

HOW TO PREVENT BRIDGE ACCIDENTS BY SENDING HEIGHT MEASUREMENT TO SHIPS

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ABSTRACT

Collisions with bridges are still a problem in inland navigation and often result in restricted or blocked transportation of people and goods. In addition to the impact on the statics of the bridge, the passing roads, railroads, and power & communication lines, logistics companies and their suppliers are deprived of an important lifeline. Insufficient height clearance also poses a high risk of serious injury to the crew due to damage to the vessels bridge. The vast majority of accidents (e.g. insufficient lowering of the lookout, incorrect readings of staff gauges or excessive container loads) are caused by human error. Tidal rivers and water level effects from nearby locks also affect the under-bridge clearance over time.

As part of the EU project 'RIS-COMEX II', a feasibility study is being carried out to determine the vessels height in relation to the water level using LiDAR (Light Detection and Ranging) sensors. The installed sensor system detects vessels approaching a bridge and measures their highest point (including all superstructures) in relation to the current water level. The measurements are transmitted via AIS as an Application Specific Message (ASM) containing the vessel's MMSI, Name, position and its height for display in the Inland ECDIS on board. The aim of the study is to evaluate the accuracy and precision of the system over a period of one year. This study is also done to gain experience on the extent to which environmental conditions affect the height measurements and also physically degrade the installed setup. In addition, the study investigates transmission frequencies, latencies of tidal measurements, and time from measurement to on-board display.

The study will be conducted in an area that has recently experienced two consecutive serious bridge collisions, disrupting logistics to major German ports. The vessel height measurement is performed with LiDAR sensors covering the entire river width of about 50 m and capable of measuring traffic from both directions. The paper reports on the initial study results based on first traffic measurements.

Keywords: *accident prevention, laser sensors, under-bridge clearance, shore-based assistance system*

1 INTRODUCTION

When ships pass under river crossings (e.g. bridges), there is a risk of collision that can cause fundamental damage to the structure of the river crossing as well as the ship. In European inland navigation, collisions with bridges and other infrastructures account for around 40% of all accidents (Henk 2019). Accident analyses have identified human error as the predominant cause of collisions (Henk 2019; Sánchez-Beaskoetxea et al. 2021).

If a river crossing infrastructure is damaged, it cannot be used by e.g. pedestrians, trains, or any road transport until it has been inspected by a structural expert. Supply networks depend on bridges for an efficient transport. Thus, blocking of bridges often induce economical damage to suppliers and other companies which is of great importance especially if goods are critical (e.g. medications) (Lützen 2002; Zeit 12/25/2024). If a collision occurs, the first things to be damaged are gas, water, district heating, electricity or communication links, which run under a bridge, that are to a certain extent, bottlenecks in a country's energy and communication supply. If a ship gets damaged, this results in an accident, e.g. the ship sinks or the ship being no longer maneuverable, which can end up in the ship positioning itself sideways on narrow waterways. The German waterway network offers, with only few exceptions, no alternative routings, so that nearly every single blocking accident ends up in long-lasting waterway traffic jams.

Skippers face the following specific problems:

1. *Estimating the clearance height.* Most crossings have a fixed construction height and no movable bridge elements. The clearance height here depends on dynamic parameters such as the water level (influenced, among other things, by the tidal system), the flow rate in the river over the course of the year, displacement of the water masses by ships, draught and height of the ship (ballast, additional load and height-adjustable control stands), height of the additional load (general cargo transport containers, special cargo like offshore structures), influences of the infrastructure: e.g. lock wave generated by opening a lock chamber, as well as navigational decisions (ratio of speed to water

- displacement). Manual level readings on staff gauges can be influenced by lock waves as well as by the bow wave of the ego ship.
2. *Attention*: The bridge heights are shown at a standardized “normal zero” value in the official electronic nautical charts. An inland waterway skipper navigates under numerous bridges at different heights every day. Individual goals of cost-efficient transportation led to maximum possible loads, maximum possible travel times and these lead to fatigue, inattention, risk of confusion and mis-judgements. Opening crossings also require special attention in poor visibility situations: swing bridges can approach the ship. Numerous accidents also occur when bridges opening upwards are entered too early.
 3. *Reaction speed*: However, the inertia of watercraft means that maneuvering decisions must be made at an early stage in order to avoid accidents. The wheelhouse of an inland waterway vessel is usually extended when underway to provide a better overview, making it one of the highest points of a vessel and therefore often has to be retracted when passing under bridges. In an accident analysis from 2011 to 2017, the German Ministry of Transport reported that (in order of frequency): forgotten lowering, no lowering and driver error were the most common human-caused causes of accidents (Kliche 2019).
 4. *Narrow underpass areas*: Depending on the water level and in perspective with the progressing climate change, the waterways become narrower and sediment shifts, especially during storms and flooding situations, change experienced and thus learned approaches. Ships pass under bridges not only individually, but also in pushed convoys and then have high ship lengths or widths and require a high degree of attention with regard to a straight (or deliberately inclined) and possibly exactly centered passage (depending on the bridge contour or the structure in general).
 5. *Environmental influences*: Larger structural crossings, which are also passed under by seagoing vessels, pose further nautical challenges, as the forces acting on the moving vessel (in particular wind and currents) change abruptly before, during and after the passage due to structural shading. The effects of the environment are unpredictable, especially in areas with cross currents.

