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Long Term Validation of High Precision RTK Positioning Onboard a Ferry Vessel Using the MGBAS in the Research Port of Rostock

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ABSTRACT: In order to enable port operations, which require an accuracy of about 10cm, the German Aerospace Center (DLR) operates the Maritime Ground Based Augmentation Service (MGBAS) in the Research Port of Rostock. The MGBAS reference station provides GPS dual frequency code + phase correction data, which are continuously transmitted via an ultra-high frequency (UHF) modem. Up to now the validation of the MGBAS was rather limited. Either a second shore based station was used as an artificial user, or measurement campaigns on a vessel with duration of a few hours have been conducted. In order to overcome this, we have installed three separate dual frequency antennas and receivers and a UHF modem on the Stena Line ferry vessel Mecklenburg-Vorpommern which is plying between Rostock and Trelleborg. This paper concentrates on the analysis of the highly accurate phase based positioning with a Real Time Kinematic (RTK) algorithm, using correction data received by the UHF modem onboard the vessel. We analyzed the availability and accuracy of RTK fix solutions for several days, whenever the ferry vessel was inside the service area of the MGBAS.

1 INTRODUCTION

It has been recognized that the increasing global transportation of goods is not only pushing the rapidly growing vessel dimensions, but also the amount of vessels sharing the same routes at the same time. As a consequence the requirements for the provision of reliable and accurate navigational information increase, in order to minimize the probability of situations that could compromise the safety of the ship, crew and the environment. The capability to provide onboard Position, Navigation and Timing (PNT) data compliant with the accuracy, integrity, continuity and availability requirements in accordance to the different phases of vessel navigation is one core element of the International Maritime Organizations (IMO) e-Navigation strategy [1]. The Global Navigation Satellite Systems (GNSS), in particular the Global Positioning System (GPS) is the key component in maritime navigation for the provision of absolute positioning, navigation and timing information. In order to fulfil these requirements, the German Aerospace Center (DLR) has developed a PNT (data processing) Unit concept [2] [3] (see Figure 1)).

In this concept different processing channels are used in parallel in order to provide PNT data compliant with the performance requirements for the different phases of vessel navigation.

In this research study the focus lies on navigation inside the port, where the highest requirements with respect to accuracy and integrity needs to be fulfilled. In [4] maritime user requirements with an accuracy < 1 m for port operations and < 10 cm for automatic docking are stated. These requirements cannot be fulfilled using standard GNSS code based positioning techniques. Therefore GNSS phase based techniques needs to be applied. In this analysis we focus on the application of Real Time Kinematics (RTK) [5]. RTK is a differential technique based on carrier phase ambiguity fixing using the data provided by a reference station. While RTK based positioning is a standard approach for applications like surveying, hydrography [6] and precise farming, its usage for safety of life critical applications like vessel navigation is still under development.

In this paper we will present long term validation results of RTK positioning onboard a ferry vessel using the MGBAS in the research port of Rostock. The rest of the paper is organized as follows. In section 2 the realization of the MGBAS in the port of Rostock will be described. In section 3 the setup of the measurement campaign will be given, before in section 4 the validation results will be presented.

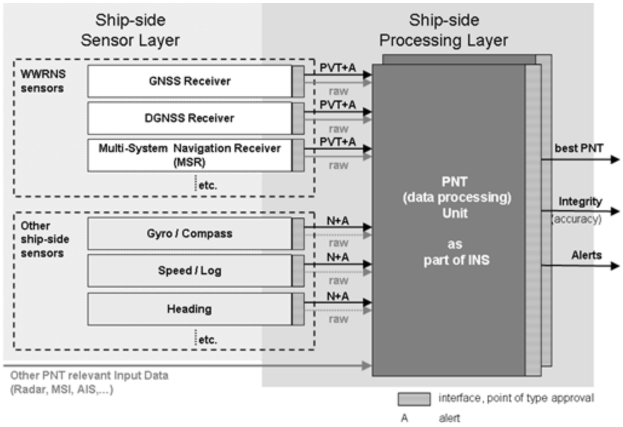

Figure 1. Concept of a PNT data processing Unit as part of a future Integrated Navigation System (INS)

