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Low Bandwidth Network-RTK Correction Dissemination for High Accuracy Maritime Navigation

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ABSTRACT: More than half of the incidents reported to EMSA relate to nautical events such as collision, groundings and contacts. Knowledge of accurate and high-integrity positioning is therefore not only a need for future automated shipping but a base for today's safe navigation. Examples on accidents include Ever Given in the Suez Canal and HNoMS Helge Ingstad in Norway.
A Network-RTK (NRTK) service can be used as an augmentation technique to improve performance of shipborne GNSS receivers for future positioning of manned and unmanned vessels in restricted areas, such as port areas, fairways, and inland water ways. NRTK service providers generate RTK corrections based on the observations of networks of GNSS reference stations which enables the users to determine their position with centimeter accuracy in real-time using a shipborne GNSS receiver. Selection of appropriate communication channels for dissemination of NRTK corrections data is the key to a secure positioning (localization) service. In PrePare-Ships project, the modern maritime communication system VDES (VHF Data Exchange System) is proposed to distribute SWEPOS (NRTK in Sweden) correction data to shipborne positioning modules. VDES is a very reliable technique and it is compatible with most onboard functionalities. In order to minimize the impact on the overall VDES data capacity in a local area, NRTK correction data shall only occupy a single VDES slot with a net capacity of 650 bytes. Update rates may vary but are preferably at 1Hz. However, NRTK correction data size changes instantly, depending on the number of visible GNSS satellites, and the data rate can therefore sometimes reach in excess of 1000 byte/s. In this study, a smart technique is proposed to reduce size of NRTK correction data to instantly adapt with the VDES requirements by choosing a combination of specific signals, satellites or even constellations such that the data rate is not more than 650 byte/s, and at the same time it achieves optimal positioning performance with the accuracy required by the PrePare-Ships project application.

1 INTRODUCTION

The main types of serious accidents in shipping are collisions, contacts and groundings. While there are many studies indicating that ship accidents are influenced by many internal and external factors, some characteristics on decision making just prior to accidents. Statistics have shown that these categories represent around 2/3 of all accidents in Europe [3], Japan [8] and Canada [12]. Earlier studies [1, 6, 13] and statistics from incident [4] and accident statistics [3] have shown that root causes for collisions are found in human performance, expressed by poor communication, situational awareness, unfamiliarity with equipment and fatigue. For contact and grounding incidents the reasons can be found in similar categories as for collisions with additional unfamiliarity with area, poor voyage plan and poor assessment of speed.

Regarding time constrains of the operator, there is a fundamental difference in near-grounding situations to in near collisions/ close quarter situations. While decisions can often be made some ten minutes or so to avoid groundings, collisions have a much shorter time-to-act span down to seconds [5]. Hollnagel [2] has found that for the humans in a system "that the reason why they sometimes fail, in the sense that the outcome of their actions differ from what was intended or required, is due to the variability of the context and conditions rather than to action failures". Thus, the ability to minimize the variability will have a potential to minimize the occurrence of undesired events.

The objectives of this study within the PrePare-Ships project is to give evidence-based criteria for designing decision support tools based on a dynamic ship predictor which require high accuracy positioning information from the shipboard GNSS receiver and the other sensors. The feedback from ship crews implies that dynamic predictors increases the understanding on how the future movement of the vessel will be in different weather conditions. The results of the literature study and data analysis indicate that the prevailing event categories can be influenced by decision support making the common understanding of the current situation more visible to the crews. Especially for collision situations, short time spans are available to make decision, therefore a constant prediction of how the ships will move can support the crews in decision making and situational awareness. Accident investigations show a significant amount of accidents where the crews internal situational picture deviated on the same as well as on all bridges of the ships involved.

The high-accuracy GNSS positioning technique is widely used in marine navigation. In general, there are several techniques for providing GNSS corrections that can be used to achieve high precision positioning like e.g. DGPS, SBAS, RTK and PPP. In the PrePare-ships project we are working to develop methods in order to use Network-RTK and PPP for positioning of ships. As NRTK technology requires land-based reference stations it will focus on positioning in inshore areas. Since the core of fast and high-accuracy NRTK positioning is the ability to provide the correction data for all constellations, satellites and signals, this study focuses on the NRTK accuracy performance when it provides the correction data to the shipboard GNSS receiver.

