GNSS Evolutions for Maritime

An Incremental Approach

iStock photo by Ivan Cholakov

At the end of 2013, the European Space Agency (ESA) started analyzing possible GNSS evolutions within the maritime sector. Various techniques have been investigated in close collaboration with the maritime community. The use of satellite-based augmentation system (SBAS) corrections in maritime receivers is currently unregulated. This article discusses two possible strategies (mid-term and long-term) for the development of a dedicated standard for combining use of SBAS with differential GNSS services to provide a resilient positioning, navigation, and timing capability for maritime applications, including e-Navigation.

MARCO PORRETTA, DAVID JIMENEZ BANOS, MASSIMO CRISCI, GIORGIO SOLARI, AND ALESSANDRA FIUMARA

Trends for marine accidents show rising numbers and costs that are mainly associated with collisions and groundings. Research indicates that about 60 percent of these accidents are caused by human error. The majority of them could have been avoided by providing suitable input to the navigation decision-making process, according to a 2008 report by the International Maritime Organization (IMO) Marine Safety Committee. (See IMO 2008 in Additional Resources section near the end of this article.).

In order to improve safety of navigation and to reduce errors, IMO is promoting the e-Navigation concept. This is defined as the "harmonised collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment" (IMO 2008).

IMO and the International Association for Lighthouse Authorities (IALA) identify several technological enablers that support the e-Navigation concept. These include, amongst others: accurate electronic navigation charts (ENCs), a robust electronic position, navigation and timing (PNT) system (with redundancy), and an agreed communications infrastructure to link ship and shore.

Further, robust PNT information requires three complementary components: a core GNSS, augmentation systems, such as differential GNSS (DGNSS) or satellite-based augmentation system (SBAS), to ensure that the GNSS performance is able to meet the application requirements, and an adequate backup in the event of a GNSS system failure.

The backup system is based on employing several independent terrestrial schemes that could be made available to users. They include, for example, enhanced Loran (eLoran), ranging mode (R-Mode) navigation using signals independent of GNSS, or enhanced radar positioning techniques. Used in conjunction with GNSS, such independent, redundant systems significantly increase the resilience of the on-board PNT system against possible "feared events" (FEs) affecting a single component of the system. This positioning approach is also known as "resilient PNT" and is currently being supported by the IMO in the development of the e-Navigation concept.

One of the most immediate benefits of resilient PNT is an increased robustness of the GNSS component against local error sources. These include, but are not limited to, multipath events, unintentional interference, and deliberate interference attacks such as jamming or spoofing.

In this context, possible roles for SBAS have been investigated and discussed with the maritime community. This article discusses preliminary results of an analysis of these roles. In it, we will first discuss the operational requirements for radio navigation systems (RNSs) to be used in maritime applications and then outline the current status of GNSS for maritime applications. Next, we will present the main features of DGNSS and SBAS as well as the possibility of offering SBAS as a possible augmentation system complementing DGNSS. Finally, we propose two strategies ("mid-term" and "long-term,") for the use of SBAS in maritime applications.

GNSS Performance Requirements for Maritime

Two IMO resolutions outline the operational requirements for the use of RNSs in maritime applications. IMO A.1046(27) specifies the requirements of an RNS as a generic component of a World Wide Radio Navigation System (WWRNS). Here, a WWRNS component can be either a satellite-based (GNSS) or a terrestrial-based system. In contrast, IMO A.915(22) focuses on GNSS as a stand-alone system and introduces the requirements for a "future," not yet identified, GNSS.

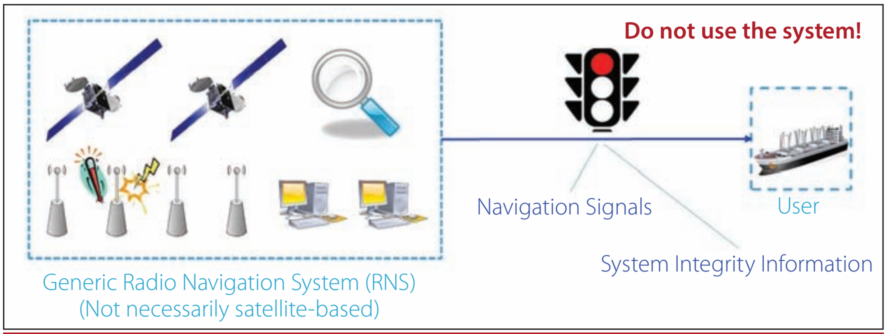


FIGURE 1 Integrity at system level

The two documents express the associated requirements using performance parameters that have a different scope and, therefore, a different approach. As a result, the two resolutions demand different methods to monitor the navigation performance and to verify the level of compliance with the associated requirements. This verification is a key element for safety-of-life (SoL) applications.