To address these problems, a system is beneficial that assists and monitors shipping traffic in the area of river crossings and automatically provides ship and situation-specific absolute height measurements. The system uses LiDAR sensors to estimate vessel heights, which uses a laser diode and the time-of-flight principle to estimate distances to objects. LiDAR sensors, specifically 3D sensors are often used in traffic automation (e.g. cars and vessels) due to high resolution object detection capabilities.

The paper is structured as follows: The next chapter reports about the state of the art from two perspectives: on-board assistance systems and systems that support under-bridge clearance from shore. Chapter 3 presents the under-bridge clearance assistance system, chapter 4 reports about the setup of a measurement experiment close to a bridge, chapter 5 presents the initial evaluation results of a first testing period, and finally chapter 6 concludes this work.

2 RELATED WORK

Bridge clearance estimation is a problem existing for decades. Many systems have been invented to support nautical personal to estimate a vessels height and issue warnings about low bride clearance. We divide these systems based on their installation location. Some are installed on the vessel to automatically detect obstacles, while other systems are installed on-shore to support navigators at critical places via a stationary display or a communication link to the vessel.

2.1 On-board Assistance Systems

On-board assistance systems use various sensing technologies, such as laser scanners, radar sensors, satellite positioning systems or even mechanical sensors to either simply warn the crew about an upcoming bridge or advise to lower the wheelhouse for low clearance situations.

The BridgeScout system gets installed on the roof to measure the height of the wheelhouse in relation to the height at the approach as well as the approach speed towards the bridge (Sensor Maritime 2023, 2025). An alarm can be configured by the ship's command in relation to speed, time and collision. The installation setup eases the measurement process as the wheelhouse roof is usually the highest point of the vessel to consider for clearance and also reduces the processing complexity as a front looking sensor on the highest point only needs to identify any obstacle in the sensing area. The disadvantage is the sensor re-calibration of a sensor that is installed on a moving cabin for that every tenth a degree impacts the measurement accuracy. Further on, the approach plays it strengths for straight waterways, while already slight curves during an approach could result in the alarm triggered too late for performing an emergency maneuver or insufficient time to lower the steering cabin.

The Alpha Height system is presumably based on radars that are usually implemented on a mast at the bow or at the steering cabin's roof structure (Grohmann 2013). The system uses water level data and can

detect the bridge height. A minimum distance to the bridge can be configured that must be maintained. Otherwise, the system reports an alarm.

The BridgeSecure (Sobotka 2019) system relies on GPS positioning information and a set of height sensors installed on board, which presumably measure the ship's own superstructure heights (steering cabin, masts). The GPS position of the ship is used to calculate the distance and travel time to the next bridge. The system obtains tidal and water level data from the authorities' forecasting system, as well as bridge heights from the authorities' cadastral or map data. A warning is issued in configurable threshold values if the measured superstructure height and the water level prediction is greater than the clearance height of the bridge.

Hesselbarth et al. (2015) investigate GNSS-based bridge warning systems and technologies. They find that in areas with good GNSS coverage, an accuracy of up to 4cm can be achieved using RTK (Precise Point Positioning 20cm, DGNS 80cm, Single Point Positioning 2.5m). However, the positioning accuracy deteriorates significantly in areas with poor GNSS coverage, e.g. in the vicinity of several bridges. As a continuation in the LAESSI project, the height of a ship is determined via a GNSS sensor installed on the bridge roof via the global satellite system (geodetic height) (Hessebarth et al. 2020). The difference between the geodetic height and the bridge height is then determined from map data. Official water level data was presumably also considered. These kind of GNSS-based Systems are already available on the market, where a similar system is called ArgoBridgePilot, which uses RTK-GNSS for 3D positioning and compares this with the bridge height according to nautical charts (Argonav 2025).

Hösch et al. (2023) propose a conceptual framework for inland water transport HD map generation based on laser- and camera-based measurements. They combine this data with geo-referenced positioning information retrieved via multi-antenna Global Navigation Satellite Systems (GNSS) and inertial measurements generate HD maps of waterway infrastructure including bridge contour. With their setup they report about a maximum target distance of 60m for laser and significantly for the camera.