2 GNSS NRTK POSITIONING FOR SAFE NAVIGATION IN THE RESTRICTED WATERS.

In order to decrease the risk of ship collisions, the situational awareness can be increased by predicting future positions and exchanging them with the surrounding. Therefore, the PrePare-Ships project develops a robust and accurate navigation solution based on the features of Galileo signals in combination with NRTK corrections and other in-ship sensors. The solution reduces the risk for ship collisions, provide decision-support in fairway navigation, decrease environmental impact and emissions and provide a cornerstone for future automated navigation. The PrePare-Ships System will receive position, attitude and velocity data from the ANavS GNSS receiver using the Galileo Open Service. The ANavS receiver use the signals from Galileo satellites, the carrier-phase positioning corrections from Network-RTK supported from SWEPOS, and information about the integrity of the RTK corrections. SWEPOS is the national CORS network of Sweden operated by Lantmäteriet (the Swedish Mapping, Cadastral and Land registration authority). By that, ANavS provides a reliable positioning service using sensor fusion.

The network RTK service in the project is based on SWEPOS. The Swedish GNSS reference station network has been developed in different stages to be able to meet the requests on better positioning uncertainty, reliability and availability. In general, SWEPOS is based on:

- Physical infrastructure (permanent reference stations and hardware of the control center);
- Distribution infrastructure capable of disseminating real-time data flow from the stations to the control center and from this to the user according to RTCM SC 104 (Radio Technical Commission for Maritime Services Special. Committee 104) standard [11];
- Processing infrastructure, consisting of third party software that improve the estimation of the various errors and make them available to users spread over the coverage area.

The current SWEPOS NRTK Service is based on the Virtual Reference Station (VRS) concept, with two-way mobile network communication between the processing center and the NRTK users. The VRS technique is currently the most popular/used NRTK technique due to its compatibility with existing software. The shipborne EGNSS receiver applies the standard differential positioning of its observations with observations from the VRS. Based on the observations from the surrounding Physical Reference Stations (PRS) in the area, the SWEPOS control center will interpolate and generate a set of GNSS observations/corrections calculated as if they were acquired by a hypothetical receiver placed at the required reference position, thus obtaining a VRS. The network computing center is located in Lantmäteriet (Gävle) and it generally perform the following steps:

- Determine various errors of different origin, including atmospheric errors, clock errors, and local multipath with cm-accuracy by fixing the ambiguities of the baselines within SWEPOS network,
- Simulate the position of the VRS by geometrically displacing the data of the reference station closest to the rover,
- Interpolate the estimated errors at the VRS location using mathematical models,
- Transmit the corrections to the users in real-time.

The current SWEPOS infrastructure consists of approximately 460 permanent GNSS reference stations located as shown in Figure 1. The distances between these stations can be classified into the following configurations [9].

– Normal Configuration (NC): It's the original form of SWEPOS NRTK which was built through establishing NRTK service in 2002-2010. The distances be-tween the stations are 70 km.
– Densified Configuration (DC): It's the densified form of NRTK service. The distances between the stations are 35 km. The densification from 70 to 35 started in 2010 for improving the network performance.
– High-Densified Configuration (HDC): It's a special form of NRTK service and implemented for the areas that need very high performance (project-oriented positioning services). The distances between the stations are 10 km.

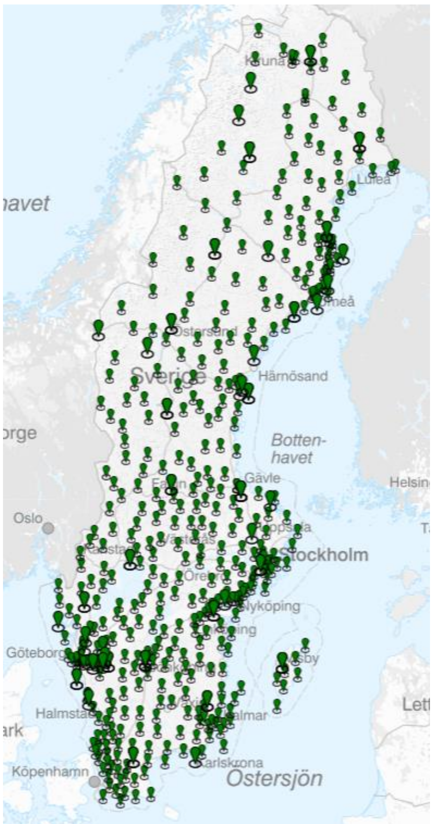

Figure 1. Map of SWEPOS reference stations.

All SWEPOS stations are equipped with very modern GNSS receivers which can receive and process the signals/frequencies from all current GNSS constellations (GPS, GLONASS, Galileo, Beidou,…). Figure 2 shows two types of GNSS receivers (Trimble Alloy and Septentrio PolaRx5) which are the most common types on the SWEPOS stations. Data is collected every second and a 5 degrees elevation mask (in data processing software) is used. A Choke ring antenna of Dorne Margolin design mounted under a radome is used at every SWEPOS reference station. The radomes are made of clear acrylic. Figure 3 shows an example of the class A station.

Figure 2. GNSS receivers used in most of SWEPOS stations.

Figure 3. The SWEPOS station Leksand.

