

MEASURING THE SPEED OF DOCKING SHIP WITH TOTAL STATION

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Resume

The big modern ships are the largest mobile objects that exist in nowadays world. Their huge mass and length in combination with their limited maneuverability can result in the risk of extreme destructions of the infrastructure, as well as environment, in the case of even minor malfunction of any of its elements. The main danger is the kinetic energy of such a colossus and in these circumstances the accuracy of information on the ship's speed becomes particularly important. This is the reason of a growing interest in various systems designed to support harbor pilots during the maneuvers. The most popular ones are based on laser-measurement of the distance, as the rule, installed as static installation in the quay.

This article presents the results of the experiments of vessel's speed measurements when approaching the quay with use the geodetic total stations in a reflectorless variant.

Article info

Received 18 March 2021

Accepted 9 June 2021

Online 7 October 2021

Keywords:

pilot systems,
speed,
laser distance meter,
total station

Available online: <https://doi.org/10.26552/com.C.2022.1.E1-E10>

ISSN 1335-4205 (print version)

ISSN 2585-7878 (online version)

1 Introduction

Maneuvering a ship, especially a large one, is an operation that bears risks resulting from her enormous kinetic energy. Besides some differences between operations of mooring the ship and movement of the ship in canal or similar waterways, all of them are characterized by the similar risk of unwanted movement of a vessel. Such operations pose risks of collision not only with other vessels also with surrounding infrastructure, as well. The main threats come from small space, huge inertia of the object and its limited maneuverability. It is proper to mention that the energy of the moving object is a product of its mass and the speed upraised to the square and in many times the mass of the ship is 100000 tons or more. Even in the case of a speed of a few decimeters per second, the energy is enormous and in addition, what is extremely important, this is in absence of any effective brake-systems. In such circumstances a maneuvering support system seems to be very attractive.

The examples of how important are such problems can be seen in two papers of [1-2] where authors presented methods that can be used for estimating the navigational risk in the restricted areas. Similar problem of berthing velocity of a large vessel is discussed for example by Roubos et al. in [3-5].

There are several variants of such systems, which is why they are sometimes referred to as dock, harbor or pilot ones. To a certain extent, this classification

can be identified with application areas, since the dock systems are used primarily while approaching the quay, when harbor or pilot systems usually mean those that are used in the course of passing dangerous or crowded waterways. In addition, depending on the location of their basic elements, the systems can be divided into the shore based and ship based [6]. On the other hand, as far as the ship's engagement is concerned, active and passive systems can be distinguished. This classification is presented in Figure 1.

1.1 Ship based systems

Ship based systems with use of the GPS receivers, were tested already in the latter part of the XX century [7]. Nowadays, they are built as active systems and are most often called "portable pilot's units" (PPUs), based on laptops or tablets with dedicated software. In many cases this variant of devices has the ability to transmit data ashore via UHF. A typical portable pilot's system provides the pilot with his own, very accurate source of information about the position, heading (HDG) of the ship and her rate of turn (ROT). The most commonly used software in these devices is, in fact, a version of the simulation software being at the same time an overlay for an Electronic Chart Display and Information System (ECDIS). In some cases, the positions of surrounding ships come from an automatic identification system (AIS).





Figure 1 Classification of dock systems, [6]

Several levels of accuracy of the vessel's real-time positioning may be discussed, based on various augmented GPS variants [8], such as DGPS, EGNOS, RTK or PPP. Even though in this case the exact position of the ship is insufficient, more accurate position certainly allows to smooth out the information about the speed over ground (SOG) and course over ground (COG), calculated every second, which is the most important information for the pilot [9].

In such cases, the ship's heading (spatial orientation) is also extremely important, since the large ships length is sometime up to 400m and most often the position of the ship in fact refers to the position of a point near its stern. Therefore, if a ship is oriented not exactly along the axis of the seaway, it can occupy a much wider lane, which poses the threat of contact with its surroundings even when the controlled point (position) is exactly on the axis of the fairway.

