to maintain the service in case failure of the central facility or in case of communication outages, a **local backup system** at the transmission site may be required. The local backup system could consist of a single GNSS receiver with EGNOS raw data output and an embedded PC with RTCA to RTCM conversion and Pre-Broadcast Monitoring (PBM) software. EGNOS SiS RTCA data would be converted to RTCM corrections and GNSS observations of the local receiver would be used to generate integrity information for the output corrections. During normal operation, when corrections from the central server are available, observation data of the local GNSS receiver could be transferred to the central server and used there for integrity monitoring.

This architecture is depicted in the following figure:

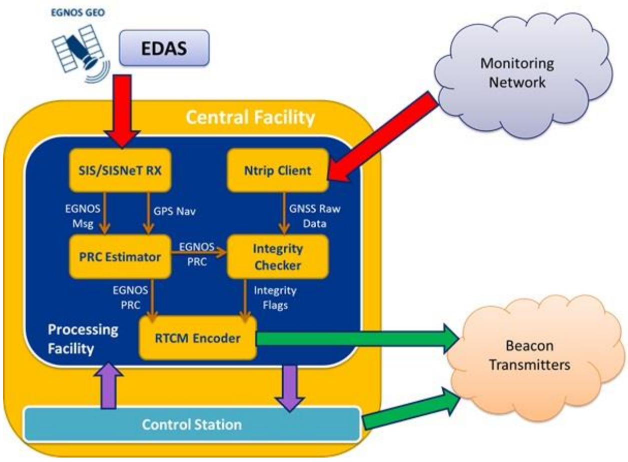

Figure 6: EGNOS-based VRS Architecture

In order to simulate the architecture described above and assess the performance that could be obtained with a network EGNOS-based DGNSS service, the AlberdingMonitor software has been used.

The test set-up, which is described in the following sections, includes the Central Facility (CF) and Monitoring Network functions. Since no actual broadcast of the EGNOS-based VRS corrections has been done, GNSS receivers from public reference stations have been used to monitor the corrections and to assess the resulting user performance.

AlberdingMonitor SW for the generation and integrity monitoring of EGNOS-VRS corrections

Alberding GmbH is a leading developer and distributor of professional GNSS system solutions supporting precise positioning, GIS and navigation applications.

DGNSS positioning performance results presented in this paper have been derived by the **AlberdingMonitor** software. Real-time status information and historical data are provided in both textual and graphical forms through the web interface of the software. AlberdingMonitor can generate scheduled and on-demand performance reports and release automatic warning messages to network operators if a service outage or performance degradation is detected.

The monitoring software is based around the **Alberding EuroNet** application, a real-time DGNSS software module with flexible and scalable design. EuroNet is able to process observation data from multiple GNSS reference stations in a networking mode and compute virtual reference station (VRS) corrections for any location within the coverage area. It can be used to provide a robust and homogeneously accurate DGNSS positioning service for a whole country or even a continent. EuroNet can also take EGNOS corrections in RTCA format from either an SBAS enabled GNSS receiver or from the EDAS service and derive EGNOS-VRS corrections in RTCM 2.x or AIS #17 messages ready to broadcast via IALA radio beacons or AIS base stations.

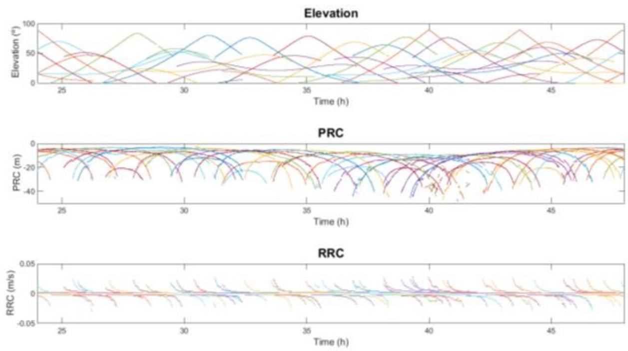

Figure 7: EGNOS-based PRC and RRC corrections generated by the AlberdingMonitor software

Another important feature of Alberding EuroNet SW is the implementation of the integrity monitoring functionality. The software supports both Pre-Broadcast

Monitoring (PBM) and Far Field Monitoring (FFM), fully in line with the IALA Guideline 1112 [17].

PBM allows for checking DGNSS corrections before transmission. This is to prevent users from applying faulty or inaccurate DGNSS corrections. Pre-broadcast integrity monitoring is performed in the **pseudorange** and **position** domains

Pseudorange (or signal) domain analysis is carried out in two steps. First the PRC and RRC values are checked during correction generation phase **at the reference station side**. If the correction values for a given satellite exceed user-defined thresholds, the PBM module sets the PRC and RRC fields in the output RTCM message for the corresponding satellite to “do-not-use” values. This single satellite health flag is applied immediately when an out-of-tolerance value is detected. As a result, the rover applying the differential corrections has to exclude the affected satellite from the position computation.
In addition, no corrections will be output for satellites marked unhealthy either by the GNSS system operator (in the ephemeris) or the DGNSS service provider.

