GNSS performance standards in the maritime domain

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Key words: GNSS, positioning, IMO, standards

SUMMARY

The primary means for electronic position fixing in use in contemporary maritime transport are shipborne GPS (Global Positioning System) receivers or DGPS (Differential GPS) receivers. More advanced GNSS (Global Navigation Satellite System) receivers able to process combined signals from American GPS, Russian GLONASS, Chinese Beidou (BDS), European Galileo, Indian IRNSS, Japan QZSS, and satellite-based augmentation systems (SBAS) are still relatively rare in the maritime domain, especially onboard vessels certified under international SOLAS convention. The issues of existing IMO recommendations, guidelines, requirements, performance standards, and future concepts of integrity monitoring for maritime position sensors are discussed and presented in the paper. Their impact on GIS, marine cadastre, and risk management systems using such maritime position, navigation and timing (PNT) data is presented as well.

SUMMARY (Polish)

Podstawowymi urządzeniami elektronicznego ustalania pozycji statków we współczesnym transporcie morskim są odbiorniki GPS (Global Positioning System) lub DGPS (Differential GPS). Bardziej zaawansowane wielosystemowe odbiorniki GNSS (Global Navigation Satellite System) wykorzystujące sygnały z amerykańskiego GPS, rosyjskiego GLONASS, chińskiego Beidou (BDS), europejskiego Galileo, indyjskiego IRNSS, japońskiego QZSS i systemów wspomagania satelitarnego (SBAS) są wciąż stosunkowo rzadko spotykane na jednostkach pływających podlegających międzynarodowej konwencji SOLAS. W artykule omówiono i zaprezentowano aktualne wymagania, wytyczne i standardy Międzynarodowej Organizacji Morskiej dotyczące GNSS oraz rozwijane badawczo koncepcje monitorowania wiarygodności (integralności) danych pozycyjnych w transporcie morskim. Przedstawiono również potencjalny wpływ standardów technicznych morskich odbiorników GNSS na jakość danych w systemach informacji geograficznej wykorzystujących informacje z katastru wodnego obszarów morskich i systemach zarządzania ryzykiem wykorzystujących dane PNT pochodzące z morskich statków transportowych.

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1. INTRODUCTION

Measures to improve the safety and security of international shipping and to prevent pollution from ships are agreed worldwide by International Maritime Organization (IMO). This specialized agency of the United Nations (UN) is responsible for facilitation of maritime traffic in international waters and sets policies, guidelines, and performance standards for positioning, measuring, detecting, and other navigation, deck or machinery equipment onboard vessels certified under its Safety of Life at Sea (SOLAS) convention. IMO's bodies also represent maritime domain among other intergovernmental and non-governmental organizations worldwide. IMO started work on the GNSS (Global Navigation Satellite System) as part of worldwide radio navigation systems (WWRS) in 1980s together with the UN International Civil Aviation Organization (ICAO). This was the time of American GPS and Russian (at that times Soviet Union) Glonass development, whose signals could be used worldwide for position-fixing and calculation of vessel's speed and course over ground. In 1989, by the IMO resolution A.666(16) [IMO, 1989], maritime community recognized for the first time the need for a world-wide radionavigation system to provide ships with navigational position-fixing globally. This resolution included the Report on the Study of a World-Wide Radionavigation System as the policy for the recognition and acceptance of suitable radionavigation systems intended for international maritime transport and other activities at sea. The study forming the basis of IMO policy had been conducted since 1983. It determined in the maritime domain: 1) the operational requirements of satellite navigation systems, which should be reliable, of low user cost and meeting the needs for general navigation, 2) the organizational structure and arrangements which would be needed for such a system to be recognized or accepted by IMO as being suitable for use by ships, 3) the arrangements by which a national or multinational satellite navigation system might be accepted mutually by other Administrations for use by their ships. This study is still ongoing and led to the development of:

- currently binding performance standards for shipborne GNSS receivers set by the resolutions MSC.112(73) on GPS [IMO, 2000a], MSC.113(73) on Glonass [IMO, 2000b], MSC.114(73) on DGPS and DGlonass [IMO, 2000c], MSC.115(73) on Combined GPS & Glonass [IMO, 2000d], MSC.233(82) on Galileo [IMO, 2006], MSC.379(93) on Beidou [IMO, 2014], MSC.401(95) on Multi System Shipborne Radionavigation Receivers [IMO, 2015] with MSC.432(98) amendments [IMO, 2017a], MSC.449(99) on IRNSS [IMO, 2018], MSC.480(102) on QZSS [IMO, 2020], and the resolution A.1046(27) on World Wide Radionavigation System [IMO, 2011],
- policies and guidelines that are only recommendations as declared in Resolution A.915(22) on Revised maritime policy and requirements for a future GNSS [IMO, 2001], in Circular MSC.1/Circ.1575 on Guidelines for shipborne position, navigation and timing (PNT) data processing [IMO, 2017b].

