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Guidelines for the coordinated enhancement of the maritime PNT system

E. Engler [1], M. Hoppe[2], J. Ritterbusch[3], T. Ehlers[3], C. Becker[4], K.-C. Ehrke[5] , H. Callsen-Bracker[6]

[6]Bundesministerium für Verkehr und digitale Infrastruktur (BMVI),
[2]German Federal Waterways and Shipping Administration, [3]Bundesamt für Seeschifffahrt und Hydrographie (BSH),
[1]German Aerospace Center (DLR), [4]Raytheon Anschütz GmbH, and [5]Wärtsilä SAM Electronics GmbH

Contact:
DLR, Institute of Communications and Navigation
17235 Neustrelitz, Kalkhorstweg 53
Germany
Evelin.Engler@dlr.de

Abstract:

A reliable knowledge of ship's position and movement in relation to other traffic participants and obstacles is a fundamental requirement for navigation and to avoid collisions and groundings. Consequently, the resilient onboard provision of position, navigation, and time data (PNT) is emphasized by the IMO e-navigation strategy, solution S3 "Improved reliability, resilience and integrity of bridge equipment and navigation information" and 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 multi-system shipborne radionavigation receiver equipment (MRR). This MRR PS supports the full use of data coming from current and future radionavigation systems and services. Consequently, the combined use of several 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 onboard PNT (data processing) Unit has been identified as supplementary and necessary. Initial point is the on board use of GNSS receivers (Global Navigation Satellite System) and autarkic systems (e.g. radar, gyro, echosounder with bathymetric data) in combination for a comprehensive provision of required PNT data. Redundancy in available data enables the application of integrity monitoring functions to evaluate the current usability of safety-critical data and components. Aim of the guidelines is the specification of data processing rules towards resilient provision of standardized PNT data and integrity information. For this purpose a modular architecture of onboard PNT system is introduced and scaled to the need on data input as well as the performance of data output.

Key words:

Standardized PNT data products, guidelines, requirements, scalability, integrity, reliability, and resilience.

1. Background and Challenges

Reliability, integrity and resilience are fundamental requirements on nautical onboard equipment identified as user needs in the frame of e-navigation and addressed as high-priority solution for safety-critical systems. In this context integrity monitoring is a prerequisite to indicate the reliability of the 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 the onboard PNT system meets these fundamental requirements can only be evaluated with respect to the required quantity and quality of PNT output data. Due to their historical development most of the existing maritime PS (see Table 1) follows an equipment-related specification of minimum requirements on individual PNT data, without consideration of integrity aspects. Furthermore at present neither the achieved, nor the target level of reliability, integrity and resilience is quantified by most sensors within today's maritime PNT system.

Table 1 Maritime performance standards of radionavigation receivers, autarkic onboard sensors and systems, and PNT related 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 und 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)*	MSC.252(83)	IEC 61924

*Systems to support or refine PNT data provision

A comprehensive specification of maritime requirements on PNT data provision and integrity monitoring is a complex task. Many factors should be taken into account: ship types and carriage requirements, diversity of nautical applications and tasks, changing complexity of situation, deviations from nominal conditions up to customized level of support. Therefore it is difficult to determine the true development needs on the 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 ship's berth-to-berth navigation the requirements on data output of onboard PNT (data processing) Unit 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 specifying current and evolving requirements on PNT data provision. The pre-specification of performance classes like explained in chapter 3 could be considered as 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 system awareness of the bridge teams and to enable the subsequent use of data for self-evaluating applications. An unambiguous meaning of usability statements can only be ensured, if applied performance key identifiers, such as rules for determination and thresholds for evaluation, are standardized for each set of PNT data and supported performance class. Only if the requirements from above are met the provision of standardized PNT output data and integrity information will be possible.

In principle, the technical feasibility of integrity monitoring depends on the available redundancy of data. A typical example in the GNSS context is the Receiver Autonomous Integrity Monitoring (RAIM) whose applicability and capability is influenced by the number of available pseudorange measurements: More than 4 allow finding the occurrence of errors and more than 5 enable the identification of an erroneous pseudorange measurement. Without redundancy the integrity evaluation is limited to simple plausibility tests and enables the detection of gross errors, only. The analysis of consistency between different and independent data sources is a high-order integrity monitoring dealing with the confidence in single data sources based on a common reference model. Like seen in the PS of Integrated Navigation Systems [MSC.252(83)] this approach can only be applied if a minimum redundancy is given in the PNT relevant sensor setup (see Figure 1).

