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EGNOS Performance in Several Maritime Campaigns

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ABSTRACT: This article presents the EGNOS (European Geostationary Navigation Overlay Service) performance observed along several maritime campaigns carried out in European waters with the objective to demonstrate the availability of corrections and the suitability of the accuracy to support maritime navigation. The regions selected correspond to those located in the border area of EGNOS coverage and include the following campaigns: Norwegian coast in 2018, Southwest of Europe in 2018 & 2019, Finnish coast in 2019, Baltic Sea in 2021 and Irish coast in 2022.
These results in real maritime environment aim at demonstrating that EGNOS L1 service is suitable to support maritime navigation in ocean waters, coastal waters and harbour entrances/approaches according to the operational requirements defined in the IMO Res. A.1046 (27), being beneficial for maritime community.

1 EGNOS L1 MARITIME SERVICE

EGNOS is the satellite-based positioning service over Europe which provides better accuracy with respect to GPS standalone position. In addition, EGNOS provides Integrity, which can be suitable for safety critical applications in the maritime sector.

The EC (European Commission) and EUSPA (European Union Agency for the Space Programme) are working on the future EGNOS L1 Maritime Service with target service declaration by end of 2023 or beginning of 2024. This service will be defined in a Service Definition Document and notifications of predicted EGNOS unavailability will be provided to mariners through Maritime Safety Information (MSI) service. At the same time, IEC TC80 (International Electrotechnical Commission Technical Committee) is developing a new standard for SBAS L1 receiver equipment (IEC 61108 7, [1]), which will include the performance requirements and methods of testing required for maritime navigation. This standard IEC 61108 7 plans to be published by end of 2023. From that moment, vessels will start using type-approved SBAS L1 receivers (compliant with IEC 61108 7) in order to ensure the required operational performance for the maritime community.

This article presents the EGNOS (European Geostationary Navigation Overlay Service) performance observed along several maritime campaigns carried out in European waters.

These results in real maritime environment aim at demonstrating that EGNOS L1 service is suitable to support navigation in ocean waters, coastal waters and harbour entrances/approaches according to the operational requirements defined in the IMO Res. A.1046 (27) [2]. Thus, this assessment is an evidence of the benefits of using EGNOS, encouraging maritime community to equip their vessels with type-approved SBAS L1 receivers and use EGNOS L1 service once it is operational.

2 METHOD OF TESTING

Different GNSS campaigns have been carried out along different European waters, trying to cover the border areas of EGNOS coverage: Northwest area within the Norwegian coast and Irish coast, Northeast within the Baltic Sea and South west within a route from South of Iberian Peninsula to Canary Ireland. Different types of receivers were installed on board of a vessel to output the SBAS corrected position and the GNSS observation measurements. Additionally, a SIS L1 recorder was also installed to be able to replay in the laboratory the recorded GNSS signals and feed them into different receivers to compute again different positioning solutions, such as GPS standalone.

There are different types of receivers in these GNSS data campaigns: high-end receivers, maritime receiver and software (SW) receiver.

- High-end receiver: It is able to provide high level of performance and output a wide variety of GNSS information useful for post-processing analysis. High-end receivers are normally used in marine engineering and surveying operations.
- Maritime receiver: A receiver brand that is commonly used for maritime navigation.
- SW receiver: This type of receiver is used in the laboratory to initially test the performance of a software implementation. The SW receiver was fed with the GNSS observation measurements provided by the other receivers installed on board the vessel in order to compute SBAS or GPS position in the laboratory.

Once the standard for SBAS L1 receiver equipment (IEC 61108 7, [1]) is published, vessels will start being equipped with type-approved SBAS L1 receivers (compliant with IEC 61108 7) in order to ensure the required operational performance (i.e. harbour entrances/approaches). These types of receivers shall have been developed according to the specification and shall have passed successfully the required methods of testing described in that IEC standard. Considering that the standard will be published by end of 2023, there were no receivers in line with potential IEC 61108 7, [1] by the time of the data campaigns. However, the software receiver used follows the guidelines developed for SBAS maritime receivers, implementing the requirements defined as the baseline for the standard under development.