IMO A.1046(27). The feasibility of a WWRNS has been investigated since 1983. These studies produced an amendment of Chapter V of the 1974 SOLAS convention that includes "a requirement for ships to carry means of receiving transmissions from suitable radio navigation systems throughout their intended voyage." The global nature of the WWRNS requires the overall system to be formed by different sub-systems (or components), possibly including GNSS together with the associated augmentation systems (e.g., DGNSS or SBAS), other regional satellite navigation systems, and other (not necessarily satellite-based) radio navigation systems, such as eLoran. WWRNS specifically allows for implementation of the resilient PNT concept, provided that independent RNSs are recognized as a component of the overall system.

Procedures and responsibilities concerning the recognition of an RNS as a component of the WWRNS are detailed in the IMO A.1046(27) resolution. In particular, a generic component (not necessarily satellite-based) of the WWRNS has two main tasks. It must first provide the users with navigation signals and must also constantly monitor the quality of the navigation service provided (the "system integrity monitoring" task). System integrity information is then broadcast to the user together with navigation signals.

Figure 1 presents a schematic of this type of integrity service, where the "Generic RNS" block indicates the WWRNS component. If a failure is detected in one of the RNS modules, the user is promptly warned that the system (or the information provided by that specific module) should not be used.

This approach for integrity monitoring considers only the "system-related failures" that might prevent the RNS from broadcasting accurate navigation signals. This concept is normally referred to as "integrity at system level" and is not able to promptly warn the user in case of performance degradations due to local error sources (i.e., multipath or interference).

If the user requires additional protection from local error sources, further checks — for example, receiver autonomous integrity monitoring (RAIM) techniques — must be autonomously performed by the user receiver, thereby locally verifying the consistency of the navigation signals provided by the system. Note, however, that these checks are recommended but not mandatory under IMO A.1046(27).

IMO specifies operational requirements in more detail using four parameters: accuracy, system integrity, signal availability, and service continuity. In particular, these requirements define service continuity as the capability of the system to provide its service (navigation signals and broadcast of system integrity information), without interrup-

Requirement/ Navigation Phase	Ocean Waters	Harbor entrance, harbor approaches and coastal waters
Accuracy (95% horizontal navigation system error)	100 meters	10 meters
Integrity: *"An integrity warning of system malfunction, non-availability or discontinuity should be provided to users …"*	*"… as soon as practicable by Maritime Safety Information (MSI) systems"*	*"… within 10s"*
Signal Availability: *"Signal availability should exceed…"*	*"… 99.8%"*	*"… 99.8%"*
Service Continuity	N/A	*"The system shall be considered available when it provides the required integrity for the given accuracy level. When the system is available, the service continuity should be ≥99.97% over a period of 15 minutes"*

Table 1 Operational requirements for a component of the WWRNS

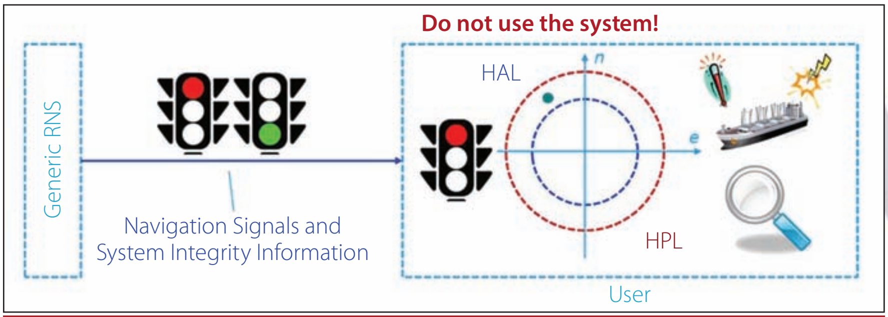


FIGURE 2 Integrity at the user level (HPL and HAL denote the horizontal protection level and the horizontal alert limit, respectively, while the actual, unknown, horizontal position error is indicated by a green dot)

tions, throughout the duration of a given operation.

Based on these parameters, IMO requirements address two navigation phases: (1) ocean waters and (2) harbor entrance, harbor approaches, and coastal waters. **Table 1** presents the parameters of these operational requirements. However, the IMO requirements do not specify the actual navigation performance at the user level.

IMO A.915(22). This IMO resolution expresses operational requirements for future GNSS based on the *actual performance at the user level.* The parameters include accuracy, integrity, continuity, and availability as defined for civil aviation applications by the RTCA Inc. (see RTCA DO-229D in Additional Resources). In other words, according to the RTCA, the properties of a GNSS system include both the GNSS service (i.e., the properties of the signal in space, or SIS, provided by both the space and the ground segments of the GNSS) and the user receiver.

This is a fundamental difference with the operational requirements needed for a single component of the WWRNS as described in IMO A.1046(27), which only considers system-related aspects. In particular, the underlying integrity concept is now at the user level and includes, for each maritime operation, the specification of three parameters, i.e., the alert limit (AL), the time to alert (TTA), and the integrity risk (IR) (See IMO, Revised Maritime Policy and Requirements for a Future Global Navigation Satellite System, GNSS," in Additional Resources section for further details.)