2 MGBAS REALIZATION

The Maritime Ground Based Augmentation System (MGBAS) was developed in 2009 [7] following the principle of IALA Beacon service formulated in IALA recommendation [8]. In difference to the well accepted and distributed IALA Beacon service, which provides accuracies of better than 10 m together with integrity information within the service area of about 300 km around service stations the MGBAS concept addresses the nautical tasks with a demand on accuracy of better than 1 m or even 10 cm together with integrity which is necessary for port operations and automatic docking. In contrast to IALA Beacon service, which provides only code corrections for GNSS measurements, the MGBAS transmits more precise phase measurements which can be utilized for RTK positioning. This approach enables higher accuracies on the cost of a reduced size of service area of few 10 km around the reference station.

The concept of MGBAS supports all available global and regional navigation satellite systems such as GPS, Galileo, GLONASS, Beidou, and QZSS [7]. It consists of a reference station, with exactly known coordinates, which receives GNSS signals and evaluates them with respect to predefined performance key identifiers (PKI). Within the service area of the reference station one or more integrity monitoring station(s) are installed. They serve as artificial users and calculate their position, based on the correction information broadcasted by reference station. The positioning results are checked against the surveyed fixed position. This allows an evaluation of the service quality. Additionally further PKI will be calculated. After the evaluation of PKI of both stations, Radio Technical Commission for Maritime Services SC-104 Version 3.x (RTCM3) messages are generated for the maritime users which comprise a consistent set of GNSS phase corrections data together with integrity information.

Currently there exists only one MGBAS reference implementation within the German research port Rostock [9] (see Figure 6). The reference station in the center of research port is equipped with a Leica GNSS choke ring antenna, which suppresses the impact of GNSS signal reflections on the water surface and constructions in the vicinity, a geodetic GNSS receiver connected to a rubidium atomic clock (reduces receiver clock jumps), a station computer connected to the internet and a radio modem with an antenna for data broadcasting. The MGBAS integrity monitoring station is set about 4 km away from the reference station near the port entrance (see Figure 6). It is equipped with a geodetic receiver a GNSS antenna from navXperience and a data processing unit which is connected to the internet.

An ultra-high frequency (UHF) radio communication link is used for data transmission. The reference station, equipped with a SATELLINE 3ASd radio modem, broadcasts MGBAS generated corrections and integrity information using an extended RTCM3 protocol. The broadcast power at the frequency of 447.95 MHz is 1 W. A data rate of 38400 bps is achieved.

All necessary data processing can be performed directly at the reference and integrity monitoring station. Additionally the entire measurement data can be received via internet at the central processing facility in Neustrelitz and the entire data processing could be done on high performance computers there. The evaluation results are sent back to the reference station, where it will be broadcasted to the maritime users of the MGBAS.

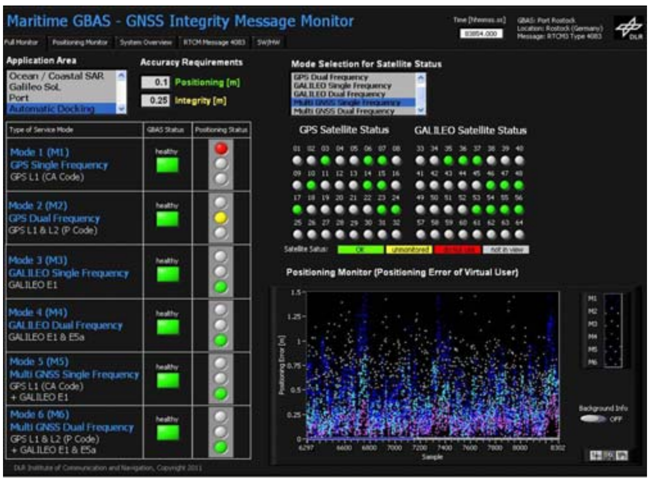

Figure 2. MGBAS Monitor for visualization of MGBAS relevant integrity statements

This approach provides the opportunity for an extensive monitoring of MGBAS, as shown in Figure 2. On the left hand side the multifunctional display shows, which of the services (different processing chains) meet (green) or fail to meet (red) the requirements of the selected performance class (e.g. port or automatic docking). The operator can make conclusions about the performance stability of the services based on the time behavior of position error per process (Fig 2, bottom right). In addition, the upper right part of the screen shows, which GNSS signals are identified as useable for service provision.