Details about the methodology of computing can be found in [3]. Receiver was configured to compute navigation data and store the associated outputs every 1 second (1 Hz frequency). Once the vessel had concluded his route and the equipment was collected, receiver outputs were analysed to obtain the following:

- Real position. The real position considered as reference for the position error estimation was computed in post-processing using Precise Point Positioning (PPP) with the GNSS observations data obtained by a high-end receiver.
- SBAS Navigation solution. The SBAS Navigation solution using EGNOS was computed by the receiver and reported in the output files.
- GPS-only solution. GNSS radio frequency L1 signal recorded during the maritime dynamic data campaign was replayed in the receiver to obtain GPS standalone solution. GPS-only solution is compared with SBAS solution to show the improvements of using SBAS.

Based on this, the following performances were obtained:

- Accuracy: Horizontal Navigation System Error (HNSE) or Horizontal Position Error (HPE) achieved 95% of the time. Horizontal Navigation System Error is the 2D radial error between the instantaneous position solution (SBAS or GPS) with respect to the instantaneous real position (computed using PPP in post-processing). It is noted that HNSE / HPE was computed every 1 second.
- Position Availability: Percentage of time that the receiver is providing the corresponding position (EGNOS or GPS).

Considering that EGNOS L1 maritime service plans to support the navigation in ocean/coastal waters and harbour entrances/approaches according to the operational requirements defined in the IMO Res. A.1046 (27) [2], these performances will be compared with the accuracy requirement of 10 meters.

3 EGNOS SIS AVAILABILITY

EGNOS Signal in Space was 100% during all the maritime campaigns, which meets the 99.8% EGNOS signal in space availability requirement of IMO Res. A.1046 (27) [2]. The fact that EGNOS system has two operational geostationary satellites ensured that at least one satellite was transmitting EGNOS corrections during the whole time. As an example, from January 2017 to January 2023, EGNOS SIS availability was 100%. Figure 1 shows the EGNOS SIS availability over the last 6 months, and the SIS availability per SBAS satellite (PRN136 and PRN 123 are the EGNOS GEO satellites in operation since March 2020).

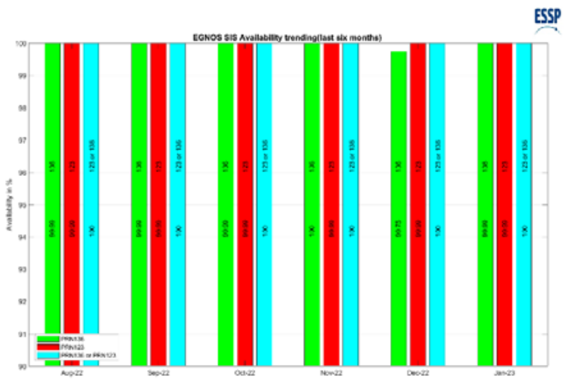

Figure 1. EGNOS SIS availability trending (last 6 months)

4 MARITIME CAMPAIGNS

4.1 *Norwegian coast in 2018*

In order to assess the EGNOS performance at user level in the maritime domain at high latitudes in

Europe, a data campaign was carried out along the Norwegian Coast. In the northbound, the vessel departed from Trondheim to Kirkenes. The southbound was from Kirkenes to Bergen.

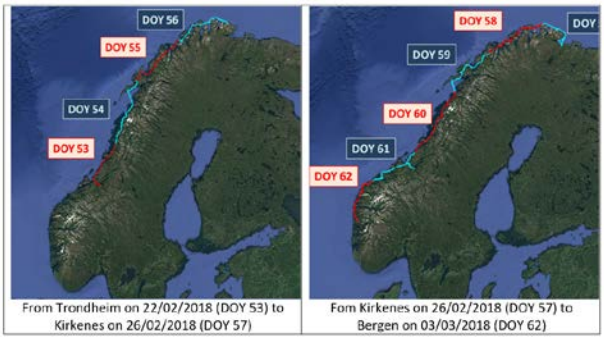

Figure 2. Vessel trajectory through Norwegian Coast

The Horizontal Navigation System Error (HNSE) histogram was computed for the EGNOS High-end receiver (coral), the EGNOS software receiver (blue) and the GPS standalone receiver (purple) and presented in Figure 3.