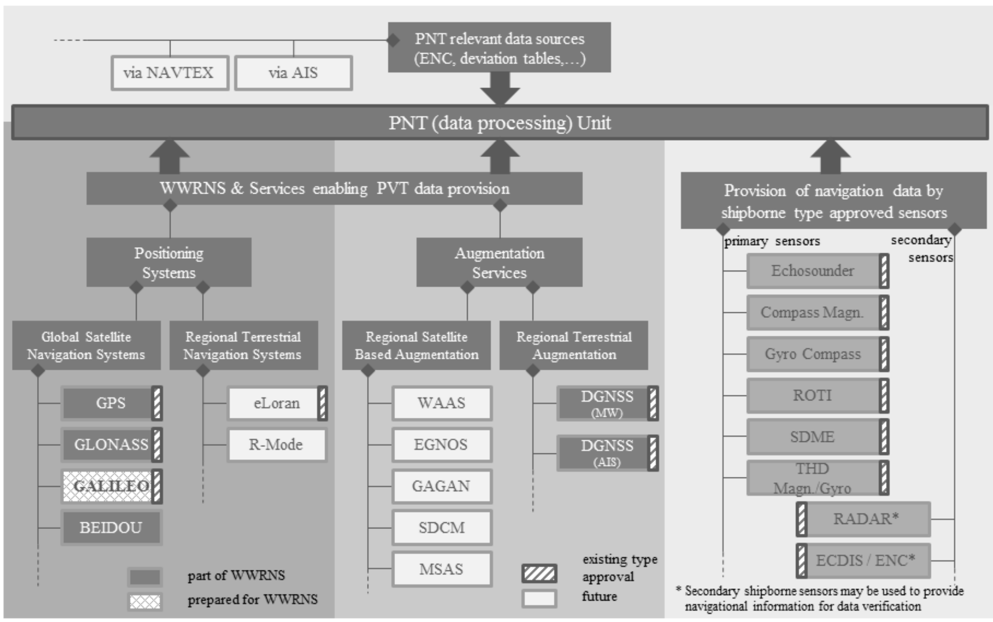

Figure 1 Overview of system, services and sensors intended for onboard PNT data processing

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 redundancy is necessary to enable that different partial errors are determined and evaluated regarding their influence on PNT data accuracy. A resulting challenge is the elaboration of dependencies between performance requirements on PNT data provision and resulting requirements on technical and functional architecture. For this purpose chapter 4 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 changes in environmental and operating conditions.

In a minimum solution the used set of services and sensors directly provides all 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, the provision of integrity information. Multi-system or multi-sensor based approaches support the combined processing of sensor and service data enabling an 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 synchronisation of input data, the improvement of data and integrity information, as well as the 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.

Generally, a modular system design is based on alternatively 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, GLONASS (GLO), and BEIDOU (BDS) are recognized by the maritime community as means for world-wide positioning. Redundancy in received GNSS signals is exploited to realize a 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 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 often limited to certain coverage areas and can therefore only be used from time to time. Consequently, DGNSS positioning is more or less a complementary processing channel in comparison to GNSS based positioning.

The GNSS related example illustrates the necessity to adjust the data processing to changing circumstances. Such an adjustment can only be based on the availability of data to determine the feasibility of individual functions and processing channels. Additionally it is possible to consider the quality of input data and intermediate results during adjustment processes. That enables to monitor effects of fault propagation and to evaluate 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 the onboard data processing should be dynamically adapted to changing operational and environmental conditions to ensure its functionality. Chapter 5 discusses briefly how the concept of parallel processing channels serves to harmonize the user needs and the technical implementation.

At the end 2 representative integrations are shown to account for generality and neutrality of the PNT Unit concept. They are used to identify the next development steps.