Once these parameters are set, the integrity at the user level is monitored by calculating, at the user receiver, a maximum error bound (protection level, PL) for the navigation system error (NSE). This estimation is done at each epoch and normally uses navigation signals (observables), system integrity information, and suitable models for the effects due to local error sources. The definition of these models requires a detailed characterization of the operational environment, including, for example, an analysis of the expected levels for multipath and interference.

Based on the input data provided by the three variables used to estimate user-level integrity, the resulting PL calculation takes into account both system-related failures and possible effects due to local error sources. The PL calculation can be completed either completely autonomously (e.g., via RAIM techniques) or based on additional information provided by the system (e.g., when SBAS is used for aviation applications per the RTCA standards). **Figure 2** represents the concept of integrity at the user level for a generic RNS that, in this case, is a future GNSS system. If the user wants to perform a given operation, the current value of the protection level is compared with the AL requirement associated with that operation. If, because of a failure, the PL exceeds the AL specification, the receiver will promptly warn the user that the position estimation cannot be trusted.

In Figure 2, the actual position error (PE), which is normally unknown, is indicated by a green dot. The PL provides a conservative estimation of the PE. In case the PL exceeds the AL specification, a "Do not use the system" warning is communicated to the end-user.

The protection level calculation should always over-bound the position error, thus avoiding critical situations where the PE exceeds the alert limit, while the estimated PL is below the AL *(PL < AL < PE).* These situations are referred to as "hazardously misleading information" (HMI) events, and their probability of occurrence must be below the integrity risk requirement.

HMI events might be due to unexpected local threats whose effects are not covered by the error models used for PL calculation. Essentially, this may happen for two reasons: the local threat was not considered as a potential feared event when designing the algorithm for PL computation, or the threat was actually taken into account but the adopted error model is shown not to be adequate in that specific situation.

Therefore, even if integrity at the user level is effectively provided by the PL in nominal conditions and for all the foreseen FEs, additional barriers should be put in place against unexpected situations. These barriers are a key element when a given operation is not performed in a "controlled" environment (e.g., an airport), where the actual levels of multipath or interference are kept below acceptable thresholds. A harbor environment is typically not controlled; so, additional protection schemes might be required. One of the most effective barriers is the concurrent use of location information from independent positioning schemes, as actually recommended by the resilient PNT concept.

The IMO A.915(22) resolution indicates the operational requirements for a number of navigation phases and maritime applications. However, several discussions with maritime community representatives confirmed that none of the existing GNSS systems is designed to fulfil this resolution and that no maritime operations currently require compliance with it. The basis for the requirements indicated in the resolution is, therefore, unclear. For example, one of the amendments under discussion is the operation duration, which may be reduced from three hours to 15 minutes to gain consistency with IMO A.1046(27).

As a result, the specifications currently indicated in IMO A.915(22) can only be viewed as a starting point for future evolutions. These are expected to target the harmonization with IMO A.1046(27) and the consolidation of the GNSS role in a resilient PNT system.

Current Status of GNSS for Maritime

At the moment, only GPS, GLONASS, and BeiDou are recognized as part of the WWRNS. The European Commission initiated the recognition process for Galileo, which is currently on-going. Although already accepted as a component of the WWRNS, these systems need proper augmentation systems to perform the most critical operations, i.e., navigation in harbor entrances, approaches, and restricted waters. Nowadays, the most used augmentation system is DGNSS. The possible use of SBAS is also being investigated in a number of different research projects (e.g., see the article by Kvam *et alia*).

DGNSS. Historically, the predominant use of DGNSS arose from the need for augmentation during the most critical maritime operations, especially when selective availability (SA) was still in place for GPS. DGNSS provides the user with differential corrections (improved accuracy) and system integrity information. Differential corrections, together with the associated user differential range error (UDRE) indicators, are evaluated at a reference station (RS), which is placed at a known location. The corrections, together with the associated UDRE, are then broadcast to the users in the RS coverage area using a dedicated medium frequency (MF) radio data link.

The nominal accuracy of IALA DGNSS beacons is typically between three and five meters. The larger the distance is between the user and the RS, the larger the expected accuracy degradation (0.67 meters per 100 kilometers from the RS, according to the IALA recommendation on DGNSS services).

As mentioned, the DGNSS integrity concept is applied at the system level only and is based on the assessment of the quality of corrections. Integrity monitoring (IM) is performed with the use of a separate DGNSS receiver, which is also placed at a known location, normally a few hundred meters from the reference station to avoid possible correlations of multipath events.

The integrity monitoring evaluates the quality of corrections in both the position and the pseudorange domains. If a pseudorange or a position alarm is generated, the user is promptly warned via a "do not use that SV" or "do not use the system" flag, respectively, which is included in the DGNSS message.