2. IMO GNSS POLICY

Resolutions A.860(20) on maritime policy for a future GNSS and A.915(22) on revised maritime policy and requirements for a future GNSS were adopted by IMO in 1997 and 2001 respectively [IMO, 1997], [IMO, 2001]. This was the time of satellite-based augmentation systems (SBAS) development whose signals could be used worldwide as an external source of GNSS corrections and integrity data. These resolutions proposed for the first time, but only as a policy to be achieved in a future, internal (user-level) and external (provided by external stations) GNSS data integrity monitoring for shipborne receivers. Integrity monitoring was defined as the process of determining whether the system performance (or individual observations conducted by the system) allows its use for navigation purposes. Overall GNSS system integrity was described by three parameters: the threshold value or alert limit (AL), the time to alarm (TTA), and the integrity risk (IR). Definitions of the following terms were introduced to maritime users:

- Accuracy: The degree of conformance between the estimated or measured parameter of a craft at a given time and its true parameter at that time (parameters in this context may be position coordinates, velocity, time, angle, etc.). Absolute accuracy (Geodetic or Geographic accuracy) is the accuracy of a position estimate with respect to the geographic or geodetic coordinates of the Earth in WGS84.
- Integrity: The ability to provide users with warnings within a specified time when the system should not be used for navigation.
- Craft autonomous integrity monitoring (CAIM): this is a technique whereby various navigation sensor information available on the craft is autonomously processed to monitor the integrity of the navigation signals.
- Receiver autonomous integrity monitoring (RAIM): A technique whereby the redundant information available at a GNSS receiver is autonomously processed to monitor the integrity of the navigation signals.
- Continuity: The probability that, assuming a fault-free receiver, a user will be able to determine position with specified accuracy and is able to monitor the integrity of the determined position over the (short) time interval applicable for a particular operation within a limited part of the coverage area.
- Availability: The percentage of time that an aid, or system of aids, is performing a required function under stated conditions where system availability is the availability of a system to a user, including signal availability and the performance of the user's receiver.
- Alert limit (or threshold value – AL). The maximum allowable error in the measured position – during integrity monitoring – before an alarm is triggered.
- Time to alarm (TTA): The time elapsed between the occurrence of a failure in the system and its presentation on the ship’s / craft’s bridge.
- IR: Integrity risk. The probability that a user will experience a position error larger than AL without an alarm being raised within the specified TTA at any instant of time at any location in the coverage area.

- Coverage: The coverage provided by a radionavigation system is that surface area or space volume in which the signals are adequate to permit the user to determine position to a specified level of performance.
- Latency: The time lag between the navigation observations and the presented navigation solution.
- Chart error (CE): Position errors in the chart caused by inaccuracies in surveying and by errors in the reference geodetic system.
- Navigation system error (NSE): The combined error of the CE and GNSS position estimate (PE) usually referenced to a common consistent reference point (CCRP) and formulated by (1):

$$NSE = CE + PE \tag{1}$$

- Vessel Technical Error (VTE): This is the difference between the indicated craft position and the indicated command or desired position. It is a measure of the accuracy the craft is controlled with. Components are cross track error (XTE) and along track error (ATE).
- Total System Error (TSE): The overall navigation performance can be described by the TSE. Assuming the contributions to TSE from NSE and VTE are random, the TSE can be described as (2) (Figure 1):

$$TSE^2 = NSE^2 + VTE^2 \tag{2}$$

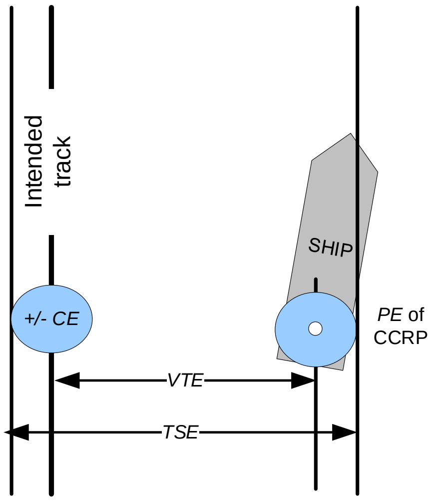

Figure 1. Contribution of GNSS position error (PE), chart error (CE), and vessel technical error (VTE) to total system error (TSE).