Figure 3. Vessel Mecklenburg-Vorpommern with positions of the GNSS antennas (red circles) and location of the board with receivers (green circle)

3 SETUP MEASUREMENT CAMPAIGN

The original sensor measurements were recorded using the ferry vessel Mecklenburg-Vorpommern from Stena Lines, which is plying continuously between Rostock and Trelleborg. The measurements, analyzed in this paper, were taken in 2015. In that timeframe the vessel was traveling a single route between Rostock and Trelleborg 3 times a day (see Figure 5). On Sundays the vessel stayed for a longer period of time (~ 4 h) in the port of Rostock and was travelling between Rostock and Trelleborg just 2 times. That results in the fact that the vessel is at least once per day for ~ 3h within the service area in the port of Rostock.

The vessel was equipped with three dual frequency GNSS antennas and receivers (Javad Delta and Sigma). The antennas were placed on the compass deck (red circles in Figure 2). The chosen geometry of the antenna placement enabled an accurate determination of the vessel 3D attitude by applying GNSS Compass algorithms. A UHF modem was used for the reception of RTK corrections data from the MGBAS station.

All relevant sensor measurements were provided either directly via Ethernet or via serial to Ethernet adapter to a Box PC (see Figure 4) where the observations are processed in real-time and stored in a SQLite3 database along with the corresponding time stamps. The described setup enables a record and replay functionality for further processing of the original sensor data. The system consists of a highly modular hardware platform (here realized with a Box PC) and a Real-Time software framework implemented in ANSI-C++.

Figure 4: Left: Installation of starboard GNSS antenna with UHF antenna (right) for the reception of MGBAS correction data
Right: Board with GNSS receivers, UHF modem, IALA Beacon receiver, serial to Ethernet adapter and Box PC for data processing and storage

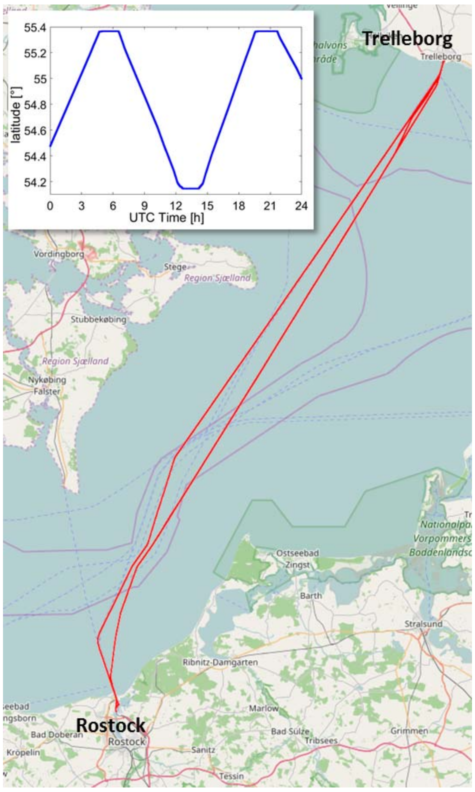

Figure 5. Overview of 24h vessel trajectory top left: latitude vs. time graph for that day

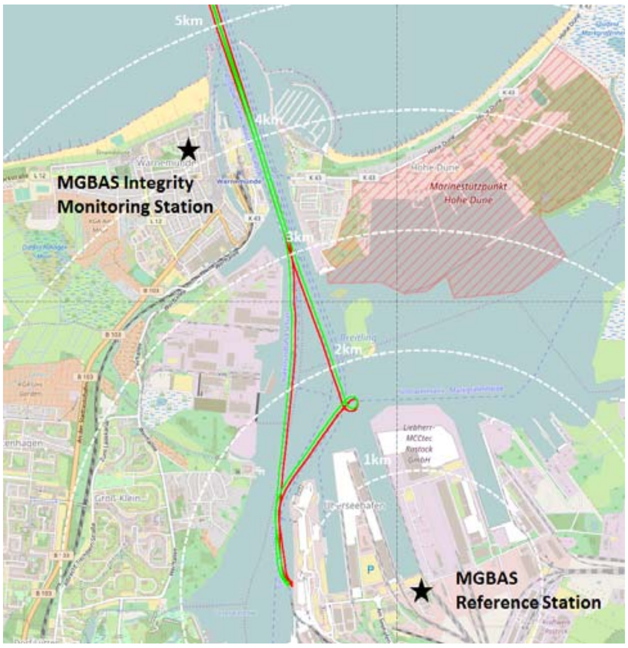

Figure 6. Vessel trajectory within the port of Rostock (green: starboard antenna, red: portside antenna), white dashed circles mark the distance to the MGBAS Reference Station