The transmission infrastructure is a very important part in Network-RTK. It should be capable of disseminating a real-time data flow from the stations to the processing center, and from the center to the ship according to own protocols or standard ones.

The NRTK correction data is generally transmitted to the ship via the RTCM format. The RTCM SC 104 on Differential GNSS (DGNSS) provides the standards for disseminating the differential GNSS and RTK information from the service provider to the users (the shipborne GNSS receivers in our case). The RTCM was mainly used for disseminating the correction data in PrePare-ships project. The data transmission from the reference stations to the control center server and from the control center server to the user for RTK corrections is mostly carried out via the Network Transport of RTCM via Internet Protocol (NTRIP) [10].

3 DISSEMINATION OF NRTK CORRECTION DATA VIA VDES.

As 4G and future 5G does not fulfil the maritime reliability requirements, the maritime Automatic Identification System (AIS) is used world-wide for exchange of position reports and other data between ships and between ships and shore based base stations. The system operates on dedicated VHF channels within the maritime band and is based on the concept of time multiplexed transmissions (TDMA) enabled by the availability of a common time reference from GNSS. Carriage of AIS transponder equipment is required for the majority of commercial ships and AIS base stations are employed by most coastal nations.

The dynamic predictor which proposed in the PrePare-ships project requires substantial communication bandwidth to sustain accurate and timely predictions ship to ship. AIS cannot deliver this bandwidth so the research in the project will be performed using VHF Data Exchange System (VDES) as communication channel. VDES is the next generation AIS with up to 32 times the bandwidth compared to AIS [7]. The VDES terrestrial link denoted VDE-TER link ID 19 can deliver 702 bytes per slot after FEC (Forward Error Correction) and the PrePare-ships project has selected this link as the primary link for the dynamic predictor research. An alternative, but discarded solution, could be VDE-ASM with link ID 5 that can deliver 36 bytes after FEC per slot. There are 2250 slots/minute in the AIS/VDES communication system with 37.5 slots per second. With VDE-TER link ID 19 the dynamic ship predictors "payload" limit has been set to 650 bytes/slot as an initial assumption and the rest of the bytes (52) have been reserved for link management.

VDES is a broader concept subject to on-going international standardization and development efforts. The goal is to enhance the amount of data that can be transmitted and to enable world-wide rather than line of sight communication capabilities, by introduction of a satellite segment. VDES is intended to be an enabler for new functions aimed to improve safety and efficiency for shipping operations.

To ensure better availability of GNSS correction data, a novel way of dissemination was developed within the PrePare-Ships project. This approach builds upon the approach previously discussed, dissemination via internet and NTRIP by adding an additional layer after the NTRIP Caster mountpoints user. Several additional considerations need to be taken into account for VHF and VDES dissemination. These can be divided into adapting the GNSS correction data stream content, and preparation and restoration of the correction data before transmission and after reception with regard to synchronization with the VDES protocol. Figure 4 shows the diagram for this method.

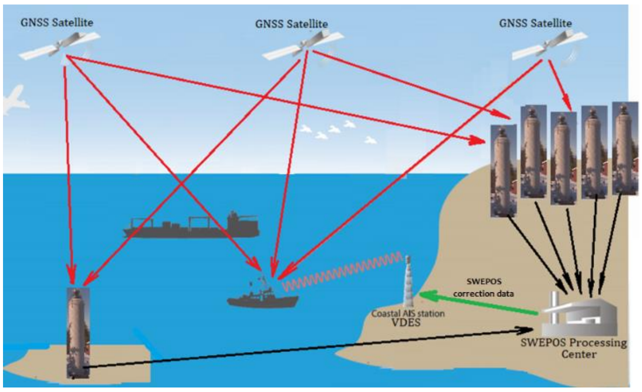

Figure 4. Dissemination of GNSS correction data via VHF and VDES.

The emerging capabilities of VDES are exploited by the PrePare-Ships project for transmission of network RTK data from shore to ship as well as for exchange of prediction information between ships. For this purpose, prototype VDES transponders are installed on the participating ships and a shore based VDES base station is provided with coverage of the intended test area.

The TDMA concept for VDES and AIS is based on slots. A slot is defined as a 2250th of a minute or approximately 26.7 ms. It is estimated that one slot per second is a reasonable load on the VDES link that can be dedicated for transmission of NRTK corrections. With allowance for some overhead, this translates to the 650 bytes/s limit required for the RTCM data stream.

The VDES base station integrates with an NTRIP client for acquisition of the compact RTCM data from SWEPOS. The received packages are formatted and broadcast as one slot messages on a VHF channel dedicated for the purpose. The transponder on a participating ship strips the received data from VDES overhead and restores the RTCM content as provided by the NTRIP client.