- Gross errors: Gross errors, or “outliers”, are errors other than random errors or systematic errors. They are often large and, by definition, unpredictable. They are typically caused by sudden changes in the prevailing physical circumstances, by system faults or operator errors.
- Marginally detectable bias (MDB). The minimum size of gross error in an observation that may be detected with given probabilities of type 1 and type 2 errors. A type 1 error occurs when an observation without a gross error is wrongly rejected, and a type 2 error occurs when an observation with a gross error is wrongly accepted.

- Marginally detectable error (MDE). The maximum position-offset caused by a MDB in one of the observations.
- Reliability of a position fix: A measure of the propagation of a non-detected gross error (outlier) in an observation to the position fix. This “external” reliability is usually expressed in terms of MDE.
- Receiver autonomous integrity monitoring (RAIM): A technique whereby the redundant information available at a GNSS receiver is autonomously processed to monitor the integrity of the navigation signals (see also Craft autonomous integrity monitoring).
- Craft autonomous integrity monitoring (CAIM): This is a technique whereby various navigation sensor information available on the craft is autonomously processed to monitor the integrity of the navigation signals.

A.915(22) also introduced detailed performance specifications to GNSS onboard equipment (service level parameters) recommended for a future GNSS:
- 10m absolute accuracy (95%) and 25m AL for most applications,
- 10s TTA,
- 10^{-5} IR per 3h,
- 99.97% continuity over 3h.
- 99.8% overall availability (considered per 30 days).

Table 1. Minimum maritime GNSS user requirements recommended for general navigation derived from [IMO, 2001]

Area	Minimum maritime user requirements for general navigation							
	System level parameters				Service level parameters			
	Absolute accuracy	Integrity			Availability [%] (per 30 days)	Continuity [%] (over 3 hours)	Coverage	Fix interval [s]
	Horizontal 95% [m]	AL [m]	TTA [s]	IR (per 3h)				
Ocean	10	25	10	1.00E-05	99.8	-	Global	1
Coastal	10	25	10	1.00E-05	99.8	-	Global	1
Port approach and restricted waters	10	25	10	1.00E-05	99.8	99.97	Regional	1
Port	1	2.5	10	1.00E-05	99.8	99.97	Local	1
Inland waterways	10	25	10	1.00E-05	99.8	99.97	Regional	1

However, some of the terms and service parameters were defined ambiguously or without specifying algorithm for their evaluation. For example there were no additional explanations provided to the formulas (1) and (2) in resolution A.915(22), so one can assume that (1) should be treated conservatively as a sum of absolute values for estimation purposes, or assuming random contributions from CE and PE it should be transformed to the Euclidean distance form of (2).

Furthermore the resolution A.915(22) has not addressed the issue of an algorithm for an upper confidence bound on the position error for IR monitoring. The contemporary shipborne GNSS receivers use mostly RAIM that takes into account only data derived from autonomous GNSS signals without any augmentation or augmented only by IALA differential signals [IMO,]. This RAIM is based on health indicator of GNSS signals and simple consistency tests to exclude faulty or disturbed data [IMO, 2017] but does not apply more comprehensive performance indicators provided for individual data to control its influence on potential PNT data output. The achievement of high level integrity evaluation as proposed in A.915(22) implicates the necessity to determine the absolute magnitude of significant errors and resulting consequences for the accuracy limits of single PNT output data via SBAS in a similar way as it was developed for aviation domain [ICAO, 2006]. In aviation such a magnitude of significant errors calculated as an upper confidence bound has been named "protection level" (PL). In order to determine horizontal PL value (HPL), the 1σ circular bound on the error in the position should be derived from augmentation data (precisely semimajor axis of elliptical uncertainty based on standard deviations of coordinates assuming multivariate normal distribution) and multiplier of this bound corresponding to IR (further called an expansion or scale k-factor: k_{HPL}) should be derived from the probability of fault-tree. The maritime world does not have an equivalent to aviation IMO certified top-down fault-tree analysis of navigation risks stemming from an allowed Target Level of Safety (TLS) so some researchers created their own as presented in Figure 2 [Hargreaves, 2018].

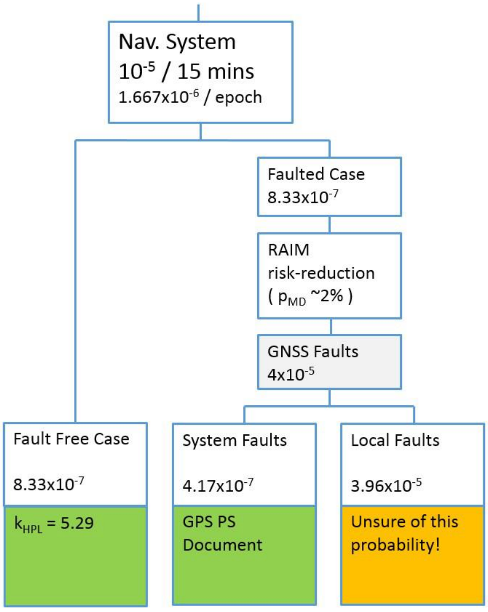

Figure 2. Integrity fault-tree branch allocating maritime integrity risk (source [Hargreaves, 2018]).

