# Enabling Assistance Functions for the Safe Navigation of Inland Waterways

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***Abstract*—Inland navigation and shipping is an important pillar of the European Transport System. To support the skipper during safety-critical operations, precise position, navigation and timing (PNT) data are required. This work discusses the role of PNT information for enabling inland waterways navigation assistance functions, such as bridge collision warning, mooring aiding or automatic guidance. Real-Time Kinematic (RTK) technique is developed to provide integrity information alongside reliable and cm-level accurate PNT data. In addition, the transmission of Global Navigation Satellite Systems (GNSS) correction data is investigated. Since Global System for Mobile (GSM) does not currently meet the availability and stability communication requirements along inland waterways, use of the Automatic Identification System (AIS) for data transmission is explored. The proposed navigation solution and the communication developments were analysed in real time on challenging GNSS signal-degraded scenarios on the authorized inland waterway testbed. Despite the further developments required on the AIS communication infrastructure, it is shown that our system architecture can nearly meet the integrity and accuracy requirements for driver assistance functions on inland waterways.**

***Index Terms*—Global Navigation Satellite Systems (GNSS); Real-Time Kinematic (RTK); Inland Shipping; Kalman Filtering (KF); Integrity; Automatic Identification System (AIS).**

## I. INTRODUCTION

CARRIAGE of goods through inland waterways is considered as an efficient and climate-friendly conveyance alternative and it plays a fundamental role for the European transportation systems. However, inland navigation poses growing challenges related to increasing ship dimension or reduced manoeuvre space. In Germany alone, approximately 25 bridge collisions occur every year [1], partially caused by the carelessness of the skipper, demonstrating the necessity of driving assistance systems during challenging or safety-critical tasks. Many of these collisions could have been avoided if the skipper had received a warning when the vertical clearance was insufficient to safely pass a bridge, and, hence, the wheelhouse and radar mast could be stirred down. Similarly, manoeuvring large vessels in confined waters is genuinely demanding, especially if the ship is operated 24 hours a day, and navigation assistance can alleviate such task.

This paper presents the outcome of the project LAESSI (Guidance and assistance systems to improve safety of navigation on inland waterways, from its German acronym) which aims to support the skipper in his or her tasks of guiding the vessel and thus makes inland shipping safer [2]. Within the framework of the project, the following functionalities were developed:

- a bridge collision warning system providing a timely alert signal whenever the wheelhouse or the radar mast would not safely pass under a bridge
- a mooring assistance depicting the distances to quay walls and other vessels
- an automatic guidance system reducing stress on the skipper during on-route navigation
- a conning display presenting the motion of the ship and incorporating information on the propulsion systems, wind and water currents.

The starting point for these four assistance functions are precise and reliable position, navigation, timing and integrity (PNTi) information (Tab. I). Unlike the maritime domain, where the requirements for radionavigation systems have been clearly defined by the International Maritime Organization (IMO) [3, 4], the navigational specifications for inland waterways scenarios have not been addressed by any international committee. In accordance to the needs of the aforementioned assistance functions, a feasibility study was conducted to characterize the navigation requirements [5]. Table I summarizes the accuracy and integrity demands for safety-critical inland waterway navigation applications. Attitude requirements are listed in Table I for completeness, as within the scope of this paper the valuation of the navigation solution will encompass the positioning accuracy and availability, making use of Global Navigation Satellite Systems (GNSS).

GNSS are the cornerstone and main information source for PNTi data. Despite offering a fairly good open sky performance, standard differential code-based GNSS techniques can only achieve metre-level accuracy. Such a differential GNSS technique has been well established and is standardized by the International Association of Marine Aids to Navigation and Lighthouse Authorities; the required infrastructure, such as a beacon system along the inland waterway, has been shown to perform well [6, 7]. Nevertheless, the accuracy potential for this approach is nearly exhausted and a transition to carrier phased-based techniques is required to reach positioning accuracies below the decimetre-level [8].

Depending on the applied set of correction data, two types of phase-based positioning techniques are distinguished. First, Precise Point Positioning (PPP) is a technique that achieves

TABLE I
ACCURACY AND INTEGRITY REQUIREMENTS OF ASSISTANCE FUNCTIONS FOR INLAND WATERWAYS NAVIGATION [5]

| Requirements | Bridge collision warning | Automatic guidance | Mooring assistance | Conning display |
|---|---|---|---|---|
| Positioning accuracy [cm] | 20 | 30 | 10 | 20 |
| Height accuracy [cm] | 10 | – | – | – |
| Heading accuracy [°] | 0.3 | 0.17 | 0.07 | 0.1 |
| Integrity risk | 10 $10^{-5}$ / 2 min | 0.55 $10^{-5}$ / 3 h | 18 $10^{-5}$ / 10 min | 18 $10^{-5}$ / 1 h |
| Time to alarm [s] | 4 | 2 | 6 | 6 |

high level of accuracy by removing or modelling GNSS system errors, such as ionospheric or tropospheric delays. PPP depends on GNSS satellite clock and orbit corrections, generated from a network of stations, which are then delivered to the end user. While no base station near the vehicle is required, the unknown parameters for the positioning problems need a convergence time ranging from 5 to 20 minutes [9], which is excessive for a safety-critical application. Alternatively, the real-time kinematic (RTK) technique is a relative positioning procedure whereby the position of the vehicle is determined with respect to a stationary base station of known coordinates. The RTK approach has been well established in the GNSS community since the early 1990s and was mainly used for surveying applications due to its high accuracy and fast initialization [10], [11]. Although accuracies of up to the centimeter level can be reached almost immediately, RTK requires a dense network of reference stations and a sufficient communication channel between the moving and static receivers.