2. Approach

The development of Guidelines for onboard PNT data processing has been identified as supplementary and necessary step towards resilient provision of PNT data and integrity information. Consequently, this working task is anchored as planned output in the high-level action plan of IMO’s Maritime Safety Committee and should be finalized until 2017 (MSC 95/22/Add.2). Aim of these guidelines is to define the major principles and functions of onboard data processing taking into account differences in requirements and pointing out dependencies on technical and functional system architecture. Within this development process the need for sensors and services will be clarified as well as the standardization of the PNT output data and integrity information. 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 guidelines. The following explanations inform about the current draft of Guidelines for onboard PNT data processing (Issue 1 of 31st July 2015) used by the WG as basis for further discussion and improvement.

3. Requirements

As mentioned above an essential prerequisite for further harmonisation and enhancement of the maritime PNT system is the comprehensive and unambiguous specification of requirements on 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 application. Status information and contributions to alert management are more or less extracted from monitoring of PNT Unit’s data input, processing, and output.

A safe execution of nautical tasks (e.g. perform of evasive manoeuvre, route planning) and applications (e.g. track control, collision avoidance) requires a certain set of PNT data with respect to

[1] amount and types;

[2] accuracy;

[3] evaluated integrity of certain data; and

[4] continuity and availability.

The variety of nautical tasks and changing environmental conditions (e.g. area, weather, traffic situation) are the main reasons that requirements on PNT data provision vary during 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 aimed level of support are additional reasons that PNT data will meet different performance level. Basically, a structured description of the diversity of requirements can only be achieved, if several performance level and classes for PNT data provision are introduced.

Basically, a structured description of the diversity of requirements can only be achieved, when several performance levels and classes for PNT data provision are introduced. This approach avoids that a unit of maximum PNT performance has to be installed 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 supports the harmonization between provision and application of PNT data, is open for evolving needs, and helps to clarify responsibilities in safety-relevant systems.

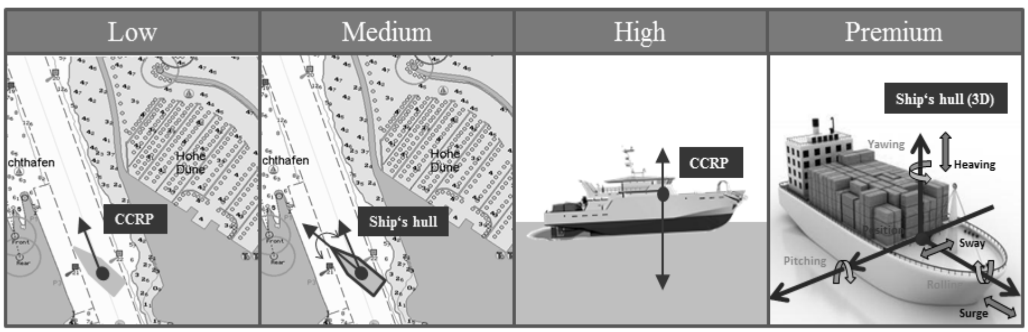

Figure 2 Proposed performance level regarding amount and types of onboard PNT data provision

First discussions result into the proposal to introduce various performance levels for a comprehensive registration of various requirements on amount, types, and quality of data. It may be sufficient to use 4 performance levels for each individual requirement: low, medium, high, and premium.

[1] An initial proposal to arrange the requirements on amount and types of onboard PNT data provision is shown in Figure 2 as beginning for further discussions. In relation to amount and 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, speed over ground (SOG), course over ground (COG), time and date. A medium level of PNT data provision could be associated to the description of attitude and movement of ship’s hull in the horizontal plane. This requires the additional provision of heading (HDG) and rate of turn (ROT) information. A high level could be achieved, if the primary PNT data are enriched with CCRP’s altitude and changes to enable that in combination with further information the under keel clearance can be evaluated. The premium version of PNT data provision could correspond with the complete description of ship’s attitude and changes of attitude by provision of yaw, roll and pitch angles and their rates.

