The on-board maritime PNT Module –

Concept and preliminary experimental results

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ABSTRACT

Improvement and Indication of Reliability have been identified as important user needs within the e-Navigation strategy of the International Maritime Organization (IMO). This paper address the question, how these user needs can be satisfied in future with respect to resilient provision of position navigation and timing (PNT) data onboard the vessel. The idea of an onboard PNT Module is proposed as front-end between an integrated PNT system and ship-side applications like INS, AIS and ECDIS. The paper focuses on the integrity monitoring within the PNT Module. The concept is introduced and first experimental results are presented.

INTRODUCTION

Position fixing systems are identified as one strategic key element of e-Navigation [1]. For the reliability improvement of position and other PNT parameter of a vessel, not only the ship-side components but the whole integrated PNT system needs to be considered. An overview of this maritime integrated PNT System is shown in Fig.1. It is the sum of satellite-based, ashore and aboard components and its related links. Only the integrated use of these components enables the accurate and reliable provision of position, navigation and timing information to all maritime applications.

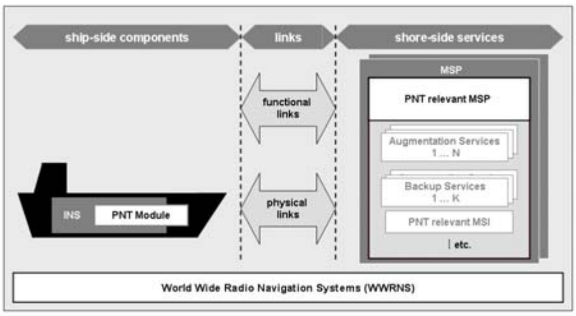

Fig. 1. *Overview Integrated PNT System*

Existing and future World Wide Radio Navigation Systems (WWRNS) like GPS, GLONASS and GALILEO are fundamental infrastructures for global positioning. Additionally, shore-side services as part of the Maritime Service Portfolio (MSP) are used or considered as candidates to improve the positioning performance (augmentation services: e.g. IALA Beacon DGNSS, RTK), to support the backup functionality (backup services: e.g. e-LORAN, R-Mode), or to provide PNT relevant Maritime Safety Information (MSI: service level, tidal information).
This paper focuses on the ship-side part of the maritime integrated PNT System. Section 1 provides an overview of the current PNT system and introduces our concept of an on-board maritime PNT Module. In Section 2 first results of a preliminary realization of such a PNT Module will presented.

1. PNT Module Concept

1.1. Overview of current situation

Currently, vessels subject to the International Convention for the Safety of Life at Sea (SOLAS) [2] can either use single sensors to provide the PNT parameter (e.g. position, heading, speed over ground) individually or use an Integrated Navigation System (INS) [3]. Fig. 2 represents the single sensor approach. Stand-alone equipment provides only sensor-specific PNT data e.g. WWRNS sensors for position, velocity and time data (PVT) and other ship-side sensors for navigation data (N). The shipboard processing layer is part of the applied sensors and represents the internal used methods for the provision of respective PNT data. The onboard staff has to fuse the information from the different sensors.