In a second step the quality of the corrections is assessed **at the monitoring station side**. Pseudorange- and range rate corrections are generated for the monitoring station using its own GNSS observations and the known antenna coordinates. These corrections are then compared to the PRC and RRC values of the reference station to derive **correction residuals**. If the residuals of a satellite exceed pre-set limits for a user-given amount of time (alert interval), the corresponding SV is marked “do not use”. Similarly, following a residual error, the PRC and RRC differences have to stay below threshold for the alert interval in order the satellite to become usable again.

In case a satellite is not tracked any more by the monitoring station, thus no residuals can be computed, the last valid health state of that satellite is still transmitted over the specified alert interval. Only following this time period the corrections for this satellite will be flagged as “do not use”.
During position domain checks a real-time DGNSS position solution is computed using raw data input from the monitoring station and the monitored differential corrections. The resulting position output is compared to the pre-surveyed coordinates of the monitoring station antenna. If the calculated difference (**horizontal position error**) exceeds a pre-defined threshold (for more than a pre-set period of time) the reference station is marked “not working”. If the monitoring station is unavailable or no DGNSS position solution could be computed for the alert interval, the reference station is marked “not monitored”. Only if the position error is constantly below the threshold again for the user-set alert interval, the reference station will be set healthy again.Position domain integrity information is output in the station health field of each broadcast RTCM message header [16].

Summarising, the following parameters can be configured in the integrity monitoring software:

- **Max PRC [m] and RRC [m/s]:** In case the pseudorange correction (or range rate correction) exceeds these configuration values for a given satellite, the satellite is flagged as “do not use” and immediately excluded from the rover differential solution. This is checked during correction generation phase at the reference station side.
- **Max PRC Residual [m] and RRC Residual [m/s]:** If the residuals of a satellite exceed pre-set limits for a user-given amount of time (Residual Delay parameter), the corresponding SV is marked as “do not use” and excluded from the rover differential solution. This is checked at the monitoring station side.
- **Max (Horizontal) Position Difference [m]:** If the horizontal position error computed at the monitoring station (using the corrections generated by the reference station) exceeds the threshold defined (for more than a pre-set period of time) the reference station is marked “not working” causing the rover to switch to standalone mode.
- **Max PRC Residual, RRC Residual and Position Difference Delay [s]:** Period of time configured before setting the satellite as “do not use” or the station as “not working” in case the residuals or the position errors exceed the pre-defined thresholds.

The software also allows comparing the performance of corrections with and without pre-broadcast monitoring. The same corrections can be applied to the rover raw data in two simultaneous computations: first with no integrity checks, second with the PBM algorithms applied.
For the EGNOS-VRS computations used in the performance analysis, the software accessed the **EDAS SL2** data stream from the EDAS server, converted the EGNOS corrections in RTCA format to RTCM data, and output that for user defined locations.

DGPS solutions are computed by applying the EDAS-based EGNOS-VRS corrections to the raw data collected by EPN (EUREF Permanent Network) GNSS receivers (used as rovers). The results obtained are compared against the “traditional” DGNSS solution computed at the rover site (using as input the DGNSS corrections provided by the EGNOS RIMS from the EDAS Ntrip Caster).

The EGNOS RIMS from the EDAS Ntrip Caster as well as the EPN receivers are also used as monitoring stations to check the integrity of the EGNOS-based VRS corrections.

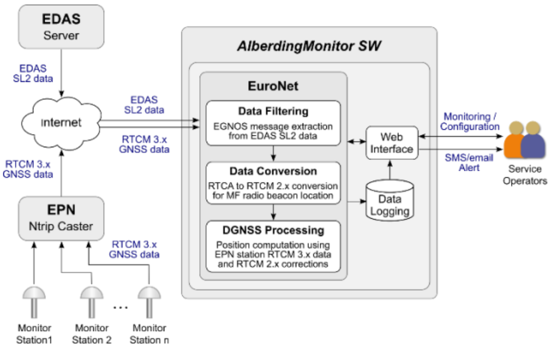

Figure 8: AlberdingMonitor SW

DATA CAMPAIGN DESCRIPTION

In order to assess the quality of the EGNOS-based VRS corrections including the PBM integrity check, a 6-week long (from 2nd July to 13th August) data campaign has been carried out at four different geographical areas of Europe. The following elements have been defined for each scenario:

- **Rover**: four different rovers (from the EUREF Permanent Network, http://www.epncb.oma.be) have been selected in France, UK, Sweden and Germany.
- **EGNOS-based VRS**: 9 VRS have been generated with different baseline lengths. It is noted that these VRS have been configured in the locations where current IALA beacons or AIS stations are located (e.g. Point Lynas lighthouse in UK).
- **Monitoring Station:** Six monitoring stations (from EDAS and the EUREF Permanent Network) have been used to check the integrity of the VRS corrections.