4 RESULTS

4.1 *Communication link*

The MGBAS reference station provides 2 Hz GPS L1 and L2 code + phase correction in RTCM3 data format. Onboard the vessel, these data are received by a SATELLINE 3ASd radio modem. The UHF antenna for that modem is placed besides the starboard GNSS antenna on the compass deck (see Figure 3). A prerequisite for RTK based positioning is the reception of timely correction data from the reference station. Therefore we first checked the performance of the communication channel.

For the purpose of this evaluation, we were not interested in the details of the communication link, but just in the final performance for this specific application. For this reason we have only evaluated the number of RTCM3 messages which have been successfully transmitted at the MGBAS station and decoded onboard the vessel. In Figure 7 (left) the data link availability as a function of the distance between vessel and reference station is plotted for the timeframe of 21 days. Here for each day and each distance interval the percentage of received messages compared to the send messages is calculated. In Figure 7 (left) the mean value (averaged over 21 days) and the minimum and maximum values are plotted. Starting with nearly 100 % availability for the moorage position, the availability drops significantly at a distance of ~2 km to ~ 92 % while increasing again at 4 km distance. Finally the mean availability drops below 90 % at ~ 7 km and below 50 % at 15 km.

In Figure 7 (center and right) the trajectory of the vessel is plotted for one arrival and departure in Rostock for day of year (DOY) 120. The green dots mark points, where a direct communication with the UHF link could be established successfully and the RTCM3 data could be decoded and used for RTK positioning. The timespan for the generation of correction data in the reference station, the encoding, transmission, reception and decoding of that data is typically < 0.5 s. Together with the applied data rate of 2 Hz, with a stable UHF communication channel, the age of applied corrections for the RTK positioning algorithm is typically $\tau = 0.5$ s. With increasing age of applied corrections the chance to get a high accurate solution with fixing the integer ambiguities is decreasing. In Figure 7 (center) significant differences between the incoming and outgoing vessel can be found. Compared to the outgoing vessel the incoming vessel shows for a longer distance a good communication channel. A possible route cause for that behavior could be the combination of the vessel track / orientation and the concrete installation of the UHF antenna on the vessel.

In order to analyze the drop of the data link availability at ~ 2 km distance in Figure 7 (right) the age of applied correction for DOY 120 only for the port area is shown. Here several short data link outages (< 5 s) can be identified, which are possibly caused by obstructions in the line of sight by the port infrastructure like cranes.

Focusing only on the service area of the MGBAS within 5 km distance from the reference station, the implemented communication channel is not perfect, but for the provision of correction data for RTK based positioning reasonable good. Looking at the age of applied corrections as the relevant parameter for RTK positioning (see Figure 8) one sees, that for all days the availability of timely correction data is higher than 98 % and for nearly 100 % of the time the age of correction data is below 5 s. Only for DOY 140 for a short period of time the age of applied corrections is between 5 s and 10 s.

