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Guidelines for the coordinated enhancement of the maritime position, navigation and time data system

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Abstract

Reliable knowledge of a ship's position and movement in relation to other traffic participants and obstacles is a fundamental requirement for navigation and avoiding collisions and groundings. Consequently, the onboard provision of resilient position, navigation and time data (PNT) is emphasized by the International Maritime Organization's (IMO) e-navigation strategy, solution S3 "Improved reliability, resilience and integrity of bridge equipment and navigation information" and by the assigned risk control option RCO5 "Improved reliability and resilience of onboard PNT systems". An initial step towards resilient PNT has been realized by the maritime community with the development of the performance standards for shipborne multi-system radionavigation receiver equipment (MRR). This MRR performance standard (PS) supports the full use of data coming from current and future radionavigation systems and services. Consequently, the combined use of several global navigation satellite systems (GNSS) and the additional use of space based augmentation systems (SBAS) as well as optional terrestrial radionavigation systems (e.g. eLoran or R-Mode) will be supported to increase the performance of positioning and timing. As a second step, the development of guidelines for an onboard PNT (data processing) unit has been identified as supplementary and necessary. The starting point is the onboard use of a combination of GNSS receivers and autarkic systems (e.g. radar, gyro, echosounders with bathymetric data) for a comprehensive provision of required PNT data. Redundancy in the available data enables the application of integrity monitoring functions to evaluate the current usability of safety-critical data and components. The aim of the guidelines is the specification of data processing rules towards the resilient provision of standardized PNT data and integrity information. For this purpose, a modular architecture for an onboard PNT system is introduced and scaled to the need for data input as well as the performance of data output.

Background and challenges

Reliability, integrity and resilience are fundamental requirements of nautical onboard equipment. They are identified as user needs in the frame of e-navigation and are addressed as high-priority solutions for safety-critical systems. In this context, integrity monitoring is a prerequisite to indicate the reliability of a PNT system as well as the provision of reliable data. Furthermore, the indication of integrity is used to support the connected applications regarding the usability of the provided data. Whether or not an onboard PNT system meets these fundamental requirements can be evaluated only with respect to the required quantity and quality of PNT output data. Due to their historical development, most of the existing maritime performance systems (PS; see Table 1) follow an equipment-related specification of minimum requirements for individual PNT data, without consideration of integrity aspects. Furthermore, at present neither the achieved nor the target levels of reliability, integrity and resilience are quantified by most sensors within today's maritime PNT systems.

Table 1. Selected maritime performance standards of shipborne equipment and data processing

Equipment			Existing performance standards IMO	IEC/EN/ISO
Radionavigation receiver		GPS	MSC 112(73)	61108-1 ed. 2
		GLONASS	MSC 113(73)	61108-2 ed. 1
		Galileo	MSC 233(82)	61108-3 ed. 1
		Beidou	MSC 379(93)	–
		Combined GPS/ GLONASS	MSC 115(73)	–
		Multi-system radionavigation receiver	–	–
		DGPS and DGLONASS	MSC 114(73)	61108-4 ed. 1
		Satellite based augmentation services (SBAS)	–	–
		Loran-C	A.819(19)	61075 (withdrawn)
Autarkic onboard	Sensors	Echo sounder	A.224(VII) MSC.74(69)	EN ISO 9875
		Compass (magnetic)	A.382(X)	EN ISO 1069 EN ISO 25862
		Gyro compass	A.424(XI)	EN ISO 8728
		Rate of turn indicator (ROTI)	A.526(13)	ISO 20672
		Speed and distance measurement equipment (SDME)	MSC.96(72)	EN 61023
		Transmitting heading device (THD)	MSC.86(70) MSC.116(73)	ISO 22090-2
	Systems	(Radar)*	MSC.192(79)	IEC 62388
		(ECDIS & charts)*	MSC.232(82)	IEC 61174
		(Integrated navigation system, INS)*	MSC.252(83)	IEC 61924

* Systems to support or refine PNT data provision

Specifying a set of comprehensive maritime requirements for PNT data provision and integrity monitoring is a complex task. Many factors should be taken into account: ship type and carriage requirements, diversity of nautical applications and tasks, changing complexity of situation and deviations from nominal conditions. In addition, the level of support offered for each of these factors should be customizable. Therefore, it is difficult to determine the true development needs of a maritime PNT system regarding architecture, components and functions to ensure a demand-driven provision of PNT data and associated integrity information. It should also be noted that during a ship's berth-to-berth navigation the requirements for data output of onboard PNT (data processing) units vary in time and space as a result of changing environmental conditions and nautical tasks. The challenge for the maritime community is to find an efficient way of specifying current and evolving requirements for PNT data provision. The pre-specification of performance classes such as those explained in the *Requirements* chapter could be considered an appropriate basis for further discussion and consolidation.