DGPS - based PPUs provide sufficient accuracy for most of the tasks associated with passing along the shipping canals or recommended routes and usually no additional information or instructions from the shore are needed. The DGPS reference stations are numerous, especially in the northern hemisphere, therefore, this variant can be considered to be a very flexible, accessible and the cheapest option. They are rivalled by the Space Based Augmentation Systems (SBAS), in Europe (not only on seas, but also on rivers); this role is played by the European Global Navigation Overlay System (EGNOS). The SBAS class systems, with accuracy similar to DGPS, are also widely available in almost entire northern hemisphere.

The **RTK - based PPUs** require additional onshore stations and dedicated receivers. This variant assures the error below 0.4m, which suggests accuracy of speed at ± 10 mm/s. It is therefore a very accurate system that can be applied at any quay, or other restricted navigation area. In addition, this variant allows to obtain excellent accuracy of a real-time heading measurement; however, for this purpose at least two antennas spaced apart from each other at a distance of more than one meter are required. Unfortunately, this variant has significant limitations in the range of operation from the base station located on the land. The use of unified EUPOS reference networks, existing in many European countries, may be a solution. Moreover, many commercial

companies offer a similar networks of reference stations (for example Leica, Topcon etc.). These networks can provide corrections via the GSM, so there is no need to install an additional base station. Sometimes it may be difficult to obtain the right range, however, usually in ports area the GSM type systems are accessible.

1.2 Shore based systems

From the point of view of a harbour pilot, who will moor the ship in the particular harbour the deck system is inconvenient, because it demands delivering some additional devices to the vessel. This is difficult and not safe if a pilot is forced to clamber on the rope-ladder for dozen of meters. On the other hand, such systems are not unified, so with difficulty to await that vessel will transport on her deck many different devices, which will be useless in a specific harbour. This is why the shore based systems are attractive.

According to [10], the shore based systems, as a rule, consist of the following components:

- Quay located sensors of distance (usually laser, sometime radar or other microwaves system, eventually sonar);
- Control system located in some operator's building/room;
- System of data presentation, which can be in a form of large display situated on quay and presenting values of important parameters in digital form or lamp signaling safety or non-safety parameters. In certain options an additional portable display/receiver can be used in a form of laptop or tablet. Transmission of the data in addition to presented on the big quay display seems be more efficient, especially in poor visibility conditions, however, in such a situation skippers of tugs should possess additional receivers, as well.

The most common sensor in this kind of devices is a laser distance meter. The use of the laser to measure the distance is a common practice. For many years, surveyors use fully developed measuring systems, the so-called total stations. These are the combinations of distance measuring instruments and electronic theodolites. The high accuracy of the distance measurements and simultaneously measured angles of

azimuth and elevation can radically change the surveys of a position of the object. Unlike the ordinary lasers, which are used in harbor systems and must be installed in the quay, the total station could be transferred to another place.

In precise laser measuring techniques, as a rule, the reflective element is used, mainly in the form of a prisms combination. However, in the case of considered systems, the so-called reflectorless measurement is applied. It is assumed that in reflectorless measurements the laser beam will bounce off any surface of the ship's hull effectively enough to be able to measure the distance. This, of course, results in a smaller range, as reflected energy is smaller. If the average total station distance meter provides a range of up to 3km, the range of reflectorless measurements is limited to 200-300m. However, with regard to the system supporting the mooring of the ship in the port basin, this is not a problem, as distances of interests are usually shorter. This solution is characterized not only by the limited range, but by the limited accuracy, as well. While with reflector measurements a millimeter accuracy can be reached, the accuracy of reflectorless measurements is lower and dependent on the source of information. Usually it varies from 10 to 60mm with the standard frequency of shots in 2 seconds. However, the possibility that the object can move within 2 seconds by a distance greater than the accuracy of measurements has to be considered, which would significantly distort the result.