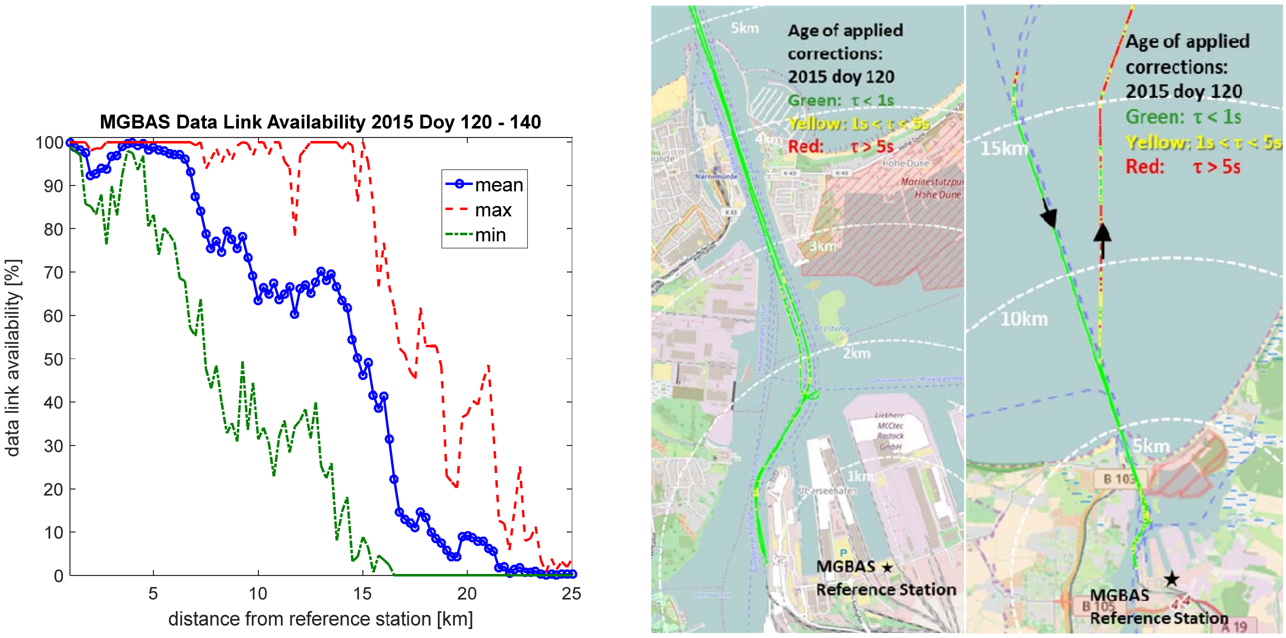

Figure 7. left - MGBAS data link availability with varying distance to the reference station;
Age of applied corrections within data reception range (center) and within the service area of MGBAS in the port of Rostock (right)

Figure 8. Age of applied correction for RTK positioning within service area of the MGBAS in the port of Rostock

4.2 *RTK Positioning performance in the port of Rostock*

In order to validate the RTK positioning performance, while using the MGBAS in the port of Rostock in a reproducible and receiver manufacturer independent way, we have decided to use the open source code RTKLib (http://www.rtklib.com) version 2.4.2. We have embedded the C code of the RTKlib in our C++ real time (RT) Framework, so that the real time positioning performance can be evaluated directly. Due to the modular structure of the RT-Framework [10] several RTK positioning solvers could run in parallel. This enables independent and simultaneous RTK positioning for the three different antennas onboard the Stena Line ferry vessel Mecklenburg-Vorpommern at ones.

The high accuracy of RTK based positioning can only be achieved, if the double difference ambiguities (the unknown number of wave cycles between receiver and satellite) can be fixed successfully. As the measure of trust in the ambiguity fixing, the ambiguity validation threshold is used [5]. For this evaluation a threshold of 2.5 is applied.

In order to estimate the positioning accuracy and to check the occurrence of wrong ambiguity fixes, the three antenna setup onboard the vessel can be exploited. Therefore for all three antennas the RTK based positions using the MGBAS correction data were calculated independently. In Figure 9 the histogram of the resulting distances between two antennas is plotted for the case, that for both antennas the RTK solver stated a successful fix of the ambiguities. For the applied configuration no distance error larger than 5 cm was found, which means that the ambiguities have been fixed correctly.

The resulting distances between the antennas show nearly Gaussian distributions with a standard deviation σ below 1 cm. The significant smaller standard deviation for the distance between the portside and starboard antenna compared to those including the mid ship antenna could be caused by the concrete installation of the antennas onboard the ferry vessel Mecklenburg-Vorpommern. The mid ship antenna is placed closer to the mean mast and therefore suffers stronger from resulting multipath and obscuration effects (see Figure 3).