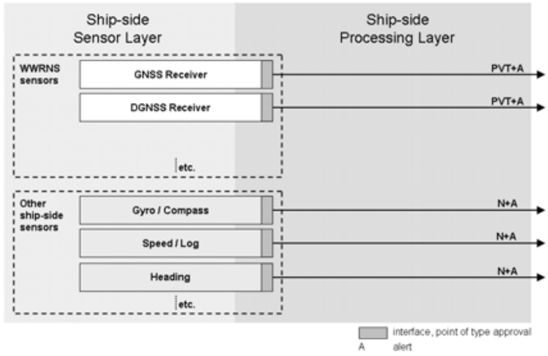

Fig. 2 *Single sensor approach*

In the current INS approach, the sensors deliver their individually determined PNT output data to a shipboard processing layer, which is illustrated in Fig. 3. The INS is performing plausibility checks on the incoming data and consistency checks on different sensors. Integrity is expected, if plausibility and consistency checks are passed [4]. For instance, the position integrity monitoring is based on: (i) comparison with a second WWRNS sensor; (ii) processing an output of the Receiver Autonomous Integrity Monitoring of a WWRNS sensor and (iii) dead reckoning. However, the WWRNS sensors might have common failure modes (like multipath, interference, and jamming) and hence not all possible failures can be detected by comparing both sensors. For the RAIM functionality, neither the RAIM functionality itself is specified nor the output of it. The last integrity step, the comparison with dead reckoning is only capable of detecting large position jumps. This means, that in last consequence the application of plausibility and consistency tests is insufficient to guarantee the reliability of INS outputs regarding accuracy assessment.

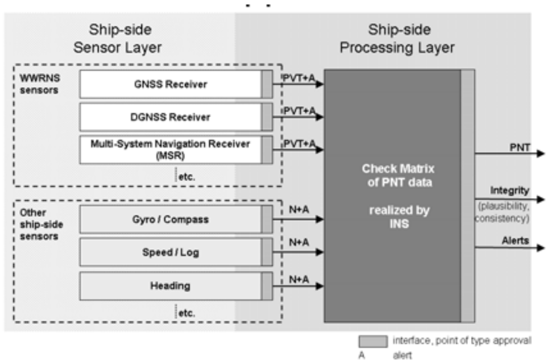

Fig. 3 *Approach of current INS*

1.2. PNT Module concept

In order to overcome these problems identified above, a PNT data processing unit (abbreviated by PNT Unit) is introduced into the shipboard processing layer of a future INS, as illustrated in Fig. 4. By means of sensor fusion techniques, this PNT Unit integrates all available PVT and N data from onboard sensors in order to provide optimal PNT output data. In addition to the current INS approach, the onboard sensors (here especially the GNSS Receivers) should also provide their raw data (e.g. code and phase measurements, navigation data) to the PNT Unit. This enables the usage of advanced sensor fusion techniques, which will improve the resilience of PNT information by application of integrity monitoring functions. As a new functionality, the PNT Unit will not only provide optimal estimations of the PNT output data but also integrity information based on accuracy estimations. A definition of integrity and an overview of our integrity monitoring concept will be given in sections 1.3. and 1.4.

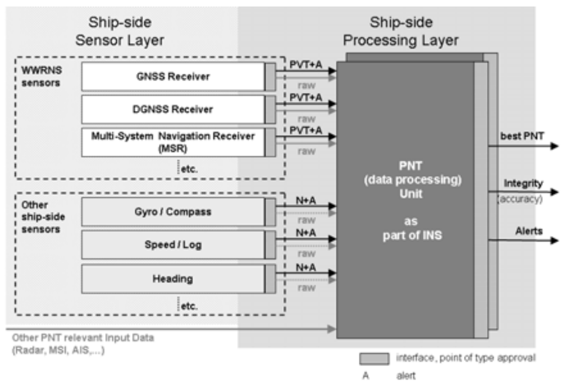

Fig. 4 *PNT Unit approach*

The PNT Module with its data processing Unit will be part of the integrated PNT System and can either be part of a future modular structured INS (see Fig. 4). Alternatively a stand-alone PNT Unit may offer enhanced functionality in the absence of an INS.