A principal problem with existing solutions installed on board are positioning the sensor on the ship. Current approaches target an installation at roof of the wheelhouse, which is often the highest installation point (besides a mast i.e. for radar installation at stern). If the wheelhouse is lowered to the bridge underpass, the sensor has no view of the approaching bridge (depending on the cargo height). Another challenge is the short measurement distance of sensors installed on board, which, assuming installation on the wheelhouse roof, corresponds to just the 2-3 times the length of the ship. If the cargo is too high, much greater distances must be considered, depending on the navigational ability and size of the ship, in order to ensure that the ship is stopped before the bridge. Furthermore, current laser scanners have a limited angular resolution, which leads to an insufficient measurement resolution (>10cm) at measurement distances over 100m, even assuming no measurement error. Similar problems occur with position-based solutions like GNSS. Positioning on movable parts (like vessel bridges or masts) must be considered with these systems and positioning error depends on satellite reception strength.

Finally, it can be observed that shipping companies are not very willing to invest and, accordingly, the fleet in Germany is technically outdated (47.1 years - cargo vessels, 65.1 years - motorized cargo vessels, data from Wasserstraßen- und Schifffahrtsverwaltung des Bundes 2021). It can therefore not be assumed that on-board solutions will prevail to a sufficient extent. It can also be assumed that the greatest risk of collision comes from ships with the lowest level of technical equipment.

2.2 On-Shore Sensor System

Within the EMMA Project (2021), a Bridge Safety Clearance Indication System was tested, which offered real-time monitoring of safe clearance, water level and clearance values on LED displays. The water level was measured by a radar sensor. The device performs measurements at set time intervals and the collected data are sent via GPRS communication to the System Central, which then sends the official clearance levels to be displayed on LED displays close to the bridge.

Chen et al. (2023) design a height warning system based on 1D LiDAR and camera, in combination with a RADAR water level meter. They install a camera in the middle of the bridge for optical detection of an approaching ship and lateral installed LiDAR sensors on the maximum bridge clearance height. The optical detection of a vessel activates the LiDAR sensors, which issue a warning if they detect an object similar to a light barrier system. The camera detection also makes it possible to recognize deviating courses of approaching ships and send out warnings if necessary. An evaluation with real measured values of the system is not carried out, so that the practical application cannot be tested.

A similar method was described by Zhuang et al. (2024) who fuse data from camera and RADAR sensors. Both sensors are used to detect the ship and its position, whereby camera data is analyzed using AI and tracking algorithms are used to process the RADAR data. The recorded trajectory of the ship is then used to identify the passage point at the bridge, whereby a distinction is made here between safe and high-risk passage zones, as the ship could collide with the bridge or its piers. By attaching the measuring sensors to the bridge, only short distances are achieved, as one of the highest and most critical point of an inland waterway vessel is often the extended wheelhouse, which is located at the stern of the vessel. With standard

ship lengths of over 100m, a sensor installation on top of a river crossing is only detected by the sensor system when the bow of the ship is already directly in front of the bridge entrance. This means that a warning can only be delivered very shortly before the collision and it depends on the reaction time of the ship's command and the speed of the bridge's lowering hydraulics whether a collision can still be avoided. At this point, an evasive maneuver by the ship is conceivable at most when sailing uphill, but this carries the risk of the ship being transversely positioned. Further on, sensors attached to the bridge are exposed to vibrations caused by the crossing traffic. Depending on the bridge design, high loads can also lead to temporary "sagging" of the crossing - depending on the bridge length, by several centimeters - and thus to a reduction in measurement accuracy, which is reflected over the measurement distance by errors in the decimeter to meter range even with minimal twisting of the sensor system. In some cases, installations on the bridge are not possible due to monument protection for historic bridges. As these were not built for modern shipping, the risk of collision is presumably higher.

Zeng et al. (2023) therefore pursue the approach of determining the ship's height from the side of the bank. They use short- and long-focus cameras that are located opposite each other and can therefore detect ship traffic from both sides. The authors achieve a range of 1.46km and an accuracy of 0.1m. The system was evaluated with a real ship journey by recognizing markers attached to the ship and comparing them with measurements from an RTK. It is unclear how well the system works in adverse weather conditions and how large the object to be detected on the ship was. It is assumed that smaller objects such as antennas are less likely detected recognized. Also, the susceptibility of the sensor system to fluctuations needs to be considered. The greater the measuring distance, the greater the influence of even minor fluctuations of the ship (in particular rolling movements) on the measurement. Also, camera data is regulated by GDPR within Europe.