An accurate determination of the position accuracy of the RTK based positioning would require a GNSS independent highly accurate positioning source and is not within the scope of that paper. The calculated error in the distance between the antennas can only be a lower bound of the absolute position accuracy. An upper bound of the position accuracy can be determined by comparing the RTK based positioning results with a post processed reference trajectory based on the Precise Point Positioning (PPP) approach, which delivers dm up to cm accuracy for continuous observations [11]. The PPP reference trajectories, which we have calculated for several days, are consistent with the RTK based positioning.

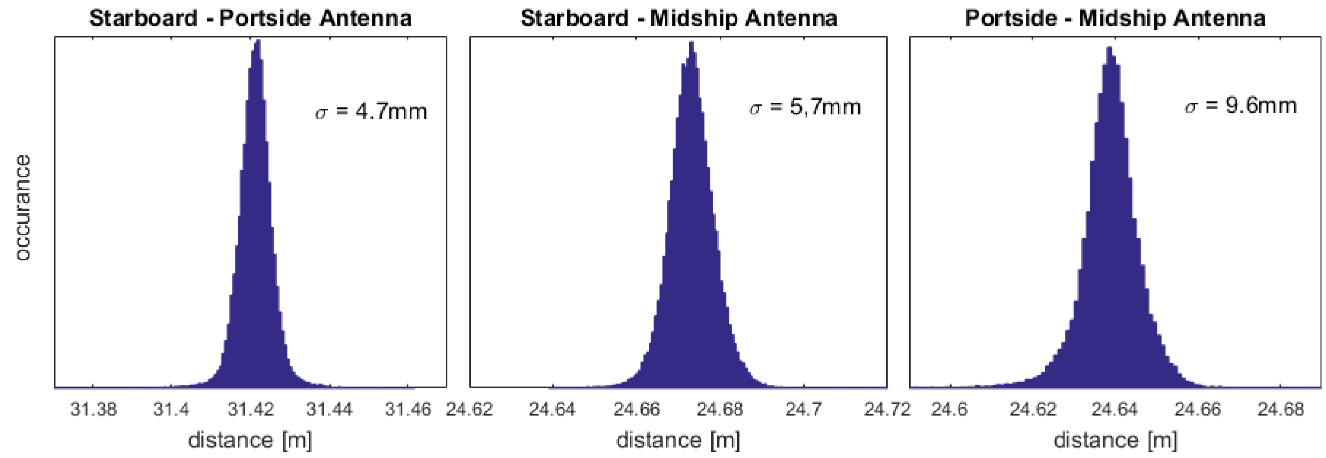

Figure 9. Histograms of calculated distances between the antennas based on RTK position results