  Additionally, for all monitored solutions, an equivalent solution has been running in parallel with no integrity check. In other words, the VRS corrections are applied to the rover raw data in two simultaneous computations: first with no integrity checks and second with the PBM algorithms applied.
- **DGNSS Reference Station:** four EDAS DGNSS stations have been selected to compare their performance with respect to the results obtained with the VRS corrections.
- **IM Settings**: Two different Integrity Monitoring settings have been defined: coastal (general navigation) and inland settings (with more demanding thresholds). For more information, refer to Table 4.

The configuration of these scenarios is summarised in Table 3 and graphically represented in Figure 9.

Rover	VRS		DGNSS		IM Settings
	Location	Baseline [km]	Location	Baseline [km]	
Ciboure (SCOA0/ France)	Cap Ferret	135	Toulouse (TLSA)	257	Coastal
	Cabo Machichaco	86			Coastal
Daresbury (DARE0/ UK)	Earls Hill Stirling	316	Swanwick (SWAA)	288	Coastal
	Point Lynas	110			Coastal
Onsala (ONSA0/ Sweeden)	Goteborg	25	Aalborg (ALBA)	127	Coastal/ Inland
	Faerder Lighthouse	200			Coastal
	Lista Lighthouse	328			N/A
Oberpfaffenhofen (OBE40/ Germany)	Oberasbach	150	Zurich (ZURA)	215	Inland
	Regensburg Grass	100			Inland

Table 3: Scenarios Definition

Figure 9: Data Campaign Scenarios

As mentioned before, two different IM settings have been defined. The values configured for these two cases (see Table 4) have been defined based on the range of settings proposed by IALA [17]. However, some of these values have been reduced, especially for the inland configuration, in order to assess the impact of defining stringent thresholds on the accuracy and availability performance (e.g. the position error threshold has been set to 2 meters when the range proposed by IALA is 5-10 meters):

- **Coastal** settings, applied to the VRS corrections generated at the IALA beacons locations (e.g. Point Lynas or Cap Ferret).
- **Inland** settings, applied to the VRS corrections generated for the inland AIS locations (e.g. Oberasbach and Regensburg Grass).

Additionally, in order to assess the impact of reducing the integrity monitoring thresholds, the coastal and inland settings have been applied to the Goteborg VRS corrections. Hence, three simultaneous computations were done for this solution: without PBM, with coastal PBM and with inland PBM settings.

Parameter	Inland	Coastal
Max PRC [m]	40	60
Max RRC [m/s]	0.5	2
Max PRC Residual [m]	5	10
Max PRC Residual Delay [s]	10	10
Max RRC Residual [m/s]	1	2
Max RRC Residual Delay [s]	10	10
Max (Horizontal) Position Difference [m]	2	10
Max Position Difference Delay [s]	10	10

Table 4: PBM Thresholds Configuration

Finally, it is noted that in the next sections, the naming convention that is used to identify the performance results from a given solution is the following one:

- Standalone Solution: "*Rover" (e.g. DARE0).*
- Traditional DGNSS Solution: "*Rover_ReferenceStation" (e.g. DARE0_SWAA_1501)*
- VRS Solution (without integrity check): *"Rover_ReferenceStatioin_*VRS *(e.g. DARE0_POINTLYNAS_VRS)*
- VRS Solution (with integrity check): *"Rover_ReferenceStatioin_*VRS_MONSOL *(e.g. DARE0_POINTLYNAS_VRS_MONSOL)*

PERFORMANCE USING EDAS-BASED VIRTUAL REFERENCE STATIONS

The results presented last year in the ION GNSS+ 2015 [19] showed that the accuracy and availability performance provided by an EDAS-based VRS solution could be comparable to the results obtained with traditional DGNSS stations, indicating that the VRS corrections could meet the accuracy and availability requirements for general maritime navigation.

Given that the analysis conducted last year did not include the integrity monitoring check and considering also that only one week of data was analysed, the present paper will go much further compared to the study presented last year, analysing the provision of integrity warnings in the EDAS-based VRS corrections and assessing the impact of the integrity check on the accuracy and availability performance during 6 weeks of data (from 2nd July to 13th August 2016).

