The Maritime Traffic Engineering Project: e-Navigation Integrity

Final Report

DLR

Authors:

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Preamble

Germany's economy concludes a substantial proportion of its trade via maritime routes and as a result is considerably dependent on maritime shipping. Off of our coasts, high-speed ferries cross the routes of slow-moving oil and gas tankers daily. Traffic in narrow passages such as the Kadet Channel or on the Elbe river is continually increasing at the same time. These situations involve risks, including growing risks. In terms of passengers, the number of Germans who are spending their vacations aboard cruise ships continues to grow. All these factors combine to make safe, economical and environmentally-friendly maritime shipping of great significance for Germany.

Yet this aim is far from being reached. In just 2012 alone, there were 48 ship collisions on the Baltic Sea. Ships ran aground with about the same frequency. People are barely aware of these events. The public at large is far more likely to know about the sinkings or accidents of the Rena, Costa Concordia, Sea Diamond, Lamma IV, Jolly Nero and MV St. Thomas Aquinas. All of these adverse events can be traced back to errors in navigation, which are to blame for about all half of all shipping accidents. This led the International Maritime Organisation (IMO) to start the "e-Navigation" initiative.

DLR's expertise in aviation – especially in "Communication, Navigation and Surveillance" – predestined it to play a key role in the e-Navigation initiative. There are many parallels between aviation and shipping, yet there are also differences so large that direct transferability of strategies and technologies is not possible. In the case of navigational uncertainties, an aircraft on approach can execute a touch-and-go or go-around manoeuvre and fly on at a safe altitude. The equivalent is not possible with a ship.

The aim of this project was to investigate two basic prerequisites for achieving low-collision navigation. These are the accurate and resilient determination of position and movement of one's own vessel, on the one hand, and reliable assessment of the remaining traffic. Analysis of the systems in use today produced sobering results. A new approach was developed to address this that combined the use of selected sensors with complementary properties and controllable error models. The results of these investigations are described in this report. Committees of the ILO and International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) have already incorporated them into the development of new concepts that are already showing their first effects. Yet the road to a comprehensive solution is going to be a long one. Nevertheless the implementation of interim results will contribute to -- as we say in German -- ensuring that there's "always a handful of water under the keel" and ships keep a safe distance from one another. The ultimate goal admittedly remains to eliminating ship collisions due to navigation errors. If this is to become a reality, the approaches must be those that can be implemented at low cost. The new systems are held much promise in this respect.

Prof. Dr. Christoph Günther
Director of DLR's Institute of Communications and Navigation

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Abbreviations

AIS	-	Automatic Identification System
ARPA	-	Automatic Radar Plotting Aid
AtoN	-	Aids to Navigation
BSH	-	German Maritime and Hydrographic Agency
COG	-	Course over Ground
DB	-	Data Bank
DGNSS	-	Differential GNSS
DNV	-	Det Norske Veritas
ECDIS	-	Electronic Chart Display and Information System
EGNOS	-	European Geostationary Overlay System
ENC	-	Electronic Nautical Chart
EVnet	-	Experimentation and Verification Network
Galileo:	-	European GNSS (under development)
GBAS	-	Ground Based Augmentation System
GL	-	Germanischer Lloyd
GLONASS	-	Глоба́льная навигацио́нная спу́тниковая систе́ма (Globalnaya navigatsionnaya cputnikovaya cistema)
GNSS	-	Global Navigation Satellite System
GPS	-	Global Positioning System
IALA	-	International Association of Marine Aids to Navigation and Lighthouse Authorities
IMO	-	International Maritime Organization
IMU	-	Inertial Measurement Unit
INS	-	Integrated Navigation System
LRIT	-	Long Rang Identification and Tracking
MGBAS	-	Maritime GBAS
MVT	-	Maritime Traffic Engineering (Maritime Verkehrtechnik in German)
NMEA	-	National Marine Electronics Association
CDGNSS	-	Code-based DGNSS
PDGNSS	-	Phase-based DGNSS
PNT	-	Position, Navigation, and Timing
PVT	-	Position, Velocity, and Timing
RADAR	-	Radio Detection and Ranging
RAIM	-	Receiver Autonomous Integrity Monitoring
ROT	-	Rate of Turn
ROTI	-	ROT Indicator
RTCM	-	Radio Technical Commission for Maritime Services
RTK	-	Real Time Kinematic
SBAS	-	Space Based Augmentation System
SDME	-	Speed and Distance Measurement Equipment
SOG	-	Speed over Ground
SOLAS	-	International Convention for the Safety of Life at Sea
STW	-	Speed through Water
TCP	-	Transmission Control Protocol
UDP	-	User Datagram Protocol
UKC	-	Under Keel Clearance
UNCTAD	-	United Nations Conference on Trade and Development
UTC	-	Universal Time, Coordinated
WAAS	-	Wide Area Augmentation System

1. Introduction

Globalisation is a driving force that has further developed and expanded global economic performance capabilities in recent decades. Since 1990, this has led to an increase in global gross domestic product (GDP) of greater than 150 percent. Globalisation also implies the necessity of securing supplies of raw materials, affordable food, and items of trade world-wide. Consequently, global transport volumes have tripled within a comparable time period. Meanwhile, maritime transport has taken on a key role in trade around the world. These days 80 percent of commodity volumes and 70 percent of commodity values are transported by sea [UNCTAD-2012].

Fig. 1: Shipping Traffic in Rostock Research Port

The increasing distances between sites of activities to meet human needs such as housing, work, recreation, education, and services leads to a trend towards rising demand for mobility. Particularly on islands in remote regions and in coastal countries, this trend is also creating an increase in maritime passenger traffic. From 2006 to 2011 alone, growth in passenger numbers ranging from 30 percent to 260 percent was observed in countries such as Lithuania, Latvia and Estonia [Eurostat-2013]. The cruise sector is booming worldwide. In just the last decade, the number of cruise ship passengers doubled and in 2013 reached 21 million [DNV-2011]. Given that, it is correct to maintain that the maritime transport system is essential for the transportation of people and goods.

The maritime transport system is the sum of all the structural components required for seaborne transport of people and commodities. Among these components are ports and maritime shipping routes with their control systems, vessels of all shapes and sizes, and organizations that plan, manage, and implement transportation and traffic processes. Economy and safety are requirements set in this context to ensure the competitiveness of the maritime transportation system.

Consequently, the line of inquiry and tasks of the Maritime Traffic Engineering Project (*Maritime Verkehrstechnik*, MVT) is directed at exploring ways that the maritime traffic system must be harmonised, technologically augmented and optimised to improve further the economy, safety and ease of traffic at sea. As a result, the project came under the auspices of the "e-Navigation" strategy that was initiated in 2006 by the International Maritime Organisation (IMO) as an internationally coordinated work programme [MSC-2008]. The MVT project placed special emphasis on the use of modern and innovative communications, navigation, and information technologies. The provision of information required to perform nautical tasks aboard ship – from assessment of a situation, to its evaluation, and on to reaching a decision – can only be realised at all through the integrated use of these technologies. Included in this information are position, the movement of a mariner's own ship, and that of other ships, up-to-date nautical charts, information on wind and current conditions, and much more. A complete and comprehensive description of the actual situation that is minimally accurate and minimally reliable is often what decides whether the danger of collision or grounding is recognised and accidents prevented. Within this context, the need for further development can be extrapolated from the fact that 50 percent of all maritime accidents continue to have navigational causes originating in insufficient assessment of position, flawed evaluation of situation, or incorrect decisions [DNV-2011]. As a result, the MVT project focused on the development of methods for implementing more reliable and interference-free processes of situation assessment and evaluation.

2. Challenges and Research Areas

2.1 Safety and its facets

Safety in the context of maritime traffic management reflects the desire for risk-free realisation of all maritime transportation processes or risk-free conditions in the entire transportation system. On its website, the IMO presents the best way to improve safety at sea as being via the development of internationally valid regulations and their implementation. Successful avoidance of collisions and groundings in this context is said to be the same as the achievement of safety at sea.

The sinking of the Titanic on 14 April 1912 after it collided with an iceberg was the driving force behind the development of the first version of what is perhaps the best-known set maritime rules – SOLAS – The International Convention for the Safety of Life at Sea. The SOLAS Convention has continued to develop during the last century. Many lessons have been drawn from daily professional maritime experience and accidents. These have then been implemented in the form of regulative, administrative, and technical regulations. The current version of the SOLAS Convention is made up of 12 chapters. Among the topics they address are ship construction, fire safety, lifesaving equipment, radio-based communication, and safety measures for special vessels (e.g. gas and oil tankers, nuclear powered ships, high-speed ships). Criminal and terrorist activities have also resulted in increased risk and required agreement be reached on inclusion in SOLAS of special measures for improving the security of the maritime transportation system.

Fig. 2: Sinking of the M/S "Explorer" in 2007

The content of the MVT project is devoted exclusively to the safety of the maritime transportation system. Special attention was paid to sensors, data and methods of position assessment, and situation evaluation that are used to navigate ships. That is why the project is dedicated primarily to the following three topical groups: Maritime use of global radio navigation systems, the maritime position, navigation and timing system (PNT), and the position assessment in the traffic area using the Automatic Identification System (AIS) and on-board radar systems. On the basis of this and in conjunction with additional information (e.g. nautical charts) avoiding collisions and groundings is possible.

2.2 Strategic measures and the definition of specifications

At its 81st session, the Maritime Safety Committee (MSC-2006) of the IMO approved a work programme – known as the "e-Navigation" strategy – to develop further improvements for the maritime transportation system. In this context, "e-Navigation" is defined as the application of electronic devices in the coordinated gathering, integrating, exchanging, depicting, and analysing of maritime information – both on ship and land side. The aim of the work programme is to develop further the required quay-to-edge of quay ship navigation services in order to guarantee safety at sea and continue to protect maritime habitats [Nav54-2006].

It was agreed that "e-Navigation" must not be interpreted to be a research programme. As a result, the development of the "e-Navigation" strategy was started with a user survey. In the next step, the current traffic system was comprehensively analysed to detect deficits within the system with respect to identified user needs. A number of gaps were identified within this framework. Ambitious development aims were then formulated that could be viewed as sufficient motivation for research and development activities in this area. A disadvantage from a technical standpoint is that most requirements are expressed in the form of verbal statements rather than a measurable form. This is also true of requirements focused on improving safety (see Fig. 3). Requirements such as the implementation of data and system integrity, use of automated functions for reporting, and smart analysis functions to support ship-side decision-making belong to the eight most important user requirements for "e-Navigation."

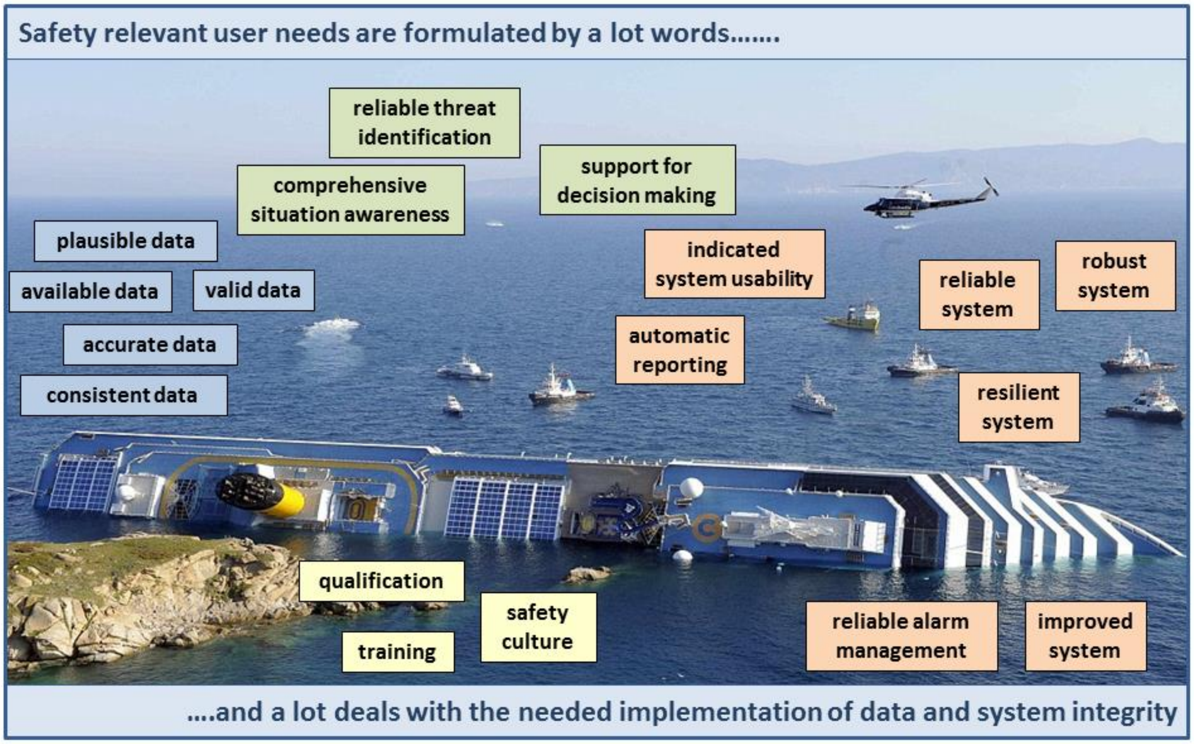

Fig. 3: Verbal Formulation of Existing User Requirements (Selection)

Reliability, integrity and freedom from interference of system operation are terms that describe the primary requirements of critical safety systems. These are defined as followed:

- **Reliability** is the capability of a system to execute required tasks within certain constraints for a prescribed time period. Consequently, reliability is measured as the probability that an available system is able to carry out without error its functions under certain conditions for a specified time. Providing data to meet specifications is a suitable measure for attained system reliability in an information technology system.

  In order to evaluate the degree of reliability achieved it is essential to have clarity about which functions, data, performance characteristics and constraints must ultimately be considered in the evaluation. On the one hand, that decides which sources of error must be recognised and compensated for. On the other hand, it sets down whether system reliability should be related to integrity monitoring functions or not.

- **Integrity** is the capability of a system to inform the user about the usability of the system (system integrity) or supplied data (data integrity) at a given moment in time. As a result, the system must be equipped with additional functions that allow for the monitoring of the integrity of systems or data and ultimately estimate if the set performance characteristics for functions or data can be met or not.

  Coherent statements about integrity can only be achieved if threshold values and decision criteria for the methods used for integrity monitoring are clearly specified. It is particularly important for systems critical to safety that the estimate of integrity achieved is as close to reality as possible. As a rule, this requires the use of superior integrity monitoring methods. Their use is only possible if a certain level of internal system redundancy can be ensured.

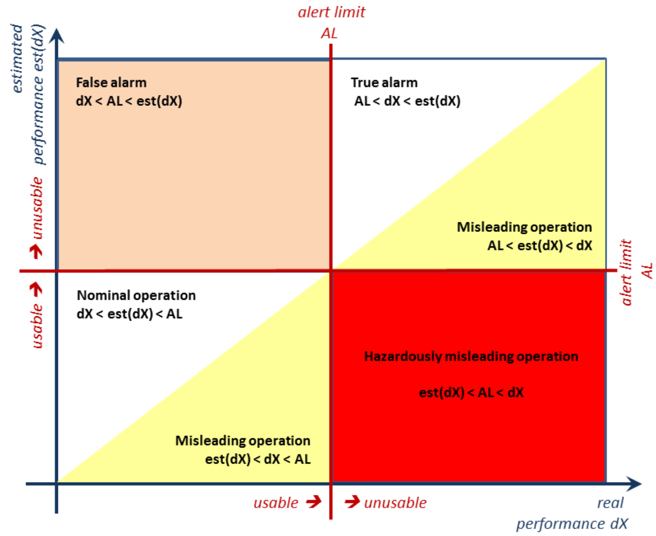

Fig. 4: Stanford-Diagram for the determination of the operation status based on the comparison between the estimated and real measurement errors

Independent of the integrity monitoring procedure, it must be expected that the remaining uncertainties in the process of estimation could lead to a real-time estimated performance that deviates from its real value (see Fig. 4). Use-specific alarm limits are applied to differentiate between usability and unusability of a system or data which is indicated by an alarm level. The alarm level can be a single threshold value (e.g. an accuracy requirement) or an end result yielded by the logical evaluation of many individual tests. Specific use is what ultimately determines how the alarm level is set. In an ideal case, integrity monitoring should successfully identify a usable system as usable or an unusable system as unusable. Problems occur when estimated and real performance values lead to differing assessments with respect to actual usability. There is a false alarm if usable systems or data are classified as unusable. This false alarm negatively affects the availability of the system or data. More critical is when an unusable system is classified as usable, making recognising and avoiding risks no longer certain.

- **Robustness:** A system is said to be robust if it has the capability to detect and compensate for external and internal interference, malfunctions, and outages in parts of the system. This should take place without limiting functionality or loss of data and preferably without worsening performance.

  Internal system integrity monitoring functions are required to detect interference, malfunctions, and outages in parts of the system. The results of the analysis are used by system control to switch between alternative, applicable processes, or redundant intermediate and end results. Which errors are ultimately recognised and for which must be compensated depends on the required system performance. The need for system-internal redundancy further increases in comparison with self-monitoring systems because in addition to error recognition, error compensation must also be carried out.

The previous definitions clarify the necessity of user requirements to be transferred into technical and measurable performance parameters. Only then will it be possible to identify suitable technologies with which the required system functions can be realised while the necessary performance classes into consideration. Building upon that paves the way for the detailed design of system architecture and internal and external interfaces.

2.3 Derivative Research and Development Areas

As has already been presented, reliable supply of navigation relevant data are a significant key element for further enhancement of safety at sea. Two complementary studies were carried out at the start of the project. The purpose of these studies was to clarify how the current maritime transportation system evaluates and manages the reliability of data and components.

The first study followed a "bottom-up" approach. It analysed which of the sensors, partial systems, and services used were already capable of assessing the data they produced with respect to accuracy and integrity. A number of documents associated with the IMO and IALA were analysed and interpreted to pursue investigation of the existence of error models and the application of integrity monitoring methods. The results led to the conclusion that to this day determining data and system integrity for most of the components of the maritime transport system is a problem that remains to be solved. The second study applied a "top-down" approach. It focused on the question of which methods are used by the maritime community to analyse and improve safety status within the maritime transportation system. In other words, it was questioning the existence of a superordinate integrity concept for the maritime transportation system. Specification of an acceptable remnant risk of the occurrence of accidents under normal operating conditions is a suitable starting point for a superordinate integrity concept. A mathematically parameterized model is required in order to find out if a system is in a safe condition or not. All of maritime traffic can only be declared safe if all the users of the system are safe. The safety of an individual ship depends, among other things, on the traffic situation, surrounding conditions, the vessel, and its current navigation status. A tolerated remnant risk cannot be distributed and optimised among individual components without comprehensive system modelling.

Although both approaches can be used either individually or in combination to develop the maritime transportation system further, the maritime community of users itself prefers the "bottom-up" approach in order to allow rapid improvement of key elements of the maritime transport system. Given that and with regard to the available resources for the project, a decision was made that the MVT project would also follow the "bottom-up" approach.

The study results helped to consolidate and prioritise initial project ideas. The gaps identified between current practices and existing user requirements provided the origin for the following, imperative step -- developing methods to bridge these gaps. These were prepared and submitted at various IALA and IMO meetings in the form of informational or concept papers [Nav58/6/1-2012; NCSR1/9/2-2014]. From an R&D standpoint, the MVT project is focused on augmentation of the maritime transport system through the gradual introduction of data and system integrity in dedicated navigational functions. The choice of the project's name – "Maritime Traffic Technology: The Integrity of E-Navigation" – already illustrates the three main research and development activities:

(1) The integrity of Global Navigation Satellite Systems (GNSS) and their supplementary services

The interference prone nature of GNSS is a justifiable reason to require integrity monitoring in the case of signals, components, and services whose applications are vital to safety. As a consequence, research and development emphasis was placed on experimental validation of methods that would serve to monitor the integrity of GNSS in system and service domains with respect to maritime performance requirements. In addition to that, suitable approaches to achieve coordinated use of integrity information and, further, to guarantee robust operation of GNSS components by using integrity based control functions were sought.

(2) Multi-sensor based unit for on-board determination of position, navigation and timing (PNT-Unit)

Integrated use of all measurements relevant for PNT that are carried out by a number of independently working sensors on board ship create the required redundancy in the data base to ensure high-performance integrity monitoring of the ship-side PNT system and generated PNT data. Research and development activity focuses ranged from development and experimental testing of data fusion processes to their alternative and complementary use within the framework of a PNT unit. Based on a multi-sensor approach and initial integrity functionalities, the aim was to demonstrate the most reliable estimation of error possible in various parameters relevant to navigation.