The VDES transponder is interfaced with other equipment on the ship by means of an Ethernet network interface compliant with IEC 61162-450. This standard dictates the required properties of the network and methods of data exchange for usage with maritime communication equipment and systems on ships.

The IEC standard does not specify any data format intended for transmission of GNSS corrections over the network. However, it is generally open for co-existence of standardized messages and messages with arbitrary data formats as long as a set of minimum requirements are fulfilled.

The transport layer used for transmission of IEC61162-450 messages is the UDP multicast protocol. This makes it possible to transmit the RTCM packages from the VDES transponder to the navigation sensor as a UDP payload without any additional formatting.

The VDES transponder thus transmits the RTCM correction data received from the base station over the Ethernet network on the ship. The navigation system retrieves the corrections from the network with knowledge of the agreed IP address and port number used by the multicast protocol.

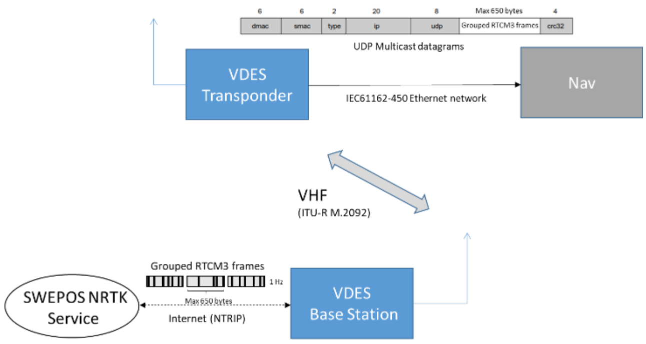

Figure 5. Transfer of GNSS NRTK corrections via VDES.

Distribution of RTK correction via VDES according to the principles described are suitable for generic port installations. A VDES base station service provider may thus provide access to high performance positioning without need for dedicated communication equipment on the ships.

4 ADJUSTMENT OF NRTK (RTCM MESSAGES) CORRECTION DATA.

When adapting the correction data stream for VDES transmission the following factors must be considered:

- Utilization of only one VDES slot gives an upper limit for the data rate of 650 bytes/s.
- The coverage area of the VHF transmitter is considerably larger than the area where correction data from one single VRS may be utilized, derived from maximum distance between user and VRS due to positioning accuracy requirements.

In VDES, multiple communication channels between ships and land-based transceivers are handled by dividing the communication over a specific number of slots (time intervals) each second. As all communicating parties within communication range share the same slots, where only one party may transmit within each slot, communication must be kept at a minimum. Thus, the solution in PrePare-Ships is to utilize only one of the available slots each second. This gives a bandwidth limitation for the transmission of GNSS correction data corresponding to 650 bytes/s. Typical data rate for corrections including GPS, GLONASS, and Galileo is between 700-1000 bytes/s. Adding corrections for BeiDou and the integrity data will of course increase this number further. As a consequence, the size of the GNSS correction data has to be reduced by applying some filtering. This especially applies for situations when corrections for several GNSS constellations are transmitted.

Additionally, the range of the VHF transmitter greatly exceeds the maximum range between the GNSS correction data user and the VRS position. In a solution where GNSS correction data is broadcasted for a grid of VRSs[14], this mean that each VHF transmitter may have to transmit GNSS corrections for more than one VRS. This is in the PrePare-Ships solution solved by serializing correction data from several VRSs into the same data stream. At the same time correction data from each VRS is down sample in order not to increase the bandwidth requirements of the transmitted corrections. This means, that if corrections for several VRSs are sent in the same correction stream, the frequency of the observation messages for each VRSs is down sampled by the number of VRSs included in the stream.

To comply with the above-mentioned conditions, the Lantmäteriet Adjustment Solution (LAS) for GNSS correction data adjustment was developed. The responsibility of this software is to produce a correction data stream that complies with the bandwidth limitation of 650 bytes/s and have the capability to combine several correction data streams from several VRSs into one single correction data stream. Figure 15 depicts the data flow between caster (black square), adjustment software (pink square), and the VHF transmitter (brown square). TCP/IP is used for transmission of correction data between these components. For dissemination via VHF and VDES, the developed adjustment software connects to the same mountpoints and performs combining, down sampling, and removal of correction data to comply with the above-mentioned conditions. The resulting correction data stream is refed into to the caster and served for the mountpoint labelled PREP in the figure 6. From this point, the VHF transmitter can connect to the mountpoint and transmit the correction data stream. The same process is repeated for other VHF transmitters and additional VRSs.