The rationale underlying this IM concept is that the IM receiver will experience the same level of performance as each user receiver in the RS coverage area. Therefore, such a concept is not able to protect the user from possible local error sources. This is an inherent limitation of all differential systems.

The effects due to local error sources can be detected by RAIM algorithms, which are able to identify possible outliers and to estimate the expected accuracy (error ellipse) of the resulting position solution. In general, these techniques can be used with both augmented and un-augmented pseudorange observations and do not depend on the particular augmentation system in use.

In order to monitor the performance of a specific DGNSS service, IALA provides some recommendations, but the scope of these guidelines is limited to service provision. For example, signal availability, A, is evaluated as:

$$A = MTBO/(MTBO + MTSR) \quad (1)$$

where $MTBO$ and $MTSR$ indicate the mean time between outages and the mean time to service restoration, respectively. This recommendation covers both scheduled outages (e.g., due to planned maintenance activities) and unscheduled outages (e.g., due to unexpected failures).

Similarly, service continuity, C, is calculated as:

$$C = e^{(-CTI/MTBF)} \quad (2)$$

where CTI is the continuity time interval (i.e., the operation duration of 15 minutes), while $MTBF$ is the mean time between (unexpected) failures.

If a user is aware of the lack of DGNSS service or that a scheduled outage is going to take place, the operation will not be executed using DGNSS. For that reason, only unexpected failures are assumed to affect service continuity

Functionality	DGNSS	SBAS
Differential Corrections (Accuracy)	**Yes:** corrections are evaluated locally at each Reference Station (RS)	**Yes:** corrections are evaluated at a central processing facility based on the monitoring station measurements.
Quality of Corrections: UDRE (System Integrity)	**Yes:** UDREs for each Space Vehicle (SV) are evaluated at the RS and broadcast to the users	**Yes:** UDREs (ephemeris and clock corrections only) for each SV and Grid Ionospheric Vertical Errors (GIVEs) for each Ionospheric Grid Point (IGP) are evaluated and checked at the central processing facility; these are then broadcast to the users.
Quality of Corrections: check in the pseudo-range domain (System Integrity)	**Yes:** additional checks in the pseudo-range domain are done at the Integrity Monitoring (IM) station; if a problem is detected for an SV, the user is warned not to use that SV.	**Yes:** additional checks in the pseudo-range domain are done at the central processing facility and, locally, at each monitoring site; if a problem is detected for a SV, the user is warned not to use that SV.
Quality of corrections: check in the position domain (System Integrity)	**Yes:** additional checks in the position domain are done at the IM station; if a problem is detected, the user is warned not to use the system.	**Yes:** additional checks in the position domain are done at the central processing facility and, locally, at each monitoring site; if a problem is detected, the user is warned not to use the system (e.g. see W. Werner et alia).
Quality of corrections: autonomous consistency check at the user level	**Yes:** it can be done at the user level based on RAIM algorithms which verify the consistency of augmented GNSS observations (e.g. UKOOA in Additional Resources); the result is an error ellipse which describes the confidence levels in the position estimation.	**Yes:** it can be done at the user level based on augmented GNSS observations; for example, the same RAIM algorithm, (UKOOA), recommended for the DGPS case can be used; only the corrections are different.

Table 2 A comparison of DGNSS and SBAS functionalities

and are, therefore, considered in the service continuity equation. Note also that, according to the IALA recommendation, all the mean times (*MTBO, MTSR,* and *MTBF*) shall be evaluated based on a two-year averaging period.

DGNSS is currently not formally recognized by IMO as a component of the WWRNS, primarily because of not being able to meet the service continuity requirement. Service continuity performance might be improved by increasing the number of reference stations, thus enlarging the areas (multiple coverage areas) where a user can receive differential corrections from more than one RS. If a failure is affecting one RS, the user will still be able to receive the corrections from another; so, the service provision will not be interrupted.

Although service continuity might be a limitation in those areas where the user is able to receive differential corrections from one RS only (single coverage areas), DGNSS is, at the moment, the incumbent GNSS solution for maritime applications.

Some DGNSS Service Providers (SPs), from both public and private sectors, are already anticipating its long-term goal of making the most of different multi-frequency GNSSs. At the same time, in order to reduce the significant maintenance costs of a DGNSS infrastructure, some SPs are also promoting the use of complementary augmentation systems. This is happening, for example, in the United States, where the U.S. Coast Guard is currently authorizing the Coast Guard vessels to use the Wide Area Augmentation System (WAAS) as a complement to DGPS. For that reason, SBASs might be effectively used to complement DGNSS, thus increasing service continuity.

SBAS. WAAS and the European Geostationary Navigation Overlay Service (EGNOS) are examples of SBASs. These systems are able to provide, over a wide (or regional) area, the same type of information offered by a DGNSS service, i.e., differential corrections and system integrity information, through the use of additional, satellite-transmitted messages (SBAS messages).

