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Challenges to PNT and driver assistance systems in inland water

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ABSTRACT

This paper discusses the basic concepts of a driver assistance system as well as the utility of a Position, Navigation and Timing (PNT) Unit for inland water vessels. In the context of the PNT-concept in inland water traffic, first analyses of data collected during measurement campaign at the Moselle River will be presented. It will be shown that the application of GPS in combination with the used dual frequency Real-Time Kinematic (RTK) software entails issues complicating the provision of reliable, accurate, continuous and therefore integer position, navigation and timing (PNT) data for safety critical manoeuvers as formulated by the International Maritime Organization (IMO).

KEYWORDS: Precise Positioning, Reliable Navigation, PNT-Unit, Integrity, Driver assistance system, Inland water traffic

1 INTRODUCTION

Transport capabilities are a key precondition to an efficient and smoothly running economic system. In the European economic area the inland traffic carriers are road, rail and inland waterways. Several studies that examine the cost per ton-mile ratio of these carriers arrive at the conclusion that inland waterways are the most efficient means of freight transport [PLANCO 2007, Transport Research Board 2002]. This assessment is made for direct transport costs as well as external costs such as noise and air pollution [U.S. Government Accountability Office 2003].

Inland waterways as a sustainable and competitive means of transport have been recognized by the European Commission through the programme NAIADES as well as by the German Government in the context of the national 'Nachhaltigkeitsstrategie' (Sustainability Strategy), aiming to increase the percentage of goods transported via inland waterways to 14 % until 2015.

With the consequent increase in traffic, new and advanced traffic management systems and technologies will be necessary, to aid maintain smooth, safe and efficient passage along the waterways. Basis of these systems is the knowledge of navigational parameters such as position, heading, and speed over ground of the own vessel as well as other relevant traffic along the waterways.

The utility of Global Navigation Satellite Systems (GNSS) in maritime applications has been widely recognized over the last decades to deliver navigational parameters, and is today an essential part of almost any maritime navigational or tracking solution. This is on the one hand due to favourable reception conditions on open water, and on the other hand to the relatively low accuracy requirements to navigation on the open sea.

When it comes to inland waterways, GNSS has been recognized as an important tool for the measurement of navigational data and position, but in critical situations navigation by sight as well as radar-imaging are considered as the standard approaches. While radar is a powerful aid to a skilled pilot, the automated analysis of the data for advanced driver assistance applications proves difficult.

In this context, a reliable GNSS-based navigational solution is a possible basis for the implementation of applications for advanced assistance during berthing as well as bridge and lock passing. However, exactly these applications pose a challenge to a GNSS-based positioning solution, since the areas that are critical to navigation are in many cases also those with restricted reception conditions.

One of the goals of the German Federal Ministry of Economics and Technology funded project ‘Precise and Integer Localisation and Navigation in Rail and Inland Water Traffic’ (PiLoNav) is the development of a driver assistance system, providing advanced assistance functions tailored for these critical navigation scenarios. Since the driver assistance will be based on absolute positioning (as opposed to relative positioning via radar), accurate position data for all environment structures and the vessel dimensions are required as well as the accurate vessel position. Based on the aggregation of all relevant data, the driver assistance system consists of several modules, creating data products of increasing abstraction levels. The intended final data product is a full plan for an optimal manoeuvre, which is used by the assistance system to propose corrections to the pilot.

To supply the necessary vessel-data, a so-called Positioning, Navigation and Timing-Unit (PNT-Unit) will be designed based on the fusion of GNSS and inertial sensors. Even for crucial manoeuvres in maritime environments, such as automatic docking, the application of a PNT-Unit is widely discussed in literature and committees [IMO 2007a].

The remainder of this paper is structured as follows. Chapter II briefly describes the goals of the project PiLoNav. Chapter III then discusses the concept of a PNT Unit and a driver assistant system in maritime applications with focus on inland water traffic. Before concluding the paper in Chapter V, collected data during a measurement campaign will be analysed in Chapter IV.