For a fault free case if GNSS error-correlation time of 150s is assumed and treated as integrity epoch correspondingly to aviation standards [ICAO, 2006], then a 3h operation interval recommended by IMO in the resolution A.915(22) will contain 3×3600s/150s=72 statistically independent epochs. This gives per-epoch integrity risk probability of:

$$IR = \frac{10^{-5}}{72} \approx 1.39 \times 10^{-7} \tag{3}$$

If IR is relaxed for 15-minute operation interval, as proposed in [Hargreaves, 2018] then:

$$IR = \frac{150 \times 10^{-5}}{15 \times 60} \approx 1.667 \times 10^{-6} \tag{4}$$

And if IR is further divided evenly into fault free and faulted case then IR=8.33×10^{-7}. Assuming that 2D positioning data is sampled from a multivariate Gaussian with zero covariance the sum of squared Gaussian data points is known to be distributed according to a Chi-Square distribution. In such a case to get the ($1–8.33\times10^{-7}$) confidence HPL a factor of $k_{HPL}\approx5.29$ should be used as in the Figure 2.

The relations among PL, AL, and true position error (PE) could be interpreted by the Stanford-ESA diagram [Tossaint, 2007] (see Figure 3).

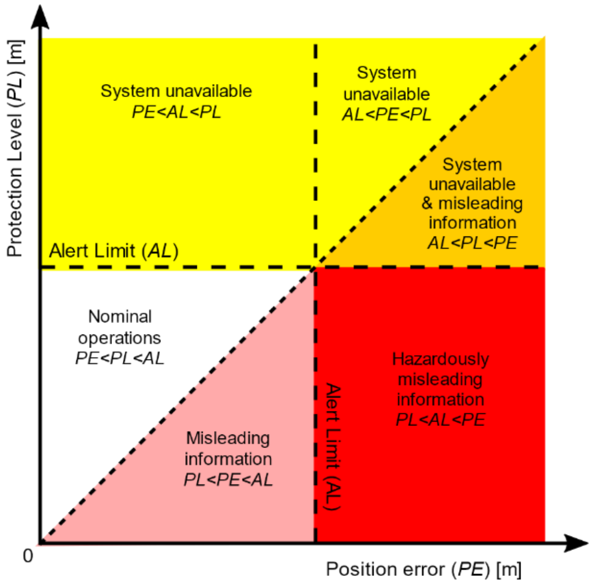

Figure 3. Interpretation of ESA-Stanford diagram based on 4 relations of system availability (source [Tossaint, 2007]).

The research on maritime IR is ongoing as currently it is still not possible to meet the requirements for any of the applications specified in IMO resolution A. 915 (22) without SBAS support or new safety dedicated services like Galileo Safety of Life (SoL) [EC, 2018].

In 2017, a Maritime Vessel Protection Area (MVPA) concept was introduced by the info note to IMO Navigation, Communication, Search and Rescue Subcommittee and the algorithm of the GNSS positioning integrity assessment based on the calculation of protection ellipses from EGNOS integrity data was presented and subsequently tested in the electronic chart display and information system (ECDIS) designed for maritime autonomous ships' operators (Figure 4) [Zalewski, 2020].

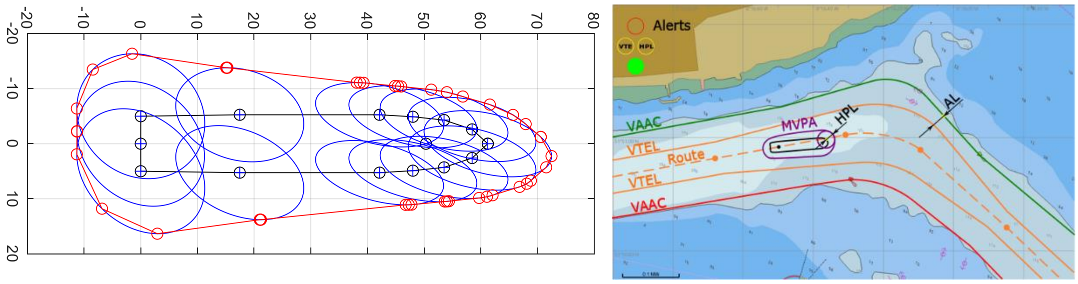

Figure 4. MVPA visualizations (source [Zalewski, 2020]).