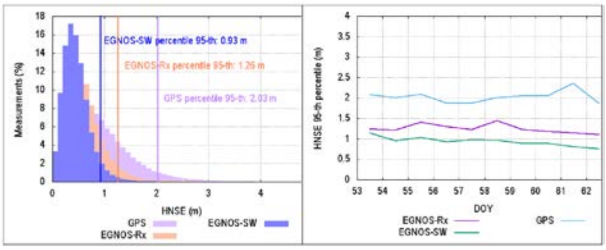

Figure 3. HNSE histogram (left). Daily HNSE 95-th percentile values (right)

These figures confirm that EGNOS SW receiver provides the best (the lowest HNSE values) accuracy performances with values about 1m. This EGNOS SW was developed implementing the receiver requirements that were considered important for the future IEC61108-7 standard [1] for SBAS L1 maritime receivers. Both, EGNOS SW and EGNOS high-end receiver (HNSE of 0.95m and 1.26m respectively), provide enhanced position solution with respect to GPS (HNSE of 2.03m).

EGNOS position availability was impacted due to the following reasons:

– The coverage area of GEO satellite PRN 120 was very limited in the Northeast European Area, which impacted the reception of EGNOS messages from PRN120 when the vessel was located in the Northeast area, positions in which the elevation angle was very low. On 23rd August 2018, PRN 136 was introduced in EGNOS operational platform replacing PRN 120, which improved the visibility over the Northeast of Europe.
– In northern altitudes, where the elevation of the SBAS GEO was very low, EGNOS signal were blocked in areas close to mountains or fiords.

The impact of the orography in the availability of the EGNOS signal received by the receiver is greater according to the elevation angle of the SBAS GEO satellite as shown in Figure 4. It is noted that the EGNOS position lower than 100% in locations lower than 62° latitude degrees was because the vessel was sailing in narrow fiords with poor SBAS satellite visibility from the vessel.

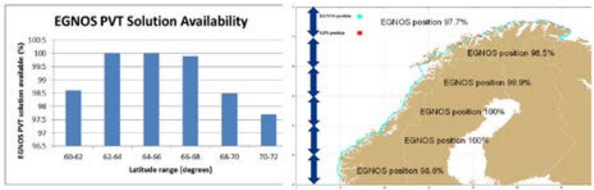

Figure 4. EGNOS position availability in function of latitude obtained from EGNOS Rx.

4.2 *Southwest of Europe in 2018 and 2019*

The oceanographic Hespérides vessel sailed from Cartagena (Spain) to Antarctica on 19th December 2018 and returned back on 25th June 2019, covering 48 days inside the EGNOS MT27 service area (longitude from -40° to 40°, latitude from 20° to 72°). In the return trip, the ship performed some inspections close to Canary Islands, being possible to test EGNOS performance in the border coverage area.

Figure 5 shows the route followed by the vessel along the mission and the number of days analysed. Additionally, this figure shows in yellow the vessel trajectory in which the EGNOS navigation solution was available with no alarms, after passing the recommended plausibility checks defined hereafter and which are included in draft IEC 61108-7 [1]. Then, a navigation position is considered as valid with no alarms when the following three conditions (plausibility checks) are met:

4. SBAS position: The navigation solution using EGNOS messages have been computed.
5. HDOP check: The Horizontal Dilution of Precision (HDOP) is equal or lower than 4 (HDOP $\leq$ 4).
6. Integrity using RAIM: The receiver autonomous integrity monitoring (RAIM) status is ok, with a selected accuracy of 10m at the 95% confidence level, which corresponds to harbour entrances/approaches and coastal waters [2].

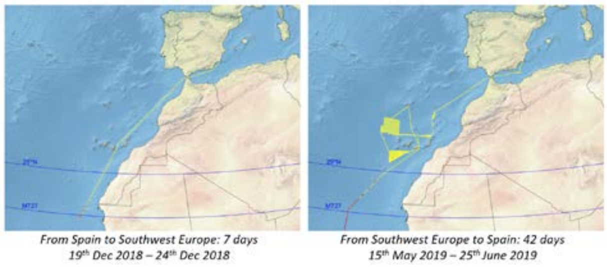

Figure 5.Vessel trajectory through Southwest Europe and EGNOS navigation solution

As it is observed in yellow, EGNOS navigation solution was available with no alarms (SBAS position computed, HDOP check passed successfully and RAIM integrity algorithm provides a safe status) in the coastal waters in Europe, covering Canary Islands, Madeira and South of Spain. As expected, EGNOS navigation solution (with no alarms) was not available when getting close to the MT27 area as expected, especially when located down to 25 degrees North. Then, the potential SBAS L1 maritime service area for harbour entrances/approaches and coastal waters could cover in the Southwest of Europe the Canary and Madeira Coasts.