1.3. Understanding of Integrity

Integrity can be categorized into “data integrity” and “system integrity”. Data integrity is given, if the desired output data is provided at the expected time in the specified formats, and meanwhile, the specific accuracy requirements are fulfilled. System integrity is given, if (1) the integrity of all output data of a system is fulfilled and (2) the output data, additional status messages, and alert messages are provided in a timely, complete, unambiguous and accurate manner. From the definitions it can be seen that the system integrity can only be given as long as the system realizes its tasks with the required performance. According to these definitions, integrity monitoring needs to include error estimations for all output data. These estimated errors need to be compared against given accuracy requirements. Whenever these

requirements are not fulfilled, an alert message should be generated within a specified time.
Compared to the current INS approach, an implementation of this integrity definition requires an introduction of an error estimation of all output data onboard a vessel. Currently, only rough assumptions are made in terms of positioning accuracy. Whenever a GNSS Standard Positioning Service (SPS) is used, an accuracy of better than 100 m is expected. Whenever an IALA Beacon DGNSS Service is used, an accuracy of better than 10m is assumed.
An implementation of integrity monitoring requires that the technical requirements on systems or required PNT data should be specified by unambiguous performance quantities (e.g. accuracy, availability..).
Such specifications are needed for all PNT data such as given in Res. A.915(22) [5] as requirements on future GNSS for horizontal position and in Res. A 1046 [6] as requirements on a World Wide Radio Navigation System (WWRNS).

1.3. Integrity monitoring concept

For a PNT unit, integrity monitoring can be carried out in three sequential steps. The first step is the test of individual sensors including provided sensor data. The second step is the compatibility test of similar data from different sensors. The third step is the fault detection and identification in the integration algorithm. A general integrity monitoring approach is depicted in Fig. 5. These steps will be briefly introduced in the following parts:

A. *Individual sensor tests*

Individual sensor tests include plausibility and validity checks. The plausibility check tests whether the sensor raw data or derived navigational result falls into predefined value range. For example, an output of 181° from a gyrocompass ranging between -180° to +180° is not plausible. The validity is tested by comparing the sensor data or derived navigational results with formal and logical criteria, such as whether they fit the ships' maneuver or dynamic properties, or whether they are consistent with the environment nearby. For example, if the output of a speed log is larger than the maximal achievable speed of the ship, a sensor failure can be assured.

B. *Compatibility test of sensor data*

Once a specific output can be provided by more than one sensor, different sensor data can be compared to perform the compatibility tests based on a common measurement model. A significant discrepancy between different sensors implies the failure of at least one of these sensors. The upper bound for deviation should be defined either *a priori* or in real-time according to the previous measurements. Additionally, compatibility tests evaluating the time behavior of successive provided sensor data can be applied. The compatibility test should be carried out before sending the sensor data to integration algorithms.

