Paper 22 – Reliable Height Determination for an Efficient Bridge Collision Warning System on Inland Waterways

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ABSTRACT:

In recent years, much effort has been devoted to the development of strategies to monitor and mitigate the risk of collision on inland waterways. In particular, collision avoidance of inland water vessels with bridges has been widely recognized as a threat to the efficiency on river transportation systems. A comprehensive feasibility study has identified GNSS-based developments as the most promising board-side techniques for a reliable height determination as basis for bridge collision warning system. This article investigates the performance evaluation of selected GNSS-based techniques for the accurate height determination with inland water traffic purposes. The performance of different techniques is discussed in relation to the availability of data provided by land-side augmentation systems and under consideration of the available infrastructure. Technical challenges are also investigated.

1 INTRODUCTION

An evaluation of ship accidents on inland waterways in the past four years (Pröger, 2010) has shown a significant number of bridge collisions. Nearly 20-30 collisions occur annually, mostly on channels and lock regulated inland waterways. Many inland waterways are crossed by bridges which have a vertical clearance of 5.25m or even lower. Although such inland waterways allow the two-layer container transport the skipper is required to lower the helmstand. A collision with a bridge construction can result in heavy physical damages and injuries to persons onboard the vessel. Furthermore such a collision could also damage light-frame bridge constructions (e.g. passenger bridges across the Main-Danube-Channel) (DIN1055-9, 2003). In addition such accidents could also have an impact for inland vessels traffic due to a ban of shipping along the river for a longer period. Roughly 50% of such collisions are caused by inattention and lack of navigational estimates. Such accidents could be avoided if the skipper was timely informed about a possible collision by an electronic height warning system before a bridge passage.

2 RELATED WORK

The large number of damages associated with high costs for ship owners and the operators of inland waterways has led to several investigations and developments over the last years

2.1 Commercial bridge warning systems

<u>"Bridgescout"</u>

The Company Jask BV (Grondmolen 89, 3352CD Papendrecht) has developed a laser based bridge warning system (Heynen 2013). This laser sensor is able to detect and warn identified obstacles in the same height as the installed laser. Typically such a laser is installed on the top of the wheelhouse. The system provides first information at a distance of 500m before an obstruction. At a distance of 175m the system starts an acoustic warning. An alarm tone will be triggered at a distance of 75m. The warning tone and alarm enables the lowering of the wheelhouse by the skipper.

<u>AlphaHeigh</u>

Alphatron Marine introduced the AlphaHeight bridge height measurement system for inland shipping (Grohmann, 2013). The system comprises a sensor on the bow that is connected to a computer in the wheelhouse. Using special software, this calculates whether the highest part of the vessel can safely pass under the bridge. The sensor of the AlphaHeight system gives a signal when an obstacle, that is higher than the highest point of the vessel, is detected, allowing the wheelhouse to take the necessary measures. The system does take account of a height-adjustable wheelhouse and the vessel's draught. The situation is visualized graphically in combination with an acoustic alarm.

2.2 Research projects

Navwat

The project Navwat (Future high precision navigaiton system for inland waterways), performed by viadonau, Austria in 2010, has investigated in the use of high precision positioning systems for the use on inland waterways (NAVWAT 2010). With respect to bridge passages the project concentrates on the avoidance of a collision with bridge pillars.

Navwat II

Main task of this follow up project was the development of a visual support for the skipper for tasks like lock operation, bridge passages and landing during bad weather conditions. The system was demonstrated at a lock in Vienna, Austria. Results are available from www.navwat.at.

PiloNav

The interdisciplinary project PiloNav (Precise and Integer Localisation and Navigation in Rail and Inlandwater Traffic 2011-2014), performed by German Aerospace Center (DLR) in cooperation with partners from research (Technical University Dresden) and development (Federal Waterways and Shipping Administration (WSV) Institute of Traffic Techniques (FTV)), used a PNT(Position, Navigation and Timing)-Unit approach. GNSS-based positing and inertial measurements sensor fusion techniques have been developed to provide continuously highly accurate and reliable PNT data (Lanca et. al, 2013). This PNT-Unit has been demonstrated in 2014 in a test bed on the Moselle River in Koblenz Germany, proving that bridge approach and crossings are the most challenging maneuvers when using GNSS for navigation (Herrera-Pinzón et. al., 2014)

2.3. Feasibility Study

The German Waterways and Shipping Administration (WSV) has performed a feasibility study to identify and assess possible technical solutions to inform and warn the skipper right in time before passing a bridge (Sandler 2014). The main task of the feasibility study was to investigate and assess a wide variety of land- and ship based solutions.