In this work, the PNTi algorithm necessary to enable aids to navigation within inland waterways scenarios is presented. GNSS code and carrier phase observations are integrated recursively synergistically with the correction data provided from base stations to estimate reliable positioning with an accuracy of centimetre-level. To serve such a purpose, a protocol has been developed for the data transmission that agglutinates the GSM and automatic identification system (AIS) communication links to maximize the service coverage Within the framework of the project, a broad area in Germany was authorized as testbed and hosted numerous kinematic experiments, data collections and real-time live demonstrations. In this contribution, the PNTi and the positioning performance are evaluated along with the capabilities of the proposed communication protocol.

## II. PNTi DATA PROVISION

### A. The Basic Principle of RTK

GNSS positioning utilizes the concept of time of arrival ranging to determine the position of the tracked vehicle from a set of satellites in view. RTK is a GNSS phased-based positioning technique which uses GNSS correction data coming from a reference station or reference station network. Hence, the influence of errors related to satellite orbit and clock or atmospheric effects can be diminished or even eliminated [8]. Fig. 1 illustrates the working principle of RTK: first, single-differencing GNSS observations between rover and base stations (hereinafter referred to using the subscripts $R$ and $B$ respectively) allow the satellite clock error to be removed and significantly reduce ionospheric and tropospheric effects. Then, a pivot satellite (referred to using the superscript $r$) is chosen for double-differencing, cancelling the clock offsets from the rover and base receivers.

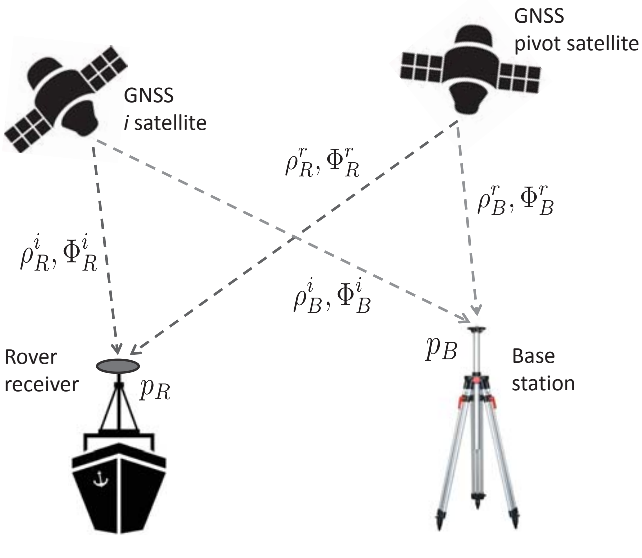


Fig. 1. RTK-principle with code and phase observations

Following the notation in [8], the code and carrier phase observations from the i$^{\text{th}}$ satellite observed at the tracked vehicle are expressed as:

$$\rho_R^i = \|\boldsymbol{p}^i - \boldsymbol{p}_R\| + I^i + T^i + c\left(dt_R - dt^i\right) + \varepsilon_R^i \quad (1)$$

$$\Phi_R^i = \|\boldsymbol{p}^i - \boldsymbol{p}_R\| - I^i + T^i + c\left(dt_R - dt^i\right) + \lambda N_R^i + \epsilon_R^i \quad (2)$$

where:

$\rho_R^i$ is the code observation[m],
$\Phi_R^i$ is the phase observation [m],
$\boldsymbol{p}^i$ is the position of the i$^{\text{th}}$ satellite,
$\boldsymbol{p}_R$ is the position of the rover,
$I^i$ is the ionospheric error [m],
$T^i$ is the tropospheric error[m],
$c$ is the speed of the light [299 792 458 m/s],
$dt_R$ is the receiver clock offset at reception time [s],
$dt^i$ is the satellite clock offset at transit time [s],
$\lambda$ is the carrier wavelength of the signal red [m],
$N^i$ is unknown number of cycles between the receiver and the satellite,
$\varepsilon^i, \epsilon^i$ are the remaining errors for the code and phase observations respectively [m],

When applying double-differences, the geometric distance between satellite and rover are usually expressed using the following linearised form

$$\|\boldsymbol{p}^i - \boldsymbol{p}_R\| = -{\boldsymbol{u}^i}^\top \boldsymbol{p}_R \tag{3}$$

where $u^i$ is the line-of-sight unit vector from the receiver to the i$^{\text{th}}$ satellite position. Thus, the mathematical model of a short-baseline (where the tropospheric and ionospheric delays are neglected) double-difference code $DD\rho$ and carrier phase measurements $DD\Phi$ can be given by:

$$\begin{aligned} DD\rho^i &= \rho^i_R - \rho^i_B - (\rho^r_R - \rho^r_B) \\ &= -\left(\boldsymbol{u}^i - \boldsymbol{u}^r\right)^\top (\boldsymbol{p}_R - \boldsymbol{p}_B) + \varepsilon^{i,r}_{R,B} \end{aligned} \tag{4}$$

$$\begin{aligned} DD\Phi^i &= \Phi^i_R - \Phi^i_B - (\Phi^r_R - \Phi^r_B) \\ &= -\left(\boldsymbol{u}^i - \boldsymbol{u}^r\right)^\top (\boldsymbol{p}_R - \boldsymbol{p}_B) + \lambda a^i + \epsilon^{i,r}_{R,B} \end{aligned} \tag{5}$$