As a standard, a pair of stationary lasers is installed in the quay and connected to an IT system, which can ensure displaying results on different devices, transmission to other users, recording the measurements and their subsequent interpretation. In comparison to the solutions discussed earlier, this type is characterized by much higher accuracy, however, it is very inflexible, because it can be used only on a specified quay on which lasers and a display to present the results must be installed. In addition, systems of this type are the most expensive ones. The goal of this researches was to verify the usefulness of the total station in real harbor as a more flexible and possibly cheaper option.

Different variants of docking systems are in use since the sixties of the last century and many publications are accessible in the literature. For example, Trelleborg Marine and Infrastructure company [11-13] is a world leader in laser's shore systems. In these products, the speed and distance information are calculated based on the data measured by laser sensors located on the jetty and can be presented on the big display board, which are clearly visible from the ships' bridge. As this kind of systems are installed only stationary, they can be used only on a dedicated pier. In addition, laser sensors are installed close to salted water and this causes some exploitation problems, especially during the winter. This, aside from the costs of this installation, causes that they are rarely applied.

On the other hand, the demand on pilot supporting

aids are considerable. For example investigators from Marine Academy in Szczecin designed the Pilot-Docking System based on three laser distance measurements for the purpose of enumeration of the position of the agreed upon water-nymph of the ship [14]. In [10] authors discuss the general architecture of the same system.

Accessible papers discuss static systems installed on the pier. In this paper a hypothesis of the opportunity to use surveyors grade total station is tested. Author suggests that such an instrument is much more flexible as it can be installed for particular operation and the speed of the vessel approaching can be easily calculated based on such measurements. It should be noticed that the laser distance meters are in use for ship's berthing since the sixties. These systems are treated as mature, thus, in the last two decades this problem was in fact not discussed. However, investigation of the laser method is still provided, for example [16-18]. The constant evolution of surveying technology has contributed to a greater variety of available tools, for example total stations and laser scanners.

Of course, these devices are designed for surveying, different tasks than berthing vessels but some similarities can be observed in such tasks as, for example, modelled buildings with total stations without reflectors [19]. Authors emphasize that the total stations are incredibly versatile instruments with the near limitless measuring capabilities [15]. Surveying with a total station allows the surveyor to choose individual points to measure and each shot is made with relatively high precision of angular and distance measurements. Authors report their experience with modeling buildings and state that, since they provided measurements almost completely by the reflectorless mode, the obtained accuracy is estimated as 10mm. What is important, the errors in vertical axis were twice larger.

2 Experiments

Measurement of the ship's distance to the quay can be taken in several ways, but the method which does not require physical interaction with the ship, in the form of either an installation of any kind of infrastructure or transferring any person onto the ship, is preferred. That is possible with precise distance measurements, using the surveying total station located on the pier, especially since these instruments can work without any extra element installed on the vessel. Some experiments of such a type are reported in the paper. The measurement was done by the geodetic total stations, which are in fact precise laser distance meters, which can additionally measure angles in horizontal and vertical planes. Use of the two such aparati in two ways was verified:

- a) tracking two selected points on the hull of the ship approaching the quay;
- b) direct measurement of distances on lines perpendicular to the quay.