DGPS Accuracy Performance using EDAS-Based VRS corrections

As mentioned before, the analysis presented last year in the ION GNSS+ 2015 [19] concluded that the accuracy performance provided by an EDAS-based VRS solution could be comparable to the results obtained with traditional DGPS.

As a starting point for the present paper, a similar analysis has been conducted but with a period of 6 weeks of data.
The results of this analysis are summarised in Figure 10 that provides a comparison of the 95th percentile of the horizontal accuracy for the traditional DGNSS (**green** colour) and EGNOS-Based VRS (**blue** colour) solutions with respect to the GPS standalone solution (**red** colour) for the same rover receiver. At this stage, no integrity function is considered
As can be observed in Figure 10, there is a significant improvement for all the VRS solutions on the accuracy performance with respect to the GPS standalone solution (errors are typically reduced to at least half of the GPS only ones), being the horizontal error at the 95th percentile below one meter for all the solutions but the ones with larger baselines (Daresbury-Earls Hill Stirling: 316 km and Onsala-Lista: 328 km).

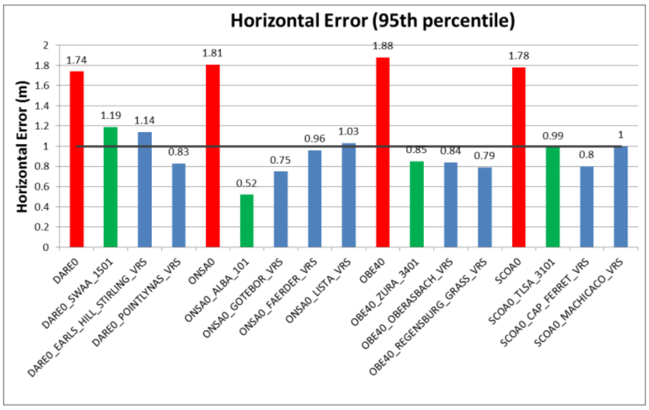

Figure 10: GPS only, traditional DGNSS and EDAS-Based VRS solutions horizontal accuracy (02/07/2016-13/08/2016).

These results show that the EGNOS-based VRS solution meet the accuracy requirement for general navigation (10 meters at the 95th percentile) and even the most stringent requirement for ports (1 meter at the 95th percentile) when the baseline is below 300 km.

Focussing on a given scenario (DARE0 - see Table 3), Figure 11 shows the cumulative distribution function of the horizontal error for the standalone, DGNSS and VRS solutions. The results obtained after applying the VRS corrections generated at Point Lynas (baseline: 110 km) show an important improvement on the horizontal accuracy performance with respect to the GPS standalone and the DGPS solutions (baseline: 288 km). Even for the Earls Hill Stirling with a baseline of 316 km the horizontal error is reduced with respect to the standalone and DGPS solutions.

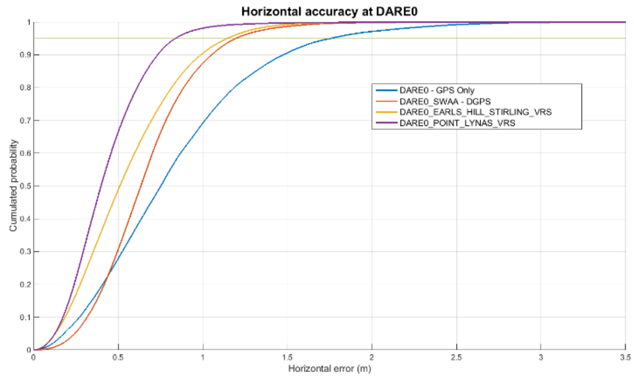

Figure 11: Cumulative distribution function of horizontal error at DARE0

Once proven that the performance provided by an EDAS based VRS solution is comparable to the results obtained with traditional DGNSS stations, the next step is to assess the impact of the PBM integrity check in the VRS corrections.

This is depicted in the following picture, where a comparison of the 95th percentile of the horizontal accuracy for the VRS (**green** colour) and "VRS Monitored" (**blue** colour) solution with respect to the GPS standalone solution (**red** colour) for the same rover receiver is provided.

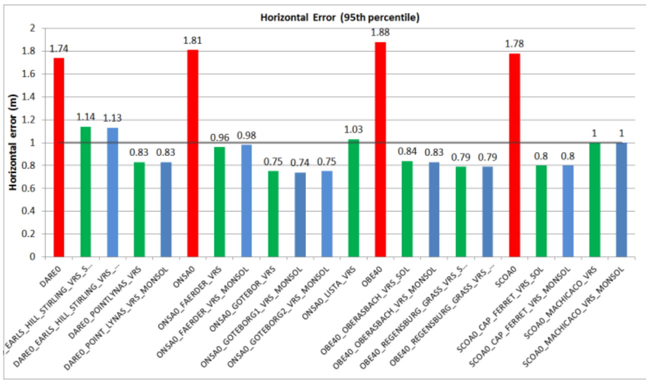

Figure 12: GPS only and EDAS based VRS solutions horizontal accuracy (02/07/2016-13/08/2016).