The feasibility study was further based on the following basic considerations and requirements:

- Reliable and accurate estimation of a safety distance between the highest point of the ship and lowest point of the bridge, taking into account the ship construction, dimensions and load. The required height accuracy must be in the dm-range. Otherwise it is unacceptable for a height warning system.
- Accurately timed warning before a possible bridge collision. This depends on various factors such ship size, speed and type of waterway. Based on estimations the feasibility study requires a safety distance of 350m which enables a safe maneuver to prevent a bridge collision,
- Consideration of dynamic ship movements,
- Consideration of water level changes caused by surrounding traffic or lock water in a channel,
- Consideration of adverse environmental conditions (weather, visibility, wind, etc.)
- Consideration of economic aspects with respect to required technical equipment on ship and ashore.

From altogether 18 different technical approaches four solutions were identified which fulfill the general requirements and the considerations listed above. Two of the solutions were ship based systems (based on GNSS and other onboard equipment) and two are systems which are land based, using optical sensors in the near vicinity to a critical bridge.

Furthermore several so-called components were identified which are part of the four selected solutions. Such components consist of onboard equipment, measurement units in the area of the bridges as well as further land based infrastructure and services. The most promising solutions and components based on the results of the study are:

- Solution 1 (ship based)

  This approach uses onboard measurements of the height above water level combined with actual bridge clearance data computed in a central service based on water level models.

  As an alternative, direct clearance measurements at a bridge can be used. Different approaches to model the clearance of a bridge are taken into account. Bridge clearances from the Inland Electronic Chart Display and Information System (ECDIS) chart are used as basic clearance data. In addition, the usage of exact bridge profiles has been considered. To take into account temporary restrictions of bridge clearance, notices to skippers have to be processed by the system. For the transmission of bridge clearances from shore to the vessel a mobile internet connection as well as the usage of AIS has been considered.

- Solution 2 (ship based)
  This approach is based on onboard DGNSS processing combined with information about the geodetic height of the bridge superstructure. For application of a bridge clearance warning system, high precision multi frequency GNSS is required. The provision of suitable correction data with high availability is a crucial point in this approach.

- Solution 3 (land based)
  This approach is based on laser scanners installed near the bridge. Here an alarm would be generated on shore. It has to be signaled by installations on the bridge or by transmitting it to a suited system on the vessel.

- Solution 4 (land based)
  The fourth approach makes use of thermal cameras monitoring the area in front of the bridge.

The different approaches are compared regarding different criteria and requirements like accuracy, availability with respect to weather or lighting conditions and costs. For the cost estimations, scenarios for one bridge, a regional roll out as well as a nationwide coverage in Germany has been taken into account. The major advantages regarding performance and cost estimations were identified in Solution 2 using high precision GNSS measurements to determine the ship´s height. Consequently, this paper is focusing on this approach investigating the utilization of augmented GNSS-positioning by using real measurement data gathered during a PiLoNav measurement campaign at the Moselle River in Koblenz, Germany, in 2014.

The remainder of this work is structured as follows. Chapter 3 gives an overview about GNSS commonly used positioning techniques which were also investigated in further analysis. Chapter 4 explains the data basis and the analysis itself. Before Chapter 6 concludes the paper, Chapter 5 presents the results of the analysis focusing on the determination of the vertical component of the position.

3 GNSS POSITIONING

The utilization of GNSS in maritime applications has been widely recognized over the last decades to deliver navigational parameters, and is nowadays an essential part of almost any maritime navigational or tracking solution. This is on the one hand due to favorable 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 have been recognized as an important tool for the measurement of navigational data and position. In this context, a reliable GNSS-based navigational solution is a possible basis for the implementation of applications for advanced assistance during bridge approach and passing. However, the latter application poses a challenge to a GNSS-based positioning solution, since bridges diminish reception conditions.

With multiple GNSS in operation (the U.S. Global Positioning System (GPS), the Russian GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLONASS), the Chinese BeiDou and in the future the European Galileo) around 70 satellites are available, enabling global, accurate positioning. Critical applications such as bridge passing require high accuracies. The feasibility study and the PiLoNav project demand an accuracy of 20cm for height determination. Atmospheric effects however, impair the signal propagation and therefore the range measurements to individual satellites. This worsens a reliable PNT determination within the demanded accuracy which requires the utilization of specific augmentation techniques for GNSS-based positioning.