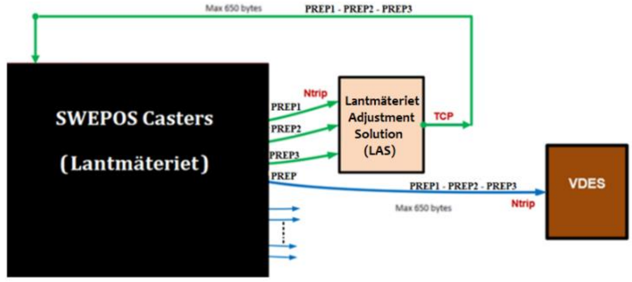

Figure 6. Data flow of GNSS correction data before dissemination via internet and VHF

Tests that demonstrates the feasibility of using GNSS correction data processed for VDES transmission have been performed in cooperation with RISE (Research Institutes of Sweden). These tests were performed for statically located antennas only. Future tests will also be done for moving antennas. The results support that processed GNSS correction data with a byte transmission limit of 650 bytes/s, including correction data for one or several GNSS constellations, and containing at least 3 VRSs, can be employed by a RTK capable GNSS receiver to obtain positioning solutions with resolved carrier phase integer ambiguities and centimeter level positioning accuracy.

The adjustment software has the capability to filter GNSS correction data in the RTCM 3 format constellation-wise, satellite-wise, and signal-wise as it shown in Figure 16. The objective is to achieve optimal performance in terms of accuracy for the user's precise positioning solution, while at the same time adhering to constraints that might apply locally for individual transmitters.

Constellation-wise filtering is achieved simply by instructing LAS about which RTCM MSM observation messages to forward. This is possible because RTCM MSM has specific RTCM number ranges for each of the constellations, e.g. 107x for GPS, 108x for GLONASS etc., where x is the MSM message type 1-7.

Satellite-wise filtering can be achieved in several ways, and the LAS supports several options regarding this.

1 1. Applying an elevation mask of specified angle
2 2. Removing satellites not supporting certain signals
3 3. Removing satellites at the lowest elevations until specified maximum transmitted size or number of satellites requirement is satisfied.
4 4. Removing satellites such that the satellite geometry is optimized in terms of DOP. Optimization of PDOP (3D), HDOP (2D), and VDOP (vertical) are supported.

5 EXPERIMENTS AND TESTING.

In order to provide a NRTK service that meet the requirements of the PrePare-Ships project in the test area (Gothenburg, Sweden), SWEPOS has established three new sites (located in Vinga, Hällsvik and Styrsö) for reference stations to support the current infrastructure of SWEPOS in the test area and one monitor station (located in Fotö) to provide the required integrity data (the data which will send in parallel with SWEPOS correction data to the shipborne GNSS receiver to describe the correction health or warnings when the system should not be used for navigation). The locations of four new stations (in black) are shown in Figure 7 as well as the existing stations (in blue).

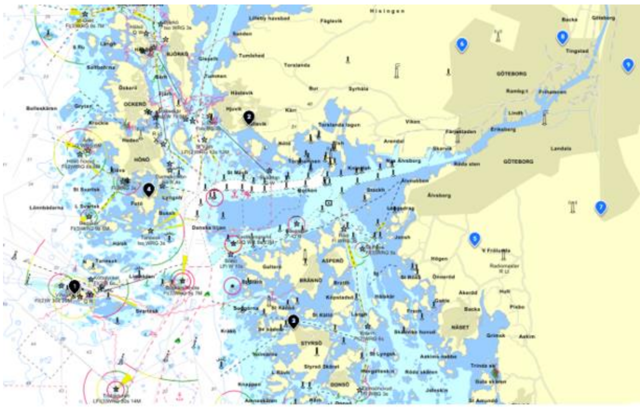

Figure 7. SWEPOS stations in the test area of PrePare-ships project.

The Choke-ring antenna has been chosen as a GNSS antenna at every station for its ability to attenuate multipath signals. Figure 6 shows the antenna in Vinga station and the Figure 7 shows the antenna in Hällsvik station. The Septentrio 'PolaRx5' was selected as a GNSS receiver for all stations. The PolaRx5 is a robust multi-frequency GNSS reference receiver and its tracking techniques provides measurements with low noise constantly monitoring and protecting against multipath, interference, and other environmental effects. SWEPOS have used two PolaRx5 receivers at each station to increase the station/system redundancy and reliability. Figure 8 shows the hut of the Styrsö station and its two GNSS receivers.

Figure 8, Vinga station antenna

Figure 9. Hällsvik station antenna

Figure 10. Styrsö station hut.

The test drive with the ship took place off the coast of Gothenburg (Sweden) and is shown in Sea chart in Figure 11. It started at Hönö Island and ended around 5 km from Gothenburg. During the drive, the bridge between Solvik and Donsö shown in Figure 12 was passed. After passing the bridge, the ship returned and passed it a second and third time. Also, a maneuver was performed, which consists of multiple turnarounds.