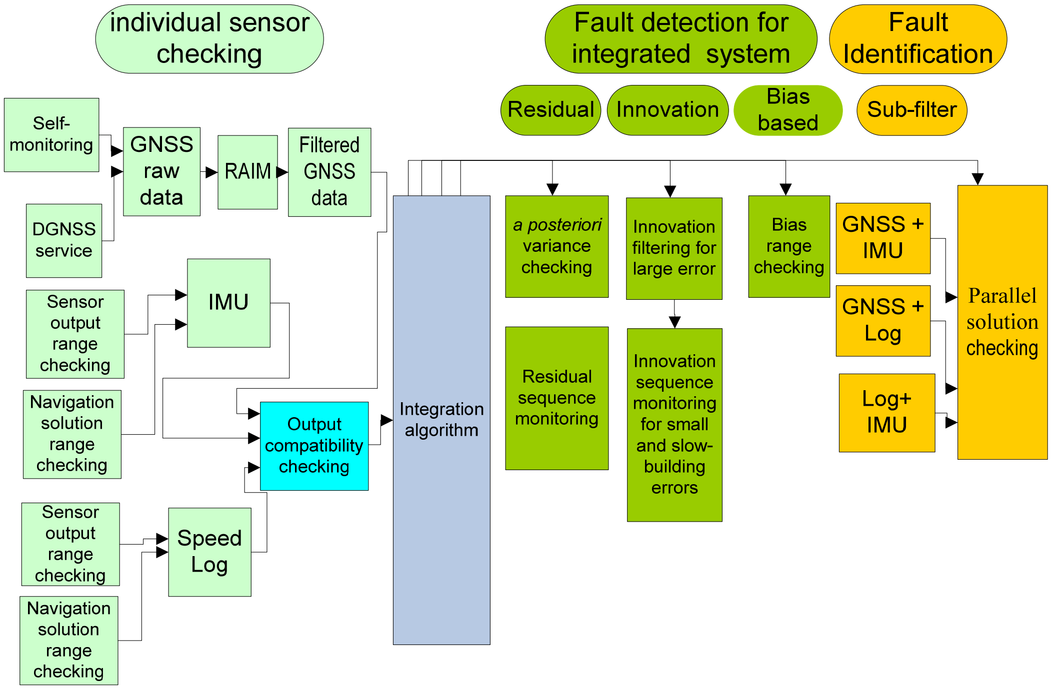

Fig. 5 *Example of integrity monitoring for PNT unit with GNSS, IMU and Log as applied sensors*

C. *Fault detection for integrated navigation system*

The plausibility, validity and compatibility tests are suitable for detecting gross sensor failure but not sensitive for slight error, time-variant errors and drifts. The Kalman filter-based algorithm could offer high sensitivity of detecting these errors. Integrity monitoring based on Kalman filter can be categorized into the following approaches [7].

1) Kalman filter estimates (bias check)
In a Kalman filter, the sensor measurement biases can be estimated. If an estimated bias is significantly larger than the error level specified by the manufacturer, there is likely a failure in the sensor.
2) Innovation-based approaches
The innovations indicate the consistency of the actual measurements and the measurements predicated by state estimates. Innovation filtering may be used to detect large discrepancies immediately, whereas innovation sequence monitoring enables smaller discrepancies to be detected over time.
3) Residual-based approaches
The above-mentioned innovation filtering and sequence monitoring can also be expanded to residuals. Residuals have a smaller covariance than innovation, making them more sensitive for error detection [7]. The only shortcoming is that the processing of residuals is not an essential part of a Kalman filter routine and needs extra computing time.
Another popular approach related to residuals is the DIA (Detection, Identification and Adaption) approach [8], which is based on the a posteriori variance factor for a least-squares adjustment.
4) Parallel solution of multiple sub-filters
Parallel-solutions integrity monitoring maintains a number of parallel navigation solutions or sub-filters, each excluding data from one sensor or radio navigation signal. Each additional navigation solution is compared with the main filter using a consistency test. A significant inconsistency indicates a fault in the sensor or signal omitted from main filter. The system output is then switched to the solution omitting the faulty sensor or signal. The main drawback lies in the increased computational burden and hence this technique is preferably used for failure identification rather than failure detection.

2. PNT Unit realization

In order to demonstrate the opportunities of a PNT Unit concept, a prototype of such a PNT Unit is under development within our research project.

2.1. Sensor selection

The provision of PNT information is seen as the basic function of a PNT Module. In the preliminary design the following parameters have been chosen as output parameters: (1) Position (longitude, latitude, height); (2) Speed Over Ground (SOG); (3) Course Over Ground (COG); (4) Attitude: roll, pitch, yaw (heading); (5) Rate of Turn (ROT); (6) UTC time.
IMO has furthermore identified the requirements for redundancy, particularly in relation to position fixing systems [1]. IALA has given a classification of alternative navigation systems in relation to their objectives [9]:
1 A redundant system provides the same functionality as the primary system, allowing a seamless transition with no change in procedures.
2 A backup system ensures continuation of the navigation application, but not necessarily with the full functionality of the primary system and may necessitate some change in procedures by the user.
3 A contingency system allows safe completion of a maneuver, but may not be adequate for long-term use.

According to this classification, sensors used in a PNT Unit as well as the relevant outputs are identified in Table 1.