When computing the percentage of time that the EGNOS position was OK at receiver level with no alarms (the three conditions met) for those days in which the latitudes were greater than 25°, it resulted in 99.5% for the Maritime SW receiver and 99.7% for the SBAS receiver. It is noted that these figures are very good, considering that they were affected by receiver local effects, such as problems in signal tracking, gaps in processing or other issues in pseudo-range measurements.

Figure 6 shows the Horizontal Navigation System Errors (HNSE) for EGNOS and GPS computed for the receivers: SBAS High-end Rx and Maritime SW. EGNOS HNSEs are lower with respect to GPS in all the cases, meeting with quite margin the 10 meters requirement for ocean/coastal waters and harbour entrances/approaches [2].

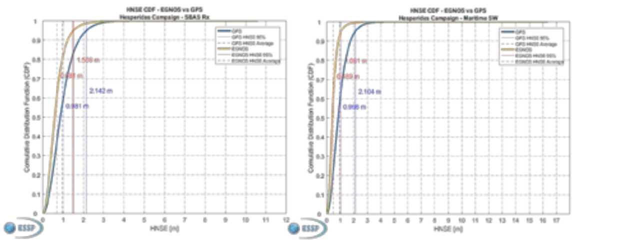

Figure 6. EGNOS accuracy: CDF figures (left: SBAS High-end Rx, right: SW Maritime)

Checking the performance per specific days, there are situations in which position errors are especially better in EGNOS with respect to GPS. Especially for areas close to equator in which the ionospheric activity is high, where EGNOS can monitor the ionosphere in real time and broadcast up-to-date corrections, providing more stable accuracy results. Below an example is presented, in which GPS solution reached instantaneously the 10-meter error, whereas with SBAS, the position errors are more stable and always lower than 4 meters (0.925 meters percentile at 95%).

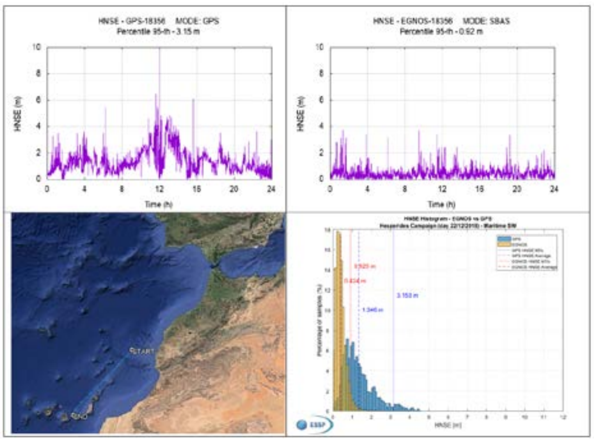

Figure 7. EGNOS vs GPS: 22/12/2018

4.3 *Finnish coast in 2019*

The vessel Mastera departed from Porvoo (Finland) to Primorsk (Russia) then until Naantali (Finland). Afterwards, the vessel went from Naantali (Finland) to Primorsk (Russia) being two days stopped close to Uusimaa waiting for orders (adrift) and finally arrived at Porvoo (Finland). The total trajectory was from 1st November 2019 to 14th November 2019.

Figure 8. Vessel trajectory through Finnish coast

Within this GNSS campaign, EGNOS position availability was 100% for both SBAS maritime receiver and high-end receiver.

For the EGNOS position accuracy, Table 1 presents daily HPE (95%) for EGNOS and GPS standalone, both for High-end and Maritime receivers. It is noted that for that the GPS position for the high-end receiver was only available for 5 days, the duration of the recorded SIS during the campaign. It is observed that the EGNOS position was always better than the GPS position. For example: 4.07 m GPS position for High-end receiver with respect to the 1.18 m for EGNOS position on DOY (GPS Day Of the Year) 305.