The aim of integrity information is the characterization of the current usability of components (e.g. sensors and services) and data (e.g. PNT data). A provision of unambiguous integrity information is essential to improve the system awareness of bridge teams and to enable the subsequent use of data for self-evaluating applications. An unambiguous meaning of usability statements can be ensured only if applied performance key identifiers, such as the rules for determination and the thresholds for evaluation, are standardized for each set of PNT data and supported performance class. Only if the above requirements are met will the provision of standardized PNT output data and integrity information be possible.

In principle, the technical feasibility of integrity monitoring depends on the redundancy of available data. A typical example in the GNSS context is receiver autonomous integrity monitoring (RAIM), the applicability and capability of which are influenced by the number of available pseudorange measurements: more than four measurements allow errors to be found, and more than five enable the identification of an erroneous pseudorange measurement. Without redundancy, the integrity evaluation is limited to simple plausibility tests and enables only the detection of gross errors. The analysis of consistency between different and independent data sources is a high-order integrity monitoring problem dealing with the confidence in single data sources based on a common reference model. As seen in the PS of integrated navigation systems (INS; MSC.252(83), 2007), this approach can be applied only if a minimum redundancy is given in the PNT relevant sensor setup (see Figure 1).

A more ambitious goal is the real-time estimation of PNT data accuracy and their indication. For this purpose, the highest level of intra-system

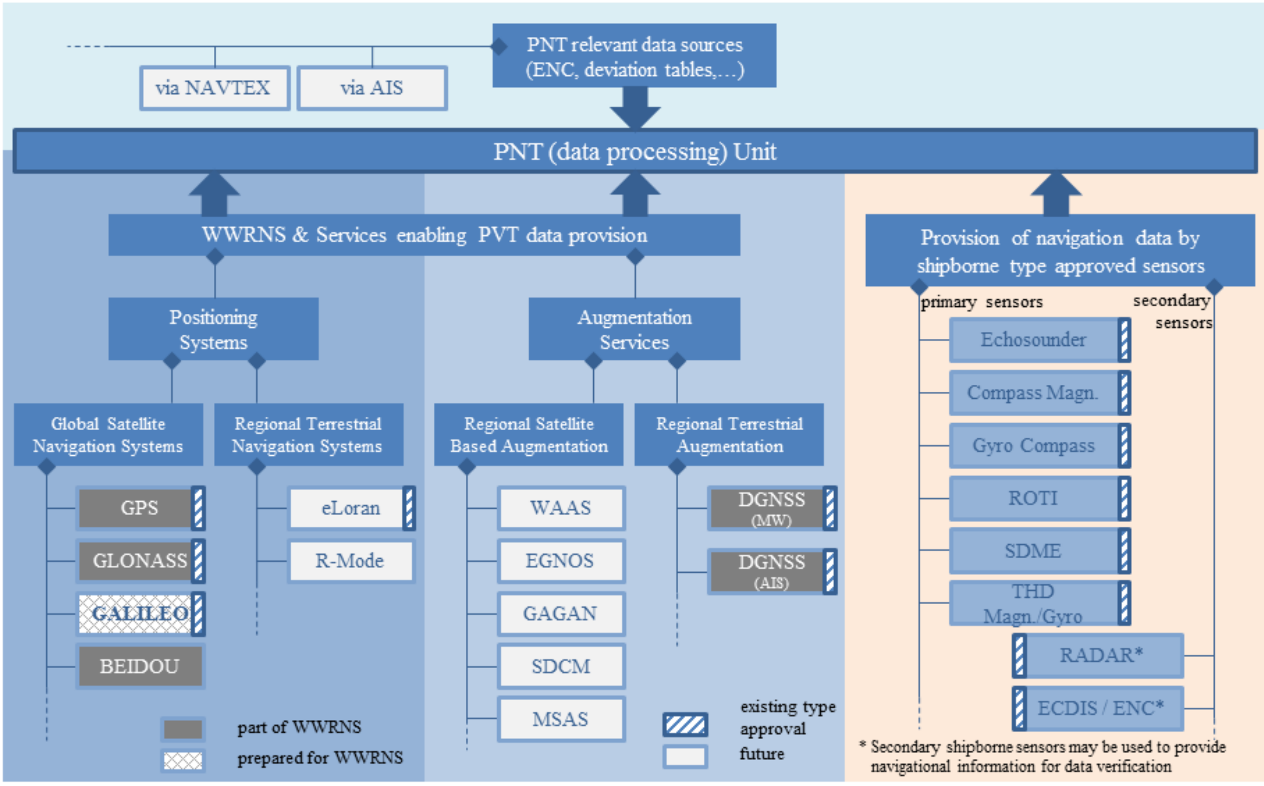

Figure 1. Overview of system, services and sensors intended for onboard PNT data processing

redundancy is necessary to allow different partial errors to be determined and evaluated regarding their influence on PNT data accuracy. A resulting challenge is the elaboration of dependencies between the performance requirements for PNT data provision and the resulting requirements for technical and functional architecture. For this purpose, the *Modular Architecture* chapter proposes a generalized functional model of an onboard PNT data processing unit. Its modular structure supports the variety of current and potential future implementations as well as the changes in environmental and operating conditions.