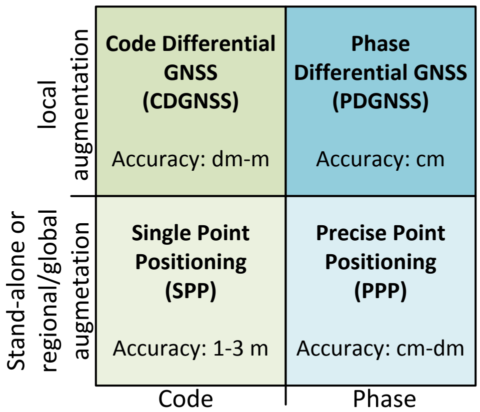

Figure 1: Observation and augmentation methods

GNSS positioning techniques can be categorized in different observations and augmentation methods (Figure 1). As the so-called carrier phase observations can be determined much more precisely than code pseudoranges, this categorization is also an accuracy-based classification. The challenge by using carrier-phase observations is to solve the unknown numbers of phase ambiguities (Xu, 2007). If the ambiguities can be estimated as float values, a dm-accuracy of the position can be achieved. If the carrier-phase ambiguities can be fixed to integer numbers, cm-accuracy is reachable. Consequently, one distinguishes between two modes – the less accurate float and the highly accurate fix solution.

Code and phase based methods, are influenced by the aforementioned atmospheric as well as satellite orbit and -clock effects. As one option to reduce these error effects, reference stations are used where the position is calculated by GNSS and compared to a precise surveyed position. In case of code-based differential GNSS (CDGNSS) the deviations will be applied to the erroneous pseudorange and the range corrections calculated. These corrections are transmitted to the user, assuming it is located within the area of coverage. The accuracy of range measurements can be improved with the aid of the range corrections provided. As a result, errors in determination of horizontal position could be reduced to less than 1m. In case of the IALA Beacon DGNSS the augmentation data are distributed by medium wave signals and are available to all users who are in the reference station's service area – within a radius of 200-300km (IALA 2015).

The phase-based differential GNSS (PDGNSS) uses the carrier-phase measurements as well as the observation set from a local reference station. If ambiguities can be fixed, accuracies up to few cm can be achieved in real-time. In literature this technique is referred to as Real-time Kinematic (RTK). A drawback of this technique is the requirement of a run-in time after losing the satellites signal. The correction data is only valid locally, reducing the service area to few km around the reference station (RTK_NAVIPEDIA).

For globally or regionally valid corrections the phase-based positioning techniques Precise Point Positioning (PPP) becomes more relevant. In contrast to the PDGNSS method the correction data were determined by the International GNSS Service (IGS) in a global or regional reference network and provided by several GNSS service providers to the user (Grinter and Roberts, 2013). The carrier-phase ambiguities are determined as float values. As major drawback this estimation requires longer convergence times of up to 20min without signal interruption (Kouba, 2009; Zumberge et. al, 1997). Using PPP dm-accuracies can be achieved.

If no correction data is available a simple fallback technique is the Single Point Positioning (SPP). Error effects are neglected and only code observations used. As no reference data are necessary, the achievable accuracy is reduced to few meters (Hofmann-Wellenhof et. al. 2008).

All mentioned accuracies refer to horizontal positioning only. Due to the particular nature of geometric conditions of all GNS systems the height determination is less accurate (ca. by factor 2) than the horizontal position (Hofman-Wellenhof et. al., 2008; Langley 1999). For a required vertical accuracy of 20cm, the horizontal positioning therefore demands an accuracy of 10cm.

4 MEASUREMENT DATA BASED EVALUATION

4.1 Demonstration area

In March 2014 measurements have been conducted during a measurement campaign near Koblenz, Germany on the Moselle River. The demonstration area covers challenging scenarios in inland water navigation (see Figure 2). With 11,500 ship passages in 2010 the Moselle River is one of the busiest waterways in Germany (WSDSW, 2010). Sailing downstream, a lock bounds the demonstration area 3km before the confluence with Rhine River. After locking three bridges of different height and width span the river in a small section of only 2km impeding a reliable, continuous positioning.

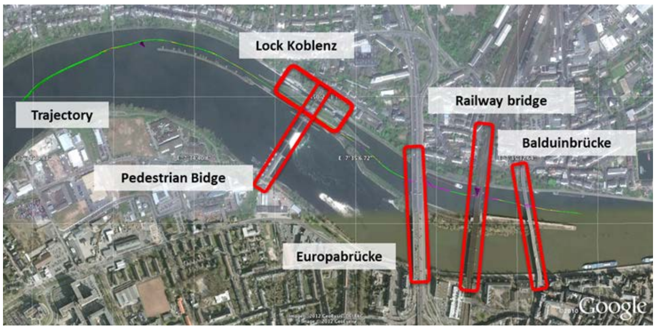

Figure 2: Demonstration Area on River Moselle (Source aerial photograph: GoogleEarth)

The first bridge is the tallest, 4-lane car bridge 'Europabrücke'. With a width of 40m and a clearance height of 13.9m it covers a relatively wide area. The following bridge is a railway bridge, 25m wide and a low clearance of only 10.2m with an oval profile. The profile is an additional challenge on the maneuver planning as the clearance height available for crossing the bridge does not only depend on the ships height and the water level. It also depend on the offset of the ship's position from the center 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 raising water levels, must be calculated for each ship type individually. The last 'Balduinbrücke', with a width of 10m and a height of 12.1m, is smaller in comparison and higher than the railway bridge.