	Pos	COG	SOG	Hea-ding	ROT	Time
Major GNSS device	M	M	R			M
Second GNSS device	R	R	R	R	B	R
Second GNSS system	R	R	R			R
Second GNSS signal	R	R	R			R
EM Log			B			
Doppler Log			M			
Magnet Compass				B	B	
Gyrocompass				M	B	
THD				B	B	
ROT indicator					M	
IMU	C	C	C	C	C	
e-Loran	B					B
R-mode	B					B
e-Pelorus	C			C		

Table 1 *Sensors and Output (M-Main R-Redundency B-Backup C-Contigency)*

An Inertial Measurement Unit (IMU) can bridge GNSS outages within certain duration and can therefore be seen as a short-term contingency for most of PNT parameters. The diversity of IMU outputs can furthermore enable integrity monitoring for relevant parameters. Due to these advantages we have chosen an IMU as an additional sensor for the PNT Unit. A limitation of IMU in maritime navigation lies in accuracy degradation for long-term operation, so that the integration of IMU with other navigation sensors is necessary to realize a long-term stable operation.

2.2. Measurement campaign

In order to collect test data for the development and test of the PNT Unit, first measurement campaigns have been performed in cooperation with the Federal Maritime and Hydrographic Agency (BSH) on the survey and research vessel DENEB. The vessel was equipped with 3 GNSS antennas and receivers (type: Javad Delta), an IMU (type iMar IVRU FCAI), a gyrocompass, a Doppler speed log, an electromagnetic speed log and other standard shipborne sensors. Fig. 6 shows the vessel DENEB, where the red circles mark the positions of the 3 GNSS antennas and the yellow circle indicates the position of the IMU installed near the centerline inside the vessel.

Fig. 6 *Vessel DENEB with sensor locations*

In this section, preliminary data analysis for the data collected on 5th July from 10:00 to 11:00 (local time) near the port of Rostock is presented. The trajectory of the vessel is shown in Fig. 7**Fehler! Verweisquelle konnte nicht gefunden werden.**.

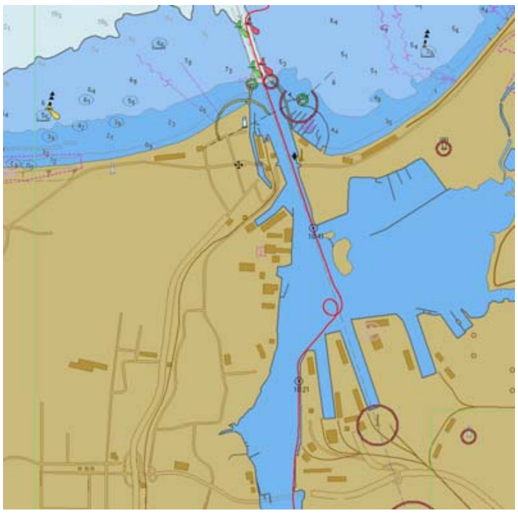

Fig. 7 *Trajectory of vessel DENEB*

Leaving the Warnow River, the vessel performed an anti-clockwise turning maneuver and finally it left the port and led into the Baltic Sea. Based on the master station located near Rostock port, differential positioning with carrier phase measurements have been performed in post-processing to obtain the reference trajectory in centimeter accuracy. The preliminary results focus on the integrity monitoring using compatibility test and Kalman filter-based approaches.

2.3. Consistent Common Reference System (CCRS)

Due to the size of vessels and the distribution of sensors, the position and velocity information measured by different sensors need to be converted to a common consistent reference point (CCRP). Heading information, as well as the other Euler angles and their change rates are needed for this conversion. Therefore, an accurate determination of ships attitude and their temporal changes are a prerequisite for PNT parameter determination. Beside that, the integrity of the other output parameters like position and velocity relies also on the integrity of the attitude information. A detailed discussion of our PNT Unit based approach of attitude determination can be found in [10]. Here only the basic ideas will be briefly introduced.
As can be seen from Table 1, the standard sensor for heading determination is the gyrocompass. If it is properly settled, it provides long-term stability. However, the accuracy depends on the actual ship motion and is limited to few degrees (see [10], [6]). The usage of a 3 antenna GNSS-Compass with a large baseline length (as we have installed it on the vessel DENEB) yields a significant higher accuracy of $\sigma < 0.1$deg.