In a minimum solution, the used set of services and sensors directly provides all the necessary PNT data. A combined consideration of sensor and service data is not realized. In such a solution, each service and sensor is responsible for its own data quality and, if possible, for the provision of integrity information. Multi-system or multi-sensor based approaches support the combined processing of sensor and service data enabling the improvement and/or evaluation of PNT data provision. Generally, the transformation of a certain set of input data into a certain set of output data can be modelled by an individual data processing channel. Each channel is based on a certain methodological realization of the main processing functions (evaluation and synchronization of input data and improvement of data and integrity information as well as evaluation and composition of output data) to meet a specific performance level for PNT data provision. The performance level will be achieved if the nominal operating conditions for this processing channel are given.

In general, a modular system design is based on alternative and complementary usable components, processing channels and functions. This modular approach is appropriate to elaborate how the onboard PNT data processing unit responds to intended as well as unintended changes in data input.

For example, the satellite-based radionavigation systems GPS, Global Navigation Satellite System (GLONASS) and Beidou Navigation Satellite System (BDS) are recognized by the maritime community as means for world-wide positioning. Redundancy in the received GNSS signals is exploited to realize the self-monitoring of positioning by application of RAIM. Therefore, GPS based positioning with RAIM can be considered as an individual processing chain. With respect to the same functionality and its technical independency from GPS, the GLONASS based positioning with RAIM represents an alternative usable processing channel. Satellite-based and terrestrial GNSS augmentation services provide correction data to support the application of differential positioning techniques (DGNSS). DGNSS service availability is limited to its coverage area and can, therefore, be used only within these areas. Consequently, DGNSS positioning is more or less a complementary processing channel in comparison to GNSS based positioning.

The GNSS related example illustrates the necessity of adjusting data processing to changing circumstances. Such an adjustment can be based only on the availability of data to determine the feasibility of individual functions and processing channels. In addition, it is possible to consider the quality of input data and intermediate results during the adjustment process. This enables the monitoring of the effects of fault propagation and the evaluation of their impact on the performance of PNT data provision.

A great challenge in this context is the development of an appropriate intrasystem monitoring and control concept specifying how onboard data processing should be dynamically adapted to changing operational and environmental conditions to ensure its functionality. The *Channels, functions, methods and scalability* chapter discusses briefly how the concept of parallel processing channels serves to harmonize the user's needs and the technical implementation.

At the end of the paper, two representative integrations are shown to account for the generality and the neutrality of the PNT unit concept. These integrations are used to identify the next development steps.

Approach

The development of guidelines for onboard PNT data processing has been identified as a supplementary and necessary step towards the resilient provision of PNT data and integrity information. Consequently, this working task is a planned output in the high-level action plan of the IMO's Maritime Safety Committee and should be finalized in 2017 (MSC 95/22/Add. 2). The aim of these guidelines is to define the major principles and functions of onboard data processing, taking into account the differences in requirements and identifying the dependencies on technical and functional system architecture. Within this development process, the need for sensors and services as well as for standardization of PNT output data and integrity information will be clarified. An international working group (WG) has been established under coordination of the Maritime and Hydrographic Agency on behalf of the German Ministry of Transport to promote the development of the guidelines. The following explanations inform about the current draft of the guidelines for onboard PNT data processing (issue 1 of 31st July 2015) used by the WG as a basis for further discussion and improvement.

Requirements

As mentioned above, an essential prerequisite for further harmonization and enhancement of a maritime PNT system is the comprehensive and unambiguous specification of the requirements for PNT data provision.

The overarching task of an onboard PNT (data processing) unit is the reliable provision of PNT data including associated integrity information to bridge teams and ship-side applications. Status information and contributions to alert management are more or less extracted from the PNT unit's data input, processing and output.

The safe execution of nautical tasks (e.g. performing an evasive maneuver, route planning) and applications (e.g. track control, collision avoidance) requires a specific set of PNT data with a certain quality. Therefore, the requirements for PNT data provision should be specified with respect to:

[1] The amount and the types of needed PNT data (application class);
[2] The accuracy (absolute or relative) of the specific data type, e.g. position, speed over ground (SOG), course over ground (COG);
[3] The evaluated integrity of certain data;
[4] The continuity and the availability of data provision.