SBASs are based on a network of ground monitoring stations located at accurately surveyed points that monitor the signals of GNSS satellites. The system integrity is monitored by checking the quality of differential corrections in both the pseudorange and the position domains. The measurements are collected and processed at a central facility where the SBAS messages are created. These data are then uplinked to one or more satellites (e.g., geostationary, GEO, satellites) and finally broadcast to the end users in the SBAS coverage area.

Differential corrections and system integrity information provided by WAAS, EGNOS, and other SBASs can, in principle, always be used to increase the position estimation accuracy and to protect the user from possible system-related failures. Therefore, depending on the application requirements, SBASs can be used to support a range of operations in various transportation domains, including maritime.

SBAS as a Complement of DGNSS

Table 2 presents a summary comparison of SBAS and DGNSS functionalities. Because both systems provide users with similar information, SBAS can be used to effectively complement DGNSS. This option might be particularly attractive in the maritime sector, where DGNSS is currently the most used augmentation system. As a matter of fact, SBASs are potentially able to fill possible gaps in the coverage area of a DGNSS service, thus providing the user with a "seamless," augmented, navigation solution.

In particular, SBAS nominal performance has the potential to meet the IMO requirements for a component of the WWRNS, as shown in Table 3, where the operational requirements for the most critical operations (navigation in harbor entrances, harbor approaches, and coastal waters) are considered.

As mentioned, the opportunity of using SBAS as a complement for DGNSS has been already taken by the USCG, which has acknowledged the use of WAAS as an official augmentation system for GPS receivers. The USCG clearly states that the "National Differential GPS (NDGPS) system and the WAAS are the only GPS corrections currently authorized for Coast Guard vessel use in high-risk (e.g., restricted waters) navigational zones/areas."

Based on these considerations, two possible strategies may be identified to promote the use of SBAS in maritime. The "mid-term" strategy consists of promoting the use of SBAS as a complement or a back-up to DGNSS. In this case, the underlying integrity concept is at the system level only. The "long-term" strategy is, on the other hand, based on the development of a novel integrity concept designed in close cooperation with the maritime community that will closely follow the evolution of the resilient PNT concept. The next two sections discuss these strategies.

'As Is': The Mid-Term Strategy

The mid-term strategy would use SBAS "as is," i.e., with no modifications to the SBAS message structure or to the ground segment infrastructure. The strategy is based on SBAS capability of providing differential corrections and system integrity information, as well as navigation performance comparable to that of DGNSS.

Based on these considerations, SBAS could be immediately promoted as a complement or a back-up to DGNSS. As indicated in **Table 3**, the interoperability between SBAS and DGNSS is expected to be beneficial especially for critical navigation phases of the WWRNS (harbor entrance, harbor approach, and coastal waters).

The use of SBAS should be encouraged through the development of standards that are specifically tailored for maritime. **Table 4** describes some of the major issues associated with such an effort. For each aspect, the table lists the underlying problem (open issue) and outlines a possible solution. These (and other) issues will need to be investigated in close cooperation with the maritime community. The objective is to make the

Operational Requirement for a Component of the WWRNS (IMO 2011)
for the most stringent operation (Navigation in harbour entrances, harbour approaches and coastal waters)

Performance Parameter	Requirement	SBAS
Accuracy	"Where a radio-navigation system is used to assist in the navigation of ships in such waters, the system should provide positional information with an error not greater than 10m with a probability of 95%."	**Yes:** SBAS nominal accuracy is typically between 3–5 meters.
System Integrity	"An integrity warning of system malfunction, non-availability or discontinuity should be provided to users within 10s."	**Yes:** System integrity information is included in SBAS messages and provided in accordance with a TTA requirement of 10 seconds.
Signal Availability	"Signal availability should exceed 99.8%" (No requirement about system availability)	**Yes:** The signal availability is actually related to the provision of SBAS corrections. - This exactly matches the availability of at least one GEO satellite broadcasting the SBAS messages in the SBAS coverage area. - Signal availability, *A*, can be calculated based on the relevant recommendations for DGPS (Equation 1), and normally exceeds the 99.8% requirement. - For example, assuming an MTBO (over two years) of $10^3\ h$, the requirement is met if the corresponding MTSR (over two years) is below 1.67 $h \cong 1.5\ h$ (Equation 1).
Service Continuity	"When the system is available, the service continuity should be ≥99.97% over a period of 15min."	**Yes:** The service continuity is actually related to the uninterrupted provision of SBAS corrections throughout the operation duration (15 minutes). - As for signal availability, service continuity, C, can be calculated based on the relevant recommendations for DGPS (Equation 2). - In this case, the MTBF value is the mean time between two subsequent failures, which completely prevents the system from SBAS messages broadcasting. These failures are so rare that the 99.97% requirement is normally met. - In particular, with CTI=15mi, the requirement is met if the MTBF (over two years) is larger than 833 $h \simeq 10^3\ h$ (Equation 2).