3 SHORE-SIDE UNDER-BRIDGE CLEARANCE SYSTEM

The proposed system is based on LiDAR sensors and installed at one side of the shore. In contrast to comparable systems, it is not installed directly at the bridge, but in a distance in front of the bridge. The system is vessel independent and integrated with IECDIS (Inland-ECDIS) systems. The upcoming section 3.1. details the principal design idea and advantages of the system to measure a vessels' height while approaching the bridge. Section 3.2 discusses the concept of the data provision via AIS and its inclusion into the inland ECIDS display.

3.1 Vessel Height Measurement System

The Vessel Height Measurement System (VHMS) makes it possible to assist and monitor a defined geographical area of a waterway with a crossing by means of heterogeneous and networked land-based sensors. The sensor system is installed in the approach to the bridge and informs the shipping traffic about small safety distance between ship and bridge height, taking into account the tidal conditions. The installation at a distance from the bridge enables early warning of shipping traffic so that there is still sufficient time to carry out a safe emergency maneuver. It also mitigates the problem that due to monumental protection sensor systems cannot be installed on bridges itself. The system can be installed on one or possibly both sides of the waterway to support vessels in both directions. This may be required depending on the river's width, as LiDAR sensors have limited range capabilities and vessels might block the sight to parallel sailing vessels. The following illustration shows the technical setup of the system on a river.

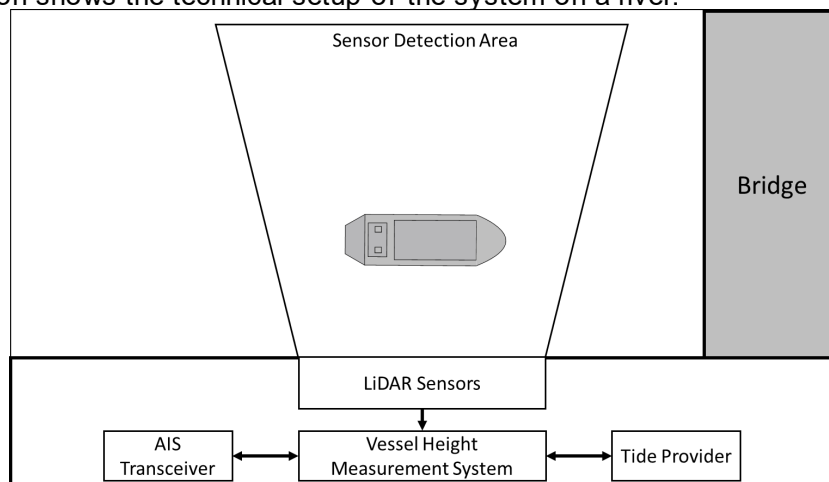


Figure 1. System setup with the basic components of the under-bridge clearance system.

The system is installed on the shore in vicinity to the bridge. The exact position depends on the stopping distance of supported vessels and tide change rate. Due to vessels inertia, height measurements must be issues early, however data may be obsolete once the vessel reaches the bridge. Thus, there must be a balance between data age and sufficient time for an emergency maneuver. The system performs lateral laser measurements to detect approaching vessels and determine their height.

Information can be issued as the difference between vessel and bridge (bridge clearance) or as the current height of the vessel above water. As the system only detects the current state of the vessel, it is possible that the vessels bridge has not yet been lowered and captain on board have options to reduce their overall height. Accordingly, we have decided to transmit the current height of the ship above water to the navigators as additional information so that they can take this into account in their decision. Thus, the estimated current height is compared with the water level (retrieved via an external tide provider). Finally, an AIS transceiver is used for receiving (e.g., for vessel identification) and transmission data to the vessel (see chapter 3.2).

In addition to the technical structure, the diagram depicted by figure 2 shows the measuring principle of the system. It starts by the system observing whether a ship is entering a supported area. Optical sensors are used to record the ship's contour in 3D (vertically and horizontally). This data is compared with received AIS messages. As the system sends height information via AIS ASM messages, only vessels equipped with AIS can be informed so far, but for instance LED panels or other means of information presentation might be added at a later stage. The vessel's height is then continuously determined in relation to the water level until the ship leaves the area. It is necessary for the ship to pass through the entire area to ensure that the entire ship has been recorded once. After leaving the area, a plausibility check is carried out and outliers (e.g. due to seagulls) are removed. The resulting height is then sent to the vessel via AIS.

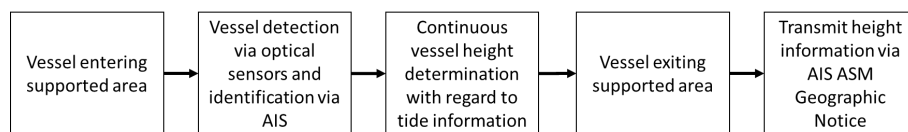


Figure 2. Measurement process flow of the system

3.2 Height Measurement Data Provision

The Automatic Identification System for inland navigation (Inland AIS) and the Inland Electronic Navigation Chart and Display System (Inland ECDIS) have been established as key systems for supporting navigation on European inland waterways, as well as for enabling the tracking and tracing of ships from shore. The provision of position reports from the surrounding traffic significantly contributes to a comprehensive situational awareness, particularly with respect to approaching vessels.