Trials (3 September 2020) on the sea for testing of the VRS were performed at different test environments such as those in non-line-of-sight scenarios for GNSS below bridges (see Figure 12) and in narrow passageways have been considered. The pilot boat used for the trial was made to take rotations with minimum possible radii in the sea at around 10 km from the VRS to study the positioning capabilities of the onboard ANavS Multi-sensor RTK module with its GNSS/INS tightly coupled RTK positioning and attitude determination.

Figure 13 shows the shipping route as determined by the ANavS Multi-sensor RTK module. The color denotes the availability of a fixed RTK solution, i.e. green sections refer to a fixed RTK solution and red sections refer to a float RTK solution.

Figure 14 shows the heading over time as determined by the ANavS Multi-Sensor RTK module. The enlarged section refers to several turns with a variation of the heading angle between 0° and 360°.

Figure 15 shows the precision of the position solution over time. It is better than 5 cm for a fixed

RTK solution, which is obtained for most of the time. The accuracy degrades to a few decimeters for a float RTK solution.

Figure 16 shows the precision of the 3D velocity estimates. It varies between 5 cm/s and 8 cm/s for a fixed RTK solution.

Figure 17 shows the number of available double difference carrier phase measurements (scale on the left y-axis) and the precision of the horizontal positioning accuracy (scale on the right y-axis) during three passages below bridges. Obviously, the number of available measurements drops significantly below the bridges but the positioning accuracy remains better than 10 cm due to the GNSS/ INS tight coupling.

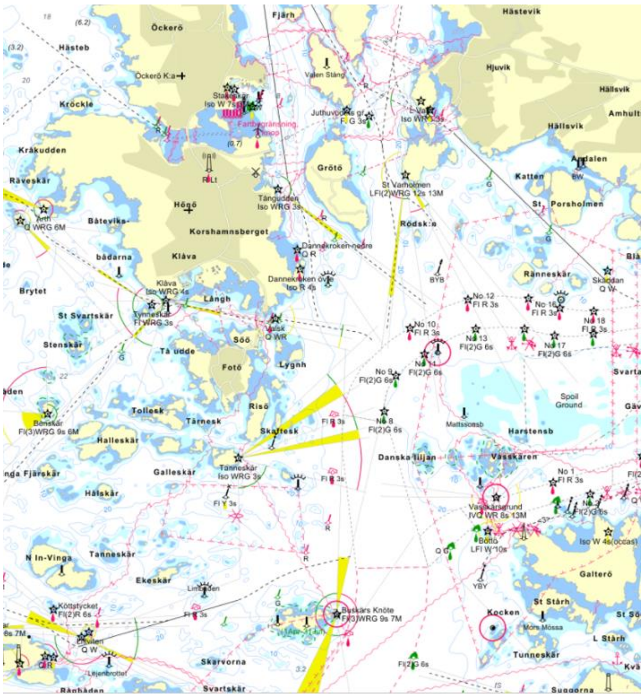

Figure 11. Sea chart showing the area suitable for a planned positioning test site.

Figure 12 The pilot boat when passing the bridge.

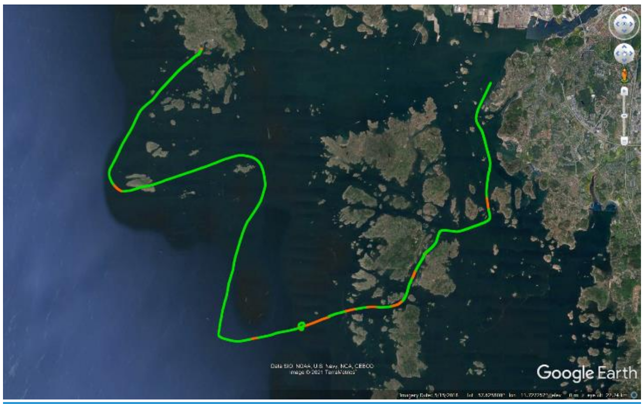

Figure 13. Shipping route of 2 hours in Gothenburg area. The color denotes the availability of a fixed RTK solution, i.e. green sections refer to a fixed RTK solution and red sections refer to a float RTK solution.

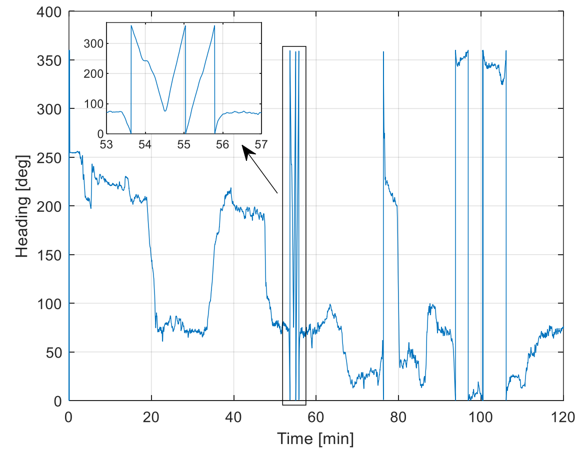

Figure 14. Heading solution over time. The enlarged section shows the variation of heading during some turns.