Table 3 SBAS nominal performance versus the WWRNS operational requirements.

Aspect	Open Issue	Possible Solution
Receiver Design (SBAS message processing)	No standard is currently available to unambiguously define SBAS message processing for maritime receivers. As a result, receiver manufacturers are now developing maritime products based on their own adaptation of the processing recommended for aviation operations (RTCA).	Especially for critical (e.g., SoL) maritime applications, a unique methodology should be standardized, where the recommended processing is able to ensure the provision of integrity at the system level.
SBAS/DGNSS interoperability	Nowadays, many commercial receivers for maritime automatically switch from DGNSS to SBAS (and vice-versa) without even telling the user what the actual augmentation system in use is. In both cases, the solution is simply marked in the receiver log file as a differential position fix, with no further indication about the source of the associated differential corrections. This uncertainty might lead to serious liability problems in case of a legal controversy, as DGNSS and SBAS are normally operated and maintained by different authorities, which act as SPs.	A suitable method should be standardized to unambiguously select (assuming both DGNSS and SBAS are available) the most convenient augmentation system. This will require a number of trade-off analyses. For example, the selection might be based on the distance between the user and the closest available DGNSS reference station and/or the number of SBAS ground monitoring stations surrounding the user. The standard should also identify how the user is notified about the actual augmentation system in use.
Receiver installation, antenna siting and Test Case Procedures (TCPs).	Performance requirements, methods of testing and required test results for ship-borne DGNSS equipment are currently standardized by the International Electrotechnical Commission (IEC). The available standard provides recommendations for a number of aspects, including receiver installation, antenna siting, or mitigation techniques for noise and interference. Each of these aspects is complemented by the relevant TCP. Log files produced by a DGNSS receiver which is installed, tested, and operated according to the IEC standard can be used as evidence in a legal controversy. A similar standard is currently not available for SBAS.	A dedicated standard, similar to that of the IEC, should be developed for SBAS.
Information about both scheduled and unscheduled outages.	Both scheduled maintenance activities and unscheduled outages may affect the provision of a DGNSS service. Information about these outages should be promptly communicated to the maritime users using suitable systems, such as coastal radio stations or the Vessel Traffic Service (VTS). According to IALA, the date and the expected downtime of scheduled maintenance shall be communicated at least one week in advance (one month is recommended), while the expected downtime for an unscheduled outage shall be communicated as soon as possible and, in any case, not more than one hour after the occurrence. A similar service should be put in place for SBAS when it is used to complement DGNSS.	An SBAS normally includes a "Notice To Air Men" (NOTAM) service which provides aeronautical users with prompt alerts about both scheduled and unscheduled outages in the system. The service is compliant with International Civil Aviation Organization (ICAO) recommendations for the Aeronautical Information Services (AIS) (see ICAO in Additional Resources), and can be potentially re-used for maritime applications as well. However, proper communication links must be established to broadcast these alerts to maritime users.

Table 4 Open issues for the use of SBAS as a complement of DGNSS (Mid-Term Strategy)

best use of the available SBAS performance in compliance with the WWRNS operational requirements.

Maritime Integrity: The Long-Term Strategy

The objective of the long-term strategy is the development of an integrity concept precisely tailored for maritime applications. This concept may benefit from the use of SBAS corrections, together with the relevant system integrity information. Depending on the specific needs expressed by the maritime community for various applications, the concept might eventually allow for protection-level calculations at the user receiver, thereby offering integrity at the user level.

This integrity concept is currently expected to be developed in the framework of a resilient PNT system, where (augmented) GNSS observations are used in conjunction with additional measurements available from other terrestrial-based RNSs and/or from on-board inertial sensors (e.g., inertial measurements units, or IMUs).

In a resilient PNT scheme, the use of differential systems, such as SBAS or DGNSS, is expected to significantly increase the overall resilience level. These systems are actually able to improve the quality of GNSS observations and to provide system integrity information. For that reason, they immediately offer a "certified" protection against possible system-related failures.

If augmented GNSS observations are then combined with additional, non-GNSS measurements, a much more robust navigation solution can be designed in which the user is also protected from the effects of local error sources. As noted, these effects cannot be mitigated by differential systems alone.

At the moment, the high-level architecture of a resilient PNT system is still being defined. However, it already appears clear that the development of a resilient PNT system will take into account future evolutions of SBAS and, in general, of GNSS. Several aspects (and trade-offs) need to be carefully evaluated. These will include, for example, the use of dual-frequency multi-constellation (DFMC) measurements (together with the relevant corrections, if available) and the method (i.e., loosely, tightly, or deeply coupled) used to combine (augmented) GNSS observations and inertial measurements.

Conclusions and Way Forward

The use of SBAS corrections in maritime receivers is currently not regulated. This article discussed two possible strategies for the development of a dedicated standard. These are based on the operational requirements specified by the IMO for a component of the WWRNS and for future GNSS, respectively.