(3) Monitoring and assessment of the traffic situation

A comprehensive assessment of the traffic situation has been achieved when the position and movement of all users of the shipping system are known with the required accuracy and reliability. The degree to which individual technologies (e.g. RADAR or AIS) currently have the capacity to completely describe the traffic situation was the focus of complementary studies. The development of various testing methods was required to pursue this. Among them, for example, were tests of the plausibility of AIS messages or associating AIS and RADAR objects for validation of their positioning accuracy. The combined use of AIS and RADAR data was viewed as a promising approach for achieving a comprehensive and reliable supply of traffic situation images. Consequentially, planned MVT project research activities directed towards developing suitable data fusion methods and experimental verification were orientated on the research port in Rostock.

3. PNT- SYSTEM CONCEPT

3.1 Status and challenges

Reliable and resilient provision of PNT data is a goal that has been recognized by the IMO and serves as motivation for further development of the maritime transport system. In order to avoid collisions and groundings, mariners require reliable knowledge of position and movement of their own ships relative to other vessels at sea and the space available for maritime traffic. This explains the critical significance of the provision of reliable PNT data to safety.

AIS, ECDIS (Electronic Chart Display and Information System) or INS (Integrated Navigation System) are systems that use PNT data for situation monitoring, indication and assessment. The efficacy of these navigation relevant tasks is dependent on whether the data base being used meets the necessary performance requirements (e.g. completeness, currency, accuracy). Regrettably, until the present day, reliability and integrity requirements resulting from the variety of nautical tasks and traffic areas are unspecified for most PNT data. Consolidated specification of required PNT data and its quality are nevertheless a prerequisite for clearly identifying and overcoming technical deficits in the current PNT system.

The completed "top-down" and "bottom-up" studies served to clarify how the reliability of today's PNT system is evaluated, indicated and managed relative to the system and experience. It appears that currently integrity monitoring is only intended for the following PNT components:

- A recommendation exists that GNSS receivers should apply the RAIM (Receiver Autonomous Integrity Monitoring) process in order to improve accuracy and reliability of position determination.
- Integrated navigation systems, these must – with the aid of plausibility and consistency tests -- evaluate the reliability of the sensors and data sources being used. This is to be achieved by equipping systems with redundant sensors.
- The IALA Beacon DGNSS was developed in the 1990s as a maritime GPS augmentation service in order to meet the requirements for accuracy and integrity in determining position in coastal areas. The service provides range corrections and flags that indicate the current usability of individual GNSS signals and provided augmentation data.

Further development of the maritime PNT system is nevertheless required in order to meet user requirements such as "improving reliability", "indicating reliability", and "improved alert management" for all PNT data. The gap between technologies that have been standardised for maritime use and commercially available technologies has become so immense that coordinated exploitation of the current state of technology could clearly increase safety in the maritime traffic system. That becomes apparent when observing the used/usable PNT components in Fig. 5.

In general, ship-side PNT data provision is based on the combined use of GNSS, PNT relevant terrestrial services, and on board sensors. The core elements of the ship-side PNT system are its GNSS receivers, which compute position, velocity, and time information (PVT) from GNSS distance measurements. In coastal areas, where services such as IALA Beacon DGNSS and AIS DGNSS additionally provide code-based correction and integrity data, greater PVT accuracy can be reached and initial integrity information be applied relative to used GNSS signals and provided services. Although Satellite Based Augmentation Systems (SBAS) can already be operationally used in Europe and America, their recognition as maritime PNT services remains unresolved until today. It is, however, inarguable that SBAS enlarge the coverage area for code based DGNSS and can improve the availability of integrity information.

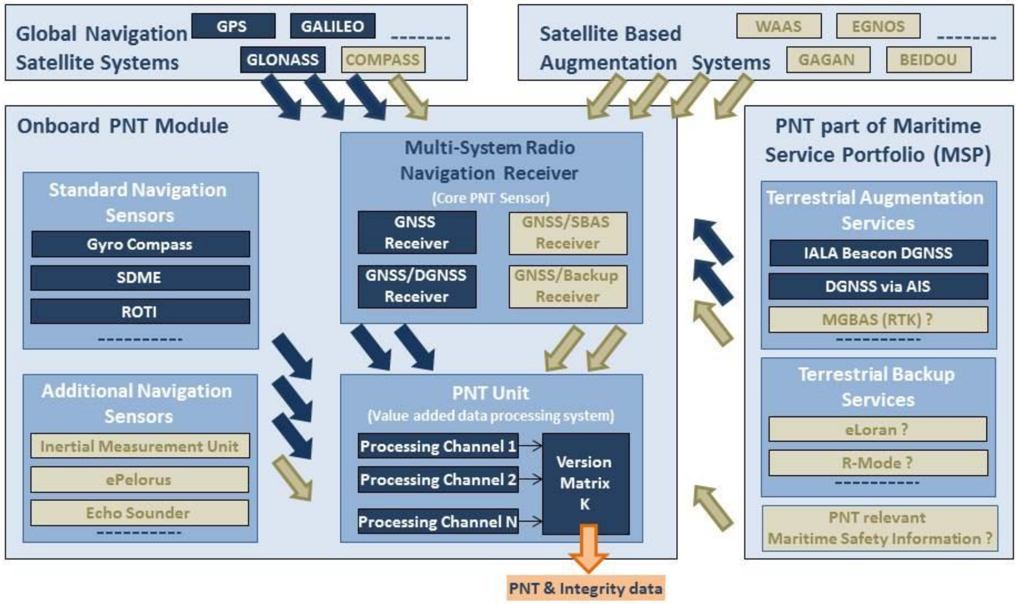

Fig. 5: Overview of PNT Components (dark blue: standardised/used, beige: usable)

Following the concept of "e-Navigation", PNT data should be provided in such a way that the performance requirements for all operational areas (e.g. high seas, coasts, ports, inland waterways) and nautical tasks (e.g. automatic docking, monitoring of manoeuvres) are achieved when and where they are required. As a result, the architecture of the maritime PNT system must also contain augmentation services in order to fulfil the requirements of port navigation and automatic docking. Currently the vulnerability of GNSS is seen as a sufficient reason to encourage setting up additional, terrestrial radio navigation services (e.g. eLORAN or R-Mode) in order to improve the resilience of PVT data provision. A further object of this investigation is whether the provision of PNT relevant safety information could increase the reliability of ship-side provided PNT data.

The resilient provision of PNT data is a more significant objective because in this context PNT data covers PVT data and ship’s parameters describing the current movement and attitude of the ship (e.g. heading, rate of turn, roll angle). The required safe clearance between the envelope of the vessel's hull and obstacles must be determined, evaluated, and monitored for safe navigation through locks, under bridges, narrows, and congested seaways. To achieve this, the attitude that describes the three-dimensional movement of the ship must be accurately determined. This creates the necessity of monitoring the accuracy and integrity of navigation data and the operation of on-board sensors such as, e.g. Speed and Distance Measurement Equipment (SDME), Rate of Turn Indicators (ROTI), or gyros.

3.2 Framework of definitions for the maritime PNT system

The IKN has developed a provisional definition of the maritime PNT system that was consolidated within the PNT Working Group of the IALA E-Navigation Committee in June 2011 (Table 1). This definition reflects the user requirement that all navigation relevant data and systems should be monitored with respect to their integrity. Nevertheless this definition fails to answer which performance requirements must be met and which services and components are necessary to reach that end. In order to achieve gradual realisation, consolidation, and implementation of the required components in existing structures, the scalability of data products, specifications, sensors, and services has to be depicted on the supported PNT processing channels.

Table 1: Definition of the Integrated PNT System

The "Integrated PNT System" specifies the required overlay of satellite based, shore-side and ship-side components, whose integrated use ensures accurate and reliable provision of ships' position, navigation, and time (PNT) data and assigned integrity data (PNT system and data integrity) to applications during all phases of vessel navigation in a timely, complete, and unambiguous manner. The "Integrated PNT System" monitors current HW and SW configuration in use as well as the complete PNT output data to generate PNT relevant alerts and provide PNT status messages (reporting) in a timely, complete, and unambiguous manner.

An integrated PNT system should at least be capable of supplying primary PNT data (see Table 2). The draught of a ship (under keel clearance) is also relevant for safe ship navigation. Data of this type, however, is derived through nautical application functions, in which PNT data and other data, such as tidal range and electronic nautical charts are processed in combination.

Table 2: Primary PNT Data

Position data are latitude, longitude, and altitude of a ship's Consistent Common Reference Point given in a global coordinate system such as WGS84. Primary navigation data serves the horizontal description of a ship's attitude and movement and covers SOG, STW, ROT, heading and COG. Secondary navigation data includes the three-dimensional description of a ship's attitude and movement. Therefore yaw, pitch, and roll angles as well as their rates should complete the navigation data set. Time data describes the current time and date in a common time system, e.g. UTC.

Integrity monitoring is aimed at evaluating whether the systems and data actually fulfil the set performance requirements. Binding performance standards must be specified by means of the criteria that ultimately decide if data and system integrity has been achieved or not. PNT relevant integrity data (Table 3) ultimately serves to convey the result of the integrity evaluation. The result can be a flag that indicates if the actual standards could be met. Alternatively, parameters can be supplied that would describe the actual characteristics on the basis of which the user or the applications could determine usability themselves.

Table 3: PNT Relevant Augmentation Data

Integrity of each item of PNT data describing either the estimated accuracy of provided PNT data or indicating the fulfilment of momentary accuracy requirements, if they are available; Integrity of the current Integrated PNT System in use describing either the usability of the PNT data products in a scalable manner or the fulfilment of all current requirements, if they are available; Alerts announcing abnormal situations and conditions of the current Integrated PNT System in use requiring attention, decisions, or caution within the framework of ship navigation; Status messages describing the current HW and SW configuration in use (or their change) for automatic reporting and certification purposes.

A by-product of system monitoring is what is known as status information. This includes, for example, the hard and software configurations currently being used (or their change) for automatic creation of reports or certification processes. Alerts, however, are only used to indicate abnormal situations and conditions within the system currently being used that require particular attention, decisions, or caution within the framework of ship navigation. Integrity data also generates alerts if unusable data is detected or systems have consequences critical to safety.

3.3 Generic architecture of the PNT System

Following the definition (Table 1), the maritime PNT system is composed of terrestrial PNT services and an on-board PNT module, with both of them using globally available radio navigation systems (WWRNS) and GNSS as a space-based infrastructure. The generic architecture of the PNT system is depicted in Fig. 6.

Shore-side PNT services can carry out the following services:

- Provision of GNSS augmentation data, covering from correction and reference to integrity data with which the reliability and/or accuracy of GNSS-based PVT determination can be improved on the user's side;
- Transmission of terrestrial radio navigation signals as a backup to GNSS in order to make PVT determination possible in cases of an disturbed GNSS; and
- Providing PNT relevant, maritime safety information (MSI), with which the required service layer can be listed, tide data provided, or the currently usable maritime PNT system can be characterised and controlled.

In order to meet user integrity monitoring requirements, each service must be equipped with functions that make self-monitoring of the service possible. In systems that work with distributed components, internal and external system interfaces must be provided via which the coordinated exchange of integrity data can take place.

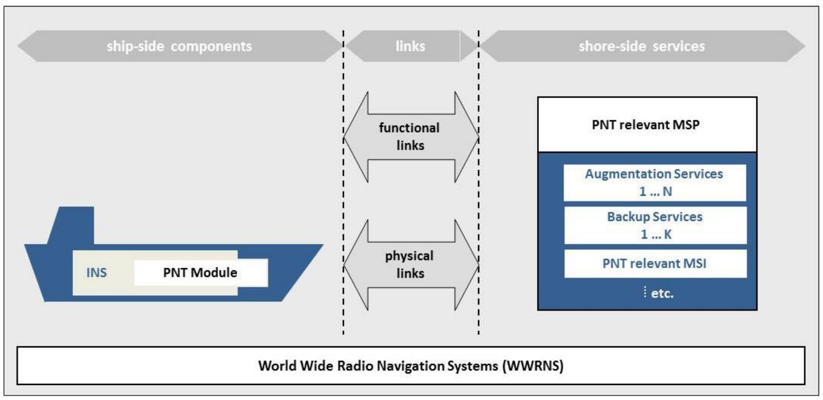

Fig. 6: Generic Architecture of the Maritime PNT System

GNSS augmentation systems have been used until the present day in the maritime sector in order to fulfil accuracy and integrity requirements for coastal areas with first generation GNSS (GPS L1 and/or GLONASS L1) [IALA-R121-2004]. In future, it will become possible to apply multi-system and multi-frequency based methods through modernisation and expansion of the satellite navigation systems. These methods will exploit the increased redundancy in the data base for self-monitoring of integrity and improved PVT determination. Consequentially, the future role of GNSS augmentation services is also scrutinised (see Chapter 5).

The PNT module is the front end of the maritime PNT system for applications such as AIS, ECDIS or INS. It represents the ship-side overlay on sensors and devices that are required for the provision of PNT data. Increased accuracy and integrity requirements for PNT data imply stricter carriage requirements on the one hand. On the other hand, improved evaluation of PNT data quality can only be achieved if data fusion based methods are applied in future. Following this idea, the MVT Project developed an integrated processing tool that is called the "PNT Unit". The concept developed for this is described in the next section. The implementation and validation of PNT Unit V1, one of the first prototypes, is described in Chapter 6.

3.4 Concept of the PNT Unit

The ship-side part of the PNT system has two complementary layers:

(1) The sensor layer includes the set of sensors that are authorised or are to be authorised in standards of providing maritime PNT data.

(2) The processing layer includes the methods used for determining PNT data and the integrity of PNT data.

The concept of a PNT Unit developed supports a scalable approach in order to gradually implement the transition from the currently used PNT system to a resilient PNT system.

The classic realisation of the ship-side PNT module is depicted in Fig. 7. Individual sensors are responsible for the provision of specific PNT data e.g. the WWRNS sensors provide PVT data and other ship-side sensors are used for navigation data. The PNT relevant data processing layer is a component of the individual sensors and represents internal sensor methods that are used to determine PVT or N data. The application of GNSS augmentation services is organised by the WWRNS sensors themselves and based on integrated or connected communication devices. The classic PNT module is not in a position to achieve improvement and indication of the reliability of all PNT data due to insufficient redundancy within individual sensors and unsupported utilisation of multi-sensor based redundancy.

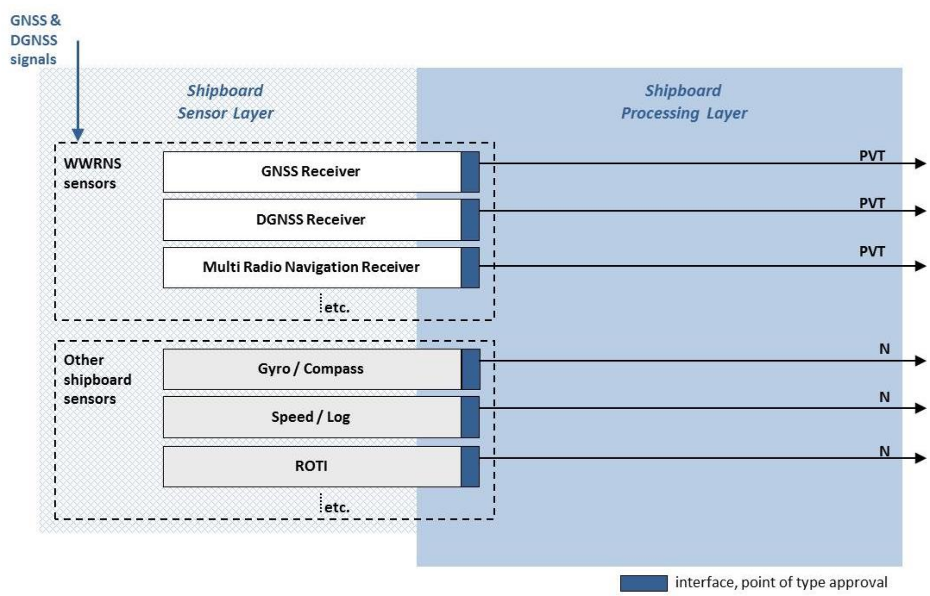

Fig. 7: Classic Realisation of Ship-side PNT Module (PVT=position, velocity, and time; N=navigation)

The INS based PNT module (Fig. 8) supports the use of an additional data processing function that combines PVT and N data from the WWRNS and other approved sensors in order to evaluate the integrity of the sensors used and the data provided. Various plausibility and consistency tests were carried out as a check matrix for PNT data. These tests are nevertheless still unsuited for estimating the actual accuracy of all PNT data.

The PNT Unit (Fig. 9) represents a further development of the INS based PNT module which rests on the integrated use of data products and raw data from a wide range of GNSS receivers and on-board sensors. As a result, high-performance data fusion methods that exploit redundancy at the raw data level could be applied in order to improve and monitor the quality of the PNT data provided.

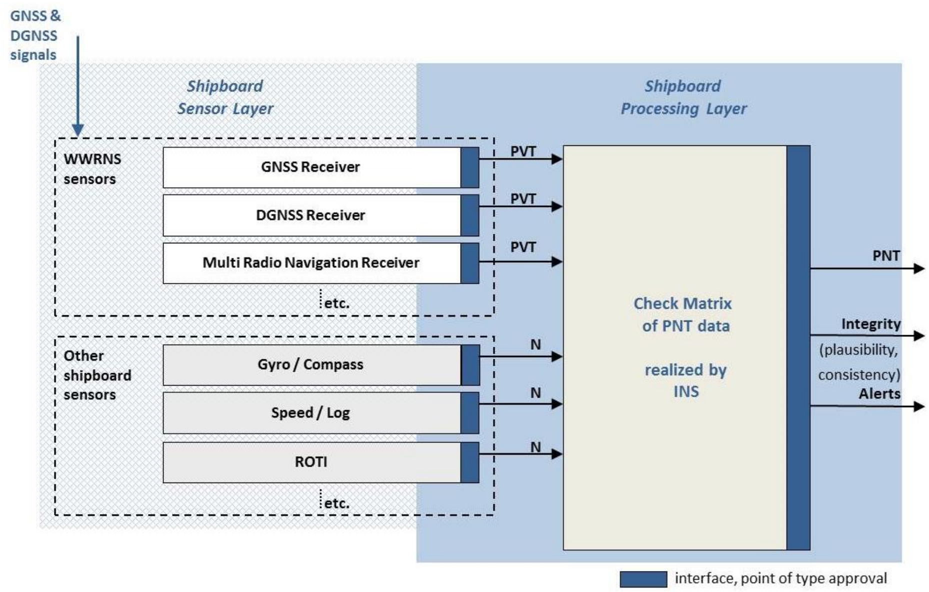

Fig. 8: INS Based Realisation of the PNT module

This approach supports the use of PNT relevant augmentation data supplied by various land-side services and the inclusion of additional data sources (e.g. ePelorus, Racon, multi-radio navigation receivers), and the future application of PNT relevant maritime safety information. The PNT Unit can be given the capability of providing the best PNT data as well as indicate their accuracy and integrity by implementing suitable integrity monitoring functions.

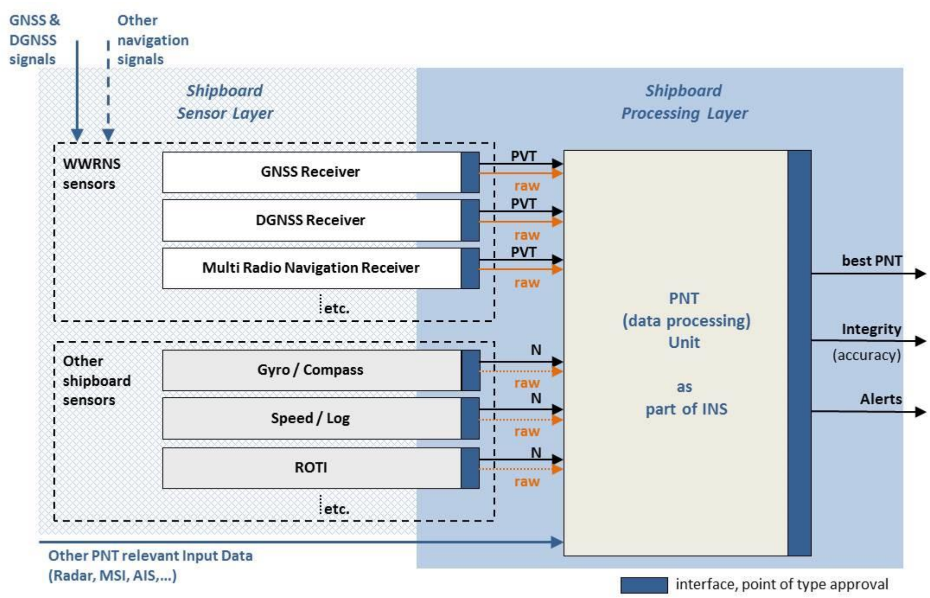

Fig. 9: PNT Unit for Accuracy Oriented Integrity Monitoring of the Ship-side PNT Module

The PNT Unit itself is made up of a set of parallel processing channels. A single channel performs a process used by the PNT unit for the determination of PNT data and possibly integrity data. Only if the data base required for the process (sensors, services, and other data sources) is available in quantity and quality can it be expected that the process work according to specifications. At least one suitable processing channel must be made available for each performance class desired. Each process is more or less susceptible to disturbances from certain sources of error. The use of data sources as independent from one another as possible and of suitable integrity monitoring processes is necessary in order to recognise significant sources of error and compensate for them in real time. Therefore, in order to achieve the intended resilience of PNT data provision, partial or complete parallelisation of process channels is required.