The latest edition of the European Standard for River Information Services ER-RIS (2025) introduces new functionalities for transmitting highly dynamic information about the waterway via Inland AIS and displaying it on the Inland ECDIS. The implementation of virtual aids to navigation (virtual AtoNs) and application-specific messages (ASMs) enable the provision of real-time navigational data to the vessel, thereby enhancing operational efficiency and safety. These ASMs include essential information such as water levels, bridge clearances, and other essential information necessary for safe passage.

In accordance with the ES-RIS Standard, the ASM Geographic notice message is used transmit and displaying measured vessel height information on the Inland ECDIS of the respective an inland vessel.

Once measurements are completed, data is encoded as an AIS ASM Geographic Notice message (ES-RIS 2025, Message Number=6, Version 0, DAC=200, FI=42) and send to the nautical personal on the vessel. Geographic Notice ASM is registered within the European Union since 18.10.2021 and allows encoding of up to nine elements of text (up to 15 characters per element) and/or geometric shapes (e.g. points, lines, polygons). How many elements are encoded influences the number of necessary AIS time slots (2-5 time slots). Thus, transmission of complex elements should be avoided in dense traffic areas to avoid blocking the radio traffic. The message is intended to alert navigators to possible dangers. We have therefore decided to personalize the message and address the ships directly, so that the ship name is included in the message as well as the vessels height. The ship's identity is recorded via AIS. The message constructed with a single point and two text elements. The point defines where the text message should appear on the map and is located near the latest vessel position. The text is encoded as "<Vessel Name> Height <Measurement>m", where "<Vessel Name>" is received via AIS (up to 20 characters, 6bit ASCII) and "<Measurement>" is the systems determined height. Worst case data size results in three text elements (< 45 characters) and a point geometry. The message is updated and repeated when a dynamic position report is received from the detected vessel. Since the dynamic position reporting frequency is high, the system uses a rate limiting approach to reduce the number of messages. By default, the system sends an update each 10s. The onboard Inland ECDIS displays a label with the ship's name and height near the own ship symbol.

To complete the set of information necessary for safe bridge passage, the ASM Water Level and ASM Bridge Clearance are broadcast via Inland AIS and displayed within the Inland ECDIS. The water level measured at a gauge station is encoded in an ASM Water Level message (ES-RIS 2025, DAC=200, FI=24), which includes the gauge station ID, a reference value to which the measurement relates and the measured water level value. The bridge clearance value is determined either direct measurement or, as in this project, derived from the water level value at the gauge station. The information is encoded in an ASM Present Bridge Clearance message (ES-RIS 2025, DAC=200, FI=25), which includes an ISRS Location Code, representing the bridge object, the time of measurement, the bridge clearance value and the indication of the measurement's accuracy.

4 EXPERIMENTAL SETUP

A test setup was set up at Huntebrück in Germany just before a bascule bridge. The trials are intended to provide initial experience and findings on lidar-based height determination from shore and to display of the ship's height on the IECDIS. All system components are installed on a mast. One of the LiDAR sensors is installed on the waterway before crossing a bridge. Due to obstacles such as piles (dolphins) and the jetty on which the system was built, a 90° positioning was not possible. Otherwise, smaller ships in particular would be overshadowed and the lowest/highest point would not be visible. Accordingly, the system is positioned at an angle of 48° to the fairway. Due to the sensors opening angle, this also increases the measurement time.