Operational requirements for a component of the WWRNS are indicated in the IMO A.1046(27) resolution. These requirements call for the provision of integrity at the system level only and do not consider possible performance degradation due to local error sources. At the moment, only GPS, GLONASS, and BeiDou are recognized as components of the WWRNS. However, these systems need augmentation to perform the most critical operations, i.e., navigation in harbor entrances, harbor approaches, and coastal waters.

DGNSS is the most used solution for augmentation. It can provide both differential corrections and immediate alerts in the event of a system-related failure. An SBAS is able to effectively provide the same type of information. It could be, therefore, immediately promoted to complement DGNSS in all the situations where augmentation is needed. Although some open issues (e.g., SBAS/DGNSS interoperability) should be unambiguously solved through standardization activities, the use of SBAS as a complementary augmentation system could be promoted in the medium term.

Operational requirements for future GNSS are indicated in the IMO A.915(22) resolution. These requirements call for the provision of integrity at the user level as defined in this article. However, no GNSS system is designed to fulfil IMO A.915(22) in its current version, and there are no maritime operations that require compliance with it.

Depending on the actual needs expressed by the maritime community for different applications, this integrity concept might be developed in the framework of a resilient PNT receiver, where (augmented) GNSS observations will be used in combination with other measurements available from terrestrial-based RNSs and IMUs. In particular, this approach is expected to provide an increased robustness against the effects due to local error sources, which cannot be tackled by differential systems.

The resilient PNT strategy is one of the technological enablers for the e-Navigation concept, which is currently being promoted by the IMO to increase the safety of maritime navigation. The evolution of this strategy is expected to give due consideration to future developments of SBAS and, in general, of GNSS. For that reason, the European Space Agency, in close collaboration with EC and GSA, is also analyzing potential benefits associated with new techniques such as (augmented) DFMC schemes or the horizontal-advanced receiver autonomous integrity monitoring (H-ARAIM) method.

Disclaimer

The views expressed in this article are solely the opinions of the authors and do not reflect those of the European Space Agency.

Additional Resources

1. Grant, A., Williams, P., Hargreaves, C., and Bransby, M., "Demonstrating the Benefits of Resilient PNT," *Proceedings of the 26th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2013)*, Nashville, Tennessee USA, pp. 598-604, September 2013

2. IALA Guideline No. 1112 on Performance and Monitoring of DGNSS Services in the Frequency Band 283.5 – 325 kHz, Edition 1, Saint Germain en Laye, France, May 2015

3. IALA "World Wide Radio Navigation Plan," Edition 2, Saint Germain en Laye, France, December 2012

4. ICAO, "Aeronautical Information Services," Annex 15 to the Convention on International Civil Aviation, 14th Edition, Montreal, Quebec, Canada, July 2013

5. International Electrotechnical Commission, "Maritime Navigation and Radio-communication Equipment and Systems – Global Navigation Satellite Systems (GNSS) – Part 4: Ship-borne DGPS and DGLONASS Maritime Radio Beacon Receiver Equipment – Performance Requirements, Methods of Testing and Required Test Results," Reference number IEC 61108-4:2004(E), First Edition, Geneva, Switzerland, July 2004

6. IMO, "Recognition of Galileo as a component of the WWRNS - Galileo GNSS provision of initial services," sub-committee on Navigation, Communications and Search and Rescue, 3rd Session, Agenda Item 5, NCSR 3/5, London, UK, December 10, 2015

7. IMO, "Revised Maritime Policy and Requirements for a Future Global Navigation Satellite System (GNSS)," Resolution A.915(22), London, United Kingdom, January 22, 2002

8. IMO, "Report of the Maritime Safety Committee on its eighty-fifth session (MSC 85/26)," London, United Kingdom, December 19, 2008

9. IMO, "Worldwide Radio-navigation System," Resolution A.1046(27), London, United Kingdom, December 20, 2011

10. International Convention for the Safety of Life at Sea (SOLAS), London, United Kingdom, 1974

11. Kvam, P. E. and Jeannot, M., "The Arctic Test Bed – Providing GNSS Services in the Arctic Region," *Proceedings of the 26th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2013)*, Nashville, Tennessee USA, September 2013

12. RTCA, "Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment," RTCA DO-229D, Washington, D.C., December 13, 2006

13. UK Offshore Operators Association (UKOOA), Surveying and Positioning Committee, "Guidelines for the Use of DGPS in Offshore Surveying," Issue 1, London, United Kingdom, September 1994

14. USCG, "Coast Guard Navigation Standards Manual," COMDTINST M3530.2E, Washington, D.C., March 2016

15. Werner, W., Rossbach, U., and Wolf, R., "Algorithms and Performance of the EGNOS CPF Independent Check Set," *Proceedings of ION GPS 2000*, Salt Lake City, Utah USA, September 2000

Authors

Marco Porretta received both the telecommunications Engineering M.Sc. and the Ph.D. in information engineering from the University of Pisa, Italy. He has more than 10 years of professional experience in telecommunications and navigation systems. This experience includes the development of high-frequency methods for electromagnetic propagation analysis, decision support tools (DST) for air traffic management (ATM), and integrity algorithms for Global Navigation Satellite Systems (GNSS). Porretta joined ESA ESTEC in September 2011, where he is currently involved in projects and studies on GNSS, with particular attention to the EGNOS and the Galileo programs.