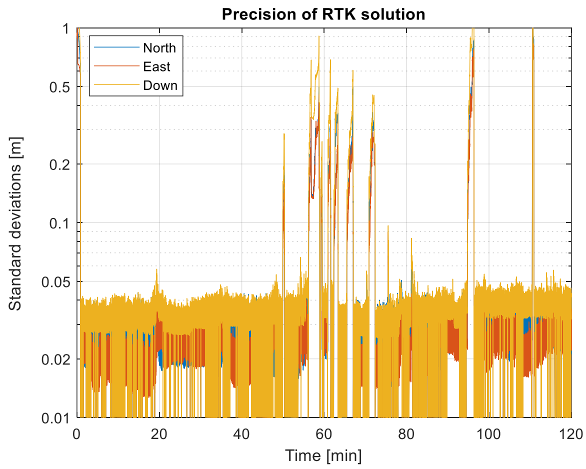

Figure 15. Precision of RTK solution over time during 2 hour shipping route: The precision is better than 5 cm for a fixed RTK solution, and degrades to a few decimeters for a float RTK solution. A fixed solution is obtained for most of the time. Position accuracy when performing the maneuver.

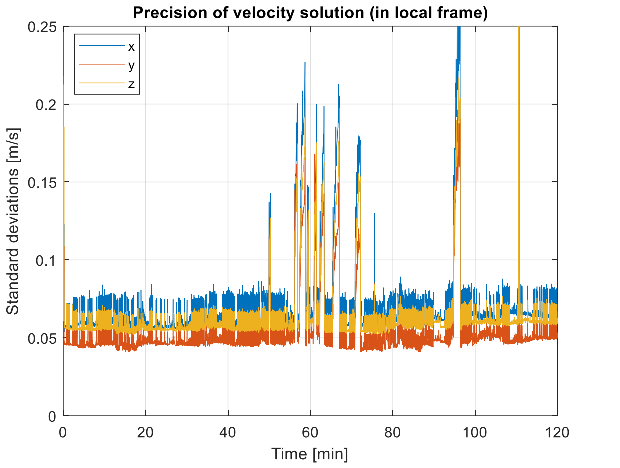

Figure 16. Precision of 3D velocity solution in local vessel coordinate frame over time. The precision varies between 5 cm/s and 8 cm/s for a fixed RTK solution and degrades to 25 cm/ s for a float RTK solution.

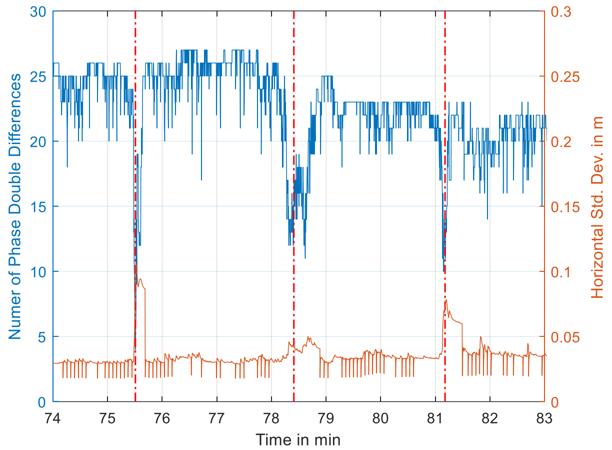

Figure 17. Number of double difference carrier phase measurements and horizontal positioning accuracy during three passages below bridges.

6 DISCUSSION OF TEST RESULTS

The positioning results of the vessel show that a fixed RTK solution with a precision of 5 cm was obtained for most of the time. Similarly, a fixed attitude solution was obtained for most of the time. The precision was mainly limited by phase noise and multipath during fixed RTK solutions.

A temporal degradation in precision was observable and clearly related to temporal losses of the 4G communication link. The latter one was used to obtain the RTK corrections. There were several communication outages in the order of one minute with a maximum outage of 1.7 minutes (Figure 18).

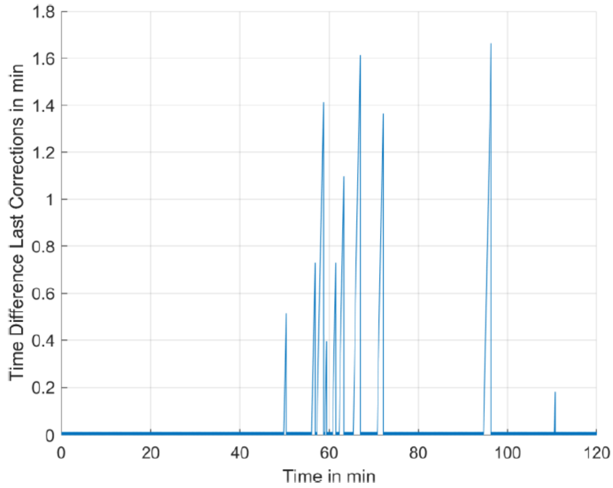

Figure 18. Outages of the RTK correction data.