2 PROBLEM STATEMENT

The navigational tasks and corresponding requirements to the pilot of a vessel can be divided according to the scenarios the pilot encounters. This paper considers three distinct scenarios. The standard scenario is the passage of an inland waterway clear of particular obstructions. The borders of the waterway are given by physical structures like bulkheads, by fairway limits defined by buoyage or by depth contour lines that can be extracted from nautical charts. The IMO requires an accuracy of 10,0 m for inland waterways [IMO 2001]. As these requirements do not take several scenarios (such as high traffic etc.) into account, the demanded position accuracies within PiLoNav have been increased to 3,0 m in standard waterways. In favourable conditions, this accuracy can be achieved with a standard Differential-GPS Receiver, which is a prevalent part of the navigational equipment of commercial inland vessels. Its use as input to an Electronic Chart Display and Information System (ECDIS) is widespread. Combined with a receiver for the Automatic Identification System (AIS) this combination provides the pilot with an easily accessible overview of the ships position along the fairway as well as the positions of other ships. However, the accuracy of the underlying data cannot be measured in this setup.

The second and third scenario, which both have considerably higher requirements to position and navigational data are the entrance, docking and exiting of locks as well as the passage of bridges. The IMO requires a position accuracy of 0,10 m for maritime automated docking applications [IMO 2001]. This value is also considered as minimum accuracy requirement for inland shipping scenarios like lock and bridge passing [IRIS 2009]. Since inland transport vessels are built specifically to make the best use of the spatial capacity of the locks in the intended waterways, the manoeuvres during lock entrance have to be performed with extremely small clearance distances.

As described below, these accuracy requirements cannot be satisfied with the described common DGNSS equipment. Consequently, the current mode of operation for the mentioned high-accuracy scenarios is based on radar and visual navigation.

It is one of the goals of the project PiLoNav to overcome these limitations and to provide accurate and integer position and navigation data based on GNSS observations. In order to enhance GNSS-based positioning, PiLoNav aims on utilising additional sensor hardware. Moreover, as an additional output PiLoNav delivers integrity information of the determined positional and navigation data. This information will then be used in a driver assistance system, the development of which is also one goal of this project. Both concepts, PNT and the driver assistance system, will be explained in the next section in more detail.

3 CONCEPTS OF PNT-UNIT AND DRIVER ASSISTANCE SYSTEM

3.1 PNT concept

In 2006 the member states of the International Maritime Organization (IMO) started the so-called ´e-Navigation Initiative´. Hereby this initiative is defined as a harmonised collection, integration, exchange, presentation and analysis of maritime information. This collection includes on-board as well as ashore components by electronic means to enhance berth-to-berth navigation and related services for safety and security at sea and protection of the marine environment [IMO 2007a]. In a first step the concept of a shipside PNT-Unit has been developed, taking the user needs ‘improvement of reliability’ and ‘indication of reliability’ as a basis and to satisfy these with respect to the on-board provision of PNT data [IMO 2009]. Currently, vessels subject to the International Convention for Safety of Life at Sea (SOLAS) can either use single sensors to provide the PNT parameter individually or use an Integrated Navigation System (INS) [IMO 2007b]. Both concepts are depicted in Figure 1(a) and (b).