The variety of nautical tasks and the changing environmental conditions (e.g. area, weather, traffic situation) are the main reasons that requirements for PNT data provision vary during a ship's berth-to-berth navigation. Therefore, the design criteria of a certain PNT unit are determined by accumulated requirements coming from nautical tasks and applications. Furthermore, differences in installed equipment and the required level of support are additional reasons that PNT data will meet different performance levels. Basically, a structured description of the diversity of requirements can be achieved only if several application classes and performance levels for PNT data provision are introduced. This approach avoids the installation of a unit of maximum PNT performance on all types of ships if a lower performance class of PNT unit is fully sufficient for the navigational tasks. Furthermore, the quantification of requirements ensures that the harmonization between provision and application of PNT data is open for evolving needs and helps to clarify responsibilities in safety-relevant systems.

Preliminary discussions have resulted in the proposal to introduce various application classes and levels for the comprehensive registration of various requirements for the amount, types and quality of data. It may be sufficient to use a four-level scale for each individual requirement: low, medium, high and premium.

[1] An initial proposal to arrange the requirements for the amount and the types of onboard PNT data provision is shown in Figure 2 as a starting point for further discussions. In relation to the amount and the types of primary PNT output data, the low level supports the description of horizontal position and movement of an individual onboard reference point (see Figure 2). For this purpose, it is sufficient to provide the following nautical information, preferably for the consistent common reference point (CCRP): latitude, longitude, SOG, COG, time and date. A medium level of PNT data provision could be associated to the description of attitude and movement of a ship's hull in the horizontal plane. This requires the additional provision of heading (HDG) and rate of turn (ROT) information. The high level could be achieved if the primary PNT data are enriched with CCRP altitude and changes and then combined with further information to evaluate the under keel clearance. The premium version of PNT data provision could correspond to the complete description of a ship's attitude and changes of attitude by provision of yaw, roll and pitch angles and their rates.

Requirements for each type of PNT data can also be described by four levels of accuracy and four levels of integrity. This approach enables that any accuracy level can be combined with any integrity level to reflect the diversity of requirements in relation to tasks and applications. If necessary, in the future a finer categorization of requirements can be elaborated.

[2] IMO resolution A.915(22) has already introduced four accuracy levels for positioning by specification of horizontal position errors (HPE: 95%) as follows: < 100 m, < 10 m, < 1 m and < 0.1 m. Similar approaches are feasible for other types of PNT data, e.g. for errors in heading, as follows: < 2°, < 1°, < 0.5° and < 0.1°. The scaling of accuracy requirements – which may be on a four-level scale – is a sufficient basis to coordinate offer and demand in relation to the performance of PNT data provision. In general, higher levels of accuracy can be met, e.g. either by more powerful sensors (e.g. an inertial measurement unit in contrast to individual gyroscopes), by augmentation services for error reduction (e.g. DGNSS based positioning in comparison to GNSS) or by application of smart data processing techniques exploiting the redundancy in data input (e.g. error detection and exclusion methods).

[3] The increasing safety awareness in the maritime community has been the main cause of a rising need for the integrity of safety relevant data and systems in the last decade. Therefore, only recently have performance standards of radionavigation receivers (e.g. GALILEO, MSC.233(82), 2006; or BEIDOU, MSC.379(93), 2014) recommended the use of RAIM techniques for integrity monitoring. As already mentioned, the purpose of integrity monitoring is the indication of whether safety-relevant systems, signals and data are currently usable. Conversely, if unusability is attested as a result of identified failures, malfunctions or performance degradations, the affected systems, signals and data should be indicated and/or excluded from subsequent utilization. Resolution A.915(22) assumes that an integrity loss of positioning occurs when the horizontal position error exceeds 2.5 times its allowed value. In general, it is impossible to determine the real value of a total error. Therefore, the evaluation of data

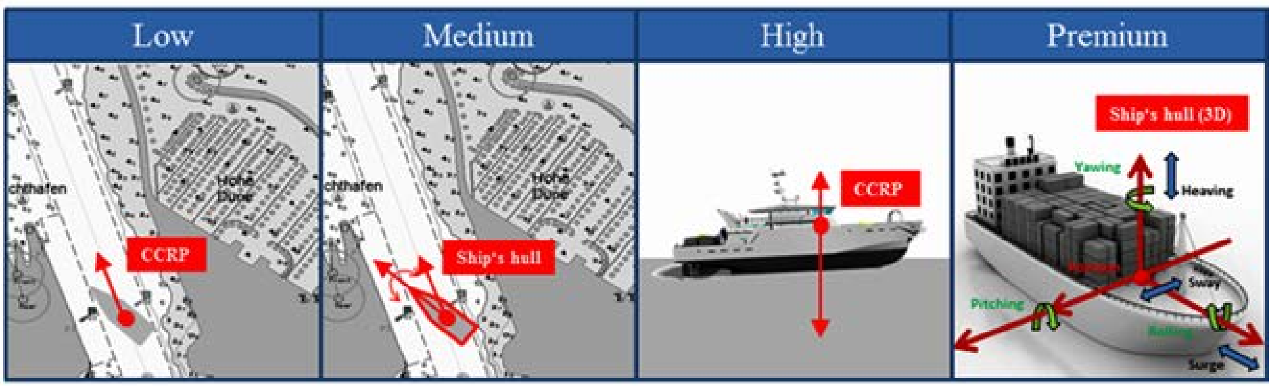

Figure 2. Proposed performance level regarding the amount and the types of onboard PNT data provision