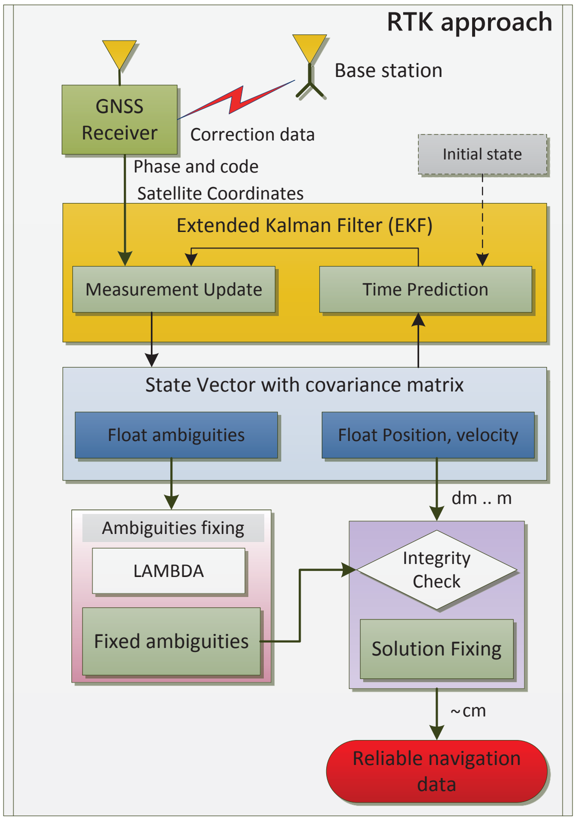


Fig. 2. RTK-approach based on Extended Kalman Filter with Ambiguity Fixing

Compared to code observations, GNSS phase measurements are more precise but ambiguous. This ambiguity is reflected in the cycles that are slipped during the tracking loop of a satellite, which are known to be an integer number remaining constant over time. Simultaneously solving the positioning and the phase ambiguities is a well-known problem which has been extensively studied within the GNSS community [8, 12, 13]. The overall estimation comprises three steps: float solution estimation, phase ambiguity resolution and fixed solution finding [14]. Fig. 2 depicts an overview of the system architecture.

During float solution finding, the phase ambiguities and the other unknowns are estimated as real numbers. This problem is generally solved applying a least-squares adjustment, which yields an optimal solution under the assumptions of Gaussian noise. (The hypothesis is generally accomplished by GNSS observations, whenever they are not affected by severe atmospheric conditions or multipaths). In this work, an Extended Kalman Filter (EKF) as one form of a Bayesian estimator is applied for determining the float solution [15, 16]. Given its recursive nature, the estimated solution improves over time even during high dynamics situations [17]. The state estimate is constituted by the set of unknown parameters: the vehicle dynamics (position, velocity and orientation) and the phase ambiguities. Kalman filters perform in two steps, prediction-correction, recursively. During the prediction step, the system evolves by following a constant-velocity dynamical model. There are handful models to select from, and the filter performance can be enhanced augmenting the prediction with sensors such as inertial measurement units (IMU). With regards to the correction step, the system is updated using the double-differenced GNSS code and phase observations, as seen in Eqs. 4, 5.

The position from the resulting float solution can reach only up to decimetre accuracy, as the parameter estimation problem is solved without taking the special integer nature of the phase ambiguities into account. Then, the ambiguity resolution process consists of finding integer values for the corresponding float phase ambiguities. The most effective method for ambiguity fixing is based on an integer least-squares, commonly referred as LAMBDA (Least-squares AMBiguity Decorrelation Adjustment) [18, 19, 20], which minimizes the following optimization problem

$$\check{\boldsymbol{a}} = \arg\min_{\check{\boldsymbol{a}} \in \mathbb{Z}} \left(\boldsymbol{a} - \check{\boldsymbol{a}}\right)^\top Q_a^{-1} \left(\boldsymbol{a} - \check{\boldsymbol{a}}\right) \tag{6}$$

Here $\check{\boldsymbol{a}}$ is the integer ambiguities, $\boldsymbol{a}$ is the previously estimated float ambiguities and $Q_a$ is the associated covariance matrix of the float ambiguities, determined during the EKF correction step.

Finally, the computed integer ambiguities are used to improve the float solution for the parameters of the vehicle dynamics, like position and velocity. Such solution improvement is again estimated following a least-squares sense, but this time with the ambiguities constrained to the integer values. This final result is generally referred to as fixed solution and it inherits a much higher precision than the previously obtained float solution.