David Jiménez-Baños has M.Sc. degrees in telecommunications engineering and information and communication technologies from the Universitat Politècnica de Catalunya. Since 2006 he has been working at the Radio Navigation Systems and Techniques section of ESA/ESTEC, The Netherlands. His main areas of work have been on GNSS receivers, signal processing for indoor applications, SBAS systems, and GNSS simulation tools for receiver performance evaluation, and, more recently, GNSS signal processing techniques for attitude and orbit control system (AOCS) applications in geostationary and higher orbits.

Massimo Crisci is the head of Radio Navigation Systems and Techniques Section at ESA. He is the domain responsible for the field of radio-navigation. This encompasses radio-navigation systems for satellite, aeronautical, maritime, land-mobile users (including indoor) applications, equipment/techniques/receivers for (hybrid satellite/terrestrial) navigation/localization for ground and space applications, signal-in-space design, end-to-end performance analysis for current and future systems. He is the head of an engineering team providing expert support to the various ESA programs (EGNOS, Galileo and their evolutions). He holds a Ph.D. in automatics from the University of Bologna and a Master's degree in electronics from the University of Ferrara.

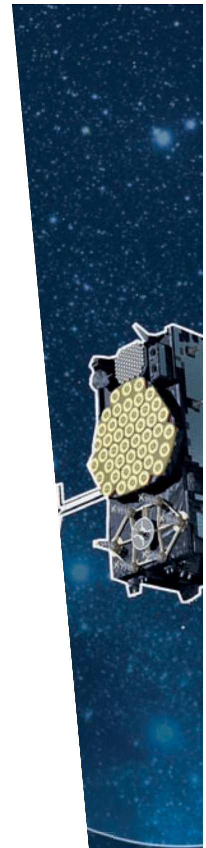
Giorgio Solari is currently serving as Head of GNSS/Safety of Life Innovation & Evolution Strategy and External Coordination Office at the European Space Agency HQ in Paris. He has been working in the space sector for more than 30 years, serving ESA since 1988. He has been managing GNSS activities for the Agency since their inception in the early 1990s and continued his career with different functions at various ESA sites in Europe Noordwijk, Netherlands, Brussels and Paris. Amongst others, he organized the first EGNOS Trials at Sea in Genoa in February 2000.

Alessandra Fiumara is the liaison officer on GNSS Evolution Program for the European Space Agency. She has been working in the space sector for 25 years, both in public and private contexts, and has acquired a deep knowledge of the related political, strategic and financial aspects. As electronic engineer, she started with technical and scientific activities in the radar application domain, then moved to strategic planning and financial control responsibilities as well as international relations. At the end of 2009, she moved from Rome to Paris to join the Navigation and Galileo-related Activities Directorate at ESA. She is involved in the analysis on the possible role of current and future GNSS systems in transport safety domains (maritime and railways).

Prof.-Dr. Günter Hein serves as the editor of the Working Papers column. He served as the head of the EGNOS and GNSS Evolution Program Department of the European Space Agency and continues to advise on scientific aspects of the Navigation Directorate as well as being a member the ESA Overall High Level Science Advisory Board. Previously, he was a full professor and director of the Institute of Geodesy and Navigation at the Universität der Bundeswehr München (UniBW), where he is now an ""Emeritus of Excellence." In 2002, he received the Johannes Kepler Award from the U.S. Institute of Navigation (ION). He is one of the inventors of the CBOC signal. IG

SIGN UP
1 APRIL – 30 JUNE
WWW.ESNC.EU

EUROPEAN SATELLITE NAVIGATION **COMPETITION 2016**



WIN PRIZES AND LAUNCH YOUR BUSINESS

Got a service, product, or business idea based on GNSS? Then put it on the fast track with help from the largest innovation and incubation network dedicated to satellite navigation.

WHY JOIN?

- 30+ awesome prizes worth EUR 1 million
- Access to 130+ space-related stakeholders
- Business support from over 40 incubators
- Great expertise from more than 240 experts

GET INSPIRED

There are thousands of ways to use satellite navigation in everyday life – what's yours?

special prize partners

GSA esa DLR Federal Ministry of Transport and Digital Infrastructure

GOT AN IDEA USING EARTH OBSERVATION DATA?
Become part of the success story and register now for the Copernicus Masters

www.copernicus-masters.com

a brand by AZO Space of Innovation