Table 1. HPE (95%) obtained using EGNOS and using GPS standalone

	EGNOS HPE 95% percentile [m]		GPS standalone HPE 95% percentile [m]	
DOY	High-end receiver	Maritime receiver	High-end receiver	Maritime receiver
305	1.179	0.869	4.073	1.444
306	0.935	0.791	3.284	1.809
307	0.970	0.792	1.653	1.222
308	0.970	0.747	2.103	1.638
309	1.023	0.835	1.738	1.307
310	0.967	0.841	2.235	2.000
311	0.950	0.907	1.832	--
312	0.956	0.718	3.818	--
313	0.873	0.762	3.312	--
314	1.000	0.786	3.527	--
315	1.057	0.808	3.860	--
316	0.911	0.784	1.208	--
317	0.870	0.792	1.228	--
318	1.049	0.872	1.688	--
TOTAL	0.971	0.815	3.149	1.551

Additionally, Figure 9 shows the HNSE and ECDF (Empirical Cumulative Distribution Function) for the first 5 days where there were results for GPS position. As it can be observed, EGNOS position errors were considerably reduced with respect to GPS and the EGNOS accuracy met with quite margin the 10 meters requirement for ocean/coastal waters and harbour entrances/approaches [2].

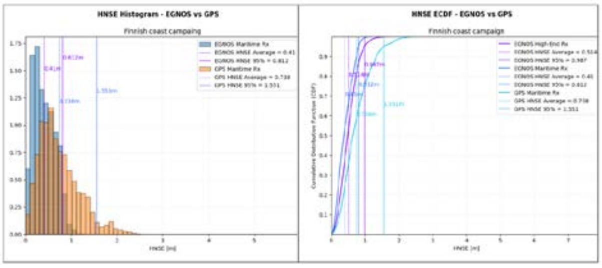

Figure 9. HNSE Histogram for Maritime Rx (left) and ECDF for both receivers (right)

4.4 *Baltic Sea in 2021*

Kiisla is a Finnish Aframax crude oil tanker operated by Neste Shipping. This icebreaking tanker transported crude oil year-round along the coast of the Baltic Sea. OSM Group, the Norwegian Oil Transport provider, manages this vessel. Kiisla, departed from Munkebo (Denmark) on September 1st 2021 and navigated up to December 1st 2021. The oil tanker visited eleven harbours placed in five different countries as seen in Figure 10: Denmark, Lithuania, Latvia, Sweden and Finland.

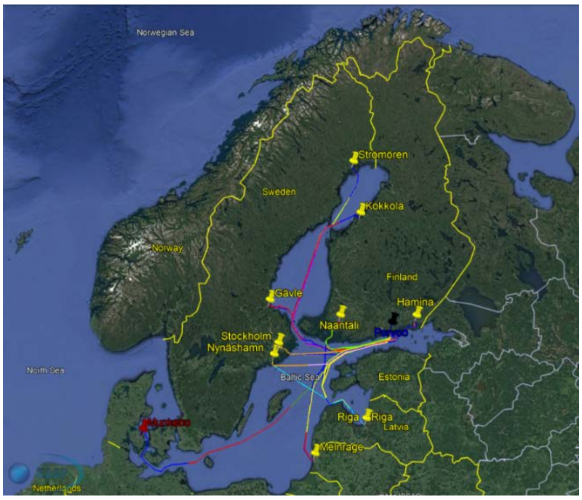

Figure 10. Baltic Sea maritime campaign in 2021

EGNOS position availability was 99.99% for the SBAS maritime receiver. All days presented 100% EGNOS position availability but one day that was 99.93% due to a local failure at receiver level.

Table 2 shows main statistics for the horizontal position accuracy when the maritime receiver was using EGNOS position solution.

Table 2. Horizontal position accuracy obtained using EGNOS

	EGNOS horizontal accuracy [m]		
Period of time (DOY)	Mean	95%-percent.	Max.
244 - 253	0.310	0.715	1.168
254 - 263	0.337	0.844	2.350
264 - 273	0.327	0.749	1.145
274 - 282	0.419	0.925	1.829
283 - 293	0.351	0.826	1.447
294 - 303	0.359	0.881	1.730
304 - 313	0.360	0.955	2.068
314 - 320	0.387	0.920	1.617
321 - 335	0.399	0.939	1.466
TOTAL	0.361	0.779	2.350

Table 2 presents daily HNSE (95%) quite close to 1m when using EGNOS solution whereas the global value for the whole data campaign is 0.779m with a maximum value of 2.35m.