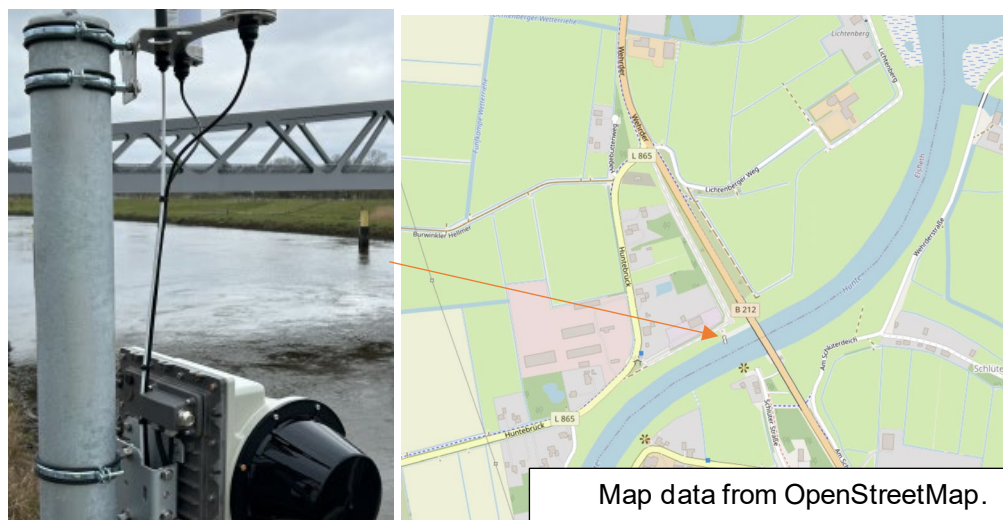


Figure 3. LIDAR Sensor with AIS Antenna close to the Huntebrück bridge (left) and map of the installation position (right).

The control cabinet contains a processing unit and storage capacity to temporarily store the point clouds. Two robust lidar sensors that have already been successfully tested in maritime environments in other research projects (Mentjes et al. 2022) were installed. Both sensors are operating at 5Hz with different configured scanning patterns. AIS is received via a standard AIS receiver device. Water level measurements are provided by the German Federal Waterways and Shipping Administration (WSV), which operates a water level measuring station near the bridge.

The following figure 4 shows the prototypical live view developed for this system and the resulting point cloud data using the initial LiDAR simulation. The ship is detected by lateral measurement of land-based LiDAR sensors (yellow points). This results in a lateral (top) and bird eye view (bottom) image of the situation. Green boxes show distance information, in the top view the estimated bridge clearance and on the bottom view the distance between LiDAR sensors and the detected vessel.

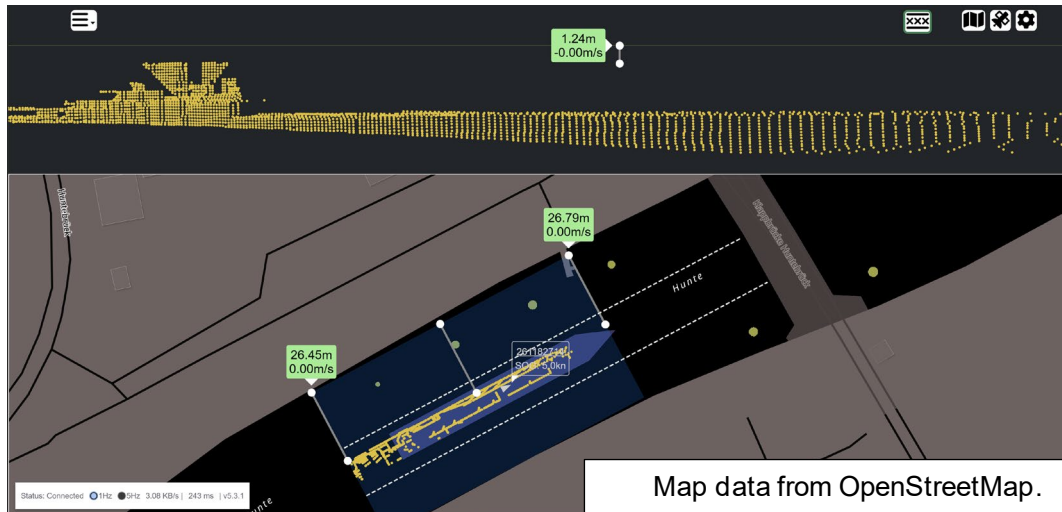


Figure 4. Screenshot of the LiDAR simulation environment used for estimating the ideal sensor position and for initial development of the system.

Different to the LiDAR simulation environment that implemented a vertical clearance measurement between the lowest part of a bridge structure and the superstructures of a vessel (c.f. figure 2), the aim is to measure the height of a vessel from the water surface up to the highest point of a vessel. This is due to current regulation, which requires a ship master to be responsible for all actions on-board. Therefore, it is important to keep the shipmaster in duty to manually read the water level and the official vertical clearance height of the bridge, to self-check if the measured above-surface ship height of the system matches the distance between water level and clearance height of the bridge.

5 EVALUATION

The system is intended to record the height profile of ships with high precision and compare it with the water level in order to determine the ship's height. From a safety point of view, data under adverse weather conditions is of particular interest during testing. Thus, the system is to be tested under real conditions and under changing weather condition by analyzing measurements of passive traffic participants. For this we used data recorded by the system over a period of 5 days. Tidal measurement at the experimentation area was one precise measurement every minute. Vessels at this area travel with speeds that limited our data recording level to a maximum of around 20-40 seconds for each vessel (depending mainly on length and travel speed, but also on distance to sensor). Therefore, the experiment was split into two parts: First, we estimated the accuracy error from a theoretical perspective and with reference targets on the other river side. Second, we evaluated the precision of the system by manually labeled recordings of a set of vessels.