Without measurable performance requirements for PNT data provision, neither the achieved nor target level of reliability and resilience can be evaluated. Until today, this has complicated technical detailing of the maritime PNT system, including among other things architecture, interfaces, methods, and responsibilities. Nevertheless, the concept of the PNT Unit is suitable for gradually advancing towards multi-dimensional harmonisation of resilient PNT data provision. This is being done with respect to:

- the selection of processes to support and apply per required accuracy class for PNT data provision;
- the harmonisation of the evaluation methods per desired integrity level with consideration of PNT processing channels in use currently and in the future;
- the comprehensive and clear specification of data content and data format for provision of PNT and integrity data; and
- the harmonisation and reduction of PNT related alerts with consideration of actual performance requirements (service areas, priority navigational tasks).

4. DEVELOPMENT, TESTING AND DEMONSTRATION PLATFORM

4.1 Status and challenges

A core aspect of the project's three research and development lines is the consolidation of information from diverse sources in order to achieve a joint assessment (integrity) and improvement of system performance capabilities (reliability, resilience). Today, data fusion based processes are only used selectively on ships. A series of sensors and other sources of information are on board. Most of the time, the information they provide is made available to the officers of the watch directly, frequently in an unevaluated form.

The project set itself the task of providing the ship officers with navigation relevant data with assessed integrity originating from the combined use of all available data sources aboard (e.g. from existing ship-side sensors, available shore-side augmentation services). This chapter addresses the suitable acquisition and provision of data required to implement this task. Algorithm-driven data processing is described in the following three chapters.

The challenges for data acquisition and provision came in the development and provision of a platform that enabled the creation of complex processing chains which process in real time and with low latency a wide array of broadly variable types of data streams from sensors and services on shore and aboard the vessel. A modular design should support the exchange of data sources, hardware and software components, and enable deployment on varied types of vessels and at land stations. As the carrier of scientific algorithms, the software module would run unchanged in the development, testing, and demonstration environment. It was necessary to find a suitable transition from the development environment (post-processing) to the demonstration system (real time processing) in order to do this.

4.2 From demonstration system to platform concept

A joint demonstration system was developed during the definition phase of the project (Fig. 10). This guaranteed that the dependencies between the project's three research areas could be recognised early on and taken into consideration. Furthermore, this also allowed investigation and optimisation of methodological approaches for coordinated use of integrity information in the project.

The orange blocks in Fig. 10 depict the shore and ship-side MGBAS (Maritime Ground Based Augmentation System) components required in order to meet the required degree of GNSS accuracy and integrity for automatic docking. MGBAS expansion was pursued on the one hand, to also enable provision and testing of augmentation services for modernised and future GNSS. On the other hand, the implementation of additional monitoring functions also created the opportunity to use the experimental MGBAS system at Rostock Research Port for the experimental validation of modernised GNSS and standard technologies as well.

The green boxes are associated with research and development line two (a multi-sensor based PNT Unit). They also depict data sources and processes used on board ships to achieve resilient provision of PNT data. As shown, GNSS and DGNSS receivers and the ship-side MGBAS terminal are a few of the PNT sensors that are used on board. Processing steps from preprocessing of data to integrity assessment reflect the general tasks required for resilient provision of PNT data.

The traffic situation monitoring make use of the on board PNT Unit , which is a data source for describing the position and movement of the ship on which it is carried (own ship). Further data sources provide AIS and RADAR data, which describe the position and movement of other vessels. In an ideal case, the dynamic AIS data distributed by the ship should be identical in content to the PNT data distributed by the PNT Unit. This would allow PNT related integrity information to be used in future as an integrity indicator for AIS data content. Otherwise, AIS and RADAR are independent data sources whose integrated use could improve the completeness and reliability of images of the traffic situation through application of suitable methods of data fusion. Components and interactions are illustrated in Fig. 10 with turquoise boxes and arrows.

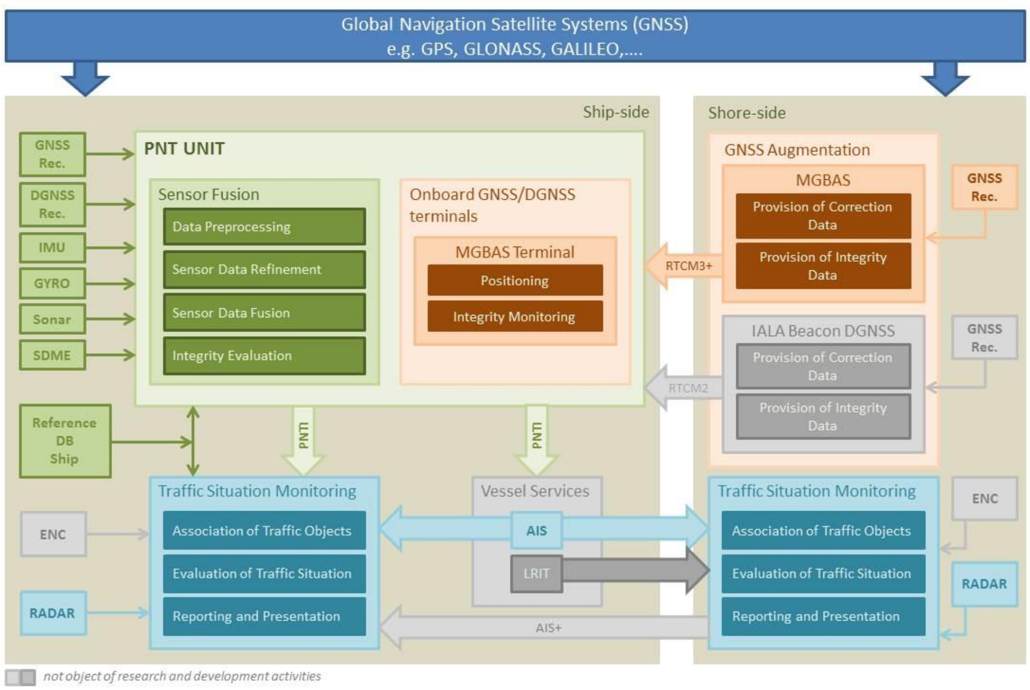

Fig. 10: Design of the Intended Demonstrator System Designed to Show the Feasibility and Usability of Integrity Monitoring

The design of the demonstrator system presented here together with the challenges summarised in Section 4.1 resulted in the overall concept for maritime data processing outlined in Fig. 11. This concept is made up of four functional layers.

1. Maritime information: the amount of information sources (sensors, communication channels) on board a ship or on shore.

2. Hardware platform: has the task of gathering all maritime information and providing these data in a combined data stream. The first synchronisation of data from the most varied of sensors and communications devices takes place based on the point in time of data provision (synchronisation level 1).
3. Middleware (software platform): handles further synchronisation tasks (second level) based on the inherent time stamps in the data streams. It also makes software modules available with which the development of real-time capable programmes is supported on the basis of complex algorithms.
4. Maritime application: is a programme that provides superior data products (e.g. PNT data evaluated for integrity) based on functionalities of the software platform that fuses maritime information.

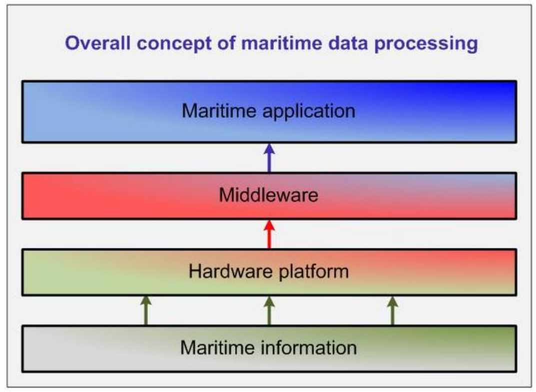

Fig. 11: Overall Concept of Maritime Data Processing

4.3 Hardware platform

<u>Ship-side hardware platform:</u> Cooperation with the "Baltic Taucher" company was set up under the auspices of the MVT Project. This made possible use of the company's vessel, "Baltic Taucher II" for experimentation and demonstration in addition to the Federal Maritime and Hydrographic Agency of Germany's vessel "Deneb". Development of the ship-side hardware platform is optimised for the "Baltic Taucher II". Nevertheless, it was openly constructed so it could also be used on other ships and traffic carriers. The "Baltic Taucher II" is 29 metres long. That makes it relatively small in comparison with many freighters, ferries, and cruise ships. Based on IMO requirements and requirements for ship use however, it has been fitted with the standard equipment found on board larger ships. Full access to this equipment was possible within the framework of the project.

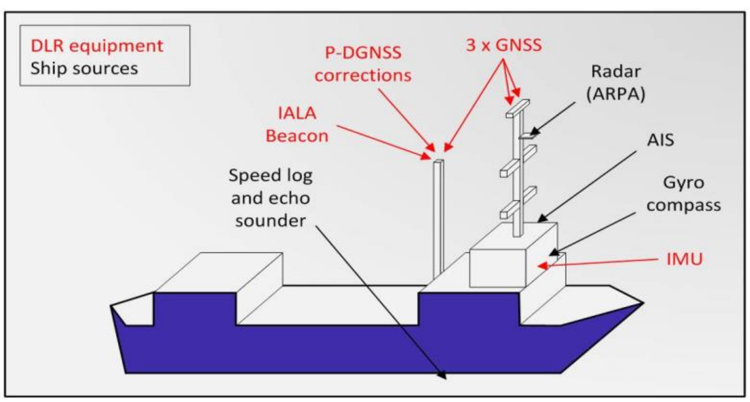

Fig. 12: Equipment Used on Board the "Baltic Taucher II"

Fig. 12 depicts the measuring arrangement on board "Baltic Taucher II" which consists of ship equipment and additional available commercial hardware.

Ship sensors subject to IMO requirements and additional DLR equipment differ particularly with respect to their data output format. The data sources on board the "Baltic Taucher II" provide their data in the form of NMEA data sets with update rates ranging between 0.1 to 10 Hz in accordance with the standard. These NMEA data sets frequently lack an inherent time stamp. As a result, the hardware platform must create the time reference of the measurement as well as for any other information. The data come from ship sensors with a rate of up to 38.4 kBit/s via the serial interface.

Sensors and communications' sources (marked in red in Fig.12) that go beyond the standard equipment of the "Baltic Taucher II" were derived from the requirements of the planned demonstration system (see Fig. 10). The additional equipment all has differing interfaces. The IALA Beacon receiver (CSI MBX-3), the receiver modem for PDGNSS (RTK) corrections, GNSS receiver (Javad SIGMA G3T and Javad DELTA G3T) as well as IMU (iMAR iVRU-FCAI) provide their data streams in RTCM2 or RTCM3 format, or apply manufacturer specific transmission protocols. Serial interfaces and Ethernet are used as output interfaces. The data transmission rate for a data stream is up to 450 kBit/s. As opposed to the NMEA data sets, all these data streams have their own inherent time stamp for the valid data. . Update rates are between 0.2 and 200 Hz.

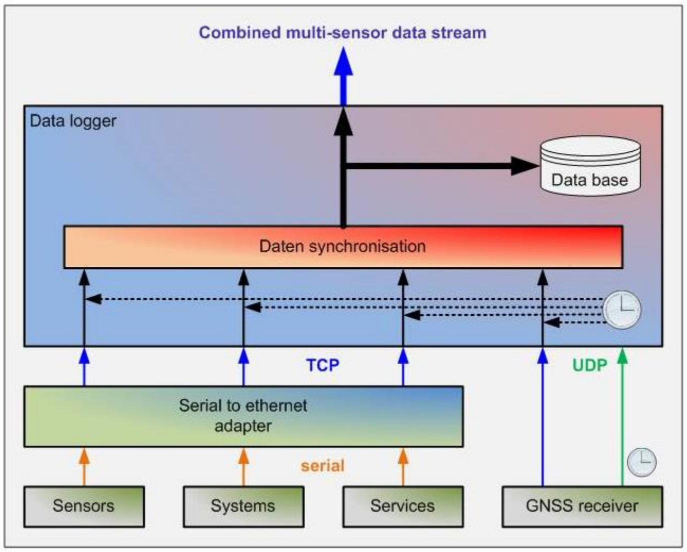

Fig. 13: Generation of a Time-stamped, Combined Data Stream on Board Ship

The following concept of a ship-side hardware platform was developed and implemented with consideration for the diversity of the data sources on board the ship (Fig. 13). It ensures the time-stamped, combined provision of all ship-side data. If the sensors don't provide their data in the Ethernet protocol TCP (Transmission Control Protocol), the data will be converted into TCP by an adapter. All the data will be recorded by a data logger which stamps every single data packet upon receipt with the actual time in UTC in order to subsequently generate a combined and synchronised data stream from all information sources. This data stream is then provided directly to the software applications via TCP on the one hand. On the other, the data stream will also be stored in a SQLite database for possible post-processing.

Services and systems are to be understood as a generalisation for further, data stream based information sources. These can generate their data, for one thing, aboard their own ship (e.g. RADAR) or on another ship (e.g. AIS), as well as on land (e.g. IALA Beacon DGNSS). Services and systems also cover any data stream based communication channel. A suitable TCP adapter was chosen for information sources that did not provide their data serially or via TCP. Great flexibility regarding the use of different maritime information sources could be achieved through rigorous implementation of TCP. A modular set up of the entire system was ensured as a result.

The data logger is software written in C++ that runs on a standard Linux system. The best stability possible of the computer clock is achieved through continual synchronisation with the three GNSS receiver clocks by Ethernet via User Datagram Protocol (UDP). This ensures that system time is generally accurate to less than 1 ms.

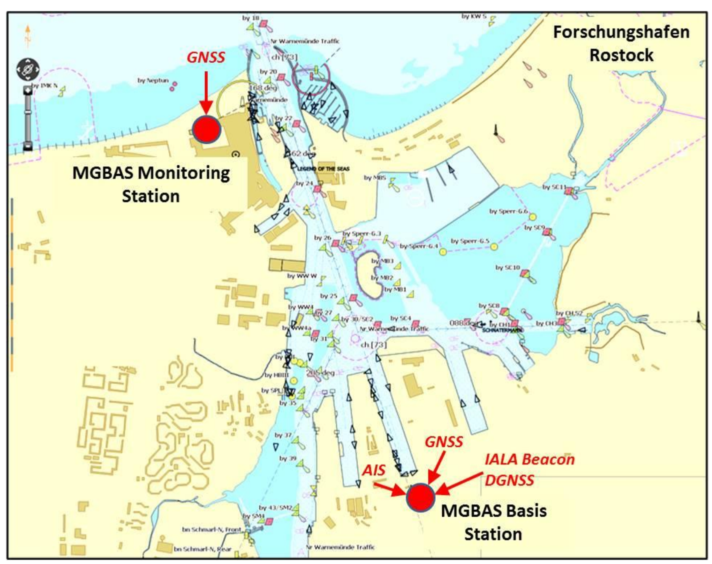

Fig. 14: Sensors and Receivers at both Shore Stations Installed within Rostock's Research Port

Shore-side hardware platform: DLR Neustrelitz has been using the research port at Rostock as a maritime testing area for several years already. During the ALEGRO and ASMS projects, two MGBAS stations were set up here in order to experimentally try out and validate processes for maritime PNT services. Further development of both sensor stations took place under the auspices of this project, in order to adapt it to additional requirements that result from shore-side traffic surveillance, monitoring of maritime GNSS services, and implementation of Galileo services into MGBAS. In Fig. 14 significant data sources that are to be managed by the shore-side hardware platform are shown in addition to the location of stations in the Rostock Research Port. Both stations are equipped with GNSS receiver technologies. The base station also has an IALA beacon receiver, AIS receiver and transmitter for PDGNSS corrections. The location of the base station in the heart of the port of Rostock ensures that service coverage is available for the entire area of the international port.

The MGBAS base and monitor stations are linked to the research network EVnet. This offers the advantage of providing real time access to station data via the Internet in addition to radio transmission. Furthermore, the supplementary maritime information emitted at the Rostock Research Port can be centrally generated in a different location.

On the shore-side, far more than compatibility drove the decision to pursue the same concept of data provision. The technology used on shore (sensors, services, systems) partially reflects the equipment on the ship-side, so that the requirements that apply here would for the most part be the same as ship-side requirements. The concept was adopted from ship-side, and adapted and implemented for the generation of combined, synchronised data streams at shore-side stations (Fig. 15). One difference is the low number of data sources and their inherent interfaces. The spatial distance between the two shore stations and the requirement of time protocolling of measurements demands each have separate provision of combined multi-sensor data streams. These can be merged into a combined multi-sensor shore-side data stream using the embedded time-stamp in the two data streams.

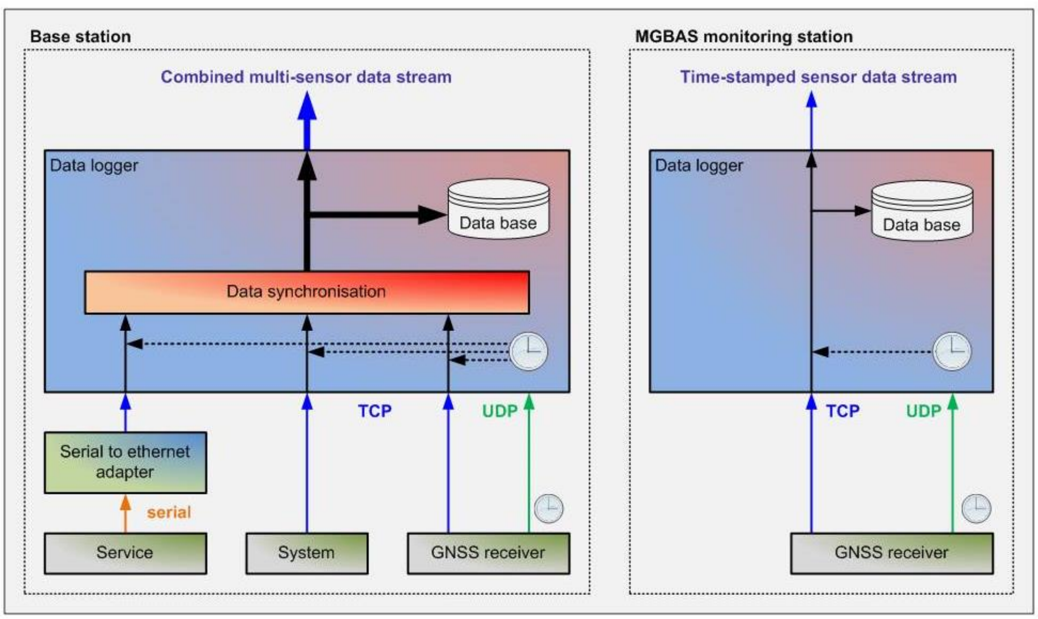

Fig. 15: Generation of a Time-stamped Data Stream at the Shore Stations

Specifically, five data streams – one from a GNSS receiver and four from systems or services – are processed at the main station. At the monitoring station, by contrast, only time stamping of a sensor data stream takes place at the moment. Through simple augmentation, the modular concept allows more sensors and data sources to be used at both stations.

4.4 Middleware - software platform

This layer within the complex software system serves, for one, to enable use and testing of programme codes developed and tested over a longer time period in various constellations with additional software components. Additionally, it offers the possibility of solution of a number of further project requirements via the platform in order to allow the programming activities built upon it to focus on the development and testing of special algorithms. Based on this approach, an existing C++ GNSS framework was further developed into a multi-sensor real-time framework (RT framework for short) during the project. This allowed the development lines – the PNT Unit, GNSS augmentation services, and traffic situation monitoring and assessment – to generate their specific applications within a single framework.

Fig. 16 shows the middleware approach based on the RT framework as followed in the project. According to this approach, a programme consists mainly of basic middleware elements (red): from decoding, data synchronisation (based on data inherent time stamp), data transport between individual software modules, coding and data transmission to a broad spectrum of further tools. Special software modules with which task specific data processing is carried out are highlighted in blue. The visualisation of the results and status information is marked in yellow. As a special service to all officers of the watch, a web-browser is used for visualisation of the information independent of the platform.