Requirements on each type of PNT data can also be described by 4 accuracy and 4 integrity levels. 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) introduced already 4 accuracy levels for positioning by specification of horizontal position errors (HPE) as follows: <100m, <10m, < 1m, and <0.1m. 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 is a sufficient basis to coordinate offer and demand in relation to performance of PNT data provision. Generally, higher levels of accuracies can be met e.g. either by more powerful sensors (e.g. Inertial Measurement Unit in contrast to individual gyroscope), by augmentation services for error reduction (e.g. DGNSS based positioning in comparison to GNSS), or by application of smart data processing techniques exploiting redundancy in data input (e.g. error detection and exclusion methods).

[3] The increasing safety awareness in the maritime community is the main cause for arising the need for integrity of safety relevant data and systems in the last decade. Therefore only recently Performance Standards of radionavigation receivers (e.g. GALILEO: [MSC.233(82)] or BEIDOU: [MSC.379(93)]) recommend the use of RAIM-techniques for integrity monitoring. As already mentioned, the purpose of integrity monitoring is the indication if safety-relevant systems, signals and data are currently usable. Reversely, 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 an integrity loss of positioning, when the horizontal position error exceeds2.5 times its allowed value. Generally, it is impossible to determine the real value of a total error. Therefore the aimed evaluation of data integrity asks for appropriate methods for monitoring. However, it is fact that differences in integrity monitoring techniques and applied thresholds result in differences of monitoring results and should therefore be indicated. A logical consequence is the introduction of different integrity levels in relation to applied monitoring techniques e.g.: level 0 corresponds with 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 parametrized error models for accuracy estimations (e.g. premium PNT Unit).

[4] For the specification of continuity and availability requirements it should be clarified, if these areto be considered in relation to individual PNT data types or certain data sets like 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 occurs or continuity is 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 availability of a data set is always less than the continuity and availability of included individual data. It can be expected that data with the highest vulnerability has the most impact on continuity and availability of a data set. It is ineffective, if only the continuity and availability of individual data is 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 2-sigma (~95%), 3-sigma (~99%), or more e.g. 99.8% and 99.9%. If a 3-sigma availability is required per day, then unavailability should be below 14.5 minutes per day. Assuming that a typical ship's manoeuvre takes 15 minutes or more makes verifiable that the availability of PNT data should be 99.8% or higher. The requirement on continuity expresses that a system should be able to perform its functionalities over a short time interval without interruptions and performance degradations. In case of the onboard PNT Unit the continuity requirement is met, when the needed PNT data (amount and types) are provided with regard to the required accuracy and integrity level. Maritime requirements on continuity are specified in amount of 99.97% for the provision of radionavigation services [A.1046(27)] as well as GNSS-based positioning [A.915(22)]. In the first case the continuity time interval (CTI) is specified with 3 hours, in the second case with 15 minutes. A reduction of CTI to one twelfth allows that the mean time between failures (MTBF) can be decreased from 416 days to a less ambitious value of ~35 days. The introduction of several continuity and availability levels could force an application-orientated consolidation of both requirements. For example, if the continuity could be reduced to 99.5%, then a MTBF of 2 days is acceptable.

Following the above explained approach enables that requirements on PNT data provision can be described by 5 parameters (type and amount (T), accuracy (A), integrity (I), continuity (C), and availability (R)) and 4 parameter-specific performance levels (low (L), medium (M), high (H), premium (P)). Therefore a certain performance level of PNT data provision can be characterized by

$$\mathrm{PNT}(t)_{\{T,A,I,C,R\}} \Rightarrow \mathrm{PNT}(t)_{\{L,M,M,H,H\}}\,. \quad (1)$$

More or less a reliable operation of the PNT Unit can be assumed, if during operational time T_{op} the performance of provided PNT data meets always the requirements coming from currently performed tasks and applications.

$$\mathrm{PNT}_{target}(t)_{\{T,A,I,C,R\}} \le \mathrm{PNT}_{achieved}(t)_{\{T,A,I,C,R\}} \quad \text{with} \quad t \in T_{op} \quad \text{and} \quad T,A,I,C,R \in \{L,M,H,P\}. \quad (2)$$

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

In the context of e-navigation the vulnerability of GNSS has been identified as justifiable reason to request a resilient provision of PNT data and integrity information. Generally, resilience can be considered as ability of a system to detect and compensate external and internal disturbances, malfunction and breakdowns in parts of the applied system. This should be achieved without loss of functionality and preferably without degradation of its 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 on redundancy of input data and processing to offer the possibility that malfunctions and failures can be detected, mitigated and compensated to avoid any loss or degradation in functionality. Then resilience will be focussed on the further improvement of reliability in terms of accuracy, integrity, continuity, and/or availability. Ultimately, an improvement of resilience is associated with an aimed increase of reliability and can be considered as enhanced design criterion to achieve a higher performance of PNT data provision.