During the measurement campaign several passes below the bridges and the lock of Koblenz have been performed.

4.2 Observation Data Set

The sensor system onboard the research vessel "MS Bingen" consisted of three geodetic GNSS antennas and receivers (to additionally determine the attitude of the vessel) and a tactical grade Inertial Measurement Unit (IMU) to stabilize the PNT data generation in case of GNSS outages. As this work focusses on GNSS only, results of this integrated solution will be briefly presented at the end of the paper. For the analyses only data of the main GNSS antenna has been used as the attitude of the vessel is subordinate priority. The analysis is based on two hours of data collected during two passages of the demonstration area, including both the lock and the bridges. The measurement rate of the GNSS receivers has been set to 20Hz. For comparison with a reference this high rate date had to be down-sampled to 1Hz. The reference trajectory was determined GNSS-independently by using a geodetic total station. The accuracy of the reference trajectory is about 1-2cm. Correction data for RTK positioning was provided by a reference station within the demonstration area. Correction data for PPP has been obtained from Nasa´s Jet Propulsion Laboratory (JPL) server (NASA_JPL).

The data has been analyzed by using the open source GNSS-processing software RTKLib ver. 2.4.2 (Takasu 2013, Takasu and Yasuda 2010).

5 RESULTS AND DISCUSSION

5.1 Single-GNSS processing

Figure 3 shows the height component of the vessel´s position determined by RTK (only fix solution), PPP, CDGNSS and SPP while passing the demonstration area. For this evaluation only GPS on the frequency band L1/L2 observations have been used. The passage started at the western edge in the head water (left green section in Figure 3), passing the lock, entering the tail water (red section in Figure 3), passing all bridges (orange lines) and returning to the starting point. The reference height is illustrated as a blue line while the GNSS-height is indicated by black points.

As can be seen from the graphic the height determination is strongly affected by disturbances caused by shadowing and interferences of the GNSS-signal. Especially the height determination in the tail water suffers from GNSS-outages. Starting inside the lock when the vessel is awaiting the lock gates to be opened, most signals are affected by multipath induced by the lock walls. The code-based SPP and CDGNSS show a noisier distribution of the positions while the phase-based techniques RTK and PPP show a smoother behavior.

The error in north, east and height components of the position with respect to the reference trajectory is depicted in Figure 4. The error for the SPP solution is up to 8m in the worst case. The average error in the head water is 1.4m for north and east components and 2.5m for the height respectively. In the tail water this error is increasing up to 2.5m for east and north and 5.0m for the height. These results show that when SPP is used as fallback technique to derive positions the requirements on PNT data generation are not met.

The CDGNSS solutions show a smaller error through the demonstration area. In the head water the average horizontal positioning error is 0.6m and for the height 0.8m respectively. The tail water with larger obstructions led to 1.3m for the horizontal positioning error and 1.8m for the height. For PPP the typical convergence time can be recognized at the beginning of the campaign. After ~20min accuracies of 0.1m in position and 0.2m in height are achievable. The loss of the signal below the