An additional special performance characteristic of the middleware software is supported access for processor wiring from three different sources of data. This enables either direct access to the combined, synchronised multi-sensor data stream of the data logger (Fig. 16, upper left) for live demonstration purposes, or simulating real time application at any time by again playing out the data base recorded with the data logger using the stored time stamps (Fig. 16, left second from the top). The third option allows for reading one or several data bases at maximum speed in post-processing specifically for the purposes of algorithm development and validation (Fig. 16 left, third from the top).

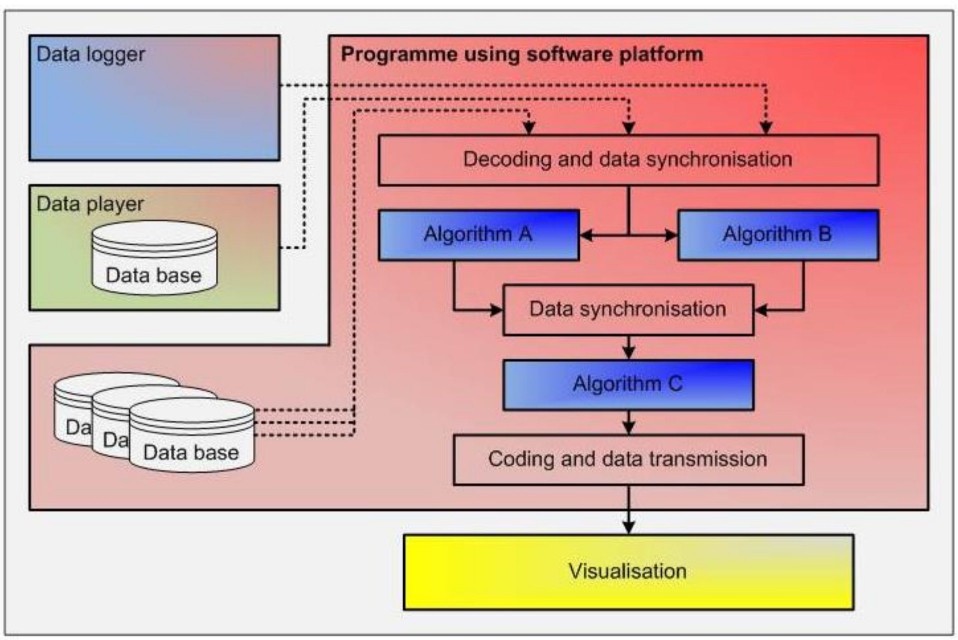

Fig. 16: Programme Development Using the Middleware

The design implemented achieved flexible code parallelisation for optimal use of hardware resources. This is necessary for realisation of the entire demonstration concept in order to enable parallel processing of various data streams on board ship and on shore in the context of service provision and monitoring.

The decoding and data synchronisation layer leads to complete decoupling of programme algorithms from data sources, allowing all data management problems to be solved in one place. Problems of this type result from among other things

- from the great diversity of data sources' differing update rates (0.5 to 200 Hz), their varied latencies (6 ms to 5 s), and the time variability of the latencies (0.4 s to 1.7 s);
- the gaps in data that occur during changes of service area or as a result of environmental conditions; as well as
- the characteristic of having one or no inherent data time stamp.

The modular design of the RT framework and keeping processors modular as implementation of special algorithms allows high re-usability of existing programme codes. In this way, little effort is required to set up new, complex processor chains that can be combined with further processor chains. This also makes carrying out performance assessments of varied algorithms rather convenient.

5. GNSS AUGMENTATION SERVICES AND INTEGRITY

5.1 Status and challenges

The maritime user community developed and set up the "IALA Beacon DGPS" service worldwide in the 1990s in order to meet valid performance requirements for GPS based position determination in coastal areas. The accuracy of distance measurements can be improved with the aid of the range corrections provided. These can also reduce the effects of artificial impairment (deactivated from May 2005) and signal dispersion. As a result, errors in determination of horizontal position could be reduced to less than 10m. Additional integrity data ensure on the one hand, that users are informed about the actual usability of GNSS and the correction values provided. On the other hand, the integrity data indicate if DGNSS based position determination can be realised at all with the required level of accuracy or not. The service's integrity assessment takes place with the help of integrity monitors which are either being operated near the reference station (LIM - Local Integrity Monitoring) or further away (FFIM - Far Field Integrity Monitoring). These function as virtual users. Ultimately, the achievable DGNSS positioning accuracy in the service area is estimated by using the position error determined on the integrity monitor. Yet it is not possible to get a hard and fast statement at the user's location in this way. The augmentation data are distributed with the aid of medium wave signals and as a result are available to all users who are in the reference station's service area – so operating within a radius of 200-300 kilometres. In principle, the modernisation of GNSS (new systems, signals, and frequencies) has led to the necessity of modernising GNSS augmentation services as well in order to provide integrity information and correction data for further GNSS signals. Whether and how that should take place is a question to be answered in future with the specification of the PNT relevant Maritime Service Portfolio (MSP).

The development of MGBAS (Maritime Ground Based Augmentation System) is a complementary GNSS service development aimed at achieving higher accuracy classes (Port: <1m, Docking manoeuvre: <1dm) with simultaneous integrity assessment [IMO A915(22)]. An experimental MGBAS system was set up within the scope of previous projects in order to prove it is possible to achieve absolute positioning accuracy in the dm vicinity with phase-based DGNSS processing (PDGNSS). In order to enable integrity monitoring of PDGNSS services, a supplementary initial integrity concept had to be conceived and monitoring methods developed to suit it.

Expansion of the shore-side MGBAS experimental system with complementary aims was pursued within the MTE project. On the one hand, the MGBAS system was to be expanded in terms of process technology so that it could also provide GALILEO and multiGNSS based PDGNSS services. On the other hand, MGBAS was to be gradually equipped with monitors to allow evaluation of the performance capabilities of modernised and future GNSS and maritime PNT services such as IALA Beacon DGNSS. Surveys and long-term validations were viewed to be necessary for both lines of development. The objective was to allow use of experimentally evaluated performance parameters to create the decision-making basis for both the technical details of the maritime PNT system design and the development of need-suitable specifications for the PNT relevant Maritime Service Portfolio.

5.2 Upgrading the MGBAS service portfolio: GALILEO and multiGNSS

During the previous projects it was proven that the experimental MGBAS at the research port can be used to achieve horizontal positioning accuracies within the dm vicinity with phase-based DGPS services. Therefore, MGBAS is a suitable augmentation system that can meet the maritime accuracy requirements for GNSS-based position determination in port and for automatic docking [IMO A.915(22)]. Experimental investigation of GPS based MGBAS services was continued within the MTE project with the aim of making further improvements in MGBAS service provision and integrity assessment. To do this it was necessary to analyse a statistically representative data base in order to extrapolate from it a substantiated description of achieved accuracy, integrity, and availability while taking into consideration system internal and external dependencies. System internal threshold and decision values with which MGBAS system operation could be monitored and controlled were optimised on this basis.

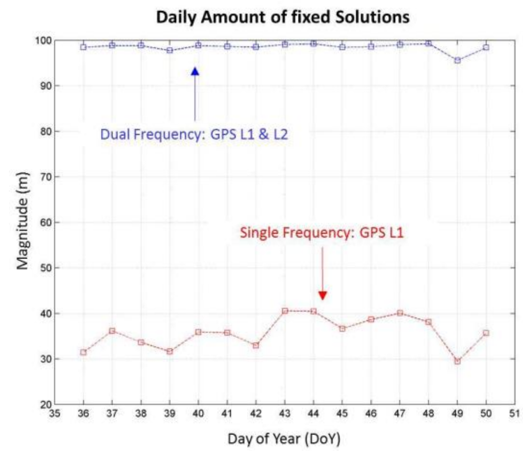

Fig. 17: Success Probability of the Ambiguity Resolution for "GPS L1"- and "GPS L1+L2"- Service of MGBAS (DOY 036-050 2011) Determined at the MGBAS

It is generally known that the positioning accuracy of GPS based and DGPS based position determination increases if the distances between satellites and receivers are determined by dual-frequency based rather than single-frequency based transmission time measurements. Through their frequency dependence, first order ionospheric transmission time errors can be corrected directly in the distance measurements. This avoids residual errors that occur if ionospheric transmission time errors are corrected with values derived from models or determined in different locations. As a result, it can be expected that ionospheric-corrected phase measurements allow more accurate resolution of the ambiguities of the phases. Experimental research indicates that in single-frequency cases the probability of success of an ambiguity fixing was only at 30% to 40%. By contrast, a process based on dual-frequencies could resolve ambiguities in more than 95 % of the cases (Fig. 17).

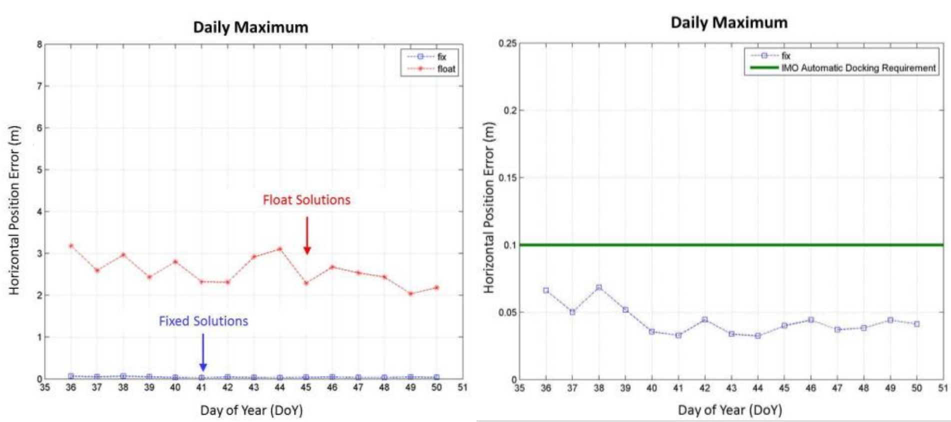

Fig. 18: Maximal Position errors at the MGBAS Monitoring Station per Day when Using "GPS L1+L2" Augmentation Service Dependent on Status of the Ambiguity Fix (left) and in Relation to IMO Requirement for Automatic Docking (right)

As becomes clear in Fig. 18 (left), phase-based DGNSS processes only achieve the desired accuracy when ambiguity resolution was successful in the phase measurements. If horizontal position was determined solely with a "float" solution – meaning without fixed ambiguities – the maximal position error per day was 2 - 3m. Yet when a "fixed" solution was achieved, the maximal position error was clearly less than 1dm. It met the accuracy requirements (Fig. 18, right), for carrying out an automatic docking manoeuvre.

Therefore, for safety-critical applications of the MGBAS, operating and use conditions must be construed to guarantee as much as possible that the user gets a stable ambiguity fix. Part and parcel of this are robust communication channels for transmission of augmentation signals and an integrity assessment of the GNSS used and corrections provided. The results also showed that a dual-frequency based PDGNSS process using the signals of a satellite navigation system (GPS here) is insufficient to achieve availability of 99.8 % in GNSS/DGNSS based position determination.

This raised the legitimate question of whether and how the performance capabilities of phase-based DGNSS processes can be increased if MGBAS services are to be made available for modernised GNSS, e.g. GALILEO or for combined use of GPS and GALILEO. Therefore, new processing channels were conceived and implemented in software technology in order to augment the service portfolio of the MGBAS experimental system by the following four services: "GALILEO E1", "GALILEO E1+E5", "GPS L1 & GALILEO E1", and "GPS L1+L2 & GALILEO E1+E5". The original consideration was that it would be possible to carry out comprehensive, experimental validation, and optimisation of these new services with real measurement values within the term of the project. Nevertheless, delays in setting up GALILEO meant that the real, available GALILEO based data base was not sufficient to allow e.g. evaluating and optimising phase-based DGALILEO processes. That is why distance measurements generated by a "Spirent" type GNSS signal simulator were used to allow estimation of the gain in performance through use of GALILEO or multiGNSS based MGBAS processes.

The comparison illustrated in Fig. 19 clearly shows that the probability of success of ambiguity fixing of even single- frequency based processes can be increased if navigation signals with increased resilience (e.g. GALILEO) or navigation signals of several GNSS (e.g. GPS+GALILEO) are used in combination [2011-09]. If the probabilities of success shown in Fig. 17 and Fig. 19 for ambiguity fixing with "GPS L1" signals are compared, the simulated results (around 10%) are below the real results (20-30%). That legitimises the premise that the achievable probability for successful ambiguity fixing for "Galileo E1" or "GPS L1 & GALILEO E1" would also be higher than the simulated results.

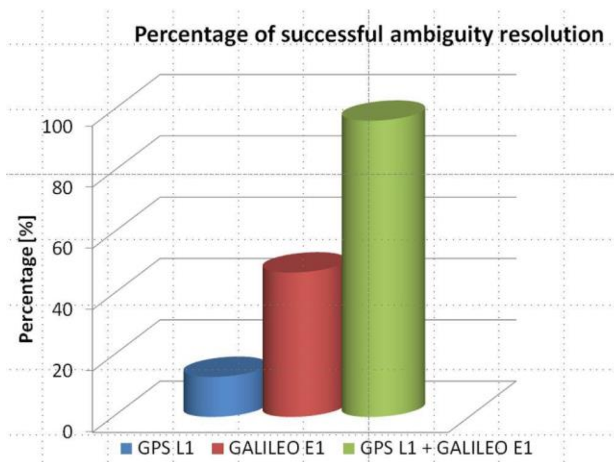

Fig. 19: Probability of a Successful Ambiguity Fix: "GPS L1", "GALILEO E1" and "GPS L1 & GALILEO E1" on the Basis of Data from the "SPIRENT" GNSS Simulator

A graphical user interface was created in addition to developments in methodology. It informs the MGBAS operator about the actual performance capability of the offered MGBAS services and integrity of the GNSS signals used for it (Fig. 20). On the left hand side the multifunctional display shows which of the MGBAS services meet (green) or fail to meet (red) the requirements of the selected performance class (e.g. port or automatic docking). The operator can make conclusions about the performance stability of the services provided based on the time behaviour of position error per process (Fig 20, below right). In addition, the upper right of the screen shows which GNSS signals are classified as useable for service provision and with that, for position determination.

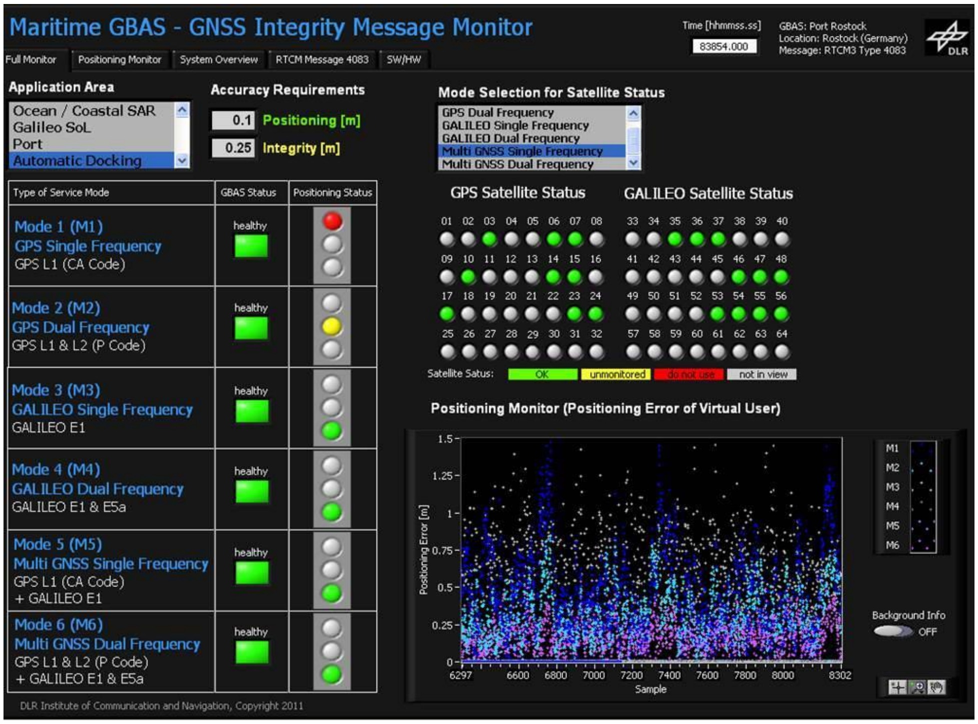

Fig. 20: MGBAS Monitor for Visualisation of MGBAS Relevant Integrity Statements

Development of a second user interface pursued a more application-friendly depiction of MGBAS performance capability (Fig. 21). Depiction of technical details in particular has been waived here. The actual position errors are shown on the lower right. The "traffic lights" (above) only go green for each service and accuracy class if a certain minimum proportion of positioning results (here 80%) has achieved the required accuracy in past epochs. This conveys the current stability of a single, working process.

5.3 IALA Beacon DGNSS validation of maritime augmentation services

Monitoring processes were implemented in the MGBAS experimental platform in addition to the generation and evaluation of original MGBAS services in order to allow for experimental validation of performance capabilities of already established maritime PNT services. To achieve this, software technology for an integrity monitor in accordance with the "IALA Beacon DGNSS" Standard [IALA-R121-2004] was developed and implemented in the

Fig. 21: User-friendly MGBAS Monitor

experimental system. This made it possible to investigate the positioning accuracy achievable with CDGPS while using RTCM2 correction messages of the Groß Mohrdorf station at the Rostock location. Through this new functionality, the MGBAS reference station now also functions as a Far Field Integrity Monitor (FFIM) in accordance with the "IALA Beacon DGNSS" Standard [IALA-R121-2004].

Fig. 22 shows examples of the 3D positioning accuracies reached without (red line) and with (blue line) use of the corrections during an hour at the Groß Mohrdorf station. It shows that the positioning accuracies achieved are in the vicinity of 1m to 2m and that, if the service is used, the accuracy requirements for GNSS based position determination in coastal areas and for port approach are clearly met (10m (green line)).

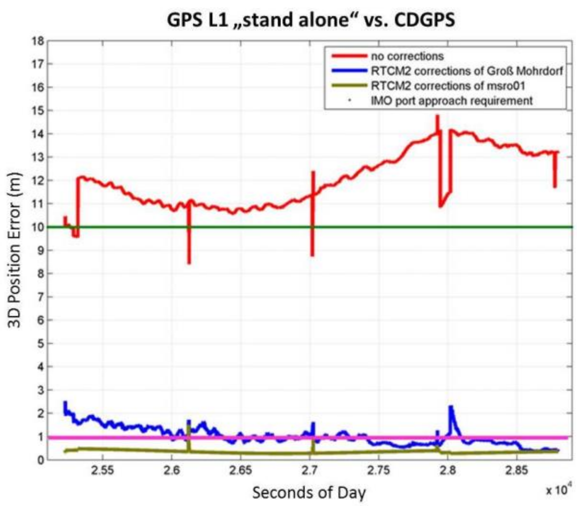

Fig. 22: Positioning Accuracy with and without Corrections from the IALA Beacon Station at Groß Mohrdorf and the MGBAS Station

A further step investigated improvements that could be achieved in the port of Rostock if the MGBAS reference station supplied its own corrections according to the "IALA Beacon DGNSS" Standard [IALA-R121-2004], which in addition are evaluated with respect to their integrity at the Integrity Monitoring Station (IMS). It could be proven that positioning accuracies below 1m could be achieved in close vicinity to reference stations (see course of lower curve in Fig. 22) and as such fulfilled IMO accuracy requirements for port areas (<1m, pink line). The difference in the achieved accuracies for alternative use of correction data from Groß Mohrsdorf and Rostock is explained by spatial error decorrelation in the correction data.

The achievable accuracy for the user is also dependent on the age of the correction data. The IALA recommends that only correction data with a maximal data age of 30s should be used [IALA-R121-2004] in order to suitably correct Selective Availability (SA) effects as well. In the meantime, the SA has been switched off so that less dependency on data age can be expected. In order to analyse this, the RTCM2 correction data generated at the MGBAS reference station were artificially delayed before they were sent to the monitoring station for position determination.