integrity requires appropriate methods for monitoring. However, it is a fact that differences in integrity monitoring techniques and in applied thresholds can result in differences of monitoring results and should, therefore, be indicated. A logical consequence is the introduction of different integrity levels in relation to the applied monitoring techniques, e.g.: level 0 corresponds to unsupported integrity monitoring; level 1 indicates the application of autarkic plausibility and consistency tests (e.g. consistency of range measurements); level 2 stands for multisensory-based plausibility and consistency tests (e.g. INS); and level 3 informs about the use of parameterized error models for accuracy estimations (e.g. a premium PNT unit).

[4] For the specification of continuity and availability requirements, it should be clarified whether these are to be considered in relation to individual PNT data types or to certain data sets such as those introduced above. The joint consideration of PNT data sets, in relation to accuracy and integrity as well as continuity and availability, is preferred. Therefore, unavailability will occur or continuity will be broken if one component of the considered data set cannot be provided or does not meet the specified data quality. In practice, the continuity and the availability of a data set are always less than the continuity and the availability of included individual data. It can be expected that data with the highest vulnerability has the most impact on the continuity and the availability of a data set. It is ineffective only if the continuity and the availability of individual data are increased far beyond the level required for the data set.

Typical probability values used for the specification of safety-relevant requirements are often related to Gaussian distribution curves and described by two-sigma (~95%), two-sigma (~99%) or more, e.g. 99.8% and 99.9%. If three-sigma availability is required per day, then unavailability should be below 14.5 minutes per day. Assuming that a typical ship's maneuver takes 15 minutes or more means that the availability of PNT data should be 99.8% or higher. The requirement for continuity expresses that a system should be able to perform its functionalities over a short time interval without interruptions and performance degradations. In the case of the onboard PNT unit, the continuity requirement is met when the required PNT data (amount and types) are provided with regard to the required accuracy and integrity level. Maritime requirements for continuity are specified at 99.97% for the provision of radionavigation services (A.1046(27), 2011) as well as GNSS-based positioning (A.915(22), 2001). In the first case, the continuity time interval (CTI) is specified as 3 hours; in the second case as 15 minutes. A reduction of CTI to one twelfth allows that the mean time between failures (MTBF) to be decreased from 416 days to the less ambitious value of ~35 days. The introduction of several continuity and availability levels could force an application-orientated consolidation of both requirements.

Following the approach explained above enables that the requirements for PNT data provision can be described by five parameters (type and amount, T; accuracy, A; integrity, I; continuity, C; availability, R) and four parameter-specific levels (low, L; medium, M; high, H; premium, P). A more or less reliable operation of a PNT unit can be assumed if during operational time T_{op} the performance of the provided PNT data almost always meets the requirements coming from currently performed tasks and applications.

The reliability analysis of onboard PNT data provision is made more difficult due to consideration of both the temporal/spatial variability of operational/environmental conditions during PNT data provision and the changing demand for supported performance level in dependence with active nautical tasks and applications.

In the context of e-navigation, the vulnerability of GNSS has been identified as a justifiable reason to request the resilient provision of PNT data and integrity information. Generally, resilience can be considered as the ability of a system to detect and compensate external and internal disturbances, malfunctions and breakdowns in parts of the applied system. This should be achieved without loss of functionality and preferably without degradation of system performance. On the one hand, resilience is a design criterion of any PNT system to ensure a certain immunity of data acquisition and processing against relevant failures and malfunctions to meet the requirements for accuracy, integrity, continuity and availability under nominal conditions. On the other hand, resilience addresses the demand for redundancy of input data and processing to offer the possibility that malfunctions and failures can be detected, mitigated and compensated for to avoid any loss or degradation in functionality. Then resilience will be focused on the further improvement of reliability in terms of accuracy, integrity, continuity and/or availability. Ultimately, an improvement of resilience is associated with a required increase of reliability and can be considered as an enhanced design criterion to achieve the higher performance of PNT data provision.