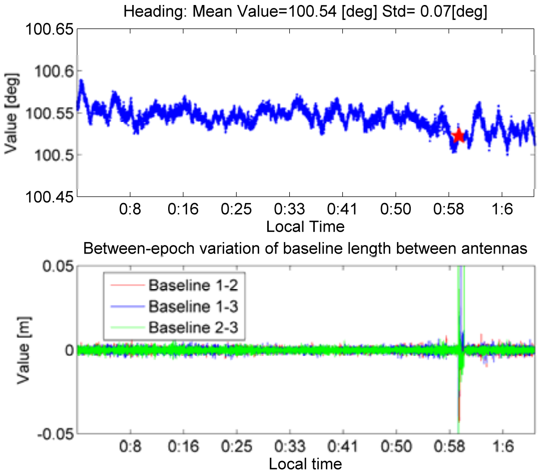

Fig. 8 *Heading determination using GNSS-compass in quasi-static scenario at port*

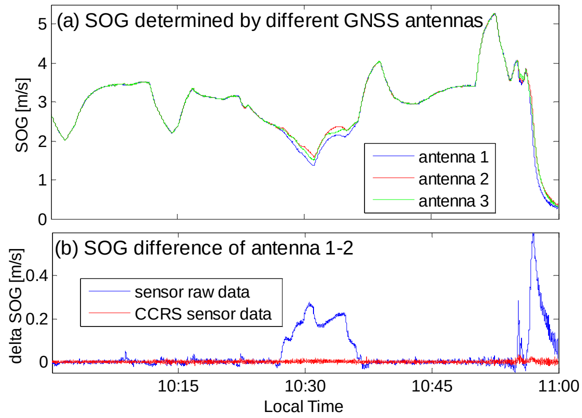

Fig. 9 *(a) SOG determined by the different GNSS antennas, (b) SOG difference of antenna 2-1 of raw sensor data and using converted data within a CCRS*

In Fig. 8 the heading determined with a GNSS-compass is shown for quasi-static scenario, where the real movement of the vessel is so week that can be neglected. Additionally, the current challenges of a GNSS-compass are shown.

The red star indicates the epochs at which GNSS-compass does not output reliable results. The quality of the GNSS-compass can be evaluated by the baseline length (see lower graph in Fig. 8), which should keep unchanged as long as the GNSS carrier phase measurements are correctly processed. It can be seen, that the unreliable heading results can be detected by larger variations in the baseline length. These outliers might occur with a failed solution of integer ambiguities, which is the most crucial step within the GNSS-compass data processing.

From the discussions above it can be concluded that a GNSS-compass offers high accuracy whereas limited availability and continuity. In order to overcome these limitations, a GNSS-compass should be used in combination with other sensors, like an IMU.

In a sensor fusion scheme, an IMU can be used for the detection of GNSS compass outliers and as well as for the provision of a backup during the times of GNSS compass outages. Therefore, within our prototype PNT Unit, an attitude determination based on the fusion of a GNSS-compass and an IMU serves as an accurate and reliable basis of a CCRS.

2.4. Integrity monitoring with compatibility tests

As mentioned before, the second step integrity monitoring refers to the compatibility test for PNT data obtained from different sensors. As an example, the compatibility tests for SOG determination are presented in the following.