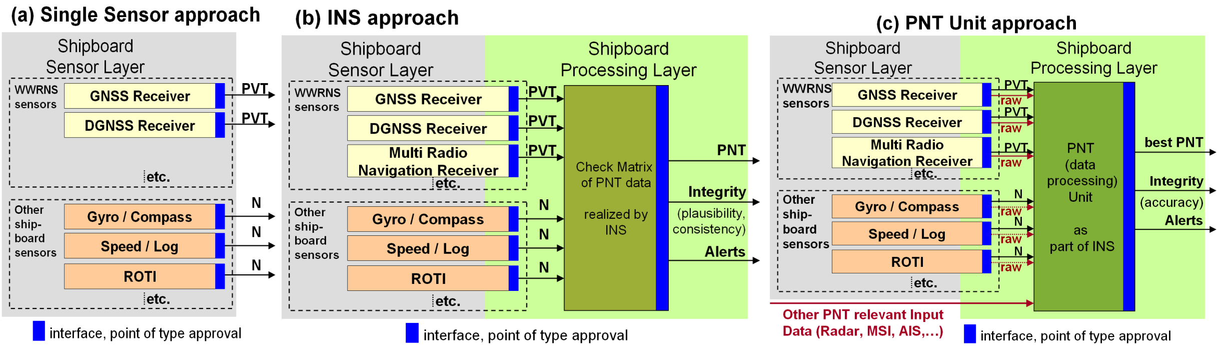

Figure 1: Concepts of single-sensor approach (a), current INS approach (b) and PNT Unit approach (c)

P – Position; V – Velocity; T – Time; N – Navigation; I – Integrity [Dai et al. 2012]

Figure 1(a) represents the single sensor approach. The associated PNT data will be generated and displayed via an interface to applications where the on-board staff has to fuse the information from the different sensors manually. In the current INS approach, the sensors deliver their individually determined PNT output data to a shipboard-processing layer, which is illustrated in Figure 1(b). The INS is performing plausibility checks on the incoming data and consistency checks on different sensors.

Integrity is expected, if plausibility and consistency checks are passed [IMO 2007b]. For instance, the integrity monitoring of heading requires a comparison with a second heading sensor and a comparison with Course Over Ground (COG) information from another sensor. However, the two heading sensors might have common failure modes and hence it is unlikely to detect all possible failures by comparing both sensors. Therefore, the reliability of the INS output cannot be guaranteed even if the plausibility and consistency checks are passed.

In order to overcome these problems, a PNT data processing unit is introduced into the shipboard-processing layer of the future INS, as illustrated in Figure 1(c). By means of sensor fusion techniques, the PNT-Unit integrates all available PNT data and if available also the raw data from the on-board sensors in order to provide the optimal PNT output data. The main advantage of this approach is the capability of improved integrity monitoring by using sensor fusion techniques. Finally, integrity information for each PNT output data is generated based on the error estimation technique [Ziebold et al. 2011].

Whereas the explained PNT concept is mainly focused on maritime traffic, the goal of PiLoNav is to extend this approach to inland water applications.

3.2 Driver Assistance System

For a complete approach to manoeuver planning, apart from the position of the own vessel, data on the surroundings must also be available. One distinguishes between static (bridges, locks, quay walls) and dynamic (position and heading of other vessels) factors. Both have to be analysed to be able to predict the development of the traffic situation and respond in a timely manner. Hereby digital maps such as Electronic Navigational Charts (ENC) can be used as sources of static data, which act as boundary conditions to the calculation of an ideal trajectory. Dynamic factors can be obtained via the Automatic Identification System (AIS). Nevertheless, highly accurate position and navigation information of the own vessel is the basis of a reliable driver assistance system.

If the required data (static and dynamic) is available, optimisation functions can be used to derive an optimised manoeuvre planning [Miele and Wang 2006]. The optimisation and monitoring process is based on following functions:

- situation awareness,
- short-term planning,
- monitoring and adaption.

Based on the aggregation of these data, the driver assistance system provides the elements of the ideal trajectory consisting of velocities and heading information as well as strategic navigational tasks such as encounters with other ships as well as tactical tasks like bridge and lock passing. The goal of this system is, in the first step, to compute a plan for an optimal manoeuvre for the next route section. The planned manoeuvres will be optimised in terms of the criteria safety as well as time- and resource-efficiency.

In the next step, the driver assistance system will supply the pilot with navigational data and comparisons between the provisioned and the actual navigational state, thereby allowing him to closely follow the optimised manoeuvre.