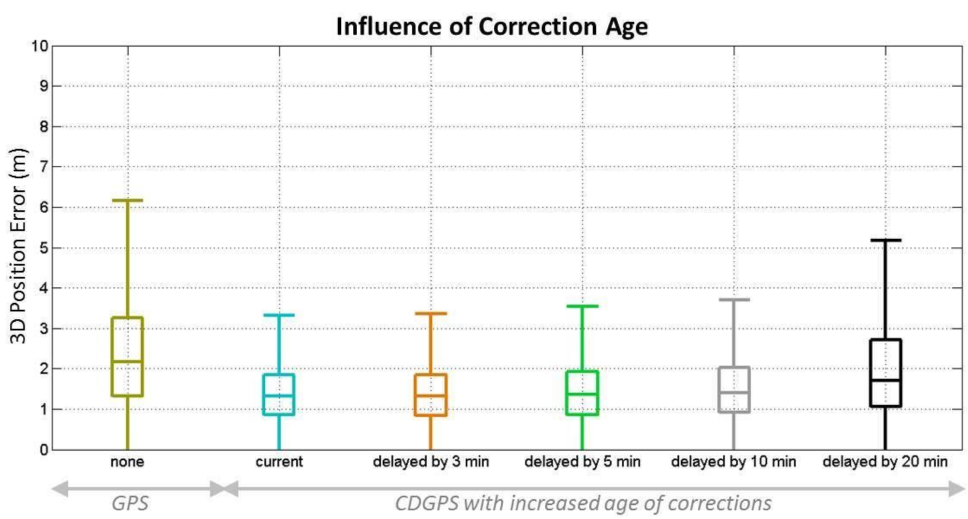

Fig. 23: Depiction of Horizontal Position Error as a Boxplot During Use of Time-Delayed RTCM2 Correction Data from the IALA Beacon DGNSS at the MGBAS Reference Station in Rostock (DOY 235, 2010)

The effect of data age on horizontal position errors is illustrated in Fig. 23. As expected, an increase in horizontal position error can be observed along with the increase in age of the pseudo-range corrections applied. Nevertheless interesting is the fact that when SA is switched off, a clear increase in position error is only observed when the correction data are greater in age than 10 minutes [2010-12B].

The portfolio of PNT relevant services in the Rostock Research Port and research opportunities were expanded with the implementation of CGNSS processes in MGBAS.

5.4 Usability analysis of PDGNSS services for maritime long-range applications

The increasing construction and operation of offshore wind turbines in the North and Baltic Seas means that even 50 to 150 kilometres away from shore, position determinations with higher accuracy are becoming necessary. In the context of e.g. exploration or maintenance, positioning accuracy in the lower dm vicinity is required. As can be seen in Fig. 22, such accuracies cannot be achieved with code based DGNSS processes, such as the IALA Beacon DGNSS (compare experiments in previous section).

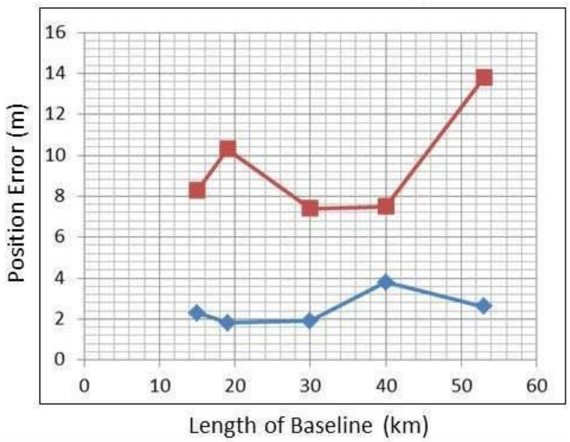

Fig. 24: Horizontal (blue) and Vertical (red) PDGPS Position Errors (1σ) Dependent on Baseline Length

An opportunity to closely meet these requirements could result from use of PDGNSS processes. It is generally known that the performance capability of DGNSS processes decrease as distance from the reference station increases due to spatial error decorrelation, meaning position error increases. For this reason, a special survey for phase-based DGPS processes was used with the intent of investigating the effect of increasing distance between the reference station and user on the achievable fix rate of phase ambiguities and therefore positioning accuracy. The survey was first carried out on the shore-side because there were no reference points at sea (comparable points with known coordinates).

At several measurement points, phase-based position determinations were carried out starting from the MGBAS reference station in Rostock to a distance of up to 60 kilometres away. Dual frequency GPS measurements (geodetic receiver and antenna) were used to do this. The result showed (Fig. 24) that at the point furthest away (54 km) the horizontal position error was less than 4 cm (HPE) and the vertical position error less than 15 cm (each for 1σ). The accuracies were nevertheless only valid for results with position determinations and achieved ambiguity fixes.

The proportion of position solutions with achieved ambiguity fixes was generally unsatisfactory because 100% success probability was not reached at any of the measurement points. It would still be possible for statistical applications – even in the case of greater distances to the reference station – to use phase-based correction processes for highly accurate position determination. Then, however, one has to tolerate that the efficiency of PDGPS based position determination would clearly decrease.

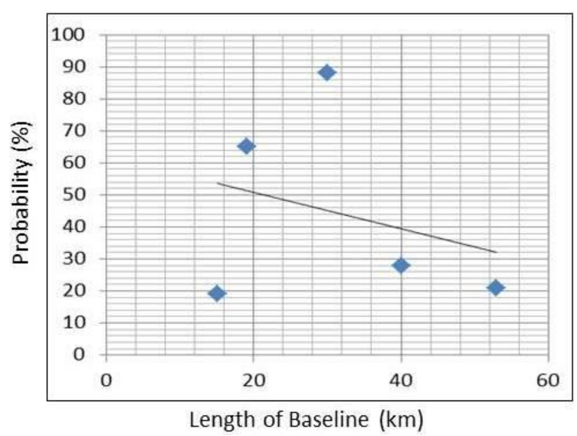

Fig. 25: Proportion of PDGPS Position Solutions with Fixed Ambiguities Dependent on Baseline Length

A clear correlation between probability and distance to the reference station could not be derived from these results. Linear interpolation (Fig 25) using the five measurement points indicates that with increased distance (from 15 km to 54 km) the probability of ambiguity fixing falls from 50% to 30%.

However, an essential conclusion based on these results is that the quality (particularly in terms of continuity and usability) of phase-based position determination that results at great distances from the reference station during use of first GNSS generation signals is insufficient for monitoring or controlling the movement of vehicles.

6. PNT-UNIT

6.1 Status and Challenges

As presented in Chapter 3, the on-board element for providing position, navigation, and time data is made up of a number of sensors, such as e.g. GPS receivers for PVT data, a gyro compass for true heading, or a speed log for speed over ground. Individual sensors of this type usually do not have the capability of characterising the integrity of their data products in real time. Therefore, when PNT data are provided solely by individual sensors, then the mariner or captain must more or less take on assessing the quality of the data. If the SOLAS ship is equipped with an Integrated Navigation System (INS), combined use of the sensor data and assessment of its integrity is possible. INS systems have up to now used plausibility and consistency tests to estimate the integrity of data. Plausibility tests check for range constraints, meaning e.g. that actual measured speed is compared with the maximum possible speed of the vessel. Consistency tests are based on a common measuring model and test the consistency of values, meaning e.g. the testing of position results from redundant data sources or coherence between time and speed measurements and consecutive position readings. The user requirements gathered within the scope of the "e-Navigation" strategy are aimed however at implementing data and system integrity in order to determine the reliability of all data relevant to navigation – if at all possible with respect to achieved accuracy – and to convey this to nautical personnel. At the moment, this requirement is not being met by an INS.

The PNT system concept (Chapter 3) set the challenge of developing a PNT Unit as a ship-side element of the maritime PNT system. Furthermore, this unit should be able to provide the user with integrity information with reference to accuracy. The combined processing of all measurements relevant to PNT with methods of data or sensor fusion was identified as a suitable approach to address this challenge. The construction of a real-time capable demonstrator was intended to create the foundation for proving experimentally the feasibility of robust PNT data provision on the basis of the entire, developed PNT concept.

Fig. 26: PNT Unit's GNSS Receiver Group

6.2 PNT Unit Sensors (V1.0)

The sensors listed in on the left in Fig. 27 were chosen for incorporation in the first PNT Unit (V1.0). The GNSS receiver group of the PNT Unit shown as an example in Fig. 26 has four GNSS receivers which are carried along as reference receivers.

The aim of the sensor choice was to ensure at least two redundant measurements (marked with "xx") could be used for all relevant PNT parameters. Among these are position, speed over ground (SOG), course over ground (COG), rate of turn (ROT), three-dimensional attitude (roll, pitch, and yaw angle) as well as time. Maritime standard sensors such as GPS receivers, gyro compass, and SDME were to be used whenever possible. The three, geodetic GNSS receivers operating ship-side make possible a redundant but not uncorrelated determination of position, velocity, and time data (PVT) possible with GNSS. The suitable arrangement of receiver-specific antenna locations ensured that it is possible also to determine the three-dimensional attitude of the ship during shared use of all GNSS data. Phase-based "GNSS Compass" algorithms were used to do this. An I The development of various testing methods was required to pursue this. Among them, for example, were tests of the plausibility of AIS messages or associating AIS and RADAR objects for validation of their positioning nertial Measurement Unit (IMU) was available to provide turn rates and accelerations in all three directions of motion. By using the corresponding "Strap-Down" integration process and initialisation it is possible to determine PNT data also in the case of short GNSS outages. The redundancy for all PNT parameters created by this choice of sensors ultimately forms the required data foundation for the development of data fusion based integrity monitoring processes.

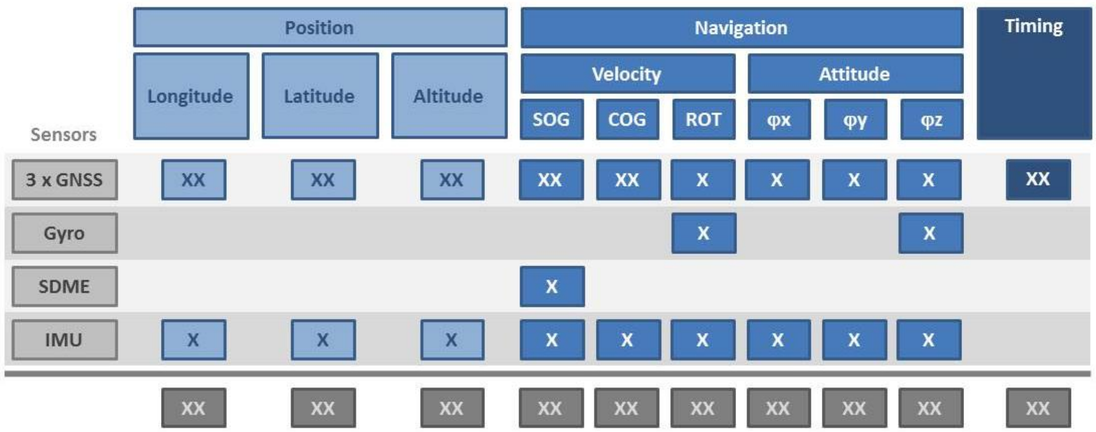

Fig. 27: Overview of Sensors Used for the PNT Unit V1.0 and their Use in Providing PNT Parameters (x) or their Provision Including Redundancy (xx)

6.3 Sensor Characterisation

In order to use data from the most varied of sensors effectively in a data fusion processes, error models were required for each individual sensor. Therefore, all the sensors used were investigated and characterised with respect to their error behaviour during the project. The characterisation of inertial sensor errors and determination of true heading with a GNSS compass are used as illustrative examples here.

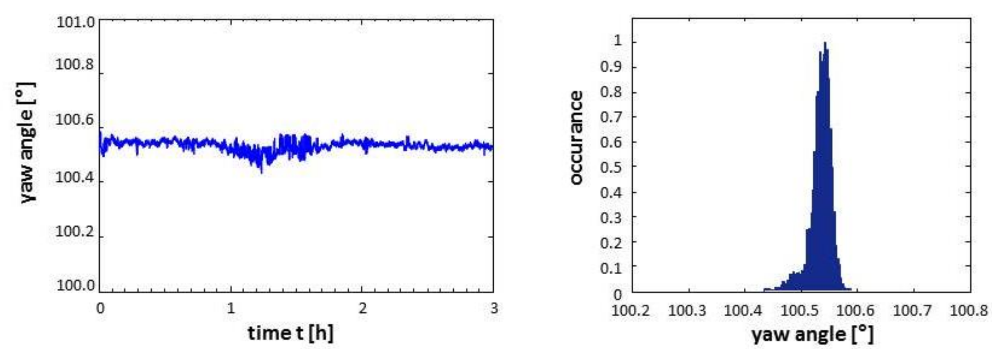

Fig. 28: Quasi-statistical Determination of Heading (yaw) for Extrapolation Accuracy Statements for the GNSS Compass: Heading over Time (left) and the Assigned Distribution Function (right)

Quasi-statistical data recorded during three hours on board the BSH research ship "DENEB" in Rostock's city port were analysed to characterise the GNSS compass (Fig. 28, left). During these measurements, the distance between the two GNSS antennas used here was around 50 m. Because a slight movement of the vessel at the pier cannot be ruled out, the distribution function shown in Fig. 28 (right) presents a more pessimistic estimation of the actual error distribution. The standard deviation σ was calculated to be 0.02° and is a good basis for the setting of a consistent ship coordinate system.

The IMU used was a "tactical grade", type: iVRU FCAI from the iMAR company. Typical IMU errors are bias, scaling factor, and cross-coupling errors. Only the bias error is relevant for the IMU used in this project. The bias error can be subdivided into a static component and a dynamic component. The static component, also known as fixed bias, includes the "run-to-run" variation of the integrated sensors and the fixed bias that remains after successful calibration. In order to characterise dynamic bias ("in-run" bias), 24 hours of IMU data were recorded in static operation and subjected to what is known as Allan variance analysis. Fig. 29 shows the dependence of the Allan variance for the applied averaging time t for the IMU's three rate of turn sensors. With increasing averaging times τ the Allan variance recognisably decreases in the first instance. Perfect white noise with $\sigma \approx 1/\sqrt{\tau}$ should yield a straight line, which when shown as a double logarithm produces a slope of -1/2. That the "Allan variance" can be described well by such a straight line is recognisable particularly when the averaging times are short. By contrast, when the averaging times τ are longer, the Allan variance increases due to the bias instability of the sensor. A standard definition of bias stability of inertial sensors is therefore described by the minimum in the Allan variance curve. The FOG based gyroscopes of the IVRU FCAI therefore have a stability of around 0.02 °/h at an averaging time of ~1/2h.

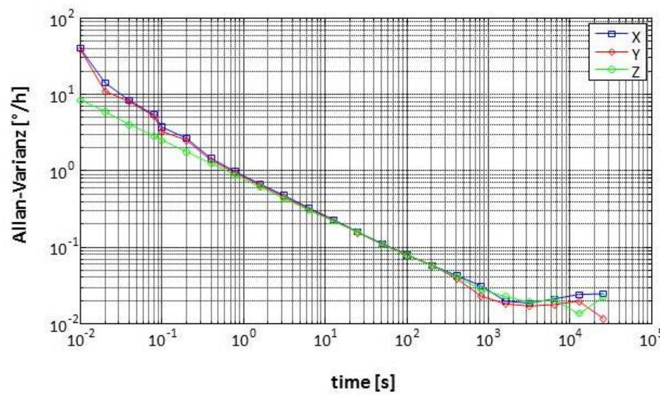

Fig. 29: Allan Variance Analysis for the Gyroscopes of the iVRU FCAI IMU Used in the Project

6.4 The PNT Unit (V1.0)'s processing chains

As presented in Section 3.4, the PNT Unit is composed of a set of parallel processing channels in order to serve different, operationally determined accuracy and integrity levels. Their specification – as already explained in Section 3.2 – is one to be addressed within the scope of the maritime PNT system concept. An individual channel represents a specific process that is effectively used by the PNT Unit for determination of PNT and integrity data in order to serve a specific performance class. The following processing chains[1] were implemented for the PNT Unit V1.0:

(1) GPS Single Point Positioning (SPP);

(2) GPS Single Point Positioning (SPP) including Receiver Autonomous Integrity Monitoring (RAIM)

(3) Code based DGPS with use of the IALA Beacon DGNSS (CDGPS)

(4) Phase-based DGPS with use of MGBAS-Service (PDGPS)

(5) Extended Kalman Filter: loosely coupled IMU + SPP including RAIM + GNSS compass

(6) Extended Kalman Filter: tightly coupled IMU + GPS + GNSS compass

(7) Extended Kalman Filter: loosely coupled IMU + CDGPS + GNSS compass

(8) Extended Kalman Filter: loosely coupled IMU + PDGPS + GNSS compass

[1] As a rule, GPS signals were used in the processes. In the case of the GNSS compass, GLONASS signals are additionally being used at the current time.

Processing chains 1-4 comprise a purely GNSS based procedure for determining position, velocity, and time (PVT), whereas processes 3 and 4 use augmented data that is provided by shore-side services. Processing chains 1 and 3 correspond to the current state of technology used for maritime purposes. In terms of performance standards, as processes they are specified for maritime GNSS receivers. The RAIM used in processing chain 2 is a purely GNSS based integrity monitoring procedure that detects erroneous satellite signals and excludes them from positioning. It exploits the redundancy of measurement technologies that take place when at least six satellite signals are available simultaneously. An RAIM process developed for an aviation safety of life critical application was adapted and implemented for the project.

Fig. 30: HW des Demonstrators der PNT-Unit (V1.0)

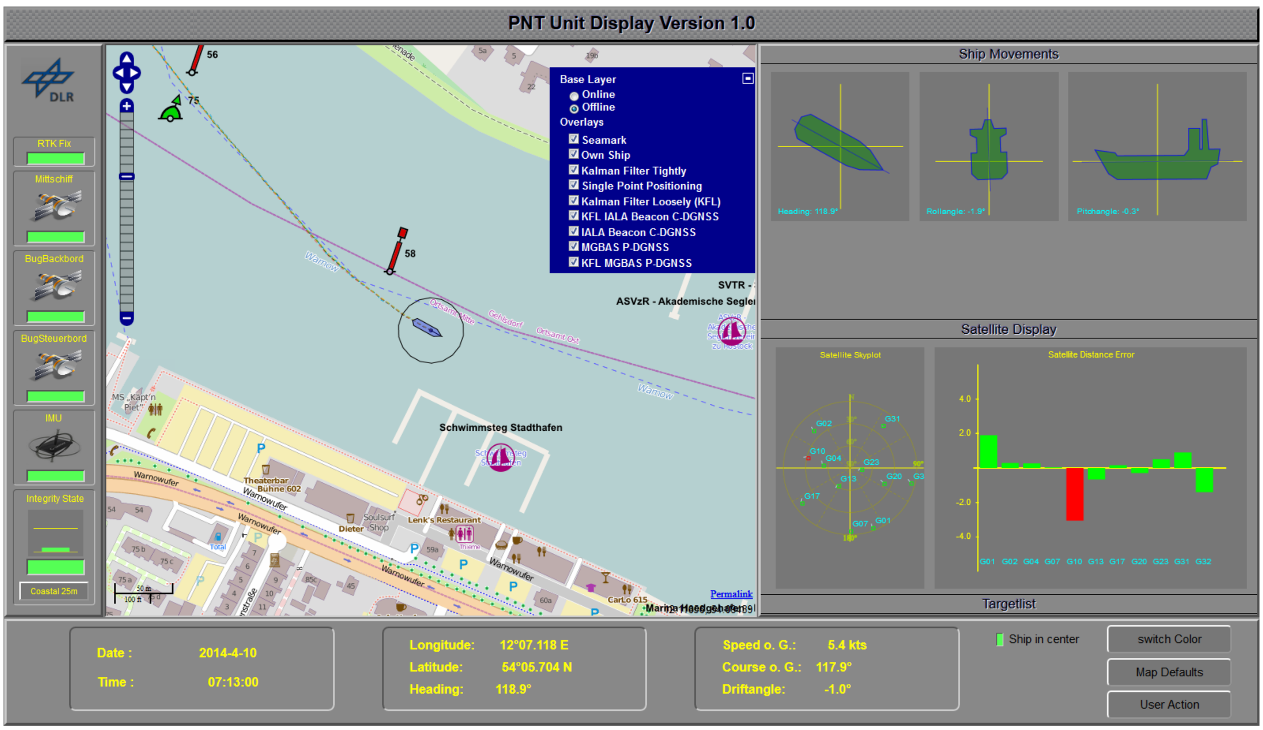

Fig. 31: Snapshot of Web Browser Based PNT Unit Visualisation

The Extended Kalman Filter (EKF) used in processing chains 5 to 8 is the simplest form of a Bayesian filter which assumes a normal distribution of errors and an approximately linearized system model. In general, one differentiates between a loosely and tightly coupled GNSS-IMU integration. In loosely coupled integration, the GNSS sensor's position and velocity data is fused with IMU data. Tightly coupled integration also fuses GNSS raw data – code and carrier phase-based distance measurements to individual satellites – with IMU data as well. The advantage of loose coupling is in the simplicity of realisation and independence of the fusion process from the GNSS or DGNSS methodology used. The loose process was implemented for the three GNSS/DGNSS processing chains SPP, CDGPS, and PDGPS. The process technology of tightly coupled GNSS-IMU integration is more complex. Its computation technology is also more complicated. This process, however, makes integrity monitoring at the sensor-raw data level possible. With it, erroneous satellite signals, for example, can be detected and excluded from further processing by the use of what is known as an innovation filter [Grooves 2007].