In Fig. 9 (a) the SOG data, determined by the three different GNSS antenna (see Fig. 6) are shown. One can clearly see systematic differences especially during the turning maneuver around 10:30 local time and at the end of the scenario. As it is illustrated in Fig. 9 (b), these systematic differences indeed vanish if the sensor raw data are converted into a CCRS. For the SOG compatibility tests within the integrity monitoring one either accepts larger systematic differences between distributed sensors or needs to convert the sensor data into a CCRS before performing the compatibility test. The second option has the disadvantage that the integrity tests for one output parameter (e.g. SOG) depends on the availability and integrity the CCRS itself.

2.5 Integrity monitoring within the sensor fusion

The PNT Unit concept (see Fig. 4) enables the usage of sensor raw data within the sensor fusion algorithm. In order to demonstrate the advantage of this approach we have implemented a tightly coupled GNSS/IMU sensor fusion algorithm based on an extended Kalman Filter. A detailed description of the implementation can be found in [11]. In this paper only the basic ideas and results are presented.

In contrast to a loosely coupled GNSS/IMU Kalman filter, where the position results of a GNSS receiver is used as an input, in a tightly coupled Kalman filter the raw pseudorange measurements from each satellite in view are processed in the filter. This allows a failure detection of each individual GNSS observable. As an essential step of the Kalman filter routine, the calculation of the innovation vector reflects the deviation of the predicted pseudoranges with respect to the real measurements. As long as the dynamic model is working properly, the innovation vector mainly reflects the potential failures hidden on each measurement. Based on this fact, the failures manifest themselves as abnormal jumps in the innovation sequence of a specific measurement. This is the basis for integrity monitoring based on innovation checks in a Kalman filter.

In this paper, we present a very simple fault detection and adaptation scheme, where we use a fixed threshold for innovation magnitude of pseudoranges in order to detect and remove faulty measurements. The trajectories processed using single-point positioning and GPS/IMU integration with satellite filter are depicted in Fig. 10, where the graph at the left-hand side shows the whole trajectory within one hour and the graph at the right-hand side is a zoom-in for the first 20 minutes for a clearer illustration.

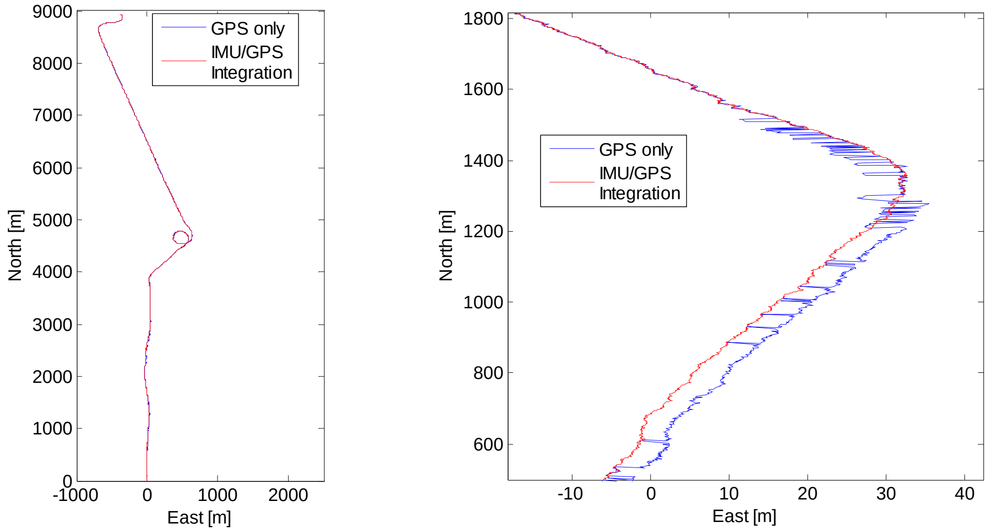

Fig. 10 ***Tightly-coupled GPS/IMU integration with satellite filtering***

The GPS/IMU integration gives a much smoother trajectory compared to the GPS-only solutions. In order to show the improvements in terms of accuracy, the absolute positioning errors in the horizontal plane are calculated by comparing with the reference trajectory and presented in Fig. 11.