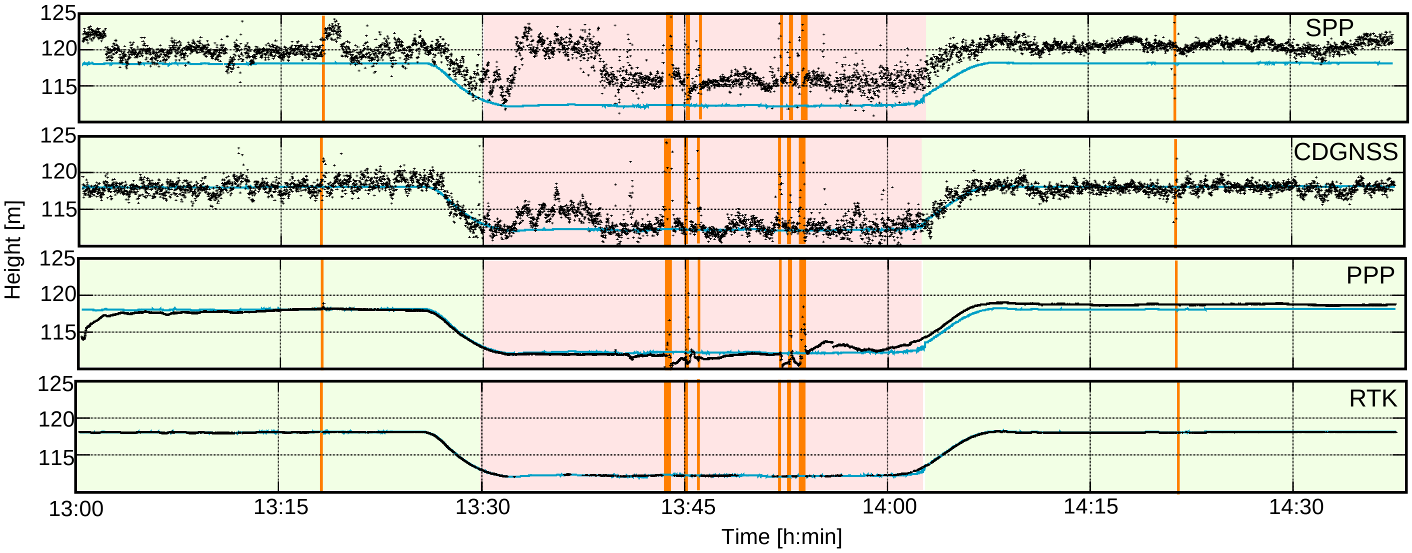

Figure 3: Height of different position techniques (RTK, PPP, CDGNSS, SPP) in comparison

bridges induced an initialization of position acquisition followed by the convergence time. This effect makes the utilization of PPP as the only position technique unsuitable for the accuracies required. However, the results, even in signal degraded areas, are promising as long as PPP is not affected by a full loss of satellite signals. Especially inside the lock between 13:31-13:35h the best results are achieved by PPP.

With closing distance to the bridge more inaccurate float positions were calculated. Immediately before and below the bridge almost no RTK-positioning was successful due to a decreasing number of satellites. The tallest 'Europabrücke' led to the largest gaps in the calculation without fix solutions. More important for the height determination is the position before bridge crossing, which is almost always an accurate fix solution.

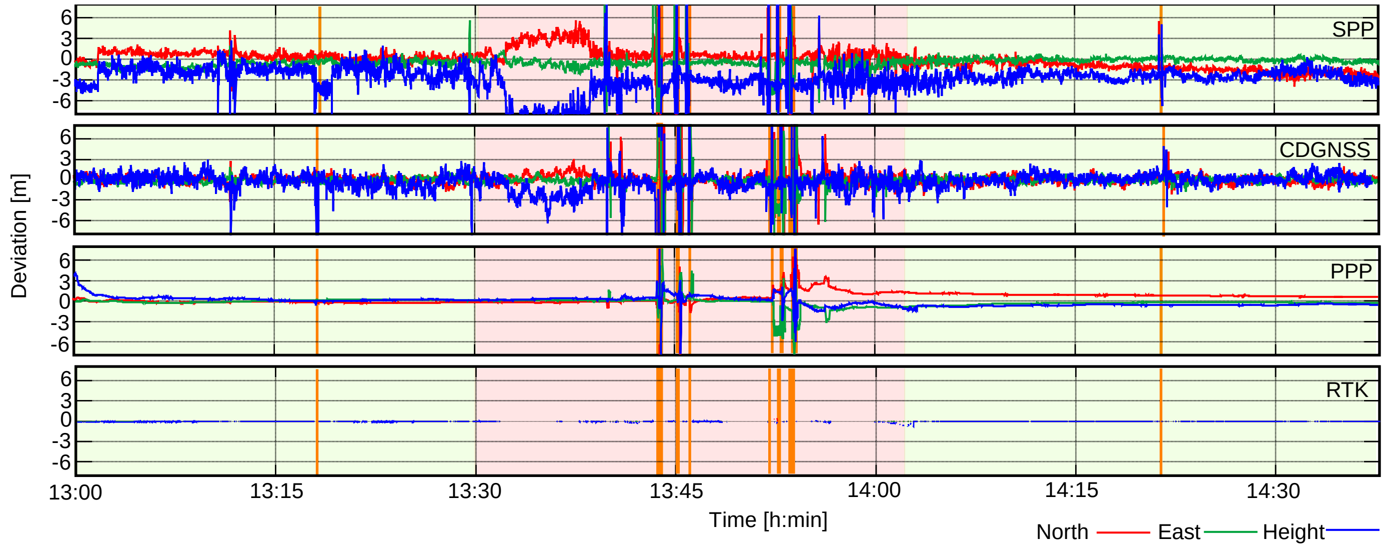

Figure 4: Errors in north, east and height for SPP, CDGNSS, PPP and RTK

In case of RTK only the fix solutions are considered. The area in the head water without relevant bridges shows a fix rate of 95%. In case of the bridges in the tail water only 45% ambiguities were fixed. This effect shows how shadowing and multipath can worsen the positional accuracy significantly. The average vertical error for the fix solution is about 4.0cm. The horizontal positioning error with 0.8 cm is smaller than the accuracy of the vertical position. During 13:31-13:35h no position fix can be achieved.