An aim of an INS is to facilitate the combined use of data inputs coming from several and redundant data sources in order to enable that the integrity of safety-relevant equipment and data can be monitored. This is considered as prerequisite for the application of high-order assistance functions. If all PNT data are consistent within the common model of ship’s position and movement, integrity is assumed [MSC.252(839)]. The Performance Standards for Multi-system Radionavigation Receiver [MSC.401(95)] focuses 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 e.g.:

- application of dual-frequency GNSS signal processing to reduce the influence of ionospheric propagation effects on GNSS ranging accuracy;
- the 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;
- the additional use of terrestrial radionavigation system (e.g. eLoran, R-Mode) to protect positioning against broadband jammer operating in GNSS’s frequency bands; as well as
- the future use of satellite-based augmentation services (SBAS) to improve the integrity monitoring of used GNSS and the availability of DGNSS correction.

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 approach to ensure the continuity of positioning in case of serious faults of GNSS positioning e.g. induced by jamming. However, the real need on redundancy in PNT data input and processing can only be answered in relation to clear development goals derived from noted deviations between achieved and target level of performance for PNT data provision.

4. Modular Architecture

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

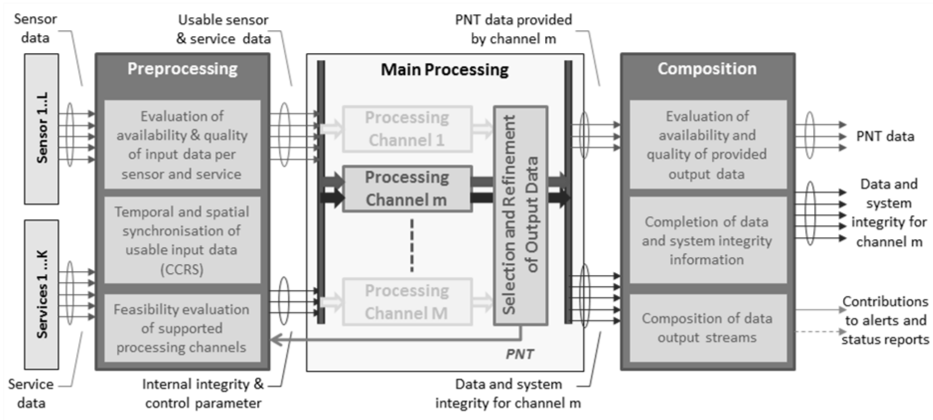

Figure 3 Generalized model of onboard PNT data processing

Tasks to be performed during pre-processing cover:

- the evaluation, if the existing data input fulfils the demand on availability and quality to ensure a nominal operation condition for the onboard PNT Unit in relation to supported processing channels;
- the temporal and spatial synchronisation of input data within ship's Consistent Common Reference System; and
- ultimately the evaluation, which of the supported processing channels of the PNT Unit can be performed.

Especially for both evaluation tasks the self-determined PNT data of preceding epochs are needed. 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 into partial or complete interruption of PNT data provision. It is quite understandable that with increasing redundancy of data input the chance grows to detect all substantial errors and to compensate their influence on PNT output data.

The main processing block is composed of one or more processing channels. Generally, 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 aimed 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,-,-}[1] 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 GPS Standard Positioning Service (SPS).

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

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[1] 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<100m; SOG<0.2knots; …
- integrity – level M: provided by RAIM.

- 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 adaption of the data processing to changing availability of sensors, services, and data sources; and
- to establish redundancy in data processing in order to achieve a higher continuity and/or availability of PNT data provision.