The processing chains were ultimately implemented on the basis of the C++ real-time framework mentioned in Section 4. They are also tested on various types of hardware. A single board system was chosen (Boxer TF AEC 6637) for ship-side use that proved to be particularly suitable due to its compactness and durability (see Fig. 30). The HW solution chosen served above all to allow testing and validation of the PNT Unit under real conditions on board ship. With respect to the PNT system concept as a whole, however, the main decisive components of the PNT Unit are found in software solutions (processor chains) that can also be included in a future INS.

In order to graphically depict the output and results from the processing chains, a graphical user interface (GUI) was developed that runs on and is operated on the web browser (Fig. 31). The GUI made it possible to get an immediate response regarding the PNT data generated during various measurement trips. The graphical tool outputs results of individual processing chains and also has additional functions to allow verification of interim results of the processing of PNT data.

6.5 Results of experimental Validation

The data base for the experimental validation presented here is from an 8-hour measurement trip carried out with the vessel the "Baltic Taucher II" in the vicinity of the port of Rostock including the city port and Warnow river (see Fig. 32). During this measurement run, the PNT data of the eight processing chains were calculated in real time and saved for further validations. In order to evaluate the positioning accuracy achieved, a reference trajectory was also determined by using the RTK post-processing software Justin.).

Fig. 32: Ship Trajectory for the Measurement Trip on 9 April 2014

SINGLE POINT POSITIONING (SPP) RESULTS

The first step was to assess horizontal position accuracy for Single Point Positioning based on the GPS L1 Code.

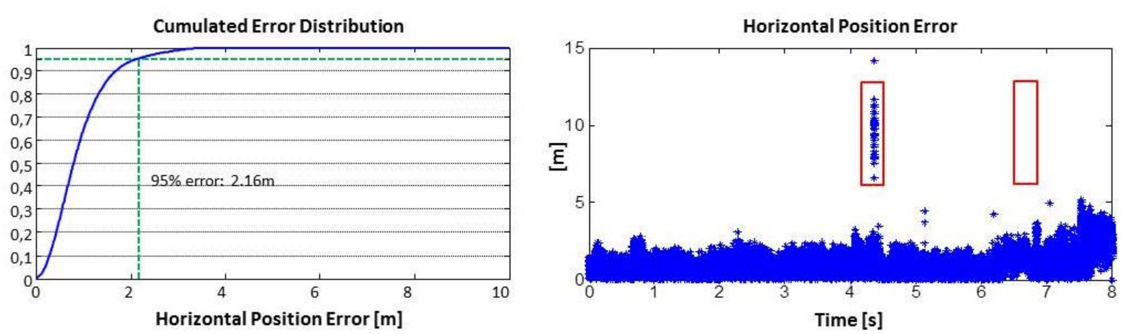

Fig. 33: Horizontal Position Error of the GPS Based SPP Process: Cumulated Distribution Function (left) and Over Time (right)

The graphic on the left in Fig. 33 shows the cumulated error distribution function of the horizontal position error. What is recognisable is that 95% of the positions determined have a horizontal position error of less than 2.16 m. This indicates very good accuracy for the SPP process. For safety of life critical applications however, the determination of 95%-error is insufficient. What is however more essential, is that significant outliers in the position accuracy (see Fig. 33 right) are recognised and indicated as a loss of integrity. These could be a risk for safe vessel navigation and consequentially result in collisions or groundings.

DETECTION AND EXCLUSION OF ERRORS THROUGH USE OF RAIM

A detailed analysis of SPP positioning showed that outliers in position accuracy were caused by jumps in the code-based distance measurements from individual satellites. An error detection and exclusion process, which is an inherent part of the RAIM algorithm, should in principle be able to detect erroneous satellite signals such as these and exclude them from the position solution.

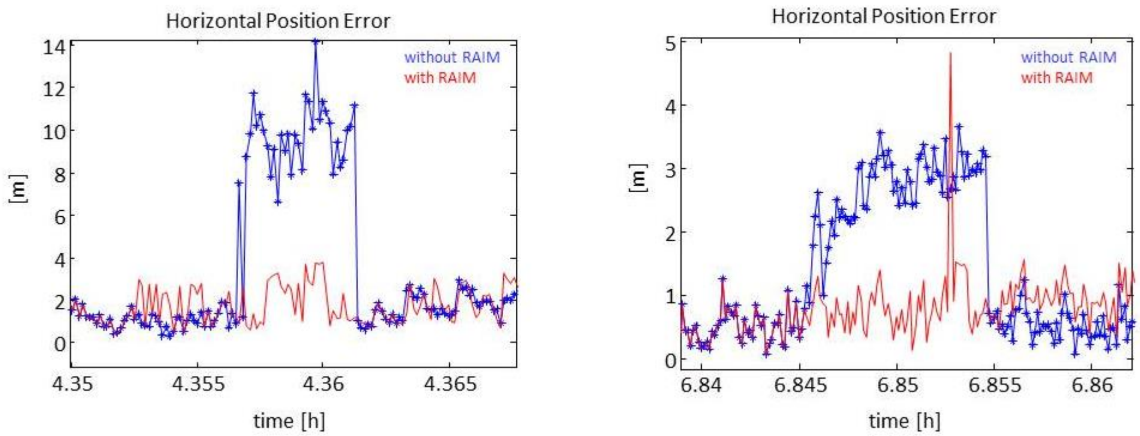

Fig. 34: Horizontal Position Error SPP without RAIM (blue) and with RAIM (red) for Two Durations of Time with Position Breaks/Jumps in the SPP Solution

Fig. 34 shows enlarged examples of 2 outliers. In the left-hand graphic, a temporary increase in position error by 10-15 m is recognisable in the solution reliant solely on SPP (blue). If RAIM is used, the erroneous measurements are excluded from position determination and position error (red) remains in the vicinity of 1-3 m.

In another example (right-hand graphic) the short time position errors of 3-4 m make it clear that a RAIM process does not always succeed in excluding erroneous navigation signals from determination of position.

DETECTION AND EXCLUSION OF ERRORS USING GNSS/IMU-BASED EKF PROCESS

As already shown in chapter 6.4, a tightly coupled EKF allows for integrity monitoring at the raw sensor data level. It also allows detection and exclusion of GNSS satellite signals that contain errors.

In Fig. 35 the position errors for loosely coupled EKF IMU + SPP without RAIM and tightly coupled EKF IMU + GNSS are shown together with the position errors of SPP with and without RAIM for the same time period as in Fig. 34 (right-hand graphic). It is recognisable that the innovation filter in tightly coupled EKF IMU + GNSS is in a position to exclude erroneous satellite signals reliably so that the best accuracy can be achieved for position determination. The loosely coupled EKF IMU + SPP without RAIM, by contrast, reduces the noise of the SPP solution in general, however, if there is an error of a longer duration Δt > 10s, the curve will follow the SPP solution that contains errors.

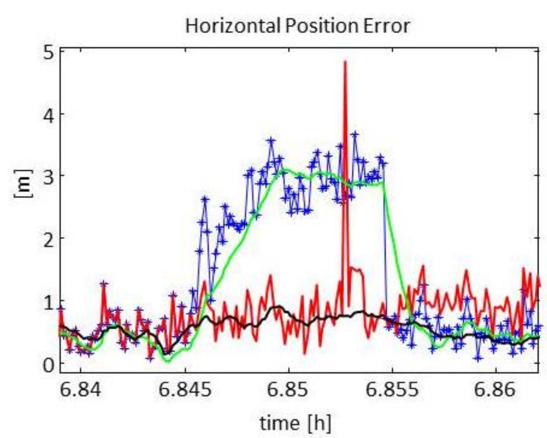

Fig. 35: Horizontal Position Error for Loosely (green) and Tightly Coupled EKF (black) in comparison to SPP with (red) and Without (blue) RAIM

ASSESSMENT OF CURRENT ACHIEVABLE POSITION ACCURACY BY MEANS OF RAIM

The RAIM algorithm implemented in the PNT Unit (V1.0) determines what is known as the Horizontal Protection Level (HPL) in real time. By definition, the HPL depicts an estimation of the horizontal position error with respect to the remaining integrity risk. The IMO has set the remaining integrity risk for uses in the vicinity of ports and coasts at 10^{-5} in [IMO-A.915(22)]. The integrity of current position solution is guaranteed if HPL could be determined and lies below the set alarm level. This is specified at 25 m for use in coastal regions and 2.5 m for use in ports in [IMO-A.915(22)]. In Fig. 36, a Stanford diagram shows HPL determined in real time against horizontal position errors of the SPP process.

It is recognisable that the estimated HPL on board ship in real time is always greater than the true position error detected in post-processing. It could be demonstrated that HPL therefore served its purpose as the upper bound for true errors for the time interval observed during the 8 hour measurement run. Originally developed for aviation, the RAIM process can in this case also be used in the maritime sector despite the very different signal environment (e.g. the multipath effect caused by the ship or surface of the sea). What is furthermore clear is that for 99.8% of the time HPL was below the 25 m alarm level specified for use in the vicinity of coastal areas. HPL only classified a sufficiently accurate position solution as unusable in just 0.2% of the cases.

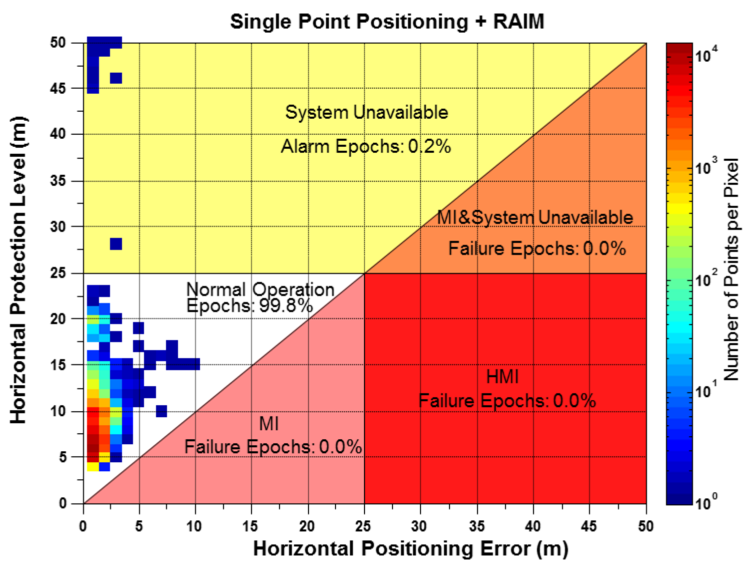

Fig. 36: Stanford Diagram for Single Point Positioning with RAIM

Higher accuracy requirements which have set alarm levels of a few meters (manoeuvres in port) to the vicinity of dm (automatic docking) cannot be met by the SPP process coupled with RAIM. In order to reach such accuracies with first generation GNSS, a differential positioning process must be used. The suitable augmentation data for this process are to be provided by DGNSS services.

Performance Capability of Phase-Based DGPS

A phase-based DGPS position solver was implemented for highly accurate uses in port. This algorithm uses correction data from the MGBAS service (see Section 5.2) in the port of Rostock. As already presented in Chapters 5.2 and 5.4, position accuracies in the vicinity of dm can only be achieved if the positioning algorithm is able to fix integer ambiguities of the phase measurements used.

When the ambiguities could be fixed (Fig. 37, left-hand graph), horizontal position could be determined with an accuracy of a few centimeters during the entire measurement trip (8h). If the ambiguity fixing was unsuccessful (Fig. 37, right-hand graph), the position errors increased to a maximum of 4 m.

What is remarkable is that the probability for fixed ambiguities was 93% and therefore clearly larger than the values from the land-side analysis (Chapter 5.4). The various areas effected by GNSS signal shadowing that are characteristic of ports and the relatively high level of effort involved in achieving a fix rate of 99% using augmented MGBAS make the sole use of phase-based DGNSS for highly accurate position determination for safety of life critical applications seem insufficient. In this respect, a reasonable approach to use to receive continually reliable solutions here would be applying e.g. loosely coupled extended Kalman filters to aid in coupling a highly accurate, but discontinuous DGPS position solutions with the intrinsically reliable, inertial sensors which slowly drift over time.

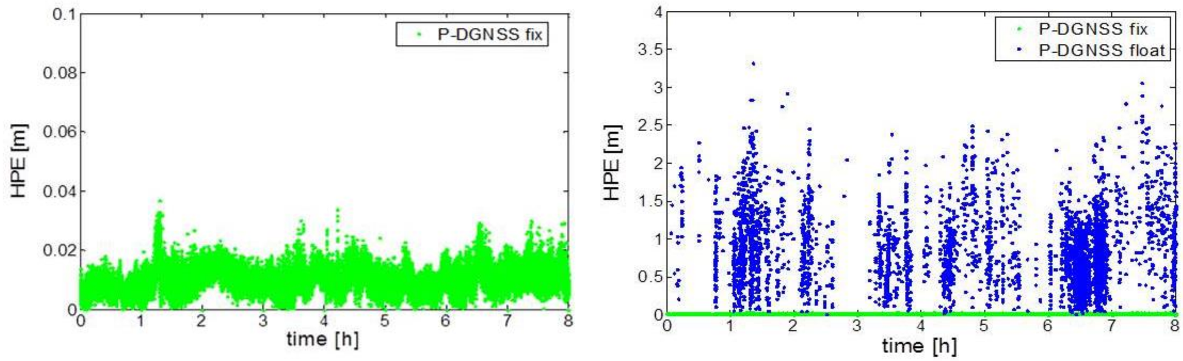

Fig. 37: Horizontal Position Errors for Phase-based DGPS: with Fixed Ambiguities (left) and with Float Solutions (right)

Fig. 38 shows the horizontal position error of a loosely coupled EKF IMU + PDGPS + GNSS compass (red line). That the position error during the 8h measurement run was less than one metre is apparent. The greatest position error has been enlarged and is shown on the right-hand side. It was not possible to fix the ambiguities of the phase measurements within 30 s. During this time interval, position determination was based solely on integration of accelerations and turning rates of the IMU. Position drift of around 0.7 m for a period of 30s is a good value for the tactical grade IMU used. This value could be achieved through good initialisation and optimal estimation of IMU bias error.

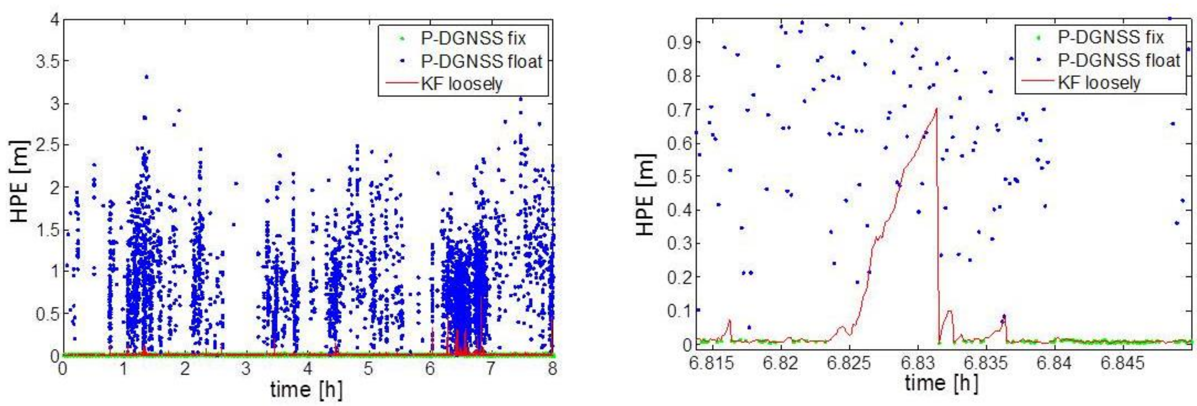

Fig. 38: Development over Time of Horizontal Position Error for pDGPS fix/Float Solutions Compared to Loosely Coupled EKF pDGPS + IMU + GNSS Compass

In this case, 100% usability of the position solution could be achieved for an accuracy of < 1m through a processing chain of a loosely coupled EKF IMU + pDGPS + GNSS compass. This processing chain is therefore a very promising approach for in port uses requiring high accuracy.

7. TRAFFIC ASSESSMENT AND EVALUATION

7.1 Status and challenges

Reliable assessment of traffic conditions is an essential prerequisite for avoiding collisions. Seen from the viewpoint of a single ship, the traffic situation would be described clearly and comprehensively if it were possible to determine own-ship position and movement in relation to the position and movement of other traffic participants while taking into consideration usable traffic space.

Currently ship-side assessment of the maritime traffic situation is based on RADAR and AIS. On-board RADAR devices use a rotating antenna to emit electromagnetic X–Band (8–12 GHz) or S-Band (2–4 GHz) waves. The direction and distance of other traffic system users is ultimately determined through reception and evaluation of reflected signals. Since 2004, AIS has been used as a communications platform in order to enable the exchange of data between ships and between ship and shore. Two VHF communications channels (AIS 1: 161.975 MHz; AIS 2: 162.025 MHz) are used for this. Among data relevant to navigation are static and dynamic data, and data related to the voyage. Dynamic data in this case is provided by on-board PNT sensors (among them GNSS, compass). Just like any other technology, these two systems have their very own strengths and weaknesses.

The advantage of RADAR is that detection of other vessels etc. is achieved with the aid of an independent system working on-board ship. That is why the IMO specifies that RADAR is the primary system to use for collision avoidance. Nevertheless, RADAR also detects more or less all objects that reflect electromagnetic waves – so in addition to other users of the traffic system it picks up everything from quaysides to wave crests to flocks of birds. Objects located in the radio shadow of other objects cannot, on the other hand, be detected with RADAR.

In comparison to RADAR, the positions provided by AIS are given as absolute values which as a rule show greater accuracy than the relative RADAR positions. The positions are determined with radio navigation systems such as GPS, whereby a GNSS receiver has either been integrated in the AIS device or connected externally. Therefore, the safety discussion about the lack of resilience of GNSS is also relevant for robust provision of AIS data content. Correct input of static as well as voyage-related AIS data and careful configuration of all sensors relevant to navigation which serve as AIS data sources are requirements that must be set for nautical personnel in order to ensure reliable provision of AIS data content. This dependency together with the level of equipment of AIS devices and the possibility of switching off AIS devices on board are arguments in favour of keeping RADAR the primary system for collision avoidance in spite of its performance limitations.

A qualitative evaluation of the performance capabilities of technologies that are relevant for determining the traffic situation was viewed as a suitable origin for characterising and consolidating the achieved standard of technology. The challenges to be resolved within this context included the acquisition of representative test data and development of validation methods to implement planned experiments and answer existing questions. One object of the investigation was orientated towards the qualitative and quantitative description of the strengths and weaknesses of RADAR and AIS. From there, detailed development aims could be specified and possible approaches to error compensation identified and evaluated. With this in mind, the first analyses of the functionality and performance capability of RADAR and its software module called "Automatic Radar Plotting Aid" (ARPA) were carried out. ARPA supports nautical personnel as they use RADAR to determine the velocity and course of other vessels. The focus of this research was on the automatic recognition of targets in order to achieve automatic combination of AIS and RADAR data for integrity assessment in future. Another development task was dedicated to error modelling as close to reality as possible for both sensors. Such error models are, for example, a necessary element to allow the fusion of RADAR and AIS data for comprehensive and reliable determination of the traffic situation.

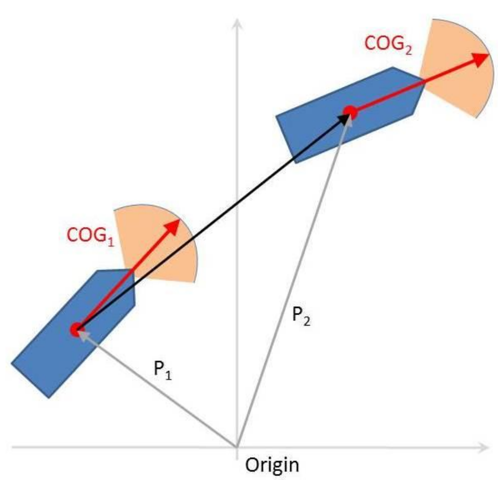

Fig. 39: Schematic Depiction of Ship Movement with Respect to Consecutive AIS Messages

Also identified as a legitimate question was which extraction and fusion methods would be at all suitable for assessing and evaluating the traffic situation on both ship and shore. The background to the question can be found on the one hand in the diversity that exists between the characteristics of AIS and RADAR data that preclude the use of specific methods of data fusion or require the use of specific methods of data management. On the other hand, the technical feasibility and usability of the most various of approaches was to be demonstrated early on in order to ultimately avoid undesirable developments.

7.2 AIS Plausibility

Plausibility and consistency tests are approaches used in practice in order to estimate data quality in cases where determination of accuracy and integrity of data content is difficult or almost impossible. Therefore, the investigation of the quality of traffic relevant AIS data began with development of suitable testing processes for carrying out a plausibility evaluation given the temporal behaviour of AIS data.