### B. *Integrity concept*

One of the most challenging tasks is the evaluation of the correctness of the estimated fixed solution. Due to multipath or signal losses, an incorrect integer solution could be labelled as right, which might lead to dramatical consequences on safety-critical applications. Thus, integrity monitoring plays a fundamental role on the provision of PNT data and it guarantees that skipper receives entirely accurate and reliable navigational information. The integrity check algorithm, illustrated on Fig. 3, has been integrated in the developed RTK approach. The integrity concept is divided into three stages.

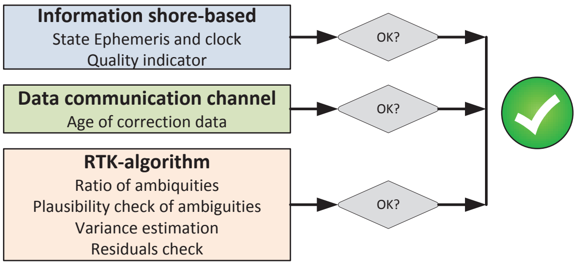


Fig. 3. Three step integrity concept

In the first stage, the shore side is equipped with monitor stations. Such stations have known coordinates and also obtain the precise correction data from the reference stations around them, allowing checking of the health status of the GNSS satellites and the validity of the correction data. In RTK-liked algorithms, GNSS observations are used to estimate a position solution which is compared against the known coordinates. Differences indicate errors in the GNSS correction data, which are then marked as untrustworthy [5].

Secondly, the age of correction data has to be controlled. Whenever the communication channels becomes unavailable, the navigation method would use the latest received information. The age of correction is defined as the difference between the positioning solution estimation and the data reception times. Based on the time to alarm in the navigation requirements on inland waterways (Table I), the limit for the age of correction data is specified to four seconds. PNTi data based on older correction data gets an invalid integrity flag. Otherwise the occurrence of an undetected satellite error could falsify the PNTi data with dramatic consequences for the navigation.

Finally, to achieve the strict requirements of the integrity risk and avoid the provision of wrong navigation data, the performance of the navigation algorithm is examined. The RTK itself delivers quality parameters which help to evaluate the solution. During the correction step of the EKF, a Chi-squared test is performed on the observation residuals to check the goodness of the filter fit. In case the Gaussian assumption is violated, a fault detection and exclusion is realized on every observation intending to mitigate the effect of outliers. Nonetheless, a dominating factor on the evaluation relates to the fidelity of the estimated integer ambiguities. First, during the LAMBDA process a discrimination analysis assesses the closeness of the float solution to the optimal integer solution compared to other integer candidates [21]. Then, if no cycle slip has occurred between consecutive epochs, the integer ambiguities remain identical, serving then as a final plausibility check.

Only when all of the integrity checks met the requirements will the navigation solution be marked as reliable and, then, used for applications relying on PNTi information.

## III. TRANSMISSION OF GNSS CORRECTION DATA

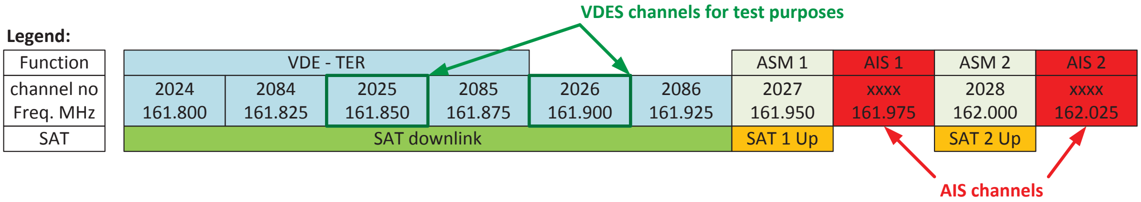
The performance of precise real-time positioning highly depends on the transmission of correction data between the reference station and the vehicle. To fulfil the stringent accuracy requirements, the carrier phase observations for GPS and GLONASS have to be broadcasted continuously to the ship-side. The data format of the GNSS correction data is the standardized Radio Technical Commission for Maritime Services Version 3.x (RTCM 3.x) Format [22]. Regarding the communication channel, the Network Transport of RTCM via Internet protocol (NTRIP) has been endowed worldwide as method for sending and receiving GNSS data, as it can handle hundreds of data streams simultaneously [23].

The amount of data needed for GNSS correction is estimated on 180 bits per satellite, according to the number of bits in the RTCM message types 1004, 1012 and the header information [22]. Additional information for the refererence station—message type 1006—and correction for the reference antenna—message type 1007—must be also transmitted to the vessel. Assuming that, todays, more than 15 satellites (GPS + GLONASS) are generally in line of sight, at least 3,000 b/s are to be transmitted, and the amount is likely to increase considering the deployment of new frequencies and constellations. Furthermore, a high update-rate is necessary to ensure that the positioning performance of the RTK algorithm does not get compromised [24]. In addition to the GNSS corrections, waterway data like water level and Notice to Skippers information (eg., the status of inland waterway infrastructure, temporarily blockages of waterways sections, etc.) have to be broadcasted [5]. To sum up, operative inland waterways navigation applications are only possible when the following data transmission requirements are fulfilled:

- data rate larger than 9,600 bit/s, enabling an update rate below two seconds;
- complete coverage (partly overlapping) along inland waterways;
- international standardized communication to enable harmonized data transmission.