Figure 12 shows that the results obtained after applying the integrity monitoring check are basically the same (differences below 0.02 meters at the 95th percentile) than the performance obtained without applying the PBM check.

Based on the above, it can be concluded that the PBM check seems not include any degradation on the accuracy results obtained with the EGNOS-based VRS solution. Consequently, these results confirm the quality (accuracy and robustness) of the EGNOS-based VRS solution since almost no corrections are filtered out by the PBM checks (i.e. no degradation in the position error due to discarded satellites).

Also, the results obtained shows that the EGNOS-VRS accuracy could be suitable even for port navigation with the most stringent accuracy requirements (1 m at the 95th percentile).

DGPS Availability Performance using EDAS-Based VRS corrections

Once it is confirmed that the addition of the PBM integrity check does not include any degradation in the accuracy performance obtained by the EGNOS-Based VRS solution, the objective of this section is to assess the impact of the integrity check on the availability performance.

In this regard, it is noted that the availability (computed as the percentage of epochs in which the solution is in differential mode) of the EGNOS-Based VRS differential solution is mainly driven by the **Availability of the EGNOS message**. Access in real time to the EGNOS SBAS message is necessary in order to generate the VRS corrections. It is noted that during the period covered by this report, the EGNOS SBAS message was always provided by at least one of the two operational GEOs (100% of the time available - for more information, please refer to the EGNOS User Support website).

In order to maximize the availability of the EGNOS-VRS solutions, it is recommended to include a GEO switching functionality in the module responsible for getting the EGNOS corrections from EDAS.

This GEO switching functionality has not been implemented for the analysis presented in this paper, being the VRS corrections generated only with the messages provided by the EGNOS GEO 120. This caused an outage on all the VRS solutions on 12th July, when there was a data gap of 30 minutes on this GEO. Assuming that on an operational environment the GEO switching functionality would be implemented, this period of time (when the GEO 120 was not available) has been excluded from the statistics presented hereafter.

On the other hand, for the solutions implementing the PBM integrity check, the following aspects may also have an impact on the availability of the differential solution in the rover:

- **Availability of the monitoring station:** In case of a data gap in the monitoring station, the corrections generated by the VRS are flagged as not monitored and therefore, discarded by the rover.
- **Integrity events** can also have an impact on the solution including the integrity check. For instance, the integrity check may decrease the number of valid satellites and eventually, prevent the user to compute the navigation solution due to lack of valid satellites. Also, in case the position error exceeds the threshold configured in the monitoring station, the VRS corrections will be flagged as "not working" (in the message header) and discarded from the navigation solution computation.

Taking into account the two factors detailed above, Figure 13 shows the availability of the EGNOS-Based VRS solution including the PBM integrity check (**blue** colour) and not including it (**green** colour).

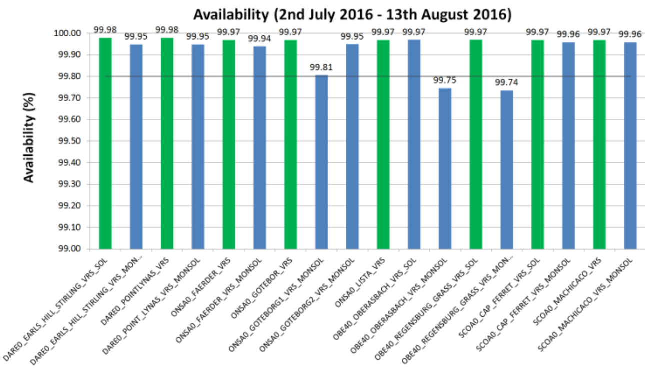

Figure 13: EGNOS-based VRS (with and without PBM integrity check) differential availability (02/07/2016-13/08/2016).

As can be easily seen in the previous figure, the availability of the EGNOS-Based VRS corrections is always above 99,9% (meeting the 99,8% requirement [20]) for all the solutions without integrity monitoring. The comparison with respect to the monitored solution, shows that the addition of the PBM check has almost no impact on the availability performance (differences lower than 0,05%) but for the three solutions configured with the inland settings (ONSA0-GOTEBORG1, OBE40-OBERASBACH and OBE40-REGENSBURG-GRAS) where the availability results are very close to or below the 99,8% requirement for the monitored solutions.