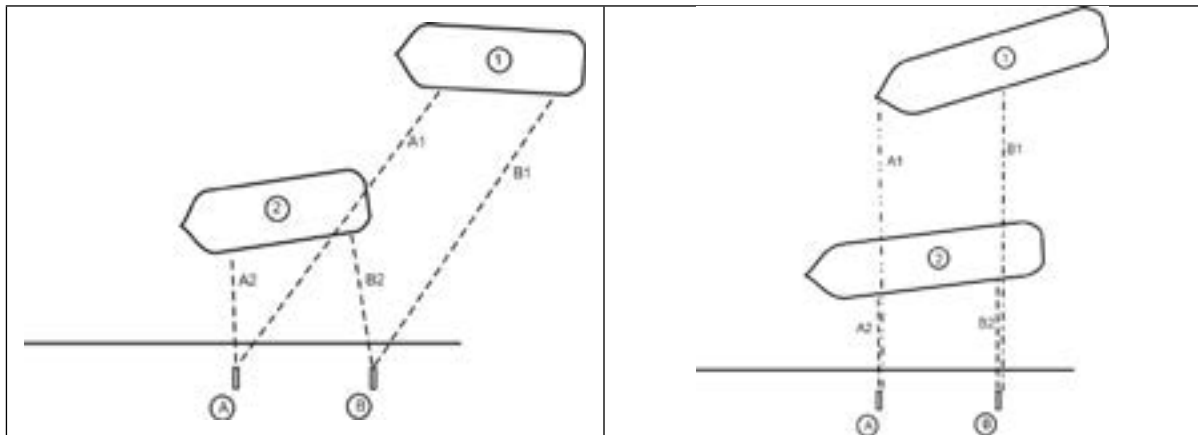


Figure 2 Differences between both possible methods of distance measurements

Table 1 The main parameters of total stations used in experiments

	TOPCON OS 103	TOPCON GT 500	TRIMBLE S3
Accuracy of distance measurement	3mm+2mm/km	2 mm + 2 mm/km	2 mm + 2 mm/km
Range of measurements	500 m	800 m	2200
Measurement time:			
Precise mode	0.9 s	0.9 s	1.2
Rough mode	0.7 s	0.6 s	
Tracking mode	0.3 s	0.4 s	0.4

Variant a) is attractive due to the fact that the total stations are perfectly suited to track movements, including the possibility of automatic implementation of this task, provided that it is possible to use the so-called robotic total station. However, in this case, the accuracy of measurement must account for the impact of both distance and angle measurements in the horizon plane (azimuth), as well as for the accuracy of tracking. In the course of measurements, assumption about the adverse impact of some ship's side colors on the range of the device was also confirmed. In some experiments two selected letters of the large lettering on the side of the ship were followed. For the ship with side lettering in black, when a back point was lit, there were numerous cases with no reflection.

On the other hand, variant b) allows to omit problems with aiming, however, as a consequence it also requires interpretation of results if the ship does not move towards the quay only. The complex hull shape sometimes causes significant and rapid changes in distance as the ship moves (please compare distances A1 and A2 in Figure 2 right).

Measurements were taken in both configurations on different days, for different large container ships in the length of more than 300m and displacement of about 150 000 tons. The measurements were taken in a good visibility, with almost calm weather, in daytime as well as at night. Due to organizational limitations, three pieces of different types of total stations have been used and, unfortunately, they could not be used simultaneously, as well as in identical configuration.

Some technical data of these devices are presented in Table 1.

Technical capacities of used devices allowed to take distance even every second, but in reflectorless mode it was not working properly. In practice it was performed with 2 seconds cycle and based on the differences between successive distances, the speed was calculated (in meters per second).

3 Description of taken measurements

3.1 Point tracking measurement method

In one of the experiments, the ship had a large lettering (MAERSK) on the side, so it was decided to follow of the first and fine letter (variant on the left in Figure 2). The measurements were taken in daytime and it turned out that at the beginning of the experiment repeated gaps in measurements occurred. This was most likely due to the dubious accuracy of aiming the device (in the daytime the reflection on the side was invisible), which sometimes hit bright side next to the lettering and sometimes the black lettering itself, which did not give enough reflection at greater distances. The measurements were stable at distances in the range of 50 meters, which is in the harbor practice normal distance. The measurements were taken with a TRIMBLE S3 total station (station A) and a TOPCON S103 station (station B). For the purpose of measurements a local coordinate system was established as presented in Figure 3,