In [Zalewski, 2020] one can also find the detailed algorithm of HPL calculation using SBAS integrity data.
Similarly to IR also the definitions of continuity and availability in the resolution A.915(22) give room for questioning as they are time dependent and availability takes into account the performance of the receiver whose reliability and technical parameters (especially its internal error's contribution) in such a case should be certified in similar way as it is done in aviation. The continuity level of 99.97% per 3h corresponds to a mean time between failures (MTBF) of 10,000 hours (5) or almost 417 days while availability level of 99.8% per 30 days corresponds to a downtime (DT) reaching 1.44 hours per month (6) that includes failures and integrity alerts:

$$MTBF = \frac{3\text{h} \times 100}{100 - 99.97} = 10000\text{h} \tag{5}$$

$$DT = \frac{(100 - 99.8) \times 30 \times 24\text{h}}{100} = 1.44\text{h} \tag{6}$$

Concluding, the resolution A.915(22) gave grounds for the application of GNSS integrity concept in the maritime domain. Its definition of reliability of position fix is equivalent to the definition of circular protection level (PL) that was concurrently developed by International Civil Aviation Organization (ICAO) [ICAO, 2006] and Radio Technical Commission for Aeronautics (RTCA) for aviation domain [RTCA, 2016] in the beginning of XXI century as an upper confidence bound on the error in the position. And the navigation service performance as presented in A.915(22) assumes a hierarchical structure (Figure 5) with positioning accuracy as the basic performance parameter.

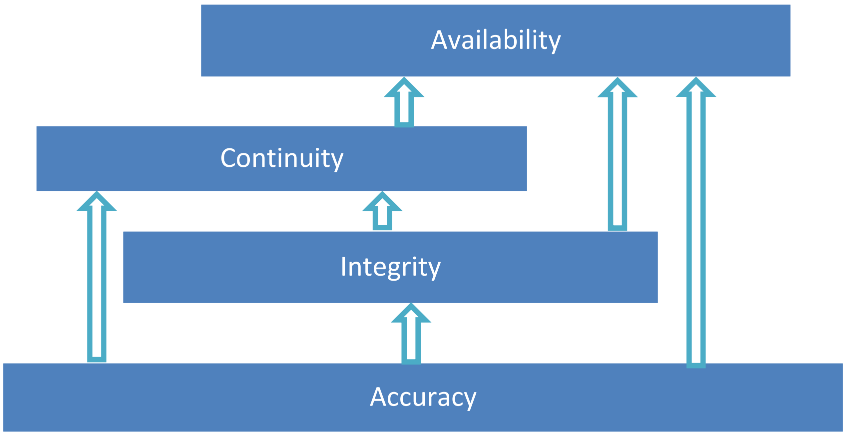

Figure 5. Dependency and hierarchy of GNSS service performance parameters in the resolution A.915(22).

In 2017 the attempt to solve some of the maritime integrity issues that emerged in resolution A.915(22) was finalized by adopting the Circular MSC.1/Circ.1575 [IMO, 2017] on Guidelines for Shipborne Position, Navigation and Timing Data Processing (PNT DP). This circular recommends in a generic way how PNT integrity should be monitored in the maritime PNT equipment without providing any data specific algorithms as in [RTCA, 2016]. Firstly, methods and thresholds used by the PNT DP for integrity monitoring should be qualified to evaluate if the supported accuracy level of PNT output data has been achieved or not. Therefore, the accuracy level was proposed once more as intra-system AL or threshold value that differentiates between fulfilled and failed requirements on PNT data output. Secondly, the TTA should be the tolerated time span for accuracy evaluation by the PNT DP. Thirdly, it is recommended to manufacturers to predetermine the IR of the applied integrity monitoring methods, taking into account application-relevant time periods under nominal conditions, if practicable. If the PNT-DP supports a redundant provision of PNT and integrity data in relation to the same accuracy level, the IR should be preevaluated for application-relevant time periods and provided as configuration parameter to ensure that the most reliable PNT data are selected for output. MSC.1/Circ.1575 also proposed some concepts of:

1) Consistency tests using two sensors or model of ship's movement.
2) Determination of PL by RAIM using such tests.

For example six position solutions can be determined with the five consistent pseudoranges: the all-in-view solution (Pos_{AIV}) and the solutions achieved with any set of five pseudoranges. The position error per solution depends on the expected standard deviation of position error and a *k* expansion factor. The largest distance of an estimated position error (for example σ_4 of the 4th position solution Pos_4) to the PosAIV is determined as a protection level.