Instantaneous EGNOS horizontal position error is drawn in the following picture, where it is observed that EGNOS position met with quite margin the 10-meter requirement for ocean/coastal waters and harbour entrances/approaches [2].

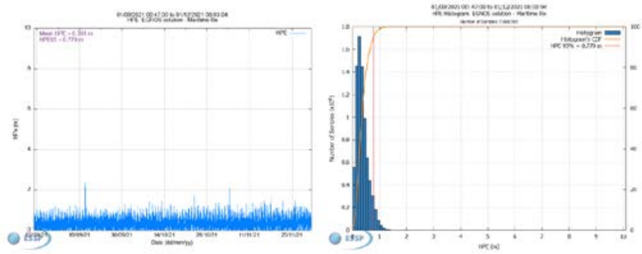

Figure 10. EGNOS HPE vs time (left) and EGNOS HPE histogram & CDF (right)

4.5 *Irish coast in 2022*

The vessel Granuaile navigated from Killybegs (North –West of Ireland) on 17th August 2022 up to Dún Laoghaire on 15th November 2022 (North – East of Ireland), going between both ports up to Oban (North England) (see Figure 11). It sailed going in anti-clockwise direction. The ILV Granuaile is a multi-functional vessel to maintain the automatic navigation buoys in Irish waters.

Figure 11. Vessel trajectory through Irish coast

EGNOS position was provided along the whole trajectory by the maritime receiver during 99.39% of time. Seven days were identified with EGNOS receiver position availability lower than 100%, which were all caused by local issues, such as lack of GNSS signal, power cut-off and other types of problems at receiver or antenna level. EGNOS system was available.

Analysing the accuracy results (see Figure 12), it can be concluded that percentile at 95% of instantaneous Horizontal Position Errors using EGNOS is 0.788 meters, meeting with quite margin the 10 meters requirement for ocean/coastal waters and harbour entrances/approaches [2].

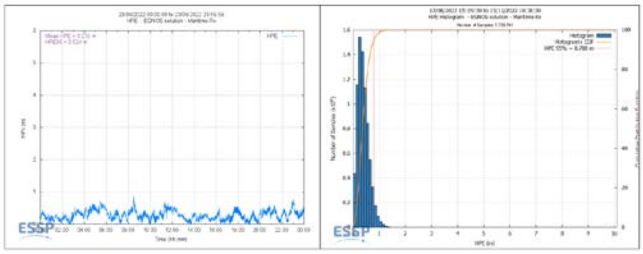

Figure 12. EGNOS HPE vs time for 23/08/2022 (left) and EGNOS HPE histogram for all trajectory (right)

5 CONCLUSIONS

This article presents the EGNOS (European Geostationary Navigation Overlay Service) performance observed along several maritime campaigns carried out in European waters with the objective to demonstrate the availability of corrections and the suitability of the accuracy to support maritime navigation. The regions selected correspond to those located in the border area of EGNOS coverage and include the following campaigns: Norwegian coast in 2018, Southwest of Europe in 2018 & 2019, Finnish coast in 2019, Baltic Sea in 2021 and Irish coast in 2022.

Analysing the EGNOS and GPS navigation position, the main conclusions are the following ones:

1. EGNOS signal in space availability was 100% during all campaigns meeting the 99.8% requirement of IMO Res. A.1046 (27) [2]. The fact that EGNOS system has two operational geostationary satellites ensures that at least one satellite is transmitting EGNOS corrections, providing 100% of EGNOS SIS availability.
2. EGNOS position availability was nominally 100% in open sky visibility in locations between 25° and 70° degrees latitude.
   - In narrow fiords in Norway the SBAS visibility was blocked, especially in latitudes over 68 degrees where EGNOS satellites were observed with low elevation. As an example, EGNOS position availability was 98.5% over the North of Norwegian coast from 68° to 70° latitudes.
   - EGNOS position availability presented high value above 25° degrees latitude (99.7% for SBAS High-end receiver), covering navigation of Canary Islands waters.
   - In nominal conditions of open sky visibility with no issues at receiver or antenna level, EGNOS position availability was 100%. This was the case of the Finnish coast campaign.
   - EGNOS position availability was impacted in sporadic moments by local issues at receiver or antenna level, the observed unavailability events were not caused by EGNOS corrections. For Baltic Sea campaign, EGNOS position was 99.99% due to a local failure at receiver level. For Irish coast trajectory, EGNOS position was 99.39% due to several local issues, such as block of GNSS signal, power cut-off and other types of problems at receiver or antenna level. It is noted that the Irish coast campaign lasted 90 days being more prompt to local problems and not related to EGNOS SiS corrections availability.
3. EGNOS position accuracy at percentile 95th was lower than 2 meters in all the campaigns, meeting with quite margin the 10 meter requirement for harbour entrances/approaches and coastal waters established in IMO Res. A.1046 (27) [2].
   - EGNOS position accuracy presented slightly higher accuracy values over the North border area and over the Southwest border area, whereas the improvement with respect to GPS was bigger and the position accuracy values were much more stable.
     - Apart from navigating close to EGNOS coverage area, GNSS position performance was more impacted over those areas due to ionospheric issues. For example, high-end receiver presented instantaneous EGNOS HNSE at percentile 95% during the Norwegian coast of 1.26m and during the Southwest Europe campaign of 1.506m, whereas in Finnish coast was 0.971m. Additionally, maritime receiver presented instantaneous EGNOS HNSE at percentile 95% during the Southwest Europe campaign of 1.061m, whereas in Finnish coast was 0.815m and in Baltic Sea was 0.779m.
     - In those areas where GNSS performance is prompted to be impacted by ionospheric issues, EGNOS enhancement with respect to GPS is bigger. EGNOS can monitor the ionosphere in real time and broadcast up-to-date corrections, providing more stable accuracy results. An example is presented for the 22nd Dec 2018, where there were peaks of GPS position error up to 10 meters, whereas EGNOS position remained lower than 4 meters during the whole day. In this case improvement of EGNOS with respect to GPS was quite notably considering that the HNSE (95%) was 0.925 m for EGNOS and 3.153 m for GPS.
   - EGNOS position accuracy at 95% was nominally lower than 1 meter for both receivers (Maritime and High-end) in trajectories that were not located in the border EGNOS coverage area, such as Finnish coast, Baltic Sea and Irish coast.
   - Position errors using EGNOS were between 30% and 70% better than GPS Standalone considering the percentile at 95% of the complete campaign. For specific cases of high solar activity or ionospheric issues, EGNOS improvement was considerably important (i.e. 70% for example presented on 22nd Dec 2018) since EGNOS navigation position was stable during the whole period whereas GPS presented important high position errors (even reaching 10 meters).

In consequence, the EGNOS performance observed on these maritime campaigns indicates that EGNOS can support "Harbour entrances/approaches and coastal/ocean waters" according to IMO Res A.1046 (27) [2] over Norwegian coastal waters, Irish coastal waters, Finnish coastal waters, Canary Ireland coastal waters and Baltic Sea. Once the IEC 61108-7[1] test standard on SBAS is published, vessels will start equipping type-approval receivers using EGNOS Service and RAIM to ensure a safe navigation in harbour entrances/approaches and coastal waters.

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We would like to kindly express their gratitude to OSM Group, the Norwegian Oil Transport provider to allow ESSP to install the receiver on board this oil tanker, Kiisla, as well as to Väylä, the Finnish Transport Infrastructure Agency to invite ESSP to perform this GNSS data campaign in the Baltic sea and coordinate it with OSM Group.

We would like to thank both Commissioners of Irish Lights to allow ESSP the installation of GNSS equipment in ILV Granuaile vessel and GLA (General Lighthouse Authorities) of the UK and Ireland (Research and Radionavigation Directorate) for its support in the installation and use of their MF antenna during the GNSS data campaign around Ireland.

Finally, the authors would like to acknowledge the efforts done by EC and EUSPA to work at programme level for the future provision of EGNOS L1 maritime service.

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