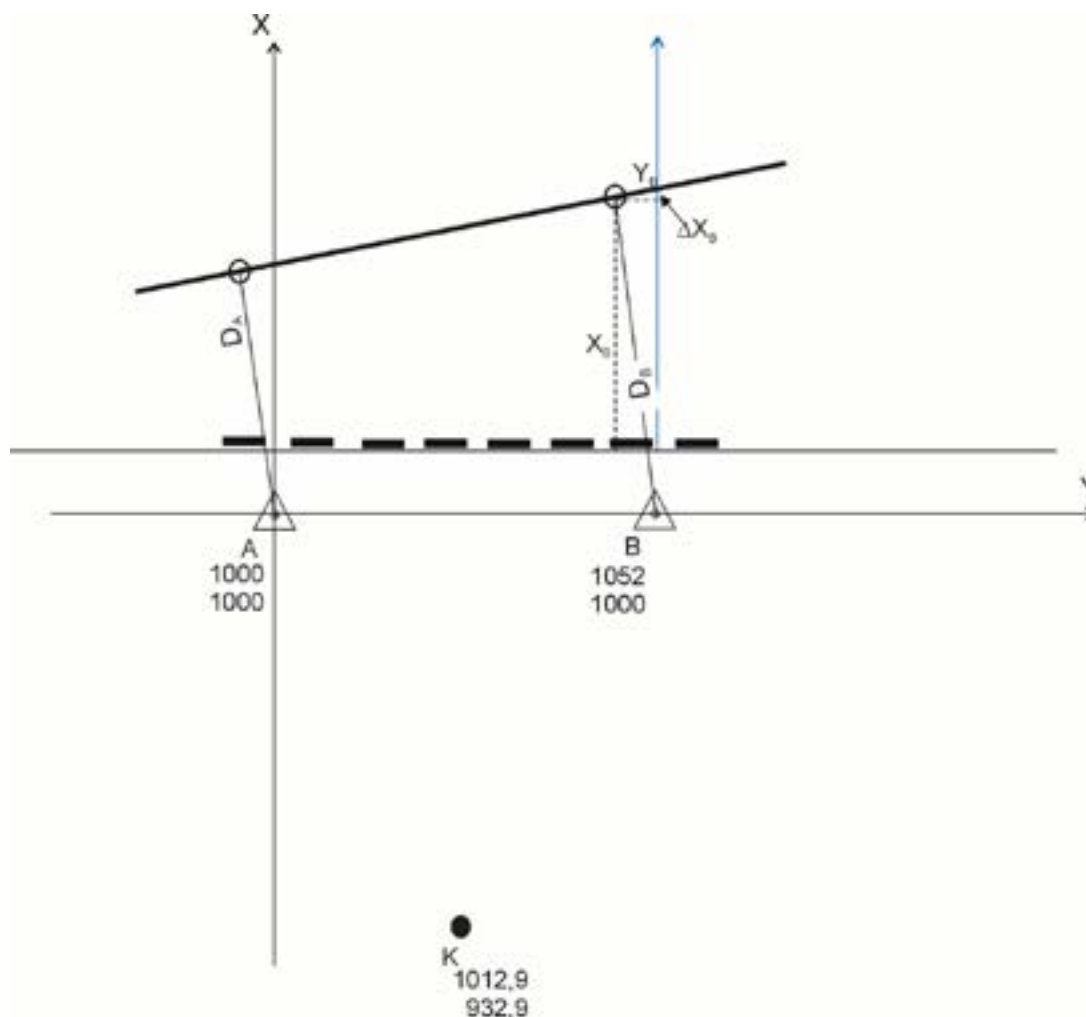


Figure 3 Situational sketch of measurements example taken in version 1, the line connecting the measurement points symbolizes the section of the ship's side

defining the coordinates of point A as (1000, 1000). Next, total station A was used to determine the coordinates for station B and control point K, which was a geodetic sign on the foundations of one of the lighthouses on the quay. Subsequently, the coordinates of station A and control point K were determined with use of the total station B. The results of the measurements taken with the first and the second total station resulted in identical coordinates for all the three points.