3. IMO GNSS performance standards

IMO resolutions on world wide-radionavigation system and on individual GNSS subsystems performance standards provide manufacturers with currently binding parameters of shipborne receivers to attain their certification by classification societies. The most important of these resolutions is A.1046(27) on worldwide radio-navigation system [IMO, 2011]. All IMO recognized radionavigation systems including GNSS must meet the provisions of this resolution or the previous one A.953(23) if recognized before 2011. A.1046(27) contains system-level specifications. It does not address any integrity algorithms and does not refer to A.915(22) explicitly. Anyway it implicitly sets 15 min. continuity time-range and indefinite value of availability time-range which was previously set to 30 days. For seafarers the most important is division of operational requirements into two zones:

- ocean waters where a radionavigation system is used to assist in the navigation of ships and provides positional information with an error not greater than 100 m with a probability of 95%, and an integrity warning of system malfunction, non-availability or discontinuity is provided to users as soon as practicable by Maritime Safety Information (MSI) systems;
- harbour entrances, harbour approaches and coastal waters where a radionavigation system provides positional information with an error not greater than 10 m with a probability of 95%, and when the system is available, the service continuity should be ≥99.97% over a period of 15 minute and an integrity warning of system malfunction, non-availability or discontinuity should be provided to users within 10 s.

In both zones signal availability should exceed 99.8% and the system shall be considered available when it provides the required integrity for the given accuracy level. The problematic question is how to evaluate signal availability according to (6) if no reference time is given – usually the previous 30 days is assumed, but it remains only as declarative non-verifiable statement of GNSS subsystem stakeholder.

The first performance standards for shipborne satellite navigation receivers meeting WWRNS specification were adopted by IMO in resolutions MSC.112(73) on GPS [IMO, 2000a], MSC.113(73) on Glonass [IMO, 2000b], MSC.114(73) on DGPS and DGlonass [IMO, 2000c], MSC.115(73) on Combined GPS & Glonass [IMO, 2000d] in 2000. They specified accuracy requirements for equipment installed after July 2003:

- GPS: static accuracy such that the position of the antenna is determined to within 100 m (95%) with horizontal dilution of precision (HDOP) = 4 (or PDOP = 6), dynamic accuracy such that the position of the ship is determined to within 100 m (95%) with HDOP = 4 (or PDOP = 6) under the conditions of sea states and ship's motion likely to be experienced in ships;
- Glonass: static accuracy such that the position of the antenna is determined to within 45 m (95%) with horizontal dilution of position (HDOP) = 4 (PDOP = 6), dynamic accuracy such that the position of the antenna is determined to within 45 m (95%) with horizontal dilution of position (HDOP) = 4 (PDOP = 6) under the conditions of sea states and ship's motion likely to be experienced in ships;
- DGPS and DGlonass: static and dynamic accuracies should be 10 m (95%);
- Combined GPS & Glonass: static accuracy such that the position of the antenna is determined to within 35 m (95%) in non-differential mode and 10 m (95%) in differential mode with horizontal dilution of precision (HDOP) < 4 or position dilution of precision (PDOP) < 6, dynamic accuracy such that the position of the ship is determined to within 35 m (95%) in non-differential mode and 10 m (95%) in differential mode with HDOP < 4 or

PDOP < 6 under the conditions of sea states and ship's motion likely to be experienced in ships.

And they required integrity status and alarm for differential IALA modes.

In 2006 the resolution MSC.233(82) [IMO, 2006] on performance standards for shipborne Galileo receiver equipment was adopted. According to this resolution the Galileo shipborne receiver equipment should indicate whether the performance of Galileo is outside the bounds of requirements for general navigation in the ocean, coastal, port approach and restricted waters, and inland waterway phases of the voyage as specified in either resolution A.953(23) (replaced by A.1046(27)) or Appendix 2 to the resolution A.915(22) and any subsequent amendments as appropriate. So, the receiver equipment should as a minimum:

- Have static and dynamic accuracy such that the position of the antenna is determined to within: i) 15 m horizontal (95%) and 35 m vertical (95%) for single frequency operations on the L1 frequency; ii) 10 m horizontal (95%) and 10 m vertical (95%) for dual frequency operations on L1 and E5a or L1 and E5b frequencies.
- Provide a warning within 5s of loss of position or if a new position based on the information provided by the Galileo constellation has not been calculated for more than 1s for conventional craft and 0.5s for high-speed craft. Under such conditions the last known position and the time of last valid fix, with the explicit indication of the state so that no ambiguity can exist, should be output until normal operation is resumed.
- Use RAIM to provide integrity performance appropriate to the operation being undertaken.
- Provide a self-test function.
- For receivers having the capability to process the Galileo Safety of Life Service, integrity monitoring and alerting algorithms should be based on a suitable combination of the Galileo integrity message and RAIM. The receiver should provide an alarm within 10s TTA of the start of an event if an AL of 25m Horizontal Alert Limit (HAL) is exceeded for a period of at least 3s. The probability of detection of the event should be better that 99.999% over a 3h period ($IR<=10^{-5}$ through 3h).