Figure 5 shows the trajectory based on RTK positioning. The yellow points illustrate the float and the green the fix solutions.

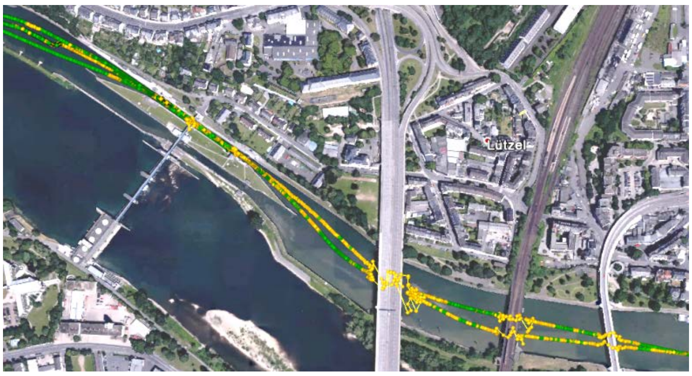

Figure 5: RTK solutions: float, yellow dots and fixed green dots (Source aerial photograph: GoogleEarth)

Figure 6 shows the height error for both, float (green) and fix (red) solutions. The height error for both solutions displayed the same behavior as for the horizontal position in Figure 5. Where a fix solution was calculated, the requirements on the positional accuracy were met.

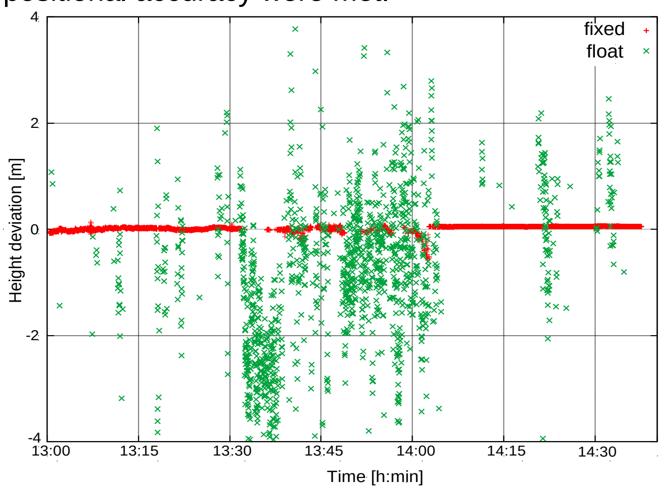

Figure 6: Height error for RTK fixed (red) and float (green) solution

At 14:00h a wrong position fix occurred. This can be explained by the ´RTK fixed and hold´ option inside RTKlib. In this case a position fix will be held as long as possible. When exceeding a particular threshold the position fix is released and the algorithm restarted. This achieves a higher fix rate by accepting higher positioning errors.

The utilization of multi-GNSS can improve or stabilize the position determination. In signal-