The aim of an INS is to facilitate the combined use of data inputs coming from several and redundant data sources in order that the integrity of safety-relevant equipment and data can be monitored. This is considered a prerequisite for the application of high-order assistance functions. If all PNT data are consistent within the common model of a ship's position and movement, integrity is assumed (MSC.252(83), 2007). The performance standards for MRR (MSC.401(95), 2015) focus on the combined use of any radionavigation system and service to exploit existing redundancy in radionavigation systems for the further improvement of PNT data provision by:

- application of dual-frequency GNSS signal processing to reduce the influence of ionospheric propagation effects on GNSS ranging accuracy;
- combined use of several GNSS to be immune against individual system outages or to improve error detection and exclusion (RAIM) by increased availability of GNSS signals;
- additional use of a terrestrial radionavigation system (e.g. eLoran, R-Mode) to protect positioning against a broadband jammer operating in GNSS frequency bands;
- future use of SBAS as additional DGNSS to improve the integrity monitoring of used GNSS and the availability of DGNSS correction data.

It becomes apparent from both examples that redundancy in data input and processing is an appropriate basis to increase the resilience of PNT data provision in terms of accuracy, integrity, continuity and/or availability. For example, the additional provision of terrestrial radionavigation systems (e.g. eLoran, R-Mode) is discussed as an approach to ensure the continuity of positioning in case of serious faults in GNSS positioning, e.g. induced by jamming. However, the real need for redundancy in PNT data input and processing can be answered only in relation to clear development goals derived from noted deviations between the achieved and the target levels of performance for PNT data provision.

Modular architecture

As shown in Figure 3, onboard PNT data processing can be realized by three main functional blocks covering the pre-processing of input data, the main processing and the composition of output data.

Tasks to be performed during pre-processing cover:

- evaluation of whether the existing data input fulfils the demand for availability and quality to ensure a nominal operation condition for the onboard PNT unit in relation to supported processing channels;
- temporal and spatial synchronization of input data within a ship's consistent common reference system; and, ultimately;
- evaluation of which of the supported processing channels of the PNT unit can be performed.

For both evaluation tasks, the self-determined PNT data of preceding epochs are in particular demand. The aim of the evaluation processes is the identification of malfunctions and failures of used sensors and services to exclude erroneous and untrustworthy input data from subsequent data processing. However, losses and performance degradations of input data could result in partial or complete interruption of PNT data provision. It is quite

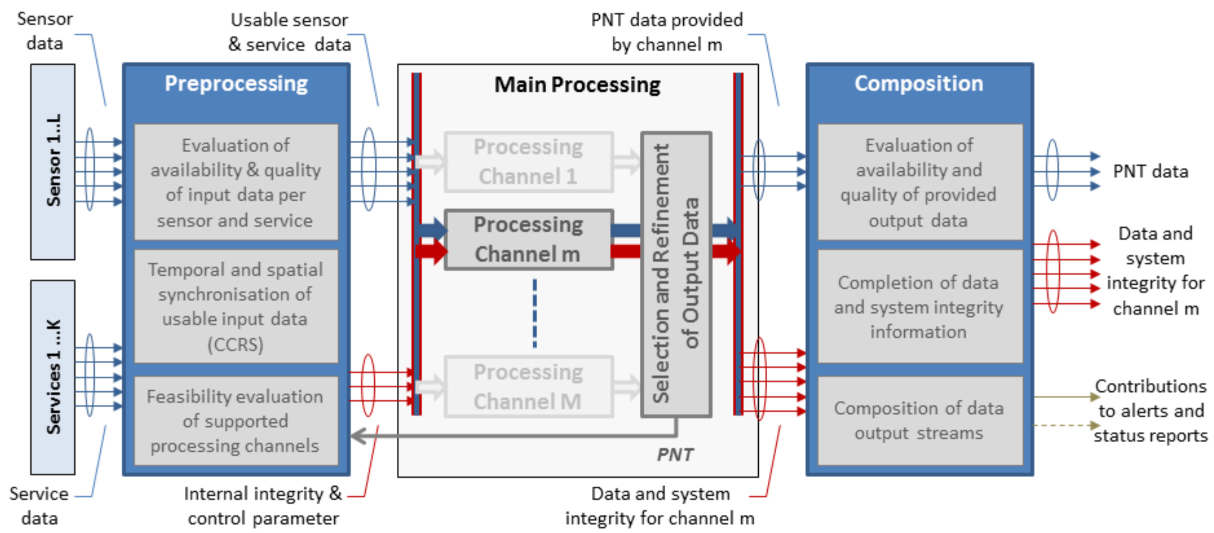

Figure 3. Generalized model of onboard PNT data processing

understandable that with the increasing redundancy of data input the probability grows for detecting all substantial errors and compensating their influence on PNT output data.