This resolution set the first standards of GNSS subsystem based on A.915(22), and it went a step ahead of GPS and GLONASS performance standards in force at that time and foreseeable future. Though it set strict requirements of IR that cannot be met even today, it left the problem of exemplary algorithms for integrity monitoring and alerting unresolved.

In 2014 the resolution MSC.379(93) [IMO, 2014] on performance standards for shipborne Beidou receiver equipment was adopted. It followed the provisions of MSC.233(82) for European Galileo with the exception of safety of life service, which is not provided by Beidou and accuracy:

- have static and dynamic accuracy such that the position of the antenna is determined to be within 25 m horizontally (95%) and 30 m vertically (95%).

In 2015 the resolution MSC.401(95) [IMO, 2015] on performance standards for multisystem shipborne radionavigation receivers was adopted. Its aim was to ensure that ships could be provided with resilient position-fixing equipment suitable for use not only with single radionavigation system but with various radionavigation systems available throughout their voyage. This resolution generalized integrity monitoring again by stipulating that the radionavigation equipment should be designed to provide means of integrity monitoring for each position, velocity and timing (PVT) source employed (e.g. as RAIM or CAIM); and multi-source autonomous integrity monitoring (envisioned to be a cross-check between independent PVT sources). Later, in 2017, this resolution was amended by MSC.432(98) [IMO, 2017]. The amendment was short but meaningful – referring performance standards to the resolutions on stand-alone ship-borne radionavigation receivers: “Type-specific performance standards for stand-alone shipborne radionavigation receivers should be taken into account when conducting type approval for multi-system receivers in accordance with resolution MSC.401(95).” Nevertheless, the MSC.401(95) enabled the full use of relevant data originating from current and future radionavigation services, thus it recognized SBAS augmentation data processing in shipborne radionavigation receivers as well, though not directly.

MSC.449(99) on IRNSS [IMO, 2018] followed exactly standards for Beidou with the exception of coverage – regional system for Indian Ocean.

MSC.480(102) on QZSS [IMO, 2020] followed the one on IRNSS but had different coverage (regional covering east coast of China, Japan, and south to Australia) and specified accuracy as:

- static accuracy such that, for the service area, where a horizontal dilution of precision (HDOP) is equal to or less than 6.7, the position of the antenna is determined to be within 50.4 m horizontal (95%), dynamic accuracy under the conditions of sea states and ships' motion likely to be experienced in ships, such that for the service area where a HDOP is equal to or less than 6.7, the position of the antenna is determined to within 50.4 m horizontal (95%).

Concluding, all binding standards are quite conservative as for accuracy values but could be quite demanding if applying integrity values according to A.915(22). Because receivers complying to these standards are used for automatic identification system (AIS) data that are part of many GIS statistical analyses their parameters should be properly taken into account.

4. SHIPBORNE GNSS DATA IN GIS BASED ON POLISH EXAMPLE

In Poland the GIS data used in vessel traffic management systems and national SafeSeaNet System is covered by the Spatial Information System of the Maritime Administration (SIPAM) [MI, 2022]. The central element of the SIPAM system is a common database of maritime administration containing among others the following collections:

- The boundaries of internal sea waters.
- The border of the Polish territorial sea.
- The border of the Exclusive Economic Zone of Poland.
- Border of the maritime zone adjacent to Poland.
- Safety zones around artificial islands, structures and devices established by the Maritime Authority.
- The boundaries of the coastal belt (technical belt and protection belt).

- Limits of the scope of jurisdiction of directors of maritime offices.
- Boundaries of sea harbours, roadsteads and anchorages.
- Zones closed to shipping and fishing.
- Dangerous zones for shipping and fishing.
- Ship traffic separation scheme.
- Established traffic routes.
- Shipwrecks and other historical objects in Polish sea areas.
- Approach tracks.
- Kilometres of the sea coast.
- Natura 2000 nature protection plans in marine areas.
- Shore line.
- Baseline.
- Country border line.
- Shore sections included in the coastal protection program.
- Bathymetric data.
- Data from the LIDAR system.
- Orthophotomaps.

For traffic safety, spatial analyses, environmental protection, designing of future fairways, routes and traffic separation schemes data from SIPAM is often supplemented by recorded ships' positions. The issues of existing IMO recommendations, guidelines, requirements, performance standards described in sections 2 and 3 of this paper should be kept in mind while analysing these data.