The RTK corrections can be predicted to some extent during GNSS outages. However, small changes of atmospheric delays of only a few centimeters are sufficient to lose an ambiguity-fixed solution. In this case, the ambiguity estimates are set to float and are re-estimated within the Kalman filter. This leads to a weaker model and, thereby, to a larger uncertainty until the float ambiguity estimates are fixed again to integer numbers. Similarly, the RTK positioning accuracy decreases with an increasing distance to the VRS as differential atmospheric delays increase with the distance. Differences in atmospheric delays are caused by differences in the mapping function and/ or by differences in the zenith delays. The ionospheric activity was low during the test drive and did not impact the positioning performance.

Future enhancements are two-fold: On the one hand, VDES will be used for a more reliable communication link. On the other hand, a Precise Point Positioning (PPP) solution will be used for a stand-alone absolute positioning solution

7 CONCLUSIONS

Trials on the sea for testing of the VRS indicate that statistical uncertainties in the order of 5-10 cm can be achieved within a distance of 12 km from the virtual reference station, which may be compared to an accuracy of around 5 m with standard equipment used in the maritime industry today. The test results proved that we can get the same required positioning accuracy by using the LAS solution which proposed to reduce size of NRTK correction data to instantly adapt with the VDES requirements.

These results proved that the chosen system design (The proposed positioning service in this study and the proposed predictor in the project) should scale well for worldwide implementations in areas of heavy traffic, where avoidance of congestion in the AIS/VDES system is crucial. The performance enhancements in Positioning Navigation and Timing (PNT) achieved in the PrePare-ships project are not limited to the shipping sector but are a cornerstone for future shapes of shipping that we now are at the dawn of. Today it can enhance maritime constructions, automated mooring, cybersecure local position corrections, more accurate information to pilots and officers in narrow fairways or heavily trafficked areas.

It enhances the capabilities of Search And Rescue (SAR), resilient PNT, enables concepts like remote operation/assistance of ships and even a future scenario of autonomous shipping.

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REFERENCES

1. Acar, U., Ziarati, R., Ziarati, M.: Collisions and Groundings – Major Causes of Accidents at Sea. Coventry, UK, Coventry University Technology Park (2007).
2. E. Hollnagel: Understanding accidents-from root causes to performance variability. In: Proceedings of the IEEE 7th Conference on Human Factors and Power Plants. pp. 1–1, Scottsdale, AZ, USA (2002). https://doi.org/10.1109/HFPP.2002.1042821.
3. European Maritime Safety Agency: Annual Overview of Marine Casualties and Incidents. , Lisbon, Portugal (2019).
4. Hüffmeier, J.: Risk assessement Ship Collision Incidents based on Foresea incident data. Foresea, Gothenburg (2020).
5. Hüffmeier, J., Wilske, E.: Decision Support Tools for VTS Operators, BaSSy SSPA Report 4005 3946-1 - rev1. SSPA Sweden AB, Göteborg (2008).
6. Hultman, A., Enström, J.: Collisions and Groundings. , Gothenburg (2011).
7. IALA: The Technical Specification of VDES.
8. Japan Transport Safety Board: Statistics of Marine Accident, https://www.mlit.go.jp/jtsb/statistics_mar.html#p02, last accessed 2020/10/01.
9. Lilje, M., Wiklund, P., Hedling, G.: The Use of GNSS in Sweden and the National CORS Network SWEPOS - OICRF. In: Engaging the Challenges – Enhancing the Relevance. , Kuala Lumpur, Malaysia (2014).
10. NTRIP: Networked Transport of RTCM via Internet Protocol (NTRIP). (2004).
11. RTCM 10403.3: Differential GNSS Services. , RTCM, Arlington (2016).
12. Transportation Safety Board of Canada: Marine transportation, https://www.tsb.gc.ca/eng/marine/index.html, last accessed 2020/10/01.
13. Türki̇stanli, T.T., Kuleyi̇n, B.: Training Situational Awareness and Decision Making for Preventing Collisions at Sea: A Theoretical Background. Mersin University Journal of Maritime Faculty. 1, 1, 10–16 (2019).
14. Nord, S., Tidd, J., Gunnarsson, F., Alissa, S., Rieck, C., Hanquist. C., Johansson, V., Hammenstedt, J., Hoxell, F., Larsson, C., Chaisset, C.: Network-RTK Positioning for Automated Driving (NPAD). Technical report, NPAD project, (2021).