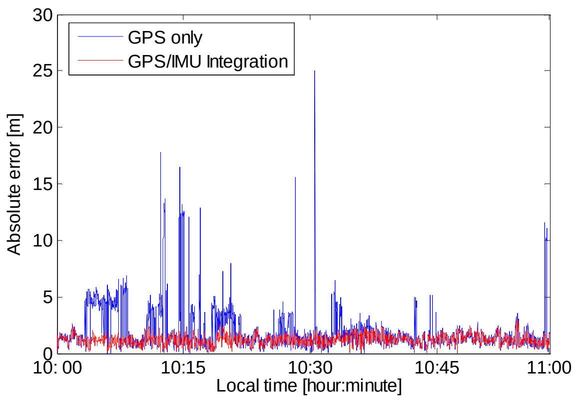

Fig. 11 *Horizontal accuracy of tightly-coupled GPS/IMU integration with satellite filtering*

The integrated system shows stable errors limited to 3 meters for most of the observation epochs. Contrarily, the GPS-only results present significant outliers. A more detailed analysis [11] shows that these errors are caused by signal distortions from low elevation satellites. The innovation filter automatically detects and removes these faulty measurements.

The conventional GPS/IMU integration works also without satellite exclusion. The dynamics measured by IMU could somehow adjust the positioning errors caused by low measurement quality. In**Fehler! Verweisquelle konnte nicht gefunden werden.** the corresponding trajectory is also illustrated, together with its counterparts using single-point positioning and using the integration with satellite filtering.

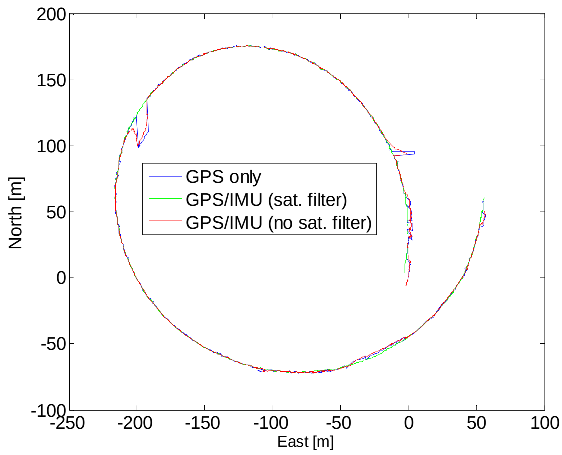

Fig. 8 *Tightly-coupled GPS/IMU integration with and without satellite filtering*

It can be seen that the innovation-based exclusion of low-quality measurements has the dominant effect in the accuracy improvement. This example also reveals the importance of the integrity monitoring in the measurement domain.

Summary

In this paper, the maritime integrated PNT Module as the on-board part of maritime PNT system is introduced. The aim of the PNT Module is the resilient provision of position, navigation and timing information taking into account performance requirements coming from different service areas and navigational tasks.
The core of the PNT Module is a PNT data processing Unit enabling the integrated utilization of all available sensor data to establish the needed redundancy for improved PNT data provision and integrity monitoring. The benefits of such a PNT Unit are shown at examples regarding different integrity monitoring methods.
The CCRS as the prerequisite for the fusion of data from different sensors at different locations is introduced. From the examples of compatibility tests for SOG sensors, the importance of conversion of sensor data into a CCRS is demonstrated. Integrity tests based on a tightly-coupled GPS/IMU integration are able to identify and remove outliers of GNSS pseudorange measurements.

The PNT Unit is on the one hand part of the integrated maritime PNT system. On the other it can be part of a future INS or alternatively a stand-alone PNT Unit may offer enhanced functionality in the absence of an INS.

This paper shows part of our works on the integrity monitoring within the maritime PNT System. Another important aspect of the integrity monitoring lies in the error estimation of PNT parameters. Corresponding results will be presented in our further publications.

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