This experiment showed that the ship was eventually positioned at the quay in such a way that the selected points shifted to the left of the laser measurement lines installed on the quay. Moreover, for some time the ship moved non-parallel to the quay. For this reason, the coordinates of the measuring points had to be converted by projecting them onto the laser lines in the small-scale study. In both cases, the ΔX correction had to be taken into account (see Figure 3) resulting from the fact that the ship for some time was positioned at an angle to the assumed coordinate system. The additional difficulty at such a solution call out an adjacent installation, which periodically curtailed the tracked point. The considerable value of the azimuth variations suggests the necessity to install the instrument further from the

border of the wharf, however then many hindrances were found on the line of sight. In Figures 4 and 5 the distances (in meters) and calculated based on the speed of approaches (in m/s) in terms of time are presented.

The speed of approaching the quay was calculated as the quotient of the difference of successive distance measurements (D_i) and 2 seconds.

$$V_i = \frac{D_i - D_{i-1}}{2 \text{ sec}}. \quad (1)$$

In Figure 5 significant changes of the speed can be noticed at the distances larger than 15 meters, where in the last stage changes in the speed are a result of a vessel touching the elastic fenders.

3.2 Direct measurements of distances on lines perpendicular to the quay

An example of measurements in the second version is presented on the example of measurements taken with a TOPCON GT 500 total station (station A) and a TOPCON OS 103 (station B) and presented in Figure 6. The basic assumption of the method is that