While GSM is currently the standard for data transmission nowadays, its coverage is limited along inland waterways and rural locations and it might not be usable under certain circumstances (e.g. when a large number of users is saturating the cellular network). Within the framework of LAESSI, AIS has been enhanced for the transmission of code and phase correction data from the shore-side. Up to now, AIS was only used for the transfer of code differential messages, so the provision of complete correction data to enable precise PNTi data results on a new and challenging task.

Since 2002, AIS has been successfully introduced and standardized by the IMO for maritime navigation. Since then more than 100,000 commercial ships and recreational vessels



Legend:

| Function | VDE - TER | | | | | | ASM 1 | AIS 1 | ASM 2 | AIS 2 |
|---|---|---|---|---|---|---|---|---|---|---|
| channel no<br>Freq. MHz | 2024<br>161.800 | 2084<br>161.825 | 2025<br>161.850 | 2085<br>161.875 | 2026<br>161.900 | 2086<br>161.925 | 2027<br>161.950 | xxxx<br>161.975 | 2028<br>162.000 | xxxx<br>162.025 |
| SAT | SAT downlink | | | | | | SAT 1 Up | | SAT 2 Up | |

Fig. 4. VDES transmission channels in the project LAESSI

have been equipped with AIS and so it is widely used in the maritime and inland waterway domain. AIS enables data exchange among ships as well as between ships and shore and vice versa [25]. Given the mandatory nature of the AIS equipment, AIS is a viable candidate for transmission of correction data and waterway information despite the limited data volume of the protocol. The maritime community is aware of the AIS data capacity limitation and the next generation of AIS, the Very High Frequency (VHF) Data Exchange System (VDES), will take into account the requirement for more data exchange capabilities. VDES will include the functionality of AIS as well as the VHF data exchange system in the maritime mobile VHF-band and provide extra channels for Application Specific Messages (ASM) [26]. In this work, VDES is considered as a new alternative to GSM for data transmission from shore to ship, providing additional terrestrial frequency channel and overpassing the data capacity limitation of standard AIS.

To serve as testbed for the LAESSI project, the German Waterway and Shipping Administration (WSV) has installed an AIS network which covers the coast and major inland waterways like Rhine, Moselle, Danube and Main. In the future, the coverage is expected to be expanded to enable a nationwide AIS shore infrastructure along the inland waterways. Along the river Main, the existing AIS infrastructure was upgraded to enable the simulation of the future VDES, whose frequency spectrum and the corresponding channel are represented on Fig. 4. To serve our test purposes, channels 2025 and 2026 hosted the transmission of the GNSS data correction, without perturbing the ordinary AIS operations.

The generation of the code and phase correction data was done with the software Alberding Beacon.net, which is a modular software solution for the operation of DGNSS services for maritime navigation in coastal areas and inland waterways [27]. Moreover, the reference network from the satellite positioning services of the German surveying and mapping (SAPOS) was used, augmented with virtual reference stations (VRS) in the selected area [28].

## IV. MEASUREMENT CAMPAIGNS AND RESULTS

During the course of three years, the LAESSI project was the cradle of numerous experiments and data collections realized on the German testbed. This experimental area covered the river Moselle in Koblenz and the river Main in Bavaria. Throughout this section, we will analyse the performance of the positioning algorithms in terms of accuracy, reliability and availability. Then, the capabilities of the communication channel will be tested. All described developments regarding the PNTi data provision were developed and realized with the DLR RealTime C++ Framework [29].

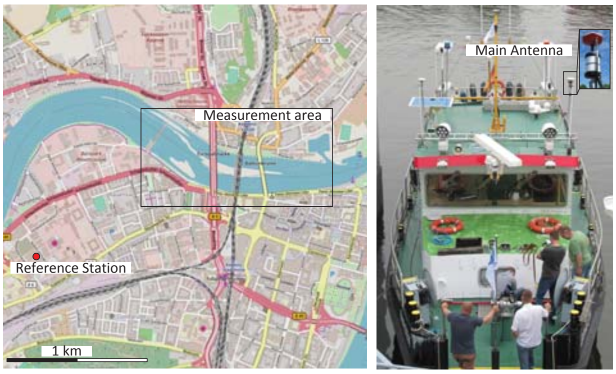


Fig. 5. Measurement campaign in Koblenz, May 2017 (Left: Measurement area, Right: MS Bingen)

### A. Positioning performance

The performance of the position determination of the proposed method is evaluated using actual data collected during the measurement campaign on 16th May 2017 (DOY 208, UTC 12:00-13:30) conducted in Koblenz (Germany) on the Moselle river. This scenario constitutes a clear example of signal-degraded situation, as the presence of three bridges and a water lock is responsible for severe multipath effects. The data is collected on board of the vessel MS Bingen, equipped with three geodetic GNSS antennas (navXperience) connected to three geodetic receivers (Javad DELTA). For the time span of the experimentation, the velocity of the vessel reached up to 6 meters per second. The base station, providing correction data for GPS and GLONASS observations on L1, L2, G1 and G2 frequencies, lies 2.5 km away from the campaign area. The experimental zone and tracked vehicle are represented in Fig. 5.