5.1 System Calibration and Accuracy Error Estimation

For initial calibration and estimating the accuracy of the LiDAR sensors several standardized measurement plates were installed within the viewing angle of the sensors (c.f. figure 5). The plates were sized from minimal required detection size (figure 5 left) down to minimal detection size. Additionally, a plate that corresponds to the smallest relevant object on an inland vessel (such as the AIS antenna) was used, in order to check whether it is detectable. The reference targets are further away than the actual ship, since they are positioned on the other river side. Due to the beam width of the LiDAR sensors, it is therefore expected that smaller objects in particular cannot be detected. Nevertheless, we were able to detect all installed objects.



Figure 5. Measurement setup of different plate sizes and corresponding LiDAR recordings

To evaluate the accuracy of the height measurement, it is crucial to determine both the maximum and average error in this safety-critical system. The error for the vessel height above water involves uncertainty in identifying the highest point of the ship and the water level.

As shown by figure 5 the target were setup in a distance of 64m (i.e. the other side of the shore) and therefore represent a maximum error, while vessels in this area are expected to travel close to the center of the river. By the same reason an exit angle of the signal of 25° and the maximum distance error of the sensor of 3 cm was set. For the highest point, there is an error due to the signal expansion and thus the smallest object size that can still be differentiated. For the sensor based on an angular resolution of 0.02° and a target at a distance of 64 m, there is an error of 2,2 cm. Added to this is the uncertainty in height of 0,85 cm, resulting from the distance error of the sensor with 2 cm, and considering a maximum signal exit angle of 25°. Consequently, there is a maximum error of 3,05 cm when determining the highest point of the ship. For the accuracy of the height above water, the error of the height of the lowest point must be added.

Georeferencing of the system in combination with a real-time capable water level measurement can be used. In this case the error due to the referencing (with RTK < 1cm) and that of the level measurement (< 1cm) must be added.

The evaluation of the accuracy of the height measurement has the following results:

- Maximum error (LiDAR highest point measurement): 3,05 cm
- Maximum error (LiDAR highest point + Water level measurement): 5,05 cm

For the calculation of the average case, the distance of the targets in the navigable channels ranges from approximately 20 to 35 meters. The error in this context is reduced:

- Average error (LiDAR highest point measurement): 2,05 cm
- Average error (LiDAR highest point + Water level measurement): 4,05 cm

5.2 Height Measurement Precision Estimation

As detailed measurements of passing vessels were not available for the study, we hypothesized based on the data that was recorded, that the system can record the highest point over several seconds (i.e. frames) and that this measurement is expected to remain stable over the recording time. To increase the number of measurements for this study, we also hypothesized that for larger passing vessels (>50m) up to two maximum height measurements can be expected. Those vessels often have a radar mast installed at stern and the steering cabin located at bow. As soon as one part of the vessel passed the maximum viewing angle of the LiDAR, the system continues to report the second-highest, respectively the highest point of measurement. Figure 6 depicts such a measurement height raw data sample (in meters over time) and shows actually two vessels: First, a cargo vessel heading north with two subsequent maximum height measurements, followed by a leisure craft heading in the opposite direction.

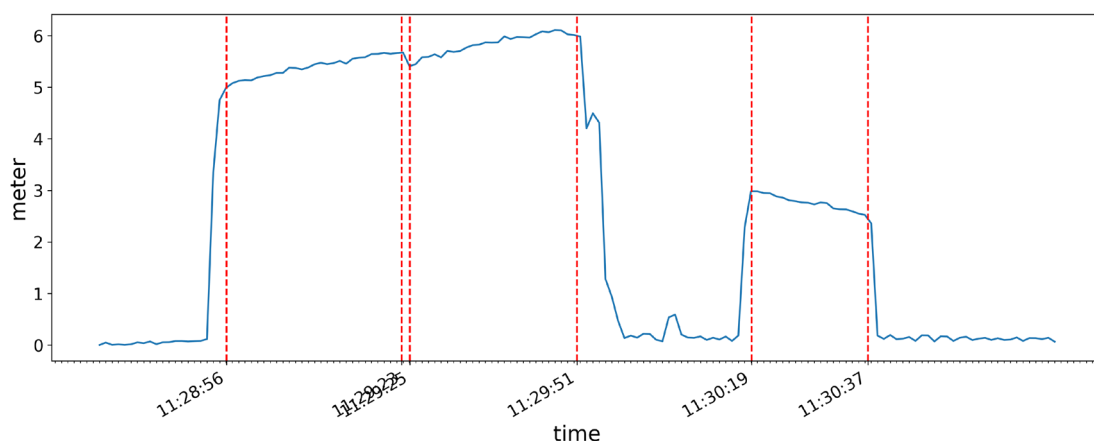


Figure 6. Continuous maximum height measurements raw data of a cargo vessel and a leisure craft heading in the opposite direction.