5. CONCLUSIONS

There are numerous challenges to achieve electronic position fixing integrity level as envisioned by IMO in A.915(22) or even better. European Union developed European Radionavigation Plan [EC, 2018] to deal with these challenges and threats from jamming or spoofing of GNSS signals.
The first challenge is the provision of resilient PNT where terrestrial radio signals as well as shipborne components are necessary in addition to GNSS. Some consider eLoran the ideal back up to GNSS and promote it at the IMO. However, the choice is challenged by the lack of international agreement and by high costs for reactivation and maintenance of infrastructures. R-Mode is also a promising technological approach that will be tested out further in near future. Another challenge is DGNSS infrastructure improvement. Maintaining and improving the IALA DGNSS service reliability by increasing the number of reference stations to enlarge the area where the user can receive differential corrections implies significant investment and maintenance cost. Potential SBAS based solutions applied over Aids to Navigation (DGNSS and AIS signals) as described in the IALA Guideline G1129 (Edition 1.0 Dec.2017) [IALA, 2017] could provide some room for the rationalization of the infrastructure and address the current limitations of legacy DGNSS systems paving the way to the uptake EGNOS services. The main problem is the limited uptake of SBAS-enabled shipborne receivers. There is no maritime standard or guidelines for the implementation of SBAS in shipborne receivers and the

majority of these implementations do not take into account the information related to the system integrity messages that the SBAS system broadcasts. Work is ongoing to develop receiver implementation guidelines for EGNOS maritime receivers in RTCM, and receivers that fulfil these guidelines. The background is to have EGNOS implemented in a similar way in all receivers to have optimal benefit from the system. The challenge is to ensure an appropriate integration of SBAS in shipborne receivers that would contribute to improve the accuracy and the reliability of the positioning information, which at the end is one of the main factors to guarantee the safety of life at sea. Work is also ongoing to define a potential maritime SoL service implementation in the upcoming EGNOS v3 system [EC, 2018]. This new service might also include a more mature integrity implementation than we have in EGNOS or other SBAS today and finally reach users widely.

Similar challenges await inland waterway navigation. Navigation in inland waterways requires position accuracy, including the vertical domain, used to calculate clearance of bridges, locks etc. and to monitor traffic situation. To increase the performance of GNSS, IALA DGPS stations have been established to some extent also to cover the inland waterways. In addition to this, distribution of DGPS data is also done in some areas with the help of inland AIS base stations, available to vessels that are equipped with an inland AIS transponder(which is compatible with the maritime AIS transponder). In comparison with maritime navigation, inland navigation faces more difficulties related to shadowing and blocking of satellites due to land shadowing, mountains or obstructions from man-made objects. Typical examples are multipath or high DOP. The inland navigators would therefore benefit from multiconstellation navigation, because more satellites are available. There are also reasons to believe that these users could benefit from the High Accuracy Service from Galileo and future dedicated EGNOS services for maritime use.

Compatibility, concerning in particular interfaces and communication links, may enhance the uptake of innovative surveying techniques and expand it to new segments of application. The need of interoperability also among devices provided by different manufacturers is of key importance. Now, many different DGNSS/RTK data formats are available (e.g. RTCM, CMR, etc.), making the use of data coming from different sources and devices quite challenging. Typically, different brands have different levels of interoperability when it comes to receiving augmentation corrections from networks operating with equipment from other stakeholders considered as competitors.

Finally the fusion of position systems data with ship hydrodynamic model data is becoming more common in maritime systems evolving from dynamic positioning (DP) systems. For reduction of TSE, prediction of ship's motion and emergency situations without GNSS position data such an approach is very promising.

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BIOGRAPHICAL NOTES

Paweł Zalewski received the B.S. and M.S. degrees in navigation from the Maritime University of Szczecin (MUS), in 1994, and the Ph.D. degree in geodesy and cartography, in 2001. From 1995 to 2001, he was a Research Assistant, and from 2001 to 2014 Assistant Professor with the Institute of Marine Traffic Engineering, and Marine Traffic Engineering Centre, MUS. He received post-doctoral degree in transport from Radom Technical University in 2014. In years 2014-2016 he was managing editor of the European Journal of Navigation issued by EUGIN. Since 2008 he has been a member of Polish Navigation Forum and expert of Polish delegation to NAV and NCSR subcommittees and MSC committee to IMO, since 2011 in charge of dynamic positioning training in MUS, since 2014 Associate Professor of MUS, since 2016 elected as Dean of Navigation Faculty, Associate Fellow of Nautical Institute, Chair of Maritime Simulation Department in MUS. He currently lectures in courses of navigation systems, satellite geodesy, applied mathematics for navigation and geodesy and hydrography students in bachelor and master degree. He has a 5 years of experience on board sea-going vessels at operational and management level. He is the author of 3 books, co-author of 4 books and more than 90 research papers and two patented inventions. His research interests include GNSS, navigation systems, safety of navigation, and marine traffic engineering.

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