The main processing block is composed of one or more processing channels. In general, an individual processing channel is designed to meet a certain performance level of PNT data provision. For this purpose, the processing channel transforms an expected set of input data into the required set of output data by application of appropriate methods with respect to the desired performance level. A specific processing channel can be applied for PNT data provision if its demand on input data is fulfilled. For example, the performance level {L,L,M,–,–} of PNT data provision can be achieved by application of GNSS standard positioning methods (least square error, Kalman filter) in combination with RAIM. In this case, the demand on data input covers the provision of a sufficient number of accurate ranging measurements extracted from, e.g. signals of a GPS standard positioning service (SPS). Performance level {L,L,M,–,–} of PNT data provision could mean:

- amount/type – level L: latitude, longitude, SOG, COG, time and date;
- accuracy – level L: HPE < 100 m; SOG < 0.2 knots;
- integrity – level M: provided by RAIM.

In principle, it can be expected that a PNT unit supports the application of several processing channels:

- to meet different performance levels during berth-to-berth navigation in relation to navigation scenarios and nautical tasks in their temporal and spatial variation;
- to support a seamless adaptation of the data processing to the changing availability of sensors, services and data sources;
- to establish redundancy in data processing in order to achieve a higher continuity and/or availability of PNT data provision.

Considering all the technological opportunities and taking into account the diversity of desired performance levels, the main processing block could be composed of M various processing channels. Furthermore, it is expected that several technological opportunities support the same performance level, e.g. {L,L,M,–,–} by GNSS positioning techniques using GPS or GLONASS or BDS signals. Therefore, for a certain PNT unit it will be sufficient to apply a subset M_{Vx} of alternative and complementary usable processing channels ($M_{Vx} < M$) in relation to the supported performance levels and the required resilience of PNT data provision. Furthermore, it should be specified how the results of individual processing channels should be used to generate the data output of the PNT unit. In the simplest case, rules for data selection are specified. If the main processing follows a redundant system layout, an additional refinement of PNT data and integrity statements is also possible. It is important that a certain version of a PNT unit is clearly specified regarding its supported channels, used methods and applied thresholds for decisions. This implies, on the one hand, that the demand for input data and, therefore, onboard equipment can be clearly determined. On the other hand, the provision of standardized PNT output data and integrity information will be achieved to enhance user awareness regarding the performance levels supported as well as currently achieved.

The final functional block is dedicated to the composition of PNT output data streams in the supported data formats (e.g. as an automatic identification system (AIS) or National Marine Electronics Association (NMEA) message). For this purpose, the proposed PNT output data are analyzed for availability and quality and merged with the provided integrity information. Finally, the valid output data are used to generate output data streams in the supported format, e.g. AIS, Radio Technical Commission for Maritime Services (RTCM) or NMEA messages.

Channels, functions, methods and scalability

In principle, an individual processing channel is composed of a sequence of functions performing the three main tasks with a specific set of methods. The methods of an individual processing channel become feasible if their specific demand for input data has been fulfilled. The demand for input data by a certain version of a PNT unit will be derived from the accumulated demands of supported processing channels.

The methods applied by an individual processing channel determine what performance level of PNT data provision will be supported. Intended and unintended performance degradations in input data may impair the functionality of several or all processing channels of a PNT unit. Consequently, a noticeable performance degradation of output data may occur. A usual change in data input may result only in a tolerable performance degradation of PNT output data, e.g. a lower accuracy of positioning outside of DGNSS coverage areas. Otherwise, increased and intended disturbances decrease the functionality in the case of non-redundant systems. The degree of resilience of a certain PNT unit can be increased if two or more processing channels are implemented using independent techniques to meet the same performance. The influence of unintended malfunctions and failures of sensors and services can be reduced or mitigated, e.g. by additional positioning with eLoran in case of a jammed GNSS. Therefore, redundancy in data input as well as in data processing is a prerequisite for improving and indicating the reliability.