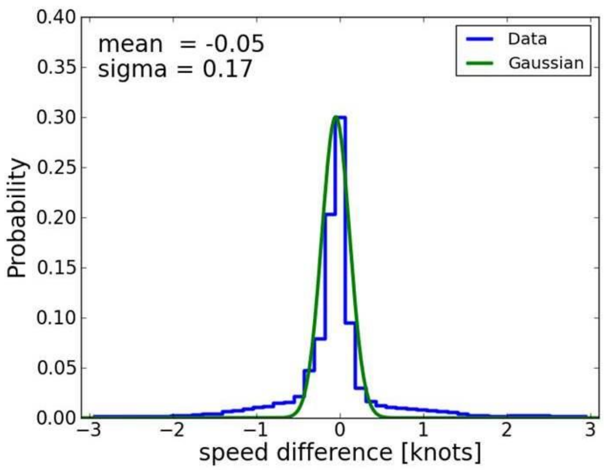

Fig. 40: Histogram of the Differences between Transmitted and Extrapolated SOG Values (blue) and the Best Possible Fit of a Gaussian Distribution

The methods developed are based on the assumption that the behaviour of moving ships can be described by a linear model for short time periods and/or distances. In order not to violate this assumption, only AIS messages whose consecutive ship positions were no further than 500 m apart were investigated. The 500 m limit was only exceeded by a few AIS messages, so this assumption did not place any significant limitations on the analysis.

The quality investigations focussed on dynamic AIS data such as speed over ground (SOG), course over ground (COG), true heading (THDG) and update rate. Fig. 39 shows schematically how two consecutive AIS messages of a vessel are associated in time with its position and movement. In this way, the average SOG and COG values can be calculated by using two consecutive positions with respect to their time references. In the case of weak currents and forward moving objects, COG also describes the THDG of the ship. Deviations between transmitted and extrapolated values of specific AIS data are to be expected in principle. They result from the linear modelling approach, the error behaviour of the measurement process, and the accuracy limits of the numeric depiction of the data. The respective data will be classified as not plausible in the event that the measured and extrapolated values deviate very greatly from each other.

More than 100 million AIS messages that have been collected and archived by the Helsinki Commission (HELCOM) in the Baltic could be used as a data base for the plausibility study that was carried out. Fig. 40 shows the histogram of SOG differences observed on 13 September 2011. It can be deduced from this plot that the deviations in 90% of the cases were less than 0.35 knots (double standard deviation). Clearly, greater deviations of several knots, however, were also observed on this day. If one assumes that the histogram depicts the errors resulting from linearization well, outliers of this type are to be viewed more likely as due to poor sensor quality. This type of critical value could also possibly lead to errors in traffic situation assessment.

Long-time analyses showed, the daily recorded statistical parameters of the deviations analysed hardly varied within a month (see Fig. 41). As is shown as the example based on SOG deviations, no significant differences can be seen between the results from the Rostock harbour and the Baltic Sea.

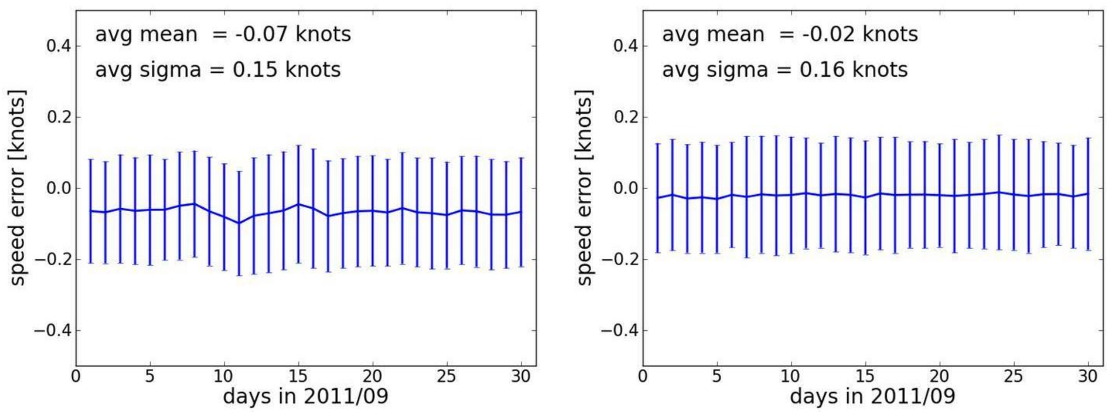

Fig. 41: Mean and Standard Deviation of SOG Differences Determined Daily in September 2011: in the port of Rostock (left) and on the Baltic (right)

During the evaluation of the entire data set for the month of September, the frequency of "default" values was analysed in addition to the frequency of critical values. As already presented, outliers that deviated strongly from the linear prediction were declared critical values (see Heymann et. al. 2012). If, by contrast, "default" values were transmitted, the AIS transmitter indicated that the actual measurements were unusable when the AIS message was composed. Possible reasons for this could be improperly attached or malfunctioning sensors. What is recognisable from the overall statistics (Fig. 42) is that there was a greater probability of both critical and "default" values in the port of Rostock. The increased number of "default" values in port areas can be explained by the switching off of certain sensors when a vessel is moored. The higher probability of critical values resulted from the fact that the inaccuracy of GNSS positions has a greater effect on derived values such as SOG and COG, if – as is to be expected in a harbour – the users of the traffic system show lower dynamics. Subsequent research is to demonstrate if that is the sole cause or not.

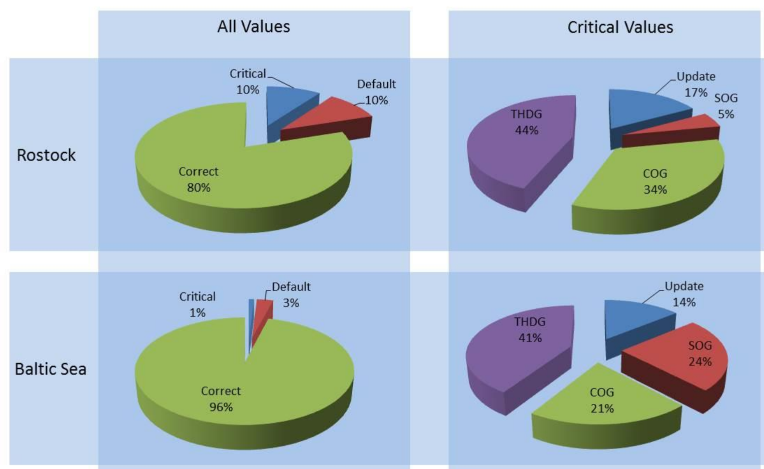

Fig. 42: Statistical Evaluation of all AIS Reports of the HELCOM Data Bank for the Month of September 2011

A processor that works in real time was developed in cooperation with the project "SaMariS". The processor is able to monitor and assess plausibility of AIS data in real time. This is being used within the scope of the DLR-experimental system to assess their usability for determining the traffic situation in the Research Port of Rostock. The system is being used to transmit the data generated by its own AIS receiver to Neustrelitz, where these are analysed with respect to their plausibility with the help of the processor. A web application (see Fig. 43) serves to inform the user about the actual usability and quality of AIS data.

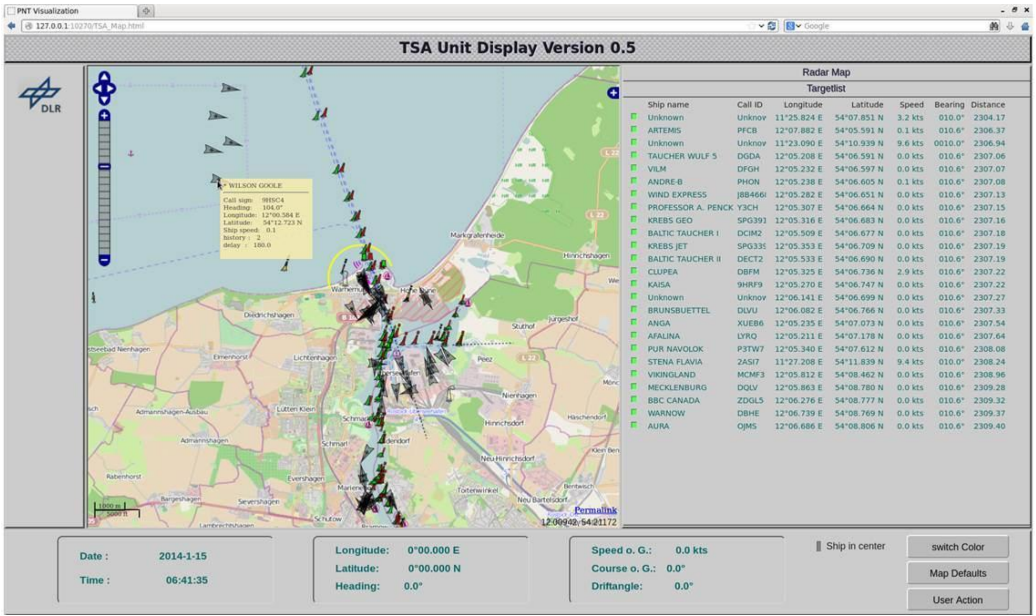

Fig. 43:   Web Visualisation of AIS Monitor in Research Port of Rostock

7.3 Automatic capture of radar images

An automatic integrity assessment of traffic situation relevant data from the most varied of sensors requires that it can be automatically provided and distributed. A performance analysis of ARPA sensors carried out in automatic target detection mode showed that the performance capability of the existing ARPA systems is insufficient for automatic object recognition that enables automatic fusion of AIS and RADAR data and, based on that, integrity assessment of images of the traffic situation. For this reason, it was necessary to find alternative approaches with which RADAR based object recognition and tracking could be improved.

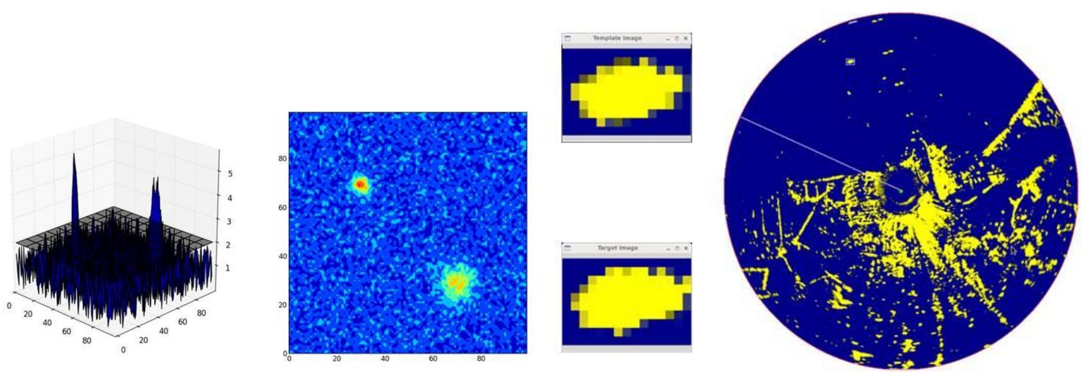

Fig. 44:   Object Detection Process (left); Template Matching Process for Radar Target Tracking (right)

One of the processes investigated produced very promising results. This method involves an object recognition tool used in astronomy that is applied for feature extraction and classification of stars and galaxies. It appears that this procedure can be used, despite lack of characteristics for recognition of maritime targets on radar images. Fig. 44 (left) illustrates the process for object detection. All the pixels whose values stand out significantly from the background noise were identified as object points in the first step. In the second step, neighbouring object points were merged into one object. The template matching process shown in Fig. 44 (right) was used in order to relocate an already detected object in consecutive images – so for a longer duration in RADAR images. Then, for each object identified in the original image, a template was created. The entire scene was investigated in subsequent images in which the objects identified were most similar to those in the template.

Initial results show that this process makes it possible to track objects in a radar image for longer periods of time. Further investigation and development are nevertheless needed to achieve robust and resilient object recognition and tracking in real time, with the ultimate goal of integrity assessment by means of AIS and RADAR data fusion.

7.4 AIS fusion (object association)

As already presented in the previous section, object recognition and tracking are two significant tasks that must be permanently coordinated to guarantee collision avoidance. In order to use complementary data sources for integrity assessment, it must first be clarified how AIS and RADAR objects can be associated with each other. Fundamentally, radar target data, provided as bearing and range can be converted into an absolute position with the help of own ship position through Gauss-Krüger coordinate transformation. This produces a direct comparison with the absolute position statements in AIS data. Differences in data rate, time synchronisation, and the achievable accuracy and usability of position statements, however, mean that an association of AIS and RADAR objects is not so simple and cannot always be achieved. In principle, an attempt at object association can produce the following results: ARPA targets are unusable for certain AIS targets, an AIS target has an ARPA target that is an exact fit, an AIS target has several ARPA targets in the vicinity, or an ARPA target exists without a fitting AIS target.

Experimental investigations were to aid in discovering which methodological approaches would allow fusion of AIS and ARPA data and which boundary conditions (thresholds, error models) were suitable. A measurement survey was taken aboard BALTIC TAUCHER II during which the fully automatically logged radar target data from ARPA, own-ship PNT Unit position data, and the AIS messages received from the surrounding traffic system users were all recorded together. All the data were saved in an SQLite database. The twelve-hour survey in the area of the port of Rostock and on the Baltic provided 70,000 AIS and 200,000 ARPA data sets. AIS data from 59 ships were received during the measurement voyage. It was determined that there are AIS targets for which no ARPA targets could be assigned. There were also few ARPA targets for which no corresponding AIS target was found. The average usability of ARPA for an AIS target was 56% (41%-46% in port, 82% at sea). The average distance between ARPA and AIS targets was around 150±30 m, and on the one hand, it could be explained by the low position accuracy of RADAR targets. On the other hand – due to varying update rates and time references – there was no exact time synchronisation of AIS and ARPA data. Therefore, it is not strange that an AIS target could by all means be assigned several ARPA targets in the vicinity. Only if an association of AIS and ARPA objects was successful, can integrity information for object recognition be definitely devised from it. Nevertheless, this integrity statement refers only to position accuracies within a vicinity of 150±30 m.

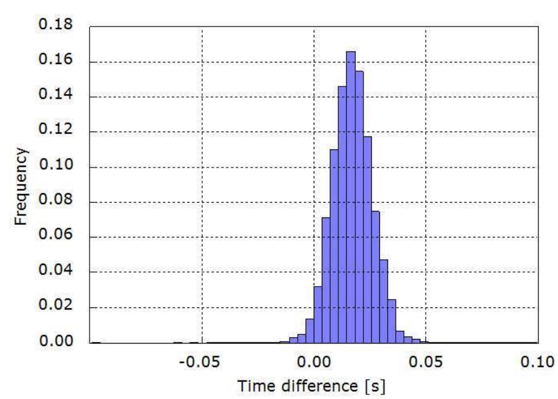

Fig. 45: Histogram of AIS Time Lags

During the measurement voyage it became clear that the usability of ARPA based target recognition was dependent on the surroundings. In areas where a great deal of radar echo interference could be expected, the object detection performance capability of ARPA decreased. Further research has been initiated in order to better estimate the partial errors caused by timing in relative position errors of associated AIS and ARPA targets.

Fig. 45 shows that dynamic ship data with an average time lag of 16 ms for an AIS receiver (here a shore-side AIS receiver in the experimental system of the Research Port at Rostock) are usable. For vessels moving at a rate of 20 knots, this time lag implies a position error in the AIS system of around 16 cm. Relative to the average distance between AIS and ARPA targets, the position error can be classified as negligibly small.

Results of a runtime experiment related to ARPA are shown in Fig. 46. The radar data were saved as TTM sets and contained the range and bearing of the radar targets. Every TTM set has a UTC time stamp generated by ARPA. The on-board ARPA runtime is the time difference between the UTC time stamp and the point in time when a TTM data set was logged in the database (as a symbolic application). On average, runtimes of 3 s were determined that had a position error of around 30 m if ships were moving at a speed of 20 knots. This error in the association of ARPA and AIS objects is not negligible. How and if these errors can be reduced is a subject for further development. Nevertheless, it appears that further causes of error must exist for which improved object association must be suitably managed.

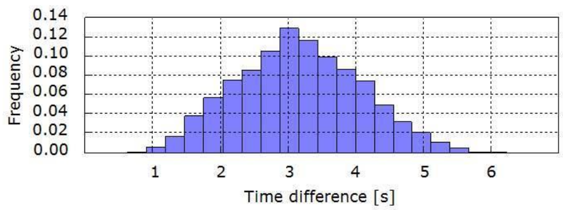

Fig. 46: Histogram of Time Lag that Arises within the ARPA System

8. SUMMARY AND OUTLOOK

8.1 Summary and project results

The research and development tasks carried out in the MVT project were directed at the topics of data and system integrity, meaning addressing the question of how systems and data critical to safety are analysed and evaluated with respect to their usability in the maritime traffic system. For this reason, the planned R&D activities were in line with the "e-Navigation" strategy of the IMO. They were focused on the high priority user requirement for monitoring and indicating actual usability of data and systems critical to safety. The maritime PNT system, including use of GNSS and traffic situation logging and evaluation were classified as equally critical to safety. Only if the data provided are complete and of the quality required (accurate enough, current, and assessed for integrity among other things), can the risk of collision and grounding continue to decrease.

Two complimentary studies of integrity in the maritime traffic system were carried out in the first project phase. The "top down" study investigated which integrity concepts had already been developed and in some cases implemented for the entire maritime traffic system. The "bottom up" study looked for technological approaches to how the integrity of data relevant to navigation and individual sensors, components, and services used were indicated and taken into consideration in decision-making processes. In this context, performance standards, implementation recommendations, and directives of the IMO, IALA, and other bodies were also analysed in order to ascertain how far the responsibilities for and obligations to monitor integrity, and in the provision and use of integrity data, have already been codified.

The results of both concept studies were rather sobering, particularly when one considers the state of technology and opportunities that exist today for monitoring and managing integrity. Both studies confirmed there is ample need to catch up and that R&D potential exists in the area of integrity. This applies equally to both the maritime traffic system in general and for PNT and TSA systems in particular. A significant conclusion drawn from the concept studies was to concentrate exclusively within the project framework on the development, implementation, and analysis of integrity monitoring functions in the areas of GNSS augmentation, PNT, and TSA.

- In the topic area of "GNSS Augmentation Services", the Maritime Ground Based Augmentation System (MGBAS) in the research port of Rostock was expanded. This was done, on the one hand, to provide and test GALILEO or GPS/GALILEO-based DGNSS services in addition to GPS services for future use. On the other hand, the MGBAS was augmented as a performance monitor and reference system to investigate experimentally the performance capabilities and usability of existing PNT services such as the IALA Beacon DGNSS as well as new PNT processes. A RTCM3+ correction signal developed specially at the institute allows the operationally available MGBAS system to provide associated integrity information in addition to phase-based DGNSS corrections in service area of the research port of Rostock. It could be proven experimentally that by using MGBAS services accuracy requirements in the dm vicinity were achievable while simultaneously evaluating integrity – as is required for automatic docking. Consistent furthering of these tasks requires investigating the advantages of multisystem and multifrequency procedures in combination with several GNSS systems (GPS, GLONASS, GALILEO, COMPASS) and integrating the associated services in MGBAS as monitors.

- In the PNT Unit topic area, the first demonstrator (V1.0) that works on the basis of a multisensor-based data processing unit was developed, evaluated, and presented on board ship in real-time operation. The concept of the ship-side PNT Unit we developed was discussed and consolidated in conjunction with the project on a national and international level within the scope of our cooperation with the "e-Navigation" committee of the IALA and its "e-Navigation" counterpart at the BMVI. What is worthy of mention is that improvement of reliability, resilience, and integrity of the bridge equipment, and navigation information was prioritised in the Strategic Implementation Plan (SIP) for "e-Navigation", and in this context, provision of resilient PNT processes is to be used as a risk control option. This makes it clear that a demand for consistent furthering of R&D work within the area of these issues exists. An important goal for future work will be above all to standardise the PNT Unit and implement it as a modular component in the Integrated Navigation System (INS) of vessels.
- The "traffic situation" topic area investigated whether the quantity and quality of currently usable AIS and RADAR data are sufficient for achieving a comprehensive, reliable description of the traffic situation. The first analytical methods for doing this were developed, and used on widely varying, more comprehensive data sets (e.g. HELCOM, BSH). Plausibility tests of AIS data showed that AIS indeed conforms to the system as it works, but can in reference to special navigation parameters provide significant, erroneous information. The methods tested could be verified as an automatically functioning processor for determining the plausibility of AIS data. They could also be implemented in the experimental MGBAS system. This now allows the plausibility testing of AIS data in real time to take place in the vicinity of the Rostock research port. It also provides information about whether navigation relevant ship-side data are outside of a defined threshold or not. The preeminent objective of fusing AIS data with RADAR data in order to evaluate the integrity of images of the traffic situation was only partially achieved. Among the reasons for this were problems that lay within the different synchronicity, usability, and accuracy of both data streams and for which suitable compensation was needed. Beyond that, the processes of automatic recognition and tracking of dynamic radar targets were developed in order to achieve fusion, e.g. on the foundation of Bayesian estimation procedures.