The reference trajectory of the vessel is obtained based on optical technology, using a total station on land and an active reflector mounted under the main GNSS antenna for automatic target tracking. This technology ensures a positioning accuracy of approximately 1 cm with an error pattern this is independent from GNSS.

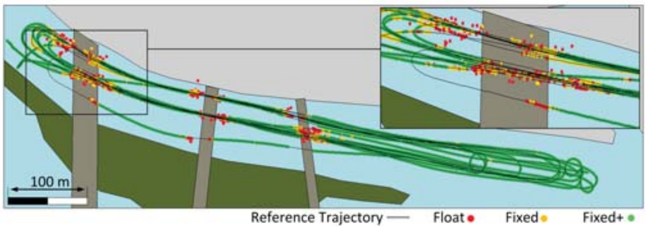


Fig. 6. Solution types (float, fixed and fixed+) for the measurement campaign in Koblenz, May 2017

In this urban area, the GSM communication channel, with Vodafone as network provider, is effective and the correction data arrives free from any latencies. Nonetheless, providing navigation assistance functions remains challenging given the strong multipath and non-line-of-sight effects. Fig. 6 shows the reference trajectory and the corresponding estimated position solution, with the colour code indicating the reliability of the positioning. Green-labeled positions 'fixed+' occur only when all of the integrity requirements are met, while solutions in yellow and red will be ignored by the navigation functionalities.

TABLE II
TIME TO FIX AFTER BRIDGE PASSING

| Name (width [m] x clearance [m]) | East to West [s] | West to East [s] |
|---|---|---|
| Balduin (14 x 7.1) | 13 | 11 |
| Railway Bridge (23 x 5.2) | 10 | 9 |
| Europa (38 x 9) | 15 | 15 |

It can be clearly seen that around the bridges, where the multipath and non-light-of-sight is quite strong, only float or unreliable position solutions are available. However, the recovery of a reliable navigation solution is achieved promptly, assuring that the skipper always receives a valid solution between consecutive bridges and offering the possibility to adjust the wheelhouse or other equipment on the vessel in real time. Fig. 7 depicts the horizontal and vertical position accuracies for the reliable fixed solution. It can be seen that the available positions achieved the cm-accuracy. The RMS value for the horizontal and vertical position is 1.2 and 1.7 centimetres respectively. The maximum error in both components is smaller than 10 cm.

During bridge passing, most of satellites signals suffers from interruption. Therefore, the time needed for the recovery of fixed solutions is analysed. Whenever the vessel drove under a bridge, the number of seconds required to get a new reliable fixed solution is counted. Table II provides an overview on the bridges dimensions and the average fixing time. Despite multipath effects and degraded satellite availability, which prevented faster solution fixing, the average recovery time after bridge passing stayed below 15 s.

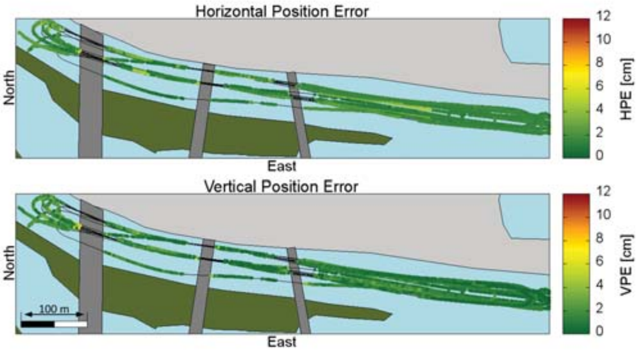


Fig. 7. Horizontal and vertical positioning error for the measurement campaign in Koblenz, May 2017

### B. Communication channel evaluation

The communication links between shore and ship sides play a crucial role on navigation-dependent safety critical applications. In this work, the performance of the new concept of data transmission based on AIS communication channel and the well-established GSM is presented. Furthermore, an approach to combine both data streams to maximize the chances of a vessel receiving correction data is proposed. A broad area along the Main River, illustrated in Fig. 8, served for the purpose of data collection over two days in October 2017. The AIS stations, with a transmitting power of 12.5 W according to recommendation of the International Telecommunication Union [30], spread on the experimental space, at a distanced 15 to 20 km. The AIS stations are indicated with red dots, while the green square marks the station providing data via GSM using the Vodafone network.

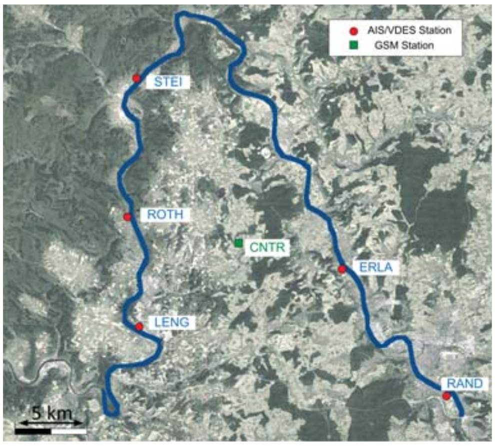


Fig. 8. Distribution of the AIS and GSM stations along the river Main.