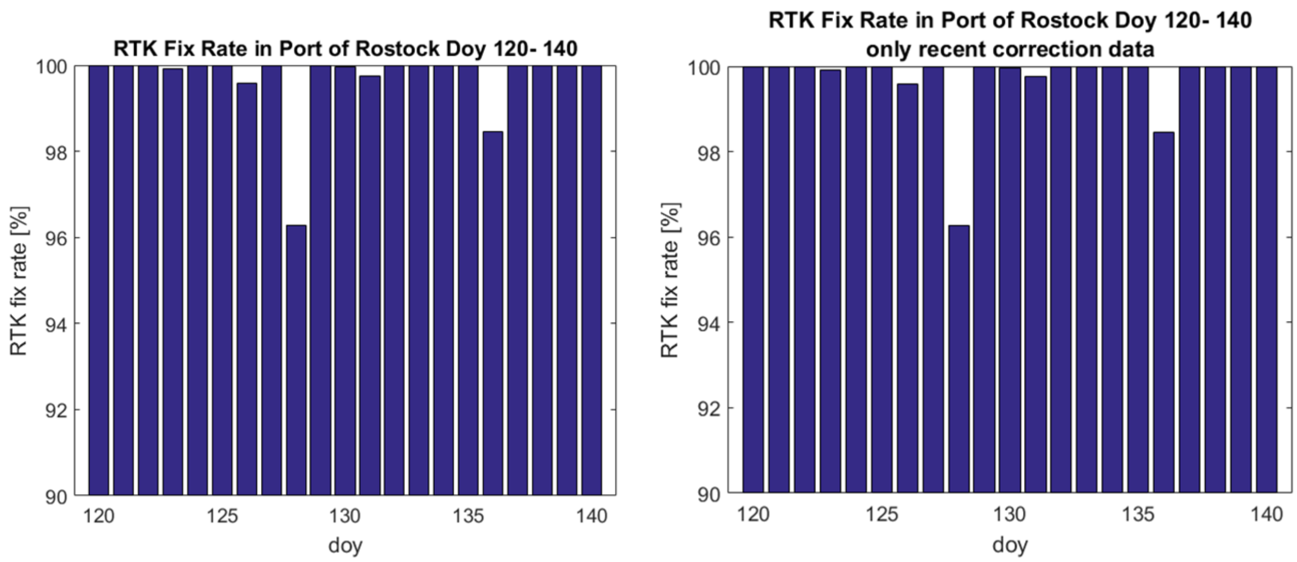

Figure 10. RTK Fix rate in the port of Rostock, left: using all data; right: using only recent correction data

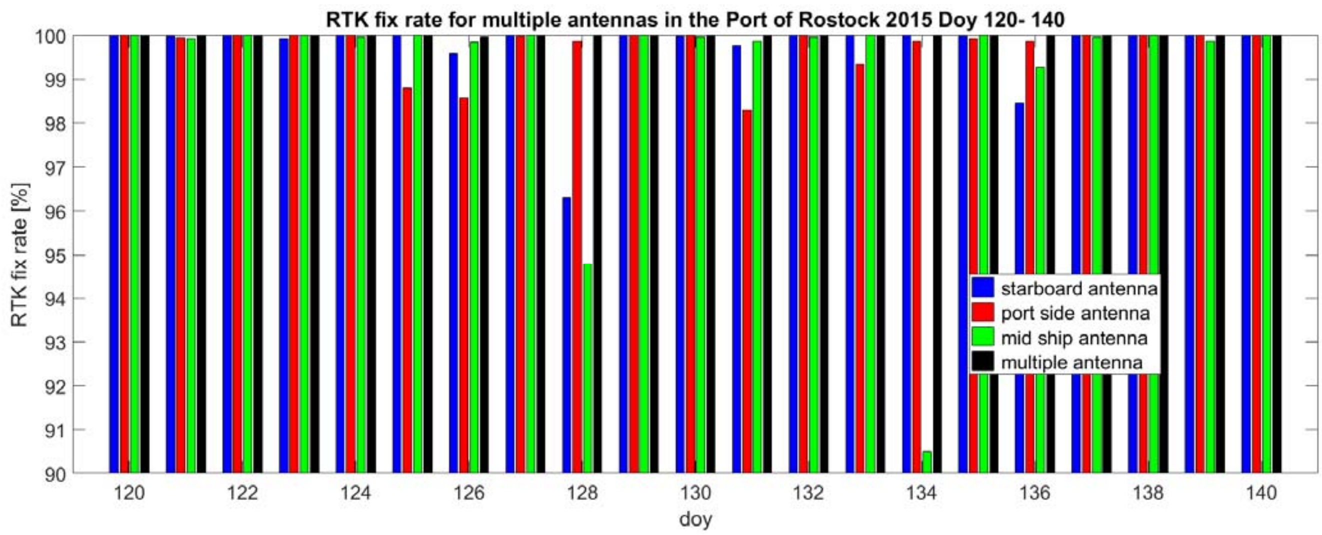

Figure 11. RTK fix rate for multiple antennas in the port of Rostock

4.3 *RTK Fix rate of a single antenna in the port of Rostock*

For the usage of RTK based positioning for safety of life critical applications, the availability of position solutions with fixed integer ambiguities is one of the most critical points. In Figure 10 the RTK fix rate for the starboard antenna for 21 days in 2015 is plotted. Here the RTK fix rate is the percentage of epochs (times), where the integer ambiguities have been fixed successfully, divided by the total number of epochs, where the vessel was inside the service area of the MGBAS in the port of Rostock. The service area has been defined by a circle with 5 km radius around the MGBAS reference station.

For 17 out of the 21 days a fix rate larger than 99.9 % can be found (see Figure 10 left side) and a minimum fix rate of ~ 96 % for DOY 128. This fix rates are astonishing high, taking multipath and non-line of sight effects from cranes, buildings and other vessels into account.