In the figure 6 a continuous increase or decrease (depending on the vessels direction) could be observed, which reflects the relative degree of the vessel passing the sensor, which was intentionally not positioned in a rectangular angle relative to the vessel to increase the time of measurement.

During the period of the test campaign a total of 23 vessels were recorded. These were 6 small-sized leisure crafts (26.1%), 1 passenger ship (4.3%) and 16 (69.6%) cargo vessels, further ships were recorded but did not transmit AIS, which was required for the identification and transmission of the Geographic Notice ASM.

Vessels without AIS were removed from our datasets. Each continuous height measurement of a vessel had between 45 and 315 data points and was afterwards corrected by the systematic error of the sensor position relative to the passing vessel. Figure 5 depicts the average standard deviation of all height measurements of $n=23$ vessels. Since the amount of data points per vessel significantly varied (because of different length and speeds), we calculated also the vessel's correction, which is $s_2=0,049\text{m}$ and therefore slightly higher as the overall average depicted in figure 5.

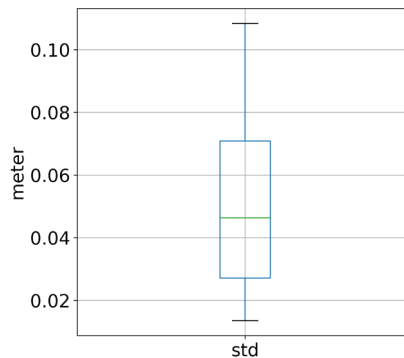


Figure 5. Box plot of all standard deviations for $n=23$ vessel height measurements.

5.3 Discussion of Results

After the evaluation we manually walked through all recordings to figure out possible disturbing factors. Birds are the most prominent effect on the height measurements and contribute to the variance. As the system should capture the highest point of the ship, only minimal filtering was applied to avoid declaring the highest point as an outlier. Another effect is that some ships can also lower the mast at the bow of the ship beside its own bridge. One recording clearly shows that the mast is raised while passing the sensor's field of view and thus influences our measurements.

The basic assumption for this study, that the maximum height can be measured over a certain amount of time also contributes to the observed variance, since it includes the reported error of accuracy reported in the prior section and also assumes that the superstructural elements reflecting the highest measured point are flat structures with sharp edges to distinguish them from other superstructural elements as shown by figure 6. In the current experiment setup, no weather data, which also might impact the system, have been considered explicitly due to the limited testing period of 5 days and no close weather station nearby the test area.

Currently a long-term recording experiment setup is being configured to gather sufficient data for implementing and testing a bird filter and also to test the robustness in bad weather situations, such as heavy rain. Also installing some plates with known dimensions on a vessel that regularly passes the installation location would help to estimate the system error more precisely.

6 CONCLUSIONS

The results show that the system is suitable for determining the ship's height. However, we have also realized that many potential interferences (e.g. birds, raising/lowering of the ship's bridge) must be considered. Due to this, simple light barriers are no longer sufficient to provide reliable information to navigators. High resolution 3D LiDAR-based systems enable high-precision detection of vessel contours but also include noise. With appropriate object detection algorithms, lidar based VHMS allow the detection and differentiation of vessel elements like vessel bridges and mast as well as birds or other geometric objects.

This will allow the system to be further improved in the future to provide more robust information to navigators. In addition to the intended functionality of the system, we see further use cases with which the system can be expanded:

1. Navigation Assistance: The 3D detection of the ship makes it possible to detect the position and orientation of the object. Accordingly, anomalous behavior can be detected and warnings issued. This can be the case, for example, with dangerous approach angles or when ships could collide with bridge piers. The system can thus continuously determine the risk of collision. A high collision risks estimation may also be used to inform bridge personal to close the bridge to traffic.

2. Extended Assistance: The transmission of the information as an AIS ASM Geographic Notice makes it possible to send further information. Recommendations for the approach such as entry corridors can be transmitted to support challenging bridge approaches.

3. Cooperative Maneuver Support: The system can be installed on both sides of the river to support both directions of travel. These systems are installed on the other side of the bridge. This offers the option of issuing warnings in the event of oncoming traffic. This additional information can reduce the risk of collision, especially when crossing bridges where AIS reception is disrupted, high-precision data is required or visibility is difficult.

4. Self-sufficient height measurement system: The results show the potential of a shore-based height measurement system. Our measurements showed that it is also possible, within this use case, to determine the water height due to spray in order to determine the ship's height above water. However, further research is required to determine the precision and reliability of these measurements.

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