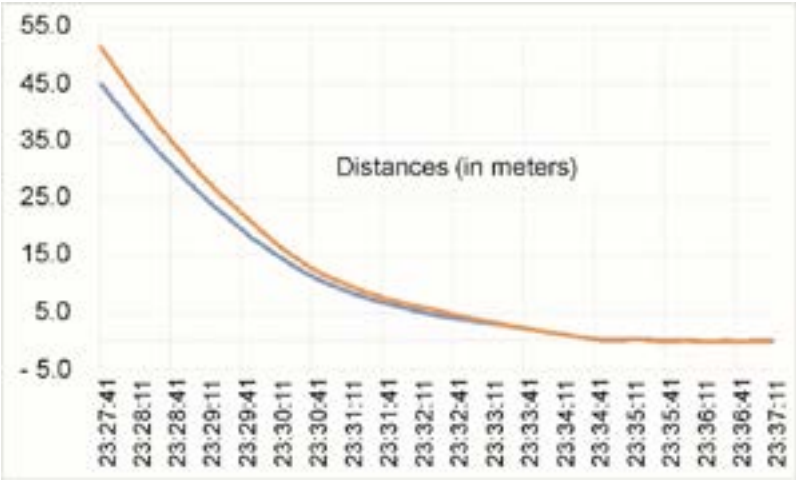


Figure 4 Changes in distance (in meters) measured with A and B total stations

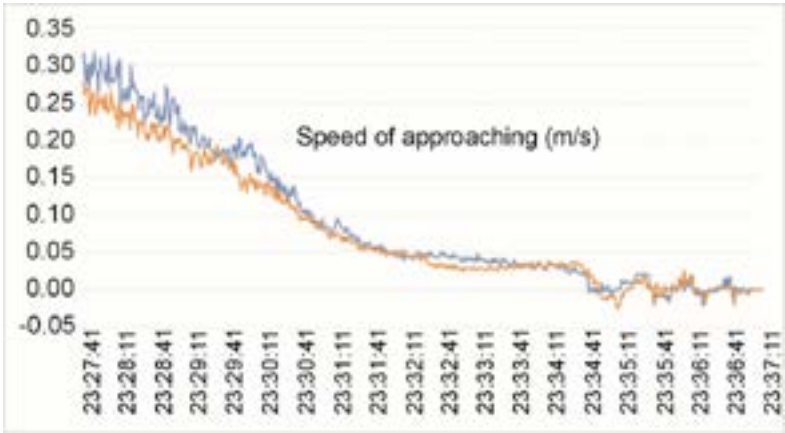


Figure 5 Speed of approaching (V_r) in m/s

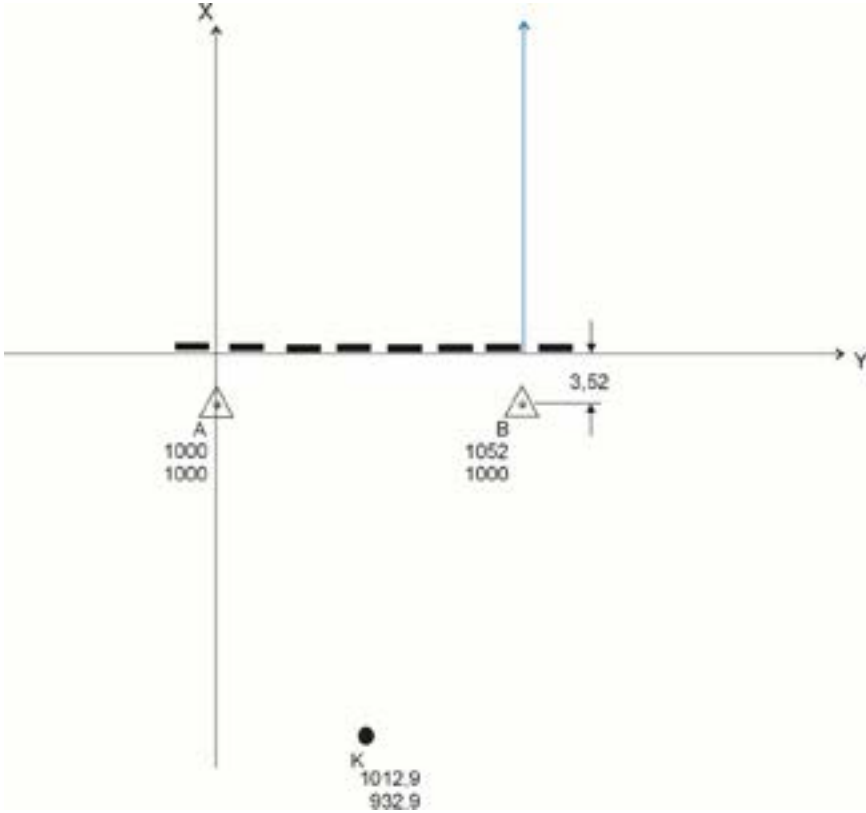


Figure 6 Situational sketch of measurements taken in version 2

repeatability of installation of the total station at the same place must retain the suitable accuracy

The next experiment was taken in the same place. Local coordinate system was re-established and the procedure of mutual determination of position coordinates was repeated, including the checkpoint K as in the previous experiment, obtaining identical coordinates. Next, the device at station A was turned with a measuring axis by 90° to the right from the orientation towards the station B. In station B the device was turned by 90° to the left from the orientation towards the device A. Coordinates was re-established with accuracy of 1mm. In both cases the distance from the total station to the edge of the quay was measured with a measuring tape. The distance was equal to 3.52m, which guarantees the mutual parallelism of the quay and base passing through both measurement stations and as a consequence the parallelism of the total stations axes. The measurement results for that day are shown in Figures 7 and 8.

4 Discussion

The presented examples allow to question the declared 3mm accuracy of distance measurements obtained with the use of the reflectorless method. It is worth noticing that in the case of lasers used in the stationary port-mounted systems, the manufacturer declares the accuracy of 10mm [19] and investigation described in [20] suggests the same value. The analysis of graphs 4 and 7 leads to the conclusion that the curves presenting distances are smooth, which corresponds to the practical experience of such maneuvers - ships with a mass of about 100000 tones have such a large inertia that it would be difficult to expect radical changes in the distance in subsequent 2-second measurement cycles. However, the declared accuracy of 3mm in the measurement cycle of two seconds, even at a few meters from the quay, cannot be observed on the speed vs. time plot (Figures 5 and 8). On both, large oscillations of the approaching speed of the ship are visible at distances