In a next step the influence of the imperfect communication channel (see 4.1) on the RTK fix rate has been evaluated. For this analysis those epochs, where the MGBAS correction data are older than 1 s, have been filtered out. The resulting fix rate is shown in on the right side of Figure 10. Here no significant differences to the left side can be observed. This leads to the conclusion that for the evaluated timeframe, the interruptions in the communication channel have no measurable influence on the RTK fix rate and therefore on the positioning performance.

4.4 *RTK Fix rate of using multiple antennas in the port of Rostock*

For our measurement campaign we have chosen a setup with three separated GNSS antennas and receivers onboard a vessel (see *Figure 3*). This setup enables a) an extremely accurate determination of the attitude (roll, pitch, heading) of the vessel by using a GNSS compassing algorithm and b) a redundant determination of ships position (and velocity) by using each antenna separately. In [12] we have shown that, using the GNSS Compass setup on the vessel Mecklenburg-Vorpommern, we can determine the attitude with an accuracy of better than 0.01°. Furthermore the combination of that GNSS Compass and a low cost tactical grade Inertial Measurement Unit (IMU) ensures not only this high accuracy, but also 100% availability of the determined attitude information under normal conditions. Note that during a longer GNSS outage the IMU based attitude information will slowly drift away (ca. 1 deg/h for a tactical grade IMU).

Within the scope of this paper we have now evaluated the advantage of using the three antennas separately for the redundant RTK based determination of the position. This redundancy could in general be used for integrity monitoring purposes, by checking the consistency between the positioning results. Here we focus just on the increase of availability of highly accurate positioning results by using the three antennas separately. For an accurate positioning it is sufficient, that only for one out of the three antennas the integer ambiguities have been fixed successfully. In *Figure 11* the RTK fix rate for the three antennas for the 21 days is plotted. For 12 out of 21 days the RTK fix rate for all three antennas is higher than 99.9%. It is remarkable, that the RTK fix rate varies significantly for the different antennas. There is no antenna, which performs always better than the others. Only when evaluating the mean RTK fix rate for the whole 21 days (see Table 1), the mid ship antenna clearly shows a slightly worse performance compared to the portside and starboard antennas. This finding is consistent with the results of section 4.2 and could be caused by the installation of the mid ship antenna close to the main mast.

The black bars in Figure 11 indicate the fix rate for the multiple antenna approach, where at least one out of the three antennas needs to have a fixed integer ambiguity. For the evaluated timeframe of these 21 days in 2015, the resulting fix rate is always larger than 99.96 % and a mean fix rate of 99.998% is achieved. So that the multiple antenna approach substantially outperforms the single antenna approach.

Table 1. RTK fix rate for the 21 day period

	starboard	portside	mid ship	multiple
mean	99,71%	99.73%	99.23%	99.998%
min.	96.3%	98.3%	90.5%	99.97%
max.	100%	100%	100%	100%

The big improvement of the multiple antenna approach could be explained by the fact, that at least for the evaluated period of time, local effects like multipath and obscurations are the dominating error sources for RTK based positioning of a vessel in a port environment.

5 SUMMARY

The MGBAS in the Research Port of Rostock provides continuously GNSS correction data enabling highly accurate phase based positioning using RTK positioning algorithms. In this paper we present the results of a long term measurement campaign using the MGBAS onboard the Stena Line ferry vessel Mecklenburg-Vorpommern, which is continuously plying between Rostock and Trelleborg.

In a first step, the performance of the UHF (447.95 MHz) radio communication channel, using a modem with 1 W output power was evaluated. The established communication link enables a 99% availability of timely correction data onboard the ferry vessel in the port area. Although short interruptions of the communication link are detected, no negative influence of those on the RTK based positioning has been determined.

The crucial point of RTK based positioning for safety of life critical application is the availability of the highly accurate (~cm accuracy) fixed solutions. By using a single antenna only an availability of 99% for the analyzed 21 days (2015, DOY 120-140) has been observed within the service area of the MGBAS. A dramatic increase of that availability to 99.997% could be realized, by using a multiple antenna setup with three separate antennas and receivers.

These encouraging results open the door for the development of real applications of the phase based MGBAS for highly accurate port operation.

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