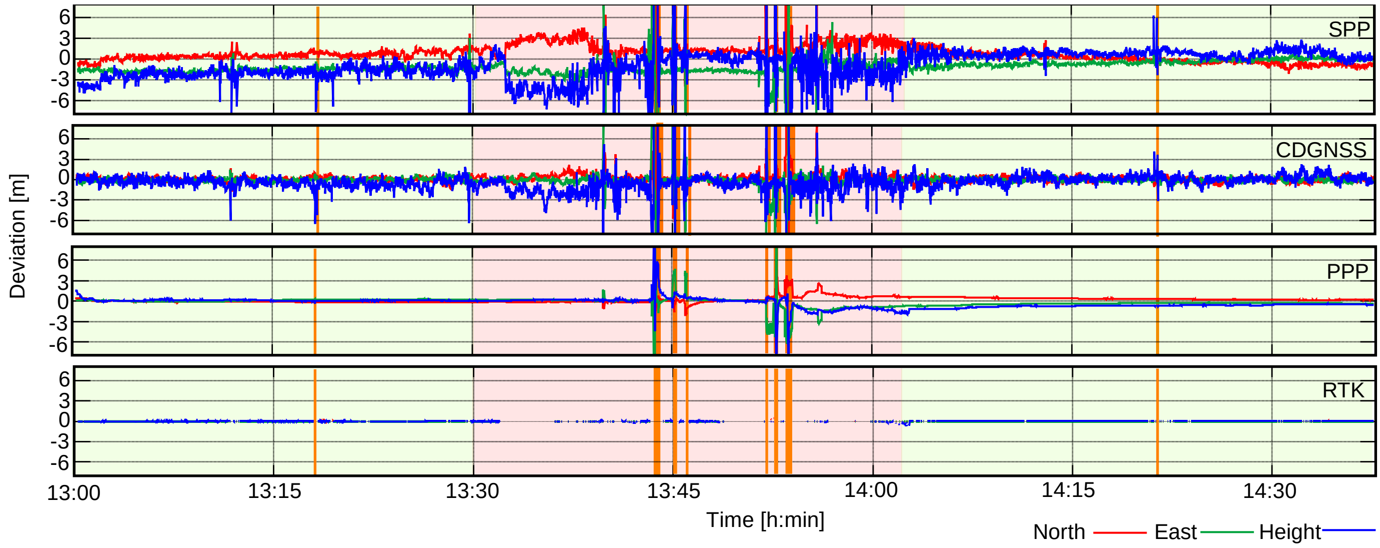

Figure 7: Errors in north, east and height for SPP, CDGNSS, PPP and PDGNSS for Multi-GNSS

With an average accuracy of ~2m the float solutions seem to be unsuitable for height determination in signal degraded areas.

5.2 Multi-GNSS processing

Nowadays more than one GNSS and therefore more satellite observations are available for positioning. Especially for short observation periods (<30min) the usage of Multi-GNSS can increase the accuracy of PPP significantly (Choy et. al., 2013, Hesselbarth and Wanninger, 2008).

For comparison, GLONASS observations have been additionally included to increase the observation set from Chapter 5.1. Figure 7 shows the results of this investigation. By using more satellites the positional accuracy was slightly increased in areas with good conditions, i.e. a large number of satellite observations. In the signal degraded area in the tail water even the use of multi-GNSS did not increase the positional accuracy significantly. For RTK an improved fix rate of 2.5% was observed. The highest impact of multi-GNSS in this area has been observed on PPP. Figure 8 shows the height error for GPS (green) and GPS+GLONASS (red).

By taking only GPS observations approx. 10 satellites have been used for position calculation. With the additional GLONASS observations the number of satellites increased to 16. At the beginning of the campaign (13:00h) a better performance of the convergence time has been observed. Even after losing GNSS signal at 13:45h the convergence time was improved. After turning the vessel, the signal was lost, resulting in an initialization process. Here, the convergence time is comparable for both constellations.

degraded areas shadowing, interferences and GNSS outages affect the PNT data generation. On the one hand this result makes the application of standalone GNSS-based techniques unsuitable for bridge collision warning systems. However, the information about sufficient clearance should be available to the ship´s master in a safe distance before the bridge, where manoeuvers to prevent a collision can still be initiated. This means, in areas the GNSS reception is not influenced by the bridge itself and is still sufficient for meeting the accuracy requirements. In deep canyons, where these techniques are not applicable, a combination with further board-side sensors can be a conceivable

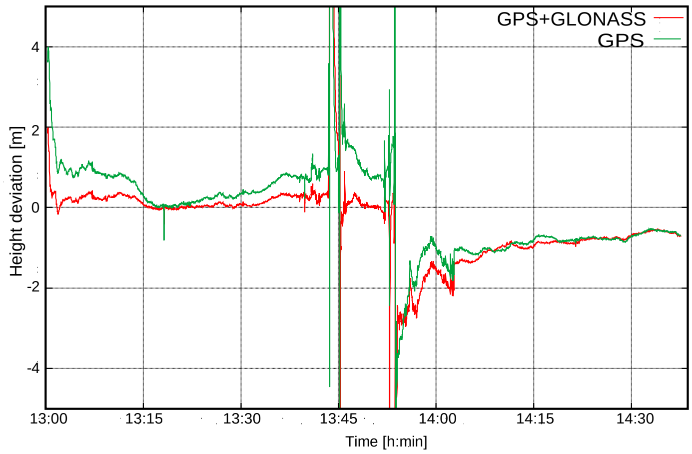

Figure 8: Height error for GPS and GPS+GLONASS using the PPP technique

approach.

5.3 Sidekick: Inertial Measurement Unit (IMU)-aided height determination

To ensure the resilience, increase the reliability, guarantee the accuracy of the data and bridge

GNSS outages caused by obstacles, an Inertial Measurement Unit (IMU) is proposed as autonomous, self-contained sensor. RTK positions derived from GNSS, together with IMU observations were fused in a loosely coupled approach, where it is assumed that the performance of the RTK solutions are generally unaffected and used to correct the errors in the IMU.