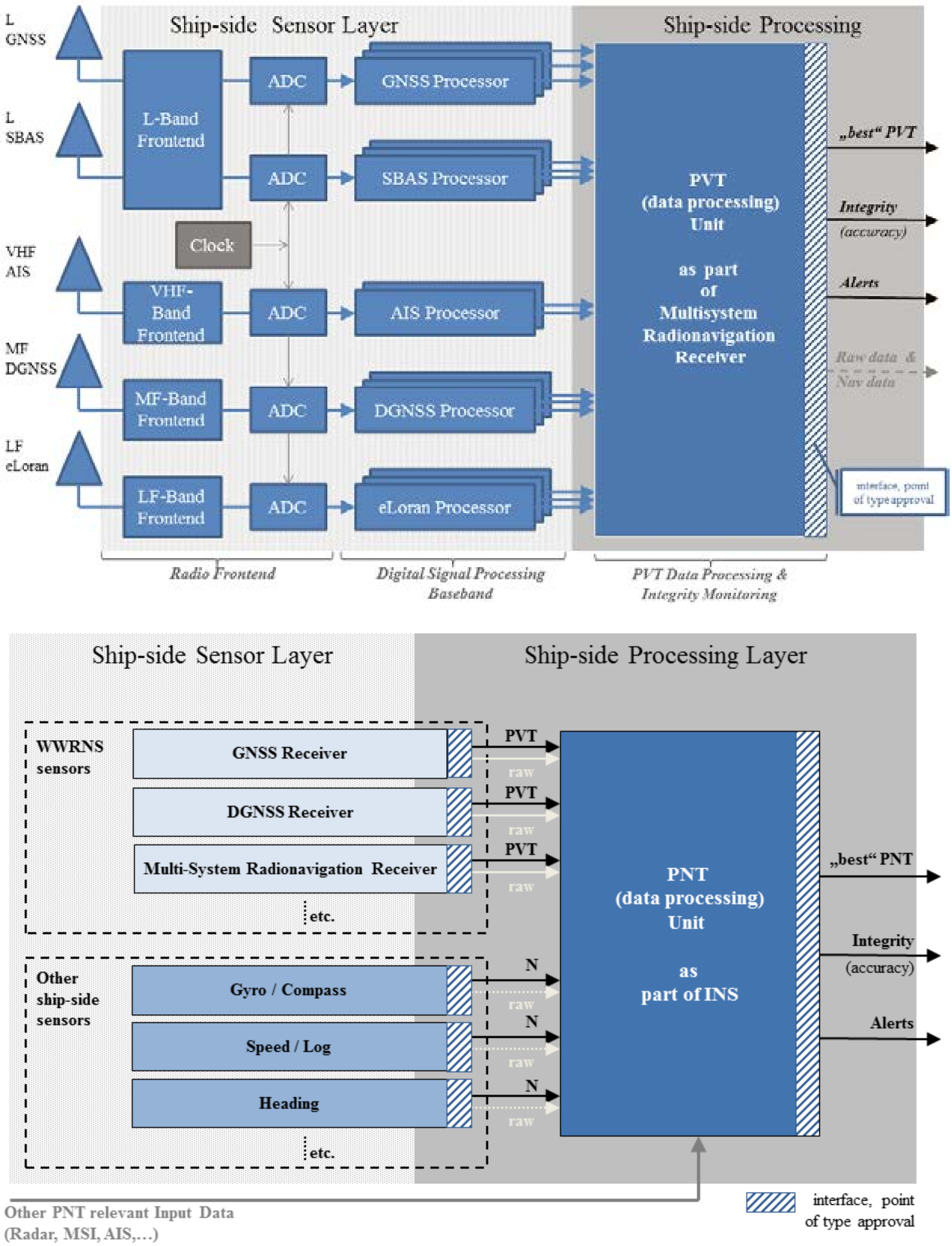

Figure 4. A PNT unit as part of MRR (top) and INS (bottom)

The proposed concept follows the rules of a modular system design in relation to architecture, functions, methods and data results. This helps, on the one hand, to elaborate all interdependencies between needed components, applied technologies and the supported performance of PNT data provision. On the other hand, PNT data provision can be scaled for carriage requirements and user needs as well as nautical applications. Furthermore, this concept serves the consequent and the coordinated introduction of data and system integrity as a smart means to protect the PNT data provision against disturbances and intrusions as well as to achieve standardized PNT output data for the system awareness of bridge teams.

Summary and outlook

As explained above, the supported performance levels of PNT data provision determine the assignment and the complexity of any onboard PNT unit. Examples of integration are shown in Figure 4: a PNT unit as part of future MMR and as a component of INS. Both realizations exploit the redundancy in data input to improve PNT data provision and to monitor data and system integrity. The example of MRR illustrates that the modular concept can be scaled for a certain set of input and output data. Both examples are based on the proposed modular architecture of onboard PNT data processing and support the necessary scalability for the diversity of ships, nautical tasks and navigation phases.

A special challenge is the consequent implementation of data and system integrity into a PNT unit and, further, the provision of standardized integrity information to establish system awareness regarding the currently achieved performance level. In this context, appropriate performance key identifiers (PKI) play an important role in the effectiveness of integrity monitoring (an indication of reliability) and management of data processing (resilient operation). A resulting demand for the further enhancement of maritime PNT systems (shore-side and ship-side) is the mandatory specification of methods for the determination of PKIs including thresholds for evaluation and rules for utilization. This is an essential prerequisite for the effectiveness of integrity monitoring (an indication of reliability) and management (resilient operation) in the whole maritime PNT system and especially in an onboard PNT data processing unit. Therefore, the feasibility of integrity monitoring and the significance of integrity results should be elaborated per individual processing channel in relation to a specific performance level. By applying the above defined rules and methods, it is possible to condition a certain PNT unit in relation to the supported performance level and the required resilience in a scalable manner. This helps to identify the real demand on resources by a redundant system layout and by its requirements for infrastructures and services.

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