Parallel to the actual research work, for the duration of the project, significant advances could be made in networking on a national and international level:

Nationally we work very closely with the German federal government’s Waterways and Shipping Administration, (*Wasser- und Schifffahrtsverwaltung des Bundes*), and in particular, with the Office of Traffic Technologies (Fachstelle für Verkehrstechnologien, FVT) and the Federal Maritime and Hydrographic Agency (*Bundesamt für Seeschifffahrt und Hydrographie, BSH*). Significant areas of cooperation were joint papers as well as publications regarding PNT and TSA. For example, the BSH provided simulated RADAR and AIS data and allowed the use of the DENEB research vessel for generation of test data. Another key contribution during the project was our cooperation within the network for maritime applications at the research port of Rostock. Through this cooperation, many contacts to companies and research institutes such as SIGNALIS, Marinesoft, HERO, EADS RST, Hochschule Wismar (HSW), the University of Rostock, und Septentrio among others, took place that in part led to the initiation of further joint projects. The research port of Rostock was the required test and development environment for the project that allowed experimental demonstration of the feasibility and performance capability of the developments. The research port will therefore also play an important role as a testing area in future. Membership of the research port in the BMVI's SATNAV-Forum could be permanently guaranteed for national coordination of GNSS relevant research and development activities in the maritime sector.

IALA, of which we have been an associated member since 2011, was a decisive catalyst for our international networking and the consolidation of our concepts primarily in the area of PNT. Our cooperation with the IALA took place within framework of the "e-Navigation" Committee and focused on the development of architecture of the maritime PNT system, and, from 2013 onwards the development and use of "e-Navigation" test beds. Submission papers for various IMO meetings were prepared as a result of this work. These presented concepts for discussions, supplied drafts for new or reworked performance standards and implementation recommendations, or commented on parallel development proposals.

8.2 Outlook for further research and development

From 2014 to 2018, the "Automated Aids for Safe and Efficient Vessel Traffic Processes" (A++Set) will continue the research and development work started during the MVT. A++Set is dedicated to furthering the methodological and conceptual development of the system for supplying position, navigation, and time data (PNT) and the system for assessing and evaluating the traffic situation (TSA). The primary aim being pursued will be to achieve a technically detailed architecture with a consolidated integration concept for both systems. Within this context, particular attention will be paid to the automation of services, processes, and systems including internal integrity monitoring.
Within the PNT topic area, expansion of the PNT Unit (V2.0) and, as a complement to that, the further development of PNT relevant services will be pursued.

- The process-technology expansion of the PNT Unit will pursue investigation of the usability and performance capability of new and combined PNT processes, resulting from further development and modernisation of GNSS (e.g. GPS2, Galileo, COMPASS) and associated GNSS receivers, the use of new terrestrial navigation services (e.g. eLoran, R-Mode), the inclusion of complementary sensors (e.g. Sonar), and specific hybridisation and low-cost sensor developments. The resulting consequences for system architecture, interfaces (PNT and integrity data in the maritime data model) and methods to be used will be worked out and used for the intended standardisation of the PNT Unit.
- Expanding the PNT relevant service portfolio results directly from two complementary conceptual approaches. On the one hand, augmentation services provided for new and modernised GNSS signals can contribute to increased accuracy and integrity. On the other hand, there is a desire in the maritime users' community to have available alternative radio navigation systems to allow continued determination of position in the case of serious disruptions in GNSS. Further experiments will address the question of the extent to which augmentation services for new GNSS signals, among other things in combination with back-up services such as eLoran and R-Mode, help to reduce the vulnerability of the PNT system. The scope of this research will also address the question of whether PNT relevant safety information (PSI) can be provided by shore-side services to lead to a gain in accuracy and integrity during ship-side PNT determination.

The Traffic Situation Assessment (TSA) topic area will dedicate itself more intensively to data analysis and development of associated methods of analysis. These will be used to make the spatial and temporal behaviour of errors in AIS and RADAR data describable and allow the modelling of causal dependencies. The aim is the certain identification of such errors and to better assess their effects on decision-making processes (e.g. for collision avoidance.

- The development work to associate AIS and ARPA based traffic objects started in the MVT project will be continued to also assess the integrity of traffic situation images in future. This will require the provision of a suitable process that will enable automatic detection of traffic objects from ARPA data.
- How the completeness and integrity of traffic situation images can be improved by means of network based or cooperative methods will be explored initially within the scope of conceptual developments. The first approaches to solutions in this context will involve observation of synthetic generation of AIS messages and the automatic comparison of traffic situation images between the different participants moving within the system with respect to their increase in value and feasibility.

Beyond the two main emphases, PNT and TSA, a further supplementary study is planned which, on the one hand, will investigate how far navigation relevant data (e.g. PNT, AIS, RADAR) can be used complementarily in order to build intermodal transport chains and also control traffic using a superordinate management system. On the other hand, how information from transport and logistics could help the carriers to operate vessels more efficiently and use them to capacity will also be analysed. A study focus will be existing and expandable data interfaces used for information exchange between ships and stakeholders of the maritime and other traffic systems.

ANNEX A LIST OF PUBLICATIONS

[2009-09]	Noack, Thoralf and Engler, Evelin and Klisch, Anja und Gewies, Stefan und Minkwitz, David (2009) *Integrity concepts for future maritime Ground Based Augmentation Systems.* 2nd GNSS Vulnerabilities and Solutions 2009, 2.-5. Sep. 2009, Baska, Kroatien.
[2009-10A]	Noack, Thoralf und Engler, Evelin und Klisch, Anja und Gewies , Stefan und Becker, Carsten (2009) *Statistical GNSS performance assessment as part of the ALEGRO Ground Based Augmentation System inside Research Harbour Rostock.* In: Proceedings of XIII International Scientific and Technical Conference on Marine Traffic Engineering, Seiten 311-317. Maritime University of Szezecin. XIII International scientific and technical Conference on Marine Traffic Engineering, 19.-22. Okt. 2009, Malmö, Schweden. ISBN 987-83-89901-38-5
[2009-10B]	Hirrle, Angelika und Engler, Evelin (2009) *GNSS Signal Error Part Determination for Satellite Based Navigation within Maritime High Precision Applications.* Scientific Journals of the Maritime University of Szczecin (18(90)), Seiten 48-53. Maritime University of Szczecin. ISSN 1733-8670.
[2009-11]	Engler, Evelin und Minkwitz, David und Noack, Thoralf und Klisch, Anja und Gewies, Stefan und Becker, Carsten (2009) *Integritätsmonitoring für ein maritimes, phasenbasiertes Ground Based Augmentation System (GBAS).* DGON PosNav 2009 Proceedings.
[2010-04]	Minkwitz, David und Engler, Evelin und Schlüter, Stefan (2010) *Maritime GBAS: Improvement of Positioning Accuracy and Reliability by Integrity Monitoring.* CERGAL 2010, 28.-29. Apr. 2010, Rostock, Deutschland. Volltext nicht online.
[2010-09]	Evelin Engler (2008), IALA Enav8: *Towards an international recognized Maritime Radio Navigation Integrity Concept* (INF Paper), 20.-24.9.2010, Paris, France
[2010-12A]	Ralf Ziebold, Zhen Dai, Thoralf Noack, Evelin Engler (2010), *Concept for an Integrated PNT-Unit for Maritime Applications.*, NAVITEC 2010, 8.-10.12.2010, Noordwijk, Netherlands
[2010-12B]	Stefan Schlüter, David Minkwitz, Angelika Hirrle (2010), *Investigations of Decorrelation Effects on the Performance of DGNSS Systems in the Baltic Sea.*, NAVITEC 2010, 08.-10.12.2010, Noordwijk, Netherlands
[2011-06]	Ralf Ziebold, Zhen Dai, Thoralf Noack, Evelin Engler (2011), *Concept for an Onboard Integrated PNT Unit*, CRC Press. TransNav 2011, 15.-17.6.2011, Gdynia, Poland. ISBN 978-0-415-96112-3
[2011-eNav9-A]	Evelin Engler, Ralf Ziebold, Michael Hoppe*, Johann Winell**, Jan-Hendrik Oltmann*** (2011), *Development of Maritime Integrated PNT System (Input Paper)*, IALA Enav9, 14.-18.3.2011, Kopenhagen, Denmark, *FVT Koblenz, **STA Norrköping, ***WSD Nord
[2011-eNav9-B]	Jan-Hendrik Oltmann*, Evelin Engler, Ralf Ziebold, Michael Hoppe** (2011), *ADDENDUM.1 to Development of a Maritime Integrated PNT System: Graphical representation of Integrated PNT System and the PNT Unit as a future INS Module*, IALA Enav9, 14.-18.3.2011, Kopenhagen, Denmark, *WSD Nord, **FVT Koblenz
[2011-06]	Dai, Zhen und Ziebold, Ralf und Born, Alexander und Engler , Evelin (2012) *Heading-determination using the Sensor-fusion Based Maritime PNT Unit.* In: IEEE/ION PLANS 2012. IEEE/ION PLANS 2012, Myrtle Beach, South Carolina, USA.
[2011-09]	David Minkwitz, Jamila Beckheinrich, Achim Hornbostel (2011), *Installation of an Experimental Galileo GBAS at Research Port Rostock*, ISIS 2011, 15.-16.09.2011, Hamburg, Germany
[2011-ENAV10]	Evelin Engler et.al. (2011), *Development of Maritime Integrated PNT System* (Input Paper) + PPT Presentation , IALA Enav10, 26.-30.9.2011
[2011-10A]	Paweł Banyś, Thoralf Noack, Evelin Engler, Stefan Gewies (2011), *The Role of Integrity for Maritime Traffic Situation Assessment*, MTE 2011, 12.-14.10. 2011, Swinoujscie, Poland
[2011-10B]	Ralf Ziebold, Zhen Dai, Thoralf Noack, Evelin Engler (2011), *The on-board maritime PNT Module –Integrity monitoring aspects and first experimental results*, MTE 2011, 12.-14.10. 2011, Swinoujscie, Poland
[2011-11]	Dai, Zhen und Ziebold, Ralf und Engler, Evelin (2011) *The on-board maritime PNT Module – a focus on integrity monitoring and preliminary results.* European Navigation Conference GNSS (ENC GNSS 2011), 28.Nov-2.Dez.2011, London, United Kingdom.
[2012-book]	Dai, Zhen (2012) *MATLAB software for GPS cycle-slip processing.* GPS Solutions, 16 (2), Seiten 267-272. Springer Verlag. DOI: 10.1007/s10291-011-0249-1 . ISSN 1080-5370.
[2012-05]	Ziebold, Ralf und Dai, Zhen und Noack, Thoralf und Engler, Evelin (2012) *The on-board maritime PNT Module – Concept and preliminary experimental results.* In: Proceedings of WMTC 2012.

	Rozhdestvesnky, K.V. World Maritime Technology Conference 2012, 29.5. - 1.6.2012- , St. Petersburg, Russland.
[2012-09]	Minkwitz, David und Zachhuber, Philipp und Engler, Evelin (2012) *MGBAS: RTK Service Validation and Service Integration Approach for a PNT Unit*. ISIS 2012: International Symposium Information On Ships, 30. - 31. Aug. 2012, Hamburg, Deutschland.
[2012-10]	Vierhaus, Ingmar und Born, Alexander und Minkwitz, David (2012) *Challenges to PNT and driver assistance systems in inland water.* In: Proceedings of the 14th IAIN Congress 2012 Seamless Navigation (Challenges & Opportunities), Seiten 1-10. AIN. The 14th IAIN Congress 2012 Seamless Navigation (Challenges & Opportunities), 01-03 October 2012, Cairo, Egypt.
[2012-12a]	Vierhaus, Ingmar und Born, Alexander und Engler, Evelin (2012) *Trajectory optimisation for inland water vessels based on a next generation PNT-Unit.* IEEE. 6th ESA Workshop on Satellite Navigation Technologies, 5-7 Dec 2012, Noordwijk, Netherlands. ISBN 978-1-4673-2010-8. ISSN 2325-5439
[2012-12B]	Gewies, Stefan und Becker, Carsten und Noack, Thoralf (2013) *Deterministic Framework for parallel real-time Processing in GNSS Applications.* In: IEEE Xplore. IEEE. NAVITEC 2012, 05. - 07. Dez. 2012, Noordwijk, Netherlands. ISBN 978-1-4673-2010-8. ISSN 2325-5439
[2013-01]	Ziebold, Ralf und Dai, Zhen und Lança, Luis und Minkwitz, David und Zachhuber, Philipp und Noack, Thoralf und Engler, Evelin (2013) *Resilient PNT: From PNT-Unit concept to first realization.* E- Navigation Underway Conference, 29-30.1.2013, Fähre Kopenhagen-Oslo.
[2013-03]	Ziebold, Ralf und Dai, Zhen und Lança, Luis und Noack, Thoralf und Engler, Evelin (3013) *Initial Realization of a Sensor Fusion Based Onboard Maritime Integrated PNT Unit.* TransNav : International Journal on Marine Navigation and Safety of Sea Transportation, Journal Vol.7 (No. 1- March 2013), Seiten 127-134. Faculty of Navigation Gdynia Maritime University. DOI: 10.12716/1001.07.01.17. ISSN 2083-6473.
[2013-04]	Heymann, Frank und Noack, Thoralf und Banyś, Paweł (2013) *Plausibility analysis of navigation related AIS parameter based on time series.* ENC2013, Wien.
[2013-06]	Heymann, Frank und Noack, Thoralf und Banyś, Paweł und Engler, Evelin (2013) *Is ARPA Suitable for Automatic Assessment of AIS Targets?* In: MARINE NAVIGATION AND SAFETY OF SEA TRANSPORTATION, ADVANCES IN MARINE NAVIGATION (1). Taylor & Francis Group, London, UK. Seiten 223-232. ISBN 978-1-138-00106-0.
[2013-11]	Engler, Evelin und Ziebold, Ralf und Noack, Thoralf (2013) *Maritimes PNT-System: Ansätze für ein koordiniertes Integritätsmonitoring und -management.* PosNav Conference Proceedings, DGON

ANNEX B LIST OF PRESENTATIONS AT CONFERENCES AND WORKSHOPS

[2010-06]	Thoralf Noack, Evelin Engler (2010), *Integrity Concepts for Maritime Ground Based Augmentation Systems*, 7th ALLSAT Open 2010, 17.06.2010, Hannover, Germany
[2010-02]	Engler, Evelin und Schlüter, Stefan (2010) *Future accurate navigational systems in port areas.* Internationaler Workshop der Maritime Universitiy Szczecin, 25.02.2010, Szczecin, Poland.
[2010-06]	Klisch, Anja und Noack, Thoralf (2010) *Integrity as Part of E-Navigation.* Baltic Future, 04.-06.05.2010, Rostock
[2010-06]	Noack, Thoralf und Engler, Evelin (2010) *Integrity Concepts for Maritime Ground Based Augmentation Systems.* 7th ALLSAT Open 2010, 17.06.2010, Hannover.
[2011-05]	Evelin Engler, Thoralf Noack (2011), *Maritime Integrated PNT System*, Satellitenbasierte Positionierung und deren maritime Anwendung, 04.05.2011, Rostock, Deutschland
[2012-01]	Engler, Evelin und Hoppe, Michael und Ziebold, Ralf und Dai, Zhen und Noack, Thoralf (2012) *Resilient PNT: Vision and Mission.* E-Navigation Underway 2012, 18.01. - 20.01.2012, Kopenhagen/Oslo.
[2012-03]	Noack, Thoralf und Engler, Evelin und Ziebold, Ralf und Dai, Zhen (2012) *Resilient Position, Navigation and Timing (PNT) Unit as part of the maritime Integrated Navigation System (INS).* Munich Satellite Navigation Summit 2012, 13.-15.3.2012, München.
[2012-06A]	Minkwitz, David (2012) *Mathematical Approaches in GNSS Positioning and Integrity Monitoring*. Freiberger Forschungsforum 2012 - 63. Berg- und Hüttenmännischer Tag, 13.-15. Juni 2012,
[2012-06B]	Ziebold, Ralf (2012) *Multisensor-Integration auf Schiffen am Beispiel einer integrierten PNT - Unit.* ALLSAT open: Multi Sensor Anwendungen mit GNSS, 21.6.2012, Hannover.
[2012-09A]	*Noack, Thoralf und Engler, Evelin und Hoppe, Michael (2012)* A new modular and open concept for the maritime Integrated PNT System. *BIT 3rd Annual World Congress of MarineTech Summit-2012, 19.-22.9.2012, Dalian, China.*
[2012-09B]	Ziebold, Ralf (2012) *Nautical Space Applications.* Polish-German Space Research Symposium at ILA Berlin Air Show 2012, 13.Sept. 2012, Berlin, Deutschland. (nicht veröffentlicht)
[2012-eNAV12]	Ziebold, Ralf und Dai, Zhen und Noack, Thoralf und Engler, Evelin (2012) *The on-board maritime PNT Module – Concept & Status of Realization as a Demonstrator.* IALA 12th Meeting of the e-Navigation Commitee , 24-28.Sept. 2012, St. Germain en Laye, Frankreich.
[2013-01]	Ziebold, Ralf und Dai, Zhen und Lança, Luis und Minkwitz, David und Zachhuber, Philipp und Noack, Thoralf und Engler, Evelin (2013) *Resilient PNT: From PNT-Unit concept to first realization.* E-Navigation Underway Conference, 29-30.1.2013, Fähre Kopenhagen-Oslo
[2013-05]	Engler, Evelin und Ziebold, Ralf und Noack, Thoralf (2013) *Herausforderung an die maritime Kommunikation: Integritätsüberwachung in verteilten Systemen am Beispiel des PNT-Systems.* DGON Schifffahrtstage 2013/1, 15. Mai 2013, Hamburg / Deutschland.
[2013-10a]	Zachhuber, Philipp und Herrera Pinzon, Ivan Dario (2013) *Towards Collision-Free Navigation on Inland Waterways based on reliable Position, Navigation and Time (PNT) Data.* Next Generation Forum, 23.-24. Okt. 2013, Stuttgart.
[2013-10B]	Heymann, Frank (2013) *Traffic monitoring - Automatic radar target tracking.* Next Generation Forum 2013, 23.-24. Okt. 2013, Stuttgart

ANNEX C REFERENCES

[Cruise-2014]	http://www.cruisemarketwatch.com/growth/
[DNV-2011]	Det Norske Veritas: Safety trends reversed. Press release 05/2011, http://www.dnv.com/press_area/press_releases/2011/safetytrendreversed.asp (Download 23.09.2011)
[Eurostat-2013]	Eurostat Pocketbooks: Energy, transport and environment indicators. 2013 edition. ISSN 1725-4566 (download: http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-DK-13-001/EN/KS-DK-13-001-EN.PDF)
[Grooves 2007]	P. D. Groves, Principles of GNSS, Inertial, and Multi-Sensor Integrated Navigation Systems (GNSS Technology and Applications). Artech House Publishers, 2007.
[IALA-R121-2004]	IALA Recommendation R-121 on the Performance and Monitoring of DGNSS Servises in the Frequency Band 283.5-325 kHz. Edition 1.1, December 2004)
[MSC-2006]	Maritime Safety Committee of IMO: Report of the maritime Safety Committee on its eighty-first Session (MSC 81/25). 1st June 2006.
[MSC-2008]	Maritime Safety Committee of IMO: Report of the maritime Safety Committee on its eighty-fifth Session (MSC 85/26). Annex 20: Strategy for the Development and Implementation of eNavigation. 19th December 2008.
[NAV54-2006]	Sub-Committee on Safety of Navigation: Development of an E-Navigation Strategy. Report from the e-Navigation Correspondence Group. NAV54/13, 28. March 2006.
[Nav58/6/1-2012]	Development of an e-navigation strategy implementation plan: Proposed architecture for the provision of resilient PNT data. Submitted by Germany (30. March 2012).
[NCSR1/9/2-2014]	Development of an e-navigation strategy implementation plan: Review and modernization of maritime PNT system. Comments on the report of the e-navigation Correspondence Group. Submitted by Germany (16. April 2014).
[SOLAS]	http://www.imo.org/About/Conventions/ListOfConventions/Pages/Default.aspx
[UNCTAD-2012]	United Nation Conference on Trade and Development: Review of Maritime Transport 2012. ISBN 978-92-1-112860-4.
[IMO-A.915(22)]	IMO: Revised maritime Policy and Requirements for a future Global Navigation satellite System (GNSS), 22.01.2001, A22/Res.915, (http://www.imo.org, Download 01.10.2008)

ANNEX D IMAGE SOURCE

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