Current implementation for the fusion of data relies in the so-called the Unscented Kalman Filter, a method to propagate mean and covariance information through nonlinear transformations. Although the Extended Kalman Filter has been widely accepted as a standard tool for the fusion of GNSS and IMU data, several studies have demonstrated that the unscented approach achieves a better level of accuracy, while is easier to implement, and with lower computational complexity of calculations (Romanovas et al., 2014; Wan and Merve, 2000).

With ca. 10min of data out of the observation set from Chapter 4.2, Figure 9 represents the vertical component in relation the pure GNSS-RTK solution (blue dots), and for the integrated RTK-IMU solution (green dots).

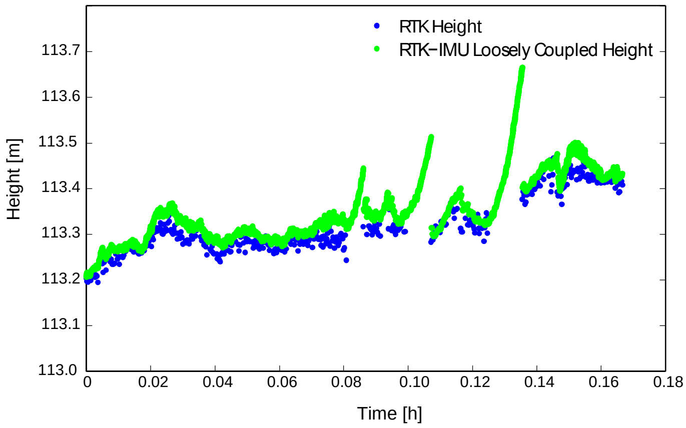

Figure 9: RTK and RTK-IMU Loosely Coupled Unscented Kalman Filter Height

On account of GNSS vulnerabilities, the RTK solution exhibits multiple outages of data, mostly due to the crossing of the vessel beneath the bridges, but also for the lack of RTK fixed solutions during several epochs. It is also noticed how the RTK-IMU loosely-coupled solution bridges smoothly this outages, with no significant difference between the two horizontal obtained positions when available.

Both solutions exhibit nearly the same behaviour, with a smoother yet biased performance for the RTK-IMU one. Bias on the RTK-IMU solution is partially explained by the larger covariance obtained on the RTK heights, with respect to the horizontal positioning. The three main challenges on this part of the channel are also represented: 'Balduinbrücke' (0.08-0.09), 'Eisenbahnbrücke' (0.10-0.11) and 'Europabrücke' (0.13-0.14). At the outage stages prominent drifts for the RTK-IMU solution are observed, 15cm, 25cm and 45cm, respectively. With 25cm and 45cm the accuracy requirement is not met. But the trend shows that an approach of fusing data from different sensors can improve the positional accuracy and availabilty. The potential of this approach should be further explored to contribute to the enhancement of the navigation within river corridors.

6 CONCLUSION

In the last four years a significant number on bridge collision on inland waterways were evaluated. These ship accidents make clear that a reliable height determination for an efficient bridge collision warning system is necessary. Feasibility studies identified solutions based on GNSS measurements as the most promising development.

This paper discussed commonly used GNSS-based positioning techniques regarding their applicability in inland waterways. Highly accurate phase-based and less accurate code-based augmentation techniques have been analyzed using real measurement data, gathered in a challenging area comprising a lock and three bridges.

Investigations have shown that in areas with good GNSS reception, e.g. in the head water, all augmentation methods met the requirements on height accuracy. Especially the phase-based RTK achieved accuracies up to 4.0cm with a fix rate of 95% followed by PPP with 20cm and the code-based IALA Beacon DGNSS with 80cm. The fallback SPP reached an accuracy of 2.5m. After locking into the tail water the bridges led to shadowing, interferences and GNSS outages decreasing the accuracy of positioning techniques. Especially RTK suffered from these effects, with a decreased fix rate of only 45%. Errors increased up to 1.6m for PPP and 1.8m for code-based respectively. The extension to a multi-GNSS-approach led to a better performance in the area with optimal satellite reception. In the signal degraded area shadowing and interferences outweigh the higher number of satellites. For PPP an improved convergence performance has been observed. Additionally an approach fusing RTK solutions with a GNSS-independent sensor has been discussed. Promising results displayed that outages in GNSS processing can be bridged for a short period of time.

Accuracies of RTK, PPP and IALA Beacon DGNSS are sufficient for inland waterway navigation with good GNSS reception conditions. In areas with highest accuracy requirements only the RTK solution with fix ambiguities is suitable for navigation. However, in signal-degraded areas, e.g. in the vicinity of bridges, this fix rate decreases, making RTK not sufficient for safety-critical applications. Therefore, a combined use of different GNSS positioning methods together with GNSS-independent sensors, to enable a continuous provision of reliable PNT data, is demanded.

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