4 MEASUREMENT CAMPAIGN AND DATA ANALYSIS

In October 2011 first measurements have been conducted during a measurement campaign near Koblenz, Germany on the Moselle River. The demonstration area covers all scenarios relevant for the PiLoNav project (see Figure 3). On the one hand Moselle River is, with 11.500 ships in 2010, a busy waterway so that oncoming traffic is common [WSDSW 2010]. Furthermore, three bridges of different height and width span the Moselle River in a small section of only 2 km followed by the lock Koblenz. The first, most westerly bridge is the newest, tallest, 4-lane car bridge ‘Europabrücke’. With a width of 40 m and a clearance height of 13,9 m it covers a relatively wide area. It has to be mentioned that the clearance height may differ with changing water-level. The clearance height mentioned here refers to the day of the measurement campaign. The following bridge is a railway bridge, 25 m wide and a low clearance of only 10,2 m with an oval profile. The profile is an additional challenge on the manoeuvre planning as the clearance height available for crossing the bridge does not only depend on the ships height and the water-level. It also depends on the offset of the ship’s position from the centre line (and therefore the highest point) of the passage. Here, it is not sufficient to calculate one clearance height only. Instead a corridor of safe passage, that becomes narrower for higher ships or water levels, must be calculated for each hull geometry individually. The last ‘Balduinbrücke’, with a width of 10 m and a height of 12,1 m, is small in comparison and higher than the railway bridge. To the west of the three bridges a lock bounds the demonstration area 3 km after the confluence with Rhine River. During the measurement campaign several passes under the bridges and the lock of Koblenz have been realised. Goal of this first measurement campaign was to investigate the usability of GPS (Global Positioning System) including a dual frequency GPS RTK service as standalone localisation technique in order to determine accurate positions and navigational data in these crucial scenarios.

The sensor system consisted of two independent GNSS receivers with individual antennas. Firstly, a Javad Delta receiver connected to a TopCon PG-A1 antenna has been used as fore antenna. Second, an Applanix system was installed at the aft antenna position, where the GNSS part consisted of a Novatel Receiver connected to a second TopCon PG-A1 antenna. The distance between the antennas was 16.48 m. The Applanix system has been equipped with an additional Inertial Measurement Unit (IMU) to ensure a continuous delivery of position data in case of loss of GNSS measurements. Moreover, a standard commercial GPS-compass and rate of turn-indicator were on board. This work focuses on the investigation of GNSS positioning with RTK post-processing only. The correction data required for RTK post-processing has been downloaded from the SAPOS service. In the following, the Javad sensor combination will be denoted as s_1 with antenna a_1 and the Applanix system with s_2 and antenna a_2 respectively.

Data for all of three scenarios has been collected during a test drive of approximately two and a half hours. RTK Solutions were calculated in post-processing using the RTKLib software package in version 2.3.0 [Takatsu 2009].

As the experimental setup does not provide redundant position measurements, which could be used as a reference, some tools will be presented which may help to assess the integrity of our measurements.

4.1 Method of Integrity and Accuracy Assessment

By using the experimental setup explained above, integrity from redundant and by definition uncorrelated measurements cannot be derived. Therefore, a set of extended plausibility checks will be introduced and explained. A plausibility check is a test, whether the received measurement falls inside the interval of plausible values e.g. between 0 and 360 degrees for a heading sensor. If the interval of possible values is derived from knowledge of the experimental setup, special properties of the application and/or previous measurements, one speaks of an extended plausibility check [Ziebold et al. 2011]. For each plausibility check, a relative measure α will be defined as a measure of how well the measurement meets the criteria ($\alpha \leq 1$), or for how much the criteria are violated ($\alpha > 1$). Measurements passing all extended plausibility checks will be defined and marked as integer. This incomplete approach to integrity will not suffice for a real application. However, in this context it is expected to yield a reliable picture of the performance of the chosen sensor system.

The first check is the check of constant height. While the vessel is en route, its height with respect to the Geoid remains constant. The variation in the difference between ellipsoidal and geoid height in the demonstration area amounts to a few millimetres. Changes in height resulting from natural movement of the vessel are expected to remain within a few centimetres. Therefore it is assumed that the main contributions to changes in height are positioning errors. The measure $\alpha^h_{t(n)}$ for a height measurement h_n will be defined as:

$$\alpha^h_{t(n)} = \frac{|h_n - h_{n-1}|}{\beta^h}, \qquad (1)$$

with the tolerance parameter β^h.

The second check tests if the velocity derived from two consequent position measurements surpasses the vessels maximum velocity of 7 m/s. The measure $\alpha^v_{t(n)}$ for the positions p_n and the preceding position p_{n-1} will be defined as:

$$\alpha^v_{t(n)} = \frac{|p_n - p_{n-1}|}{t(n) - t(n-1)} \frac{1}{v_{\max}}, \tag{2}$$

with the time t_n and the ships maximum velocity of $v_{\max} = 7m/s$. In order to measure a precise velocity Doppler measurements are used.

In the third test the three-dimensional distance d between the two antennas is calculated for every position measurement $p_t^{1,2}$ and compared with the true value $\tilde{d}$.

$$\alpha^a_t = \frac{\left\| p_t^1 - p_t^2 | - \tilde{d} \right\|}{\beta^a}, \tag{3}$$

with tolerance parameter β^a.

4.2 Data Analysis and Results

In the first part of the data analysis the extended plausibility checks will be tested. They will be applied to all 9502 two-antenna position solutions collected during the test drive of roughly 2.5 hours. The tolerance parameters used were $\beta^h = 0.15$ m and $\beta^a = 0.1$ m and are derived directly from the accuracy requirements of horizontal and vertical accuracy for critical manoeuvres. The collected data encompassed 13 bridge passages and 6 lock passages, and therefore shows a high density of reception conditions with heavy shadowing.

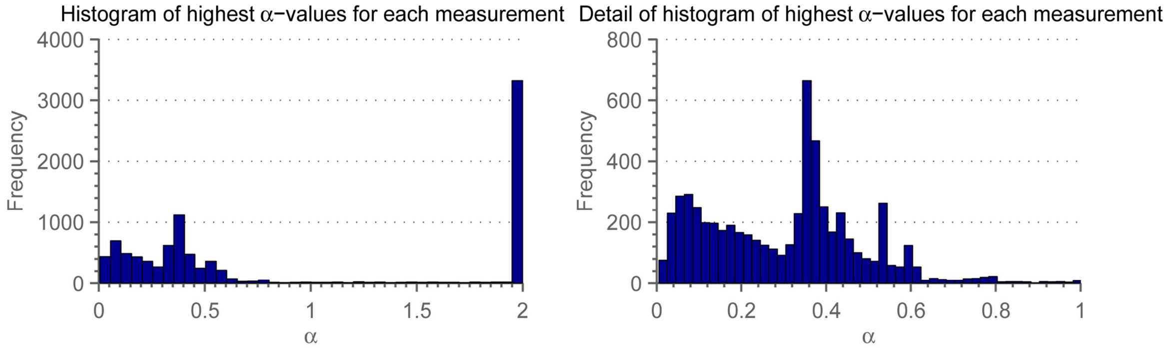

Figure 2: Histograms of highest α-values for all measurements. Values greater two have been summarized at $\alpha = 2$.

For each two-antenna measurement, there are five plausibility checks (velocity and height for each antenna and one distance check). The checks have been applied to the data, and an α-value for each check, according to the definitions (1), (2) and (3), has been received. For each measurement the highest α-values out of the five have been selected. A histogram of the selected α-values is shown in Figure 2, where the right figure outlines an extract of the left figure with refined bins for α-values between 0 and 1. The histogram shows that the measurements fall into two groups. The first group $\alpha \leq 0.6$ contains measurements that clearly passed all checks. The second group $\alpha \geq 2$ contains values that clearly failed at least one of the tests. Only 5% of all measurements do not fall into one of these groups. From this empirical study it can be concluded, that the proposed method of plausibility checks yields clear statements on the quality of the measurements. The choice of the tolerance parameters β within a given range results in very little change. For example, the reduction of $\beta^{h}, \beta^{,a}$ by one third would only affect the combined check result of 1.6 % of all measurements.

Out of all measurements 38 % did not pass at least one of the plausibility checks. Among all measurements, 33 % contained a float or single point solution (SPP) from at least one antenna. Out of these measurements 3 % still passed all plausibility checks. On the other hand, out of the measurements that did not pass the plausibility checks, 15 % resulted from two fixed solutions. In this respect, the extended plausibility checks can be considered as a stronger requirement then simply requiring two fixed solutions.

After these preliminary observations on the performance of the proposed concept of plausibility checks, these checks will be used to analyse the positioning performance for two representative sections of the test drive.

The demonstration area and the trajectory of the investigated test drive are depicted in Figure 3. The test drive starts west of the lock in east-wise sailing to the lock and taking the southern lock chamber. Before entering the lock chamber, the vessel is crossing a small pedestrian bridge. The difference in altitude between headwater and lower course is approximately 4.5 m. After leaving the lock east-wise the three bridges will be crossed before entering the harbour 500 m before the Moselle River opens into the Rhine River. The antenna positions are calculated by RTK post-processing as mentioned in Section 4.

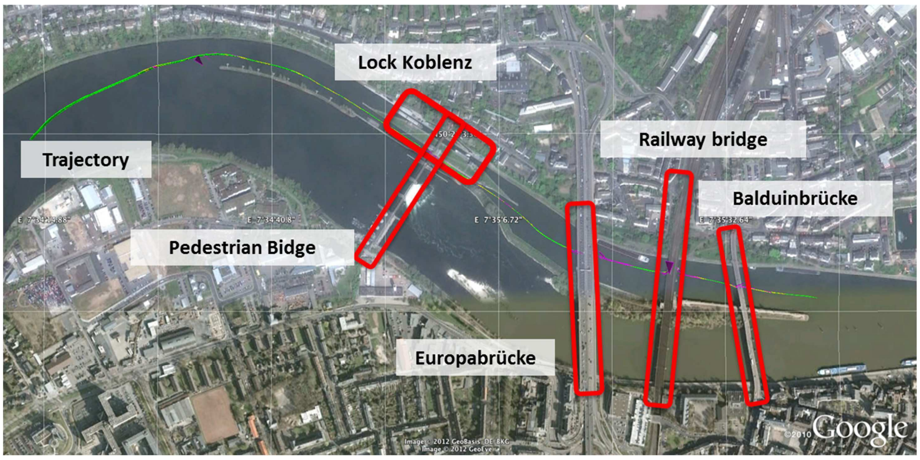

Figure 3: Demonstration Area and Trajectory Hour 14 DOY 293 Year 2011 (source aerial photograph: GoogleEarth)

The measurements collected during the locking are shown in Figure 4 (upper and middle graph). The solution quality meets the requirements at the start of the passage. As the lock is approached, there is a significant amount of inaccurate measurements, represented by red dots. Solution quality decays until the receiver connected to the fore antenna ceases to supply position solutions. This outage produces a gap of 69 seconds between two accepted solutions. It can be attributed to infrastructure located at the lock entrance, especially the pedestrian bridge (see Figure 3). After the ship has docked, the locking process is accompanied by accurate measurements as can be seen from the height measurements. As the ship is lowered interference by the surrounding walls of the lock chamber increases, and again leads to a significant number of inaccurate measurements as the ship reaches the destination level. As the ship exits the lock, the interference quickly subsides and measurements again meet the requirements.

The measurements for a passage of the bridges in eastern direction are shown in Figure 4 (lower graph). Red points mark measurements that did not pass at least one of the plausibility checks. As the plot shows, the quality of the position measurements suffers massively under the bridges, as well as some ten metres before and up to 95 meters after the actual bridge passage. The longest absence of measurements that pass all checks occurs during the first bridge passage and has a length of 49 seconds.

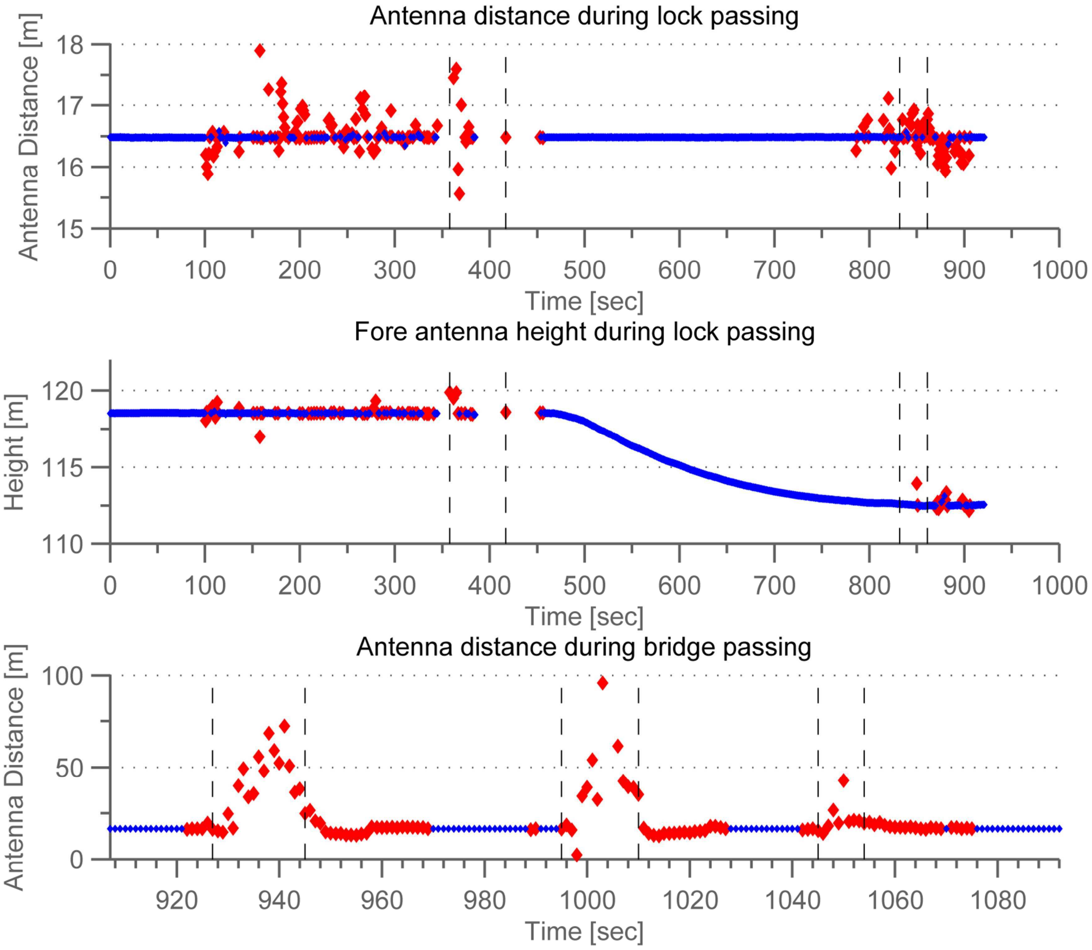

Figure 4: Measurement data for lock passing and bridge passing scenarios. Top: Measured Antenna distance during lock passing. The first vertical broken line marks passage of the top gate, second line marks the moment of docking in the lock, third line marks unmooring of vessel, fourth line marks passage of the bottom gate. Measurements that passed all checks are marked blue, others red. Middle: Measured height of fore antenna. Vertical lines as in top plot. Measurements that passed height check are marked blue, others red. Bottom: Distance between antennas during lock passing. Colors as in top plot. Vertical broken lines enclose times at which part of the ship was under one of the three bridges.

5 CONCLUSION

In this paper the concept of inland water based PNT-Unit has been presented, crucial areas for determining accurate PNT data have been identified and the need and demands on the positional accuracy were discussed.

Furthermore, first investigations regarding the usability of GNSS in connection with RTK solutions in inland water traffic have been presented. Therefore measurement data has been collected during a measurement campaign along the Moselle River.

In order to assess the accuracy of the collected data, a set of extended plausibility tests has been introduced. The application of these tests has shown that for the most part, position measurements are either clearly plausible, or clearly implausible. Based on this observation, measurements and plausibility check results during one lock passage and one passage of three subsequent bridges were evaluated. It was shown that the application of the used dual frequency GPS RTK service leads to a loss of reliable GNSS-positions of more than one minute length in our examined scenarios. Hence, in our investigations the IMO accuracy requirements could not be satisfied during restricted reception conditions.

Future work intends to overcome the outlined issues. Therefore different strategies exist. On the one hand, we intend to extend the ship-side sensor system by inertial and other ship-based sensors (IMU, AIS) in order to apply sensor fusion techniques enabling the improvement of positioning accuracy and to support the ship's master with improved integrity information about the ships navigational state. On the other hand, we aim the enhancement of reliable ambiguity resolution and validation playing the key role within RTK. Therefore, for instance the exploitation of the on-going GNSS modernisation, allowing the combination of multiple GNSS (e.g. GPS, GLONASS & GALILEO) observations within RTK, is planned. By means of the increased availability of GNSS satellites and GNSS observations on several frequencies, the enhancement of reliable ambiguity resolution can be facilitated [Odijk-2007, Verhagen-2010].

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REFERENCES

PLANCO Consulting GmbH (2007), Essen, 'Economical and Ecological Comparison of Transport Modes: Road, Railways, Inland Waterways', 2007

Transportation Research Board (2002), TR News 221, 'Comparison of Inland Waterways and Surface Freight Modes', 2002

U.S. Government Accountability Office (2011), GAO-11-134, 'A Comparison of the Costs of Road, Rail, and Waterways Freight Shipments That Are Not Passed on to Consumers', 2011

IMO (2002), 'SOLAS CHAPTER V: SAFETY OF NAVIGATION', 2002.

IMO (2007a), 'NAV 53/13 Development of an e-Navigation Strategy', 2007.

IMO (2007b), 'Resolution MSC.252(83): Adoption of the Revised Performance Standards for Integrated Navigation Systems (INS)', 2007.

IRIS Europe (2009): 'IRIS Europe – Implementation of River Information Services in Europe', Technical Report, 2009.

IMO (2009), 'NAV 55/WP.5 Development of an e-Navigation Strategy Implementation Plan', NAV55/ WP5, 2009.

IMO (2001), Resolution A.915(22): 'Revised Maritime Policy and Requirements for A Future Global Navigation Satellite System', 2001.

Ziebold R., Dai Z., Noack T., and Engler E. (2011). ‘Concept for an Integrated PNT Unit’, TransNav 2011.

WSDSW, (2010): ‘Verkehrsbericht 2010’, Technical Report, 2010.

Dai Z., Ziebold R., Born A., and Engler E. (2012) ‘Heading-determination using the sensor-fusion based maritime PNT Unit’, ION Plans 2012.

Takatsu T., (2009): ‘RTKLIB: Open Source Program Package for RTK-GPS’, FOSS4G 2009 Tokyo, 2009.

Miele A., and Wang T., (2006) ‘Optimal Trajectories and Guidance Schemes for Ship Collision Avoidance’, Journal of Optimization and Applications, vol. 129, pp. 1–21, April 2006

Odijk, D.,and Teunissen, P. J. G. (2007), ‘Sensitivity of ADOP to Changes in the Single-BaselineGNSS Model’, Artificial Satellites, Vol. 42, No. 2, 2007.

Verhagen, S., Odijk, D., Teunissen, P. J. G., and Huisman, L. (2010), ‘Performance improvement with low-cost multi-GNSS receivers’, IEEE, 2010.