Due to the AIS data capacity limitation, to broadcast the full correction data on RTCM 3.x format it is necessary to split the information in different message slots. Hence, three ASM blocks are needed to transmit the complete RTCM message. As a consequence, the current development of AIS communication presents certain transmission delay and the entire RTCM messages becomes unusable if only one ASM block is missing. In contrast, GSM communication generally provides fast and stable connection for GNSS data. However, whenever GSM service has interruption, data gaps can prolong up to five minutes.

Due to the open issues of AIS communication, the correction data is not available for every epoch. Precise PNTi data can still be provided by interpolating prior correction data, although the accuracy declines with the correction age [31, 24]. According to the system requirements (Table I), the time to alarm limit is established on four seconds and hence PNTi data using correction data older than this threshold becomes unusable for safety-critical applications.

The age of correction data for the AIS and GSM channels in relation to the geographical context is shown in Fig. 9. While AIS communication presents a higher latency than GSM, the absence of coverage is significantly lower compared to GSM. On areas such as North from 'STEI' and 'ERLA' stations, correction data gaps extend for several minutes if GSM only is used. Availability of data correction for AIS and GSM throughout the two days data collection is illustrated in Fig. 11. The transmission delay for the AIS communication channel hinders the correction availability slightly below 80% of the time. In contrast, GSM provides stable communication and considerably shorter delays.

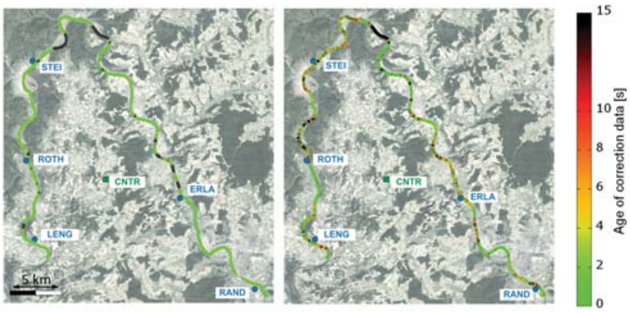


Fig. 9. Age of correction data along the river Main for the GSM (left) and AIS (right) correction channels, October 2017.

Overall, GSM channel remains generally stable and with a low latency on the correction data, although a signal interruption can last up to several minutes. On the other hand, AIS constitutes a communication with higher latencies, due to incomplete message blocks, but with very scarce interruptions of extensive duration. The longest loss of correction data was approximately 530 seconds for both communication channel. This large outage occurred in the north of the test area and was caused by missing AIS stations and poor GSM coverage. To obtain a optimal solution which maximizes data correction coverage, a combination of both PNTi data based on the two data streams appears as a promising approach. A similar conclusion can be withdrawn from Fig. 10. The top side of Fig. 10 shows the age of correction (red line) and the availability of a solution (green line) for the GSM (left) and AIS (right) communication over a time span of 75 minutes. Below, the correction age for the combined solution is given, evidencing that the AIS-GSM association leads to a lower correction age and a higher availability of correction data.

Table III covers the statistics on correction data availability and percentage of reliable PNTi data provision. The combined solution consists of two parallel navigation processors integrating GSM and AIS correction respectively. Then, the choice of the best solution is made based on the integrity check as well as the age of correction.

TABLE III
VALID CORRECTION DATA ($< 4$ SECONDS) AND RELIABLE SOLUTIONS IN RELATION TO THE USED COMMUNICATION CHANNEL

| | Valid correction data [%] | Reliable PNTi data [%] |
|---|---|---|
| AIS | 78.1 | 52.0 |
| GSM | 92.7 | 78.2 |
| AIS+GSM | 93.8 | 84.1 |

## V. CONCLUSIONS AND FUTURE WORK

Inland shipping constitutes an attractive transportation alternative, especially for conveying metals and other heavy materials, and plays an important role in the European transport system. Nonetheless, inland navigation faces evergrowing challenges in the form of increasing ship dimension and reduced maneuverability. This work introduces the project LAESSI, which aims to provide driver assistance functions for inland vessel navigation. Moreover, an architecture for the provision of accurate and reliable PNTi information is presented, based on a novel approach for the transmission of GNSS data which combines AIS and GSM communication protocols.

The navigation algorithm uses code and phase GNSS observations, as well as differential correction data from nearby base stations, to recursively estimate a positioning solution which achieves the centimetre-accuracy free from lengthy convergence times. Given the nature of safety-critical applications, the reliability of the solution is considered as a decisive factor. Thus, an integrity monitoring algorithm to proof the plausibility of the PNT data has been developed.

The realization of precise navigation is largely related to the transmission of GNSS correction information. While GSM is proven to be stable and low latency communication channel, its coverage is compromised in rural areas and often also in inland waterway scenarios. On the other hand, AIS is a standard information exchange system within the maritime community with existing infrastructure that can potentially cover the totality of the inland waterway routes. Hence, within the LAESSI project, special effort towards the enhancement of the next generation of AIS was made. The currently developed VDES channels, allocated on the slightly lower frequencies than standard AIS, were exploited to allocate and transmit GNSS code and phase correction data for the first time.