Under consideration of all technological opportunities and taking into account the diversity of desired performance levels, the main processing block could be composed by 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 GLO 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 ($M_{Vx} \leq M$) in relation to supported performance levels and aimed 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 PNT Unit is clearly specified regarding supported channels, used methods, and applied thresholds for decisions. This implicated on the one hand, that the demand on input data and therefore onboard equipment can be clearly determined. On the other hand a provision of standardized PNT output data and integrity information will be achieved to enhance user awareness regarding 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 AIS or NMEA message). For this purpose the proposed PNT output data are analysed regarding availability and quality and merged with provided integrity information. Finally, the valid output data are used to generate output data streams in the supported format e.g. AIS, RTCM or NMEA messages.

5. Channels, Functions, Methods, and Scalability

In principle, an individual processing channel is composed of a sequence of functions performing the 3 main tasks with a specific set of methods. The methods of an individual processing channel become feasible if their specific demand on input data has been fulfilled. The demand on input data of a certain version of PNT Unit will be derived from 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 the PNT Unit. Consequently, a noticeable performance degradation of output data may occur. A usual change in data input may only result in a tolerable performance degradation of PNT output data e.g. lower accuracy of positioning outside DGNSS coverage areas. Otherwise increased and intended disturbances decrease the functionality in case of not redundant systems. The degree on resilience of a certain PNT Unit can be increased, if 2 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 by e.g. additional positioning with eLoran or R-Mode in case of jammed GNSS. Therefore both, redundancy in data input as well as in data processing are a prerequisite to improve and indicate the reliability.

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 supported performance of PNT data provision. On the other hand the PNT data provision can be scaled on carriage requirements, user needs, as well as nautical applications. Furthermore this concept serves the consequent and coordinated introduction of data and system integrity as smart mean to protect the PNT data provision against disturbances and intrusions as well as to achieve standardized PNT output data for system awareness of bridge teams.

6. Summary and Outlook

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

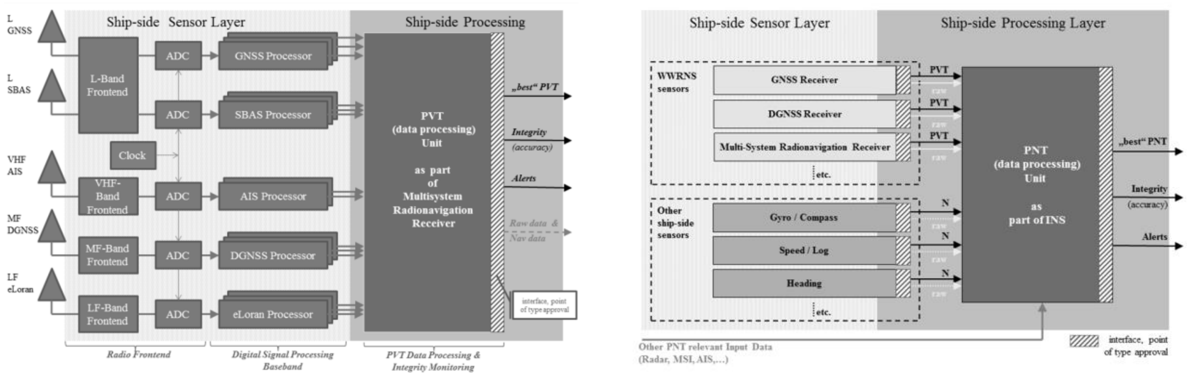

Figure 4 PNT Unit as part of MRR (left) and INS (right)

A special challenge is the consequent implementation of data and system integrity into the 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 for the effectiveness of integrity monitoring (indication of reliability) and management of data processing (resilient operation). A resulting demand on the further enhancement of maritime PNT systems (shore-side and ship-side) is the mandatory specification of methods for PKIs' determination including thresholds for evaluation and rules for utilization. This is an essential prerequisite for the effectiveness of integrity monitoring (indication of reliability) and management (resilient operation) in the whole maritime PNT system and especially in the 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 supported performance level and aimed resilience in a scalable manner. This helps to identify the real demand on resources from redundant system layout up to requirements on infrastructures and services.

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