The main reason for this availability decrease is the more demanding thresholds defined for the inland solutions. In particular, the two meters threshold configured for the position error. This means that the VRS will be flagged as not-working and therefore discarded when the position error is above two meters in the monitoring station.

The impact of the PBM settings on the availability results is evident when comparing the performance obtained with ONSA0-GOTEBORG1 (inland settings) and ONSA0-GOTEBORG2 (coastal settings) solutions, where the only differences between both scenarios are the PBM thresholds.

For instance, the following figure shows a comparison of the position error computed for both solutions, representing in red colour the epochs in which the reference station is flagged as not-working. As it may be observed, the corrections generated by the GOTEBORG1-VRS-MONSOL are discarded when the position error is above two meters for more than 10 seconds (pre-set period of time). For that reason, there are some epochs in the following figure where the error is above 2 meters but the corrections are not discarded yet (green colour). And the other way around, some epochs in red colour although the error is below 2 meters (since the software waits 10 seconds until setting the station is healthy again). It is also highlighted that no epochs are discarded for the GOTEBORG2-VRS-MONSOL since the error does not exceed the 10 meters threshold defined for this solution.

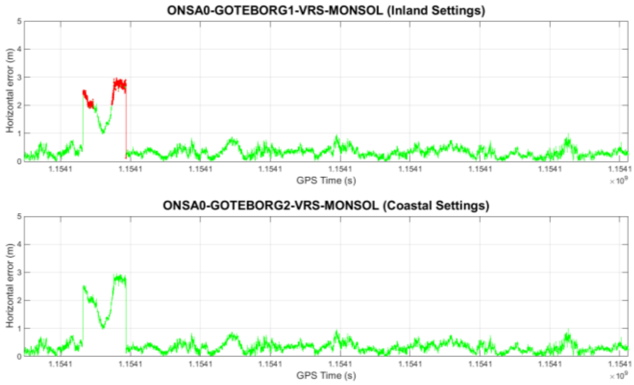

Figure 14: Horizontal Position Error: Inland PBM settings vs coastal settings (01/08/2016).

DGPS Integrity Performance using EDAS-Based VRS corrections

As a first result, Figure 15 shows the most important statistics yielded by the PBM integrity monitoring module:

- <u>Percentage of epochs the corrections are flagged as not monitored</u>: As mentioned before, in case the monitoring station is not available (or the corrections are not received by this station), the VRS stream is flagged as "not monitored".
- <u>Percentage of epochs the horizontal position error exceeds PBM threshold</u>: In that case, the station is flagged as "not working" and the corrections are discarded by the rover.
- <u>Percentage of epochs a satellite is discarded by the PRC and/or RRC check</u>
- <u>Percentage of epochs a satellite is discarded by the PRC and/or RRC residual check</u>

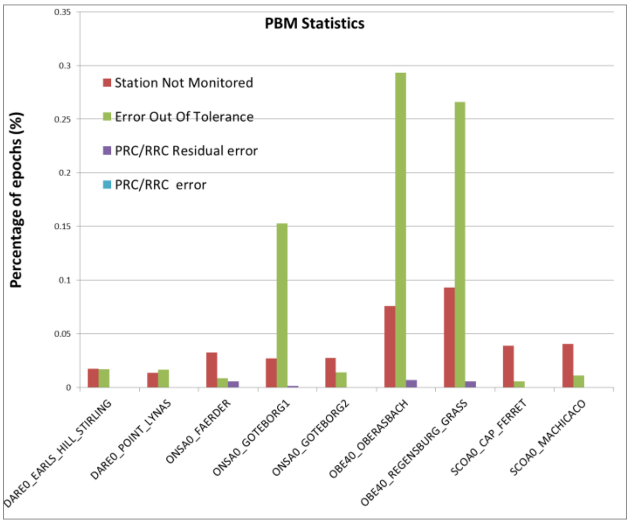

Figure 15: PBM Integrity Monitoring Statistics (02/07/2016-13/08/2016).

In the previous section, the impact of the position error threshold on the availability performance has been observed. This is also reflected in Figure 15, where a significantly increase on the corrections flagged as "not working" is detected for the three inland solutions (see Table 3) although accounting for less than 0.3% of the time.

In Figure 15, the impact of the monitoring station on the availability of the differential solution is also observed. As mentioned before, in case there is a data gap in the monitoring receiver, the VRS stream is flagged as "not monitored" and therefore, the corrections are discarded for the differential solution.

Regarding the PRC and RRC integrity checks, it is noted that during the 6 weeks of data analysed, no satellite has been discarded due to a high PRC or RRC value. This is reflected in Figure 15, but also in the following figures, depicting the maximum PRC and RRC values provided for each satellite for the Goteborg, Faerder and Oberasbach VRS streams. As it can be observed, the PRC and RRC values for all the satellites never exceed the thresholds defined for the inland and coastal solutions.

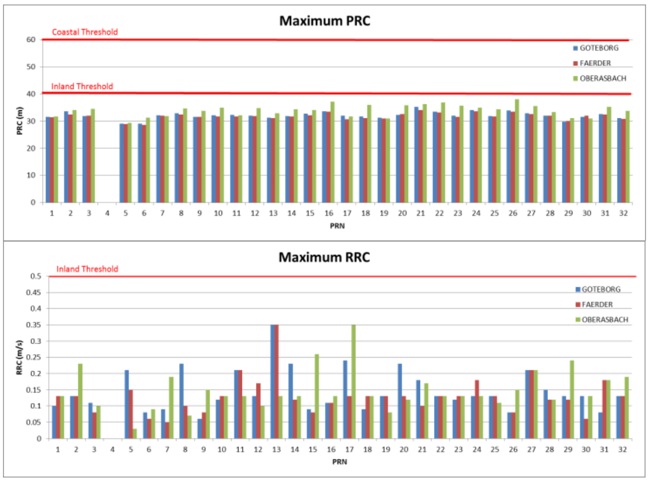

Figure 16: Maximum PRC and RRC residual values for Goteborg, Faerder and Oberasbach VRS streams (02/07/2016-13/08/2016).

However, the statistics provided by the PRC and RRC residuals check, shows that several satellites are discarded for the Oberasbach, Regensburg Grass (inland) and Faerder (coastal) VRS solutions (see Figure 15).

The analysis of the maximum residual values (see Figure 17) shows that in several occasions, the PRC residual exceeds both the inland and coastal thresholds.

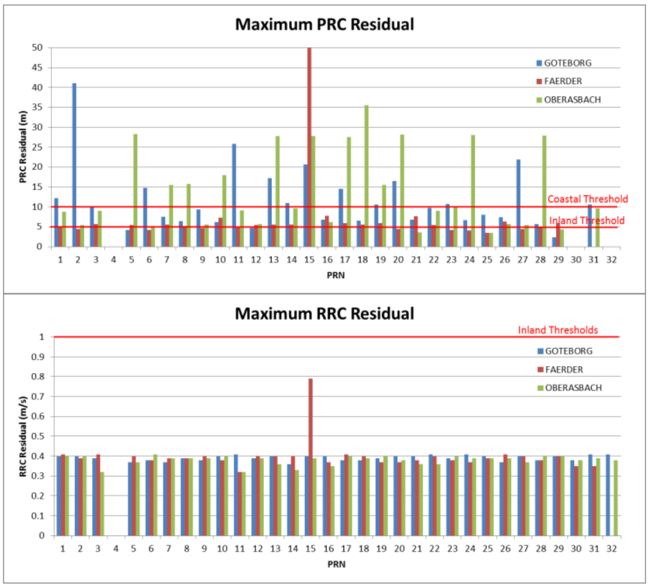

Figure 17: Maximum PRC and RRC values for Goteborg, Faerder and Oberasbach VRS streams (02/07/2016-13/08/2016).

In this point, it is important to remark that in order to set a satellite to “do not use”, the residuals shall exceed the thresholds for a pre-set period of time (10 seconds for this study). In the case of Goteborg, there are only five intervals (for the satellites 1, 11 and 15) when the PRC residual exceeds the five meters threshold defined for the inland solutions (no period longer than 10 seconds for the coastal solution – hence, these events would have had no impact on the user side due to their short duration).

Finally, it is important to remark that the analysis of the statistics yielded by the PBM integrity module shows that the percentage of epochs (for a 6-week long period) when a satellite is discarded due to the pseudorange domain checks is lower than 0.002%.

Regarding the position domain range, the percentage of epochs a station is flagged as “not working” is lower than 0.09%, even when a very demanding position threshold of two meters has been defined.

These statistics illustrates the quality of the EGNOS-based VRS corrections. This is also observed in the following figure, depicting the cumulative density function of the PRC and RRC residuals (PRC residuals at the 99th percentile below 2 meters and RRC residuals below 0.015 m/s).

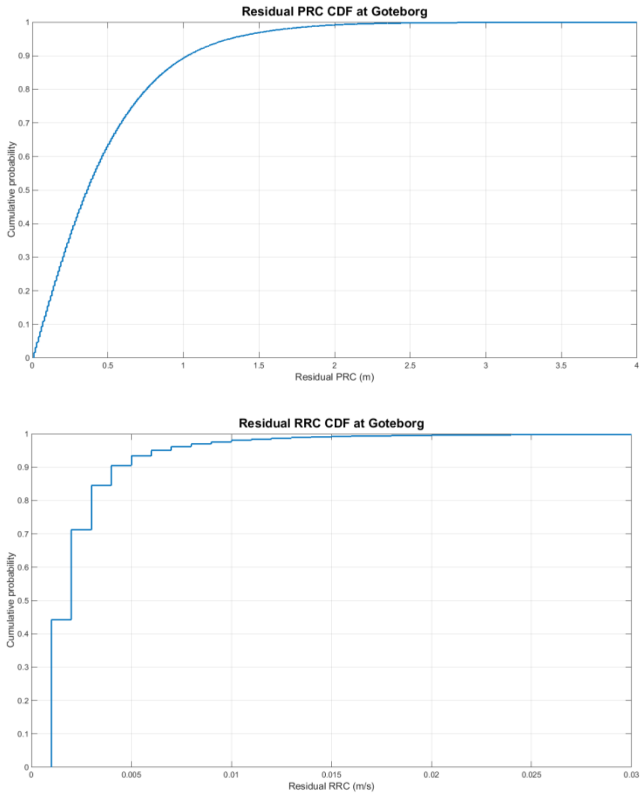

Figure 18: Cumulative density function of the PRC and RRC residuals for Goteborg.

CONCLUSIONS

EDAS is the access point to the data collected and generated by the EGNOS ground infrastructure through the EGNOS stations network in real time and offline through an FTP archive. EDAS has been freely available for the GNSS community in the European Union since July 2012, with a minimum availability of 98.5% for the main data services and of 98% for the rest of the EDAS Services [1].

EDAS has already proven to be a versatile service, supporting professional users in different commercial applications. Interested companies and research institutions are welcome to register to the EDAS Services (http://egnos-user-support.essp-sas.eu) or contact to the EGNOS Helpdesk (egnos-helpdesk@essp-sas.eu) for further information.

EDAS data could be used for maritime navigation by computing virtual differential GPS corrections based on EGNOS messages, named as EGNOS-based Virtual Reference Station (EGNOS-VRS). In this regard, it is noted that the EGNOS augmentation message delivered through EDAS is robust to local effects potentially affecting the receiver: jamming interference, receiver noise or user visibility conditions (as long as one EGNOS RIMS is tracking the GEO satellite, its messages will be output through EDAS).

A 6-week long (from 2nd July to 13th August) performance analysis has been carried out for 9 different EGNOS-based VRS solutions. The test-bed architecture used for this analysis has been based on the network approach concept [17], including a Pre-Broadcast Monitoring (PBM) module that uses the raw data collected by an independent network of GNSS receivers to check the integrity of the differential corrections. The conclusions drawn from this analysis are summarised hereafter:

- The EGNOS-VRS Horizontal Error at the 95th percentile is below 1 m on all baseline lengths up to 300 km and shows at least a similar behaviour to the standard DGPS option (with and without applying the PBM integrity check).
- A differential GPS navigation solution based on VRS corrections was computed the 99.9% of time as long as GPS measurements in the rover receiver were available.
- When including the integrity check (with a selected configuration- Table 4), the availability of the solutions configured with the coastal settings is maintained above 99.9%. Even for the inland solution, where a very demanding threshold was defined for the position error, the availability is above 99.7%.
- In order to meet the availability requirement of 99.8% for the maritime operations, the availability of the monitoring receiver and the thresholds defined in the integrity check are driving factors.
- The quality of the EGNOS-based corrections is illustrated by the fact that only 0.002% of the epochs a satellite is discarded by the pseudorange domain check (and in some cases, this is caused by a jump in the data collected by the monitoring station and not due to a failure of the differential corrections) and only 0.09% of the epochs due to the position domain check. Also, this is confirmed by the almost equivalent position accuracy of the monitored solutions when compared to the ones without integrity check.

In conclusion, EDAS could be used as part of a cost-effective solution (providing some room for the rationalization of the infrastructure), in line with the IALA recommendations and the accuracy (10 meters at the 95th percentile for general navigation and even, the 1 meter requirement for ports), availability (99.8%) and integrity requirements.

ACKNOWLEDGMENTS

The authors would like to acknowledge the efforts done by the European Commission (EC) and the European GNSS Agency (GSA) for continuously supporting the EDAS programme and for launching the evolution project that enabled the EDAS added-value services reflected in this paper. Also, ESSP fully supports GSA initiatives and efforts to analyse the potential of EDAS to support the maritime community as a promising alternative for maritime navigation infrastructure modernisation and rationalisation.

Finally, the authors would like to thank their colleague, Guillermo Montaner, who has provided invaluable support to this paper.

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