A wide area, covering the rivers Main and Moselle, has been authorized as testbed for the realization of data collections and live demonstrations of the driver assistance functionalities. During the navigation on a signal-degraded scenario, positioning accuracy at the centimeter level during 82% of time was realized, despite the challenging multipath effects motivated by the presence of multiple bridges. With regards to the communication side, the new channels of AIS have been modified to broadcast code and phase corrections and the combination with a mature technology such as GSM has been realized. Despite the immaturity of the new AIS capabilities

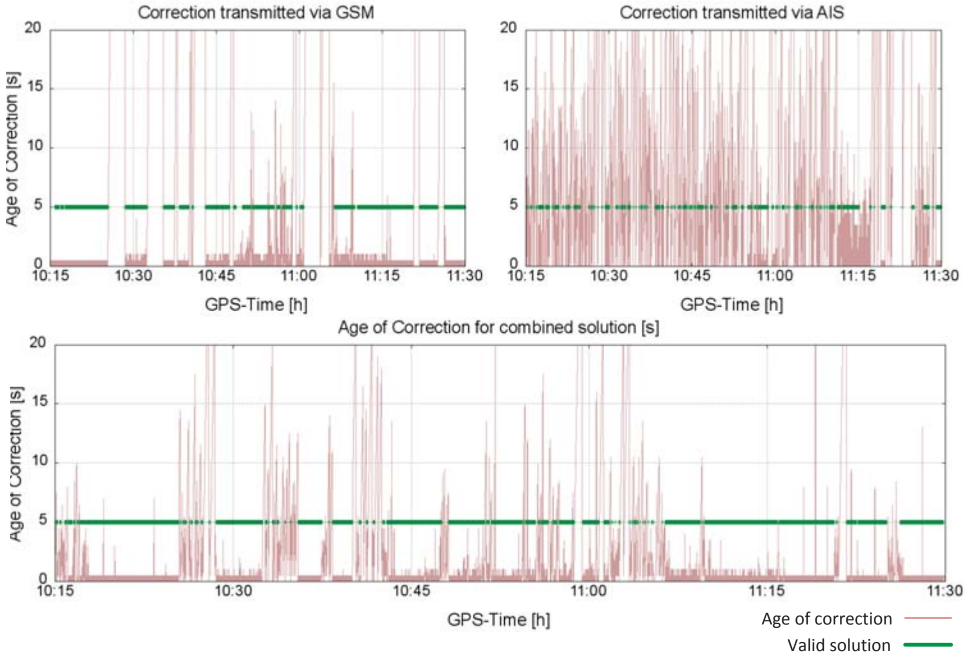


Fig. 10. On the top, the age of correction from the GNSS base station using GSM and AIS on left and right respectively. On the bottom, age of correction when tightly using GSM and AIS data. Data collected during 75 minutes on 2017 DOY 296 on the river Main.

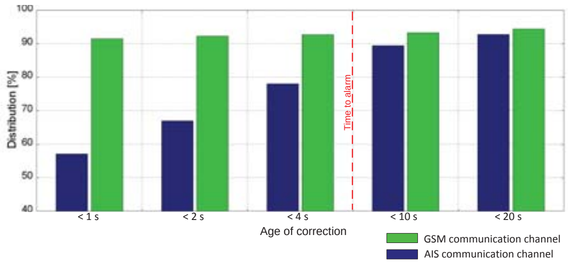


Fig. 11. Age of Correction for AIS and GSM, measurement campaign on the river Main, October, 2017

and the latency of the service, a high rate of success on the provision of PNTi data was reached. Finally, the combination of GSM and AIS for the transmission of GNSS data appears as a promising and robust technique.

The major challenge on the provision of PNT data lies on the transmission of the complete correction data. On the one side, the potential of AIS communication channel is yet to be fully exploited. The maritime community is working on further development of AIS, the VDES system, which promises channels with a higher capacity for transmission. On the other side, reducing the amount of data to deliver is an alternate solution to the communication bottleneck. An interesting approach consists of splitting the complete correction messages into the single error components with individual update rates. This kind of data reducing, illustrated in Fig. 12, is known as transition from the observation state representation (OSR) to the state space representation (SSR) [32]. Although the use of such kind of correction data would require an extension of the navigation algorithm, slightly increasing its complexity, it would bring as consequence a even higher availability of the navigation-related services. Another major challenge is constituted by the radio threats on satellite-based navigation, mainly in the form of jamming and spoofing [33, 34, 35]. To overcome such concerning safety issue, the integration of GNSS with sensors of different error modalities (e.g. accelerometers, gyroscopes, LiDAR, etc.) is highlighted as one of the main lines of future work.

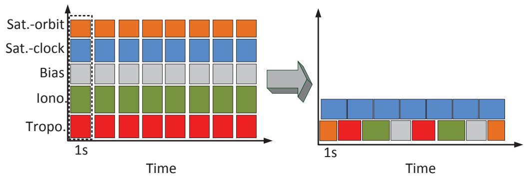


Fig. 12. Correction data reducing concept, SSR2OSR (according to [32]).

The driver assistance functionalities here presented set a precedent for the safe navigation on inland waterways. Despite the long road ahead for achieving the prospective autonomous shipping, especially regarding the legal and social aspects, the outcome of LAESSI evidenced that accurate and safe navigation can be a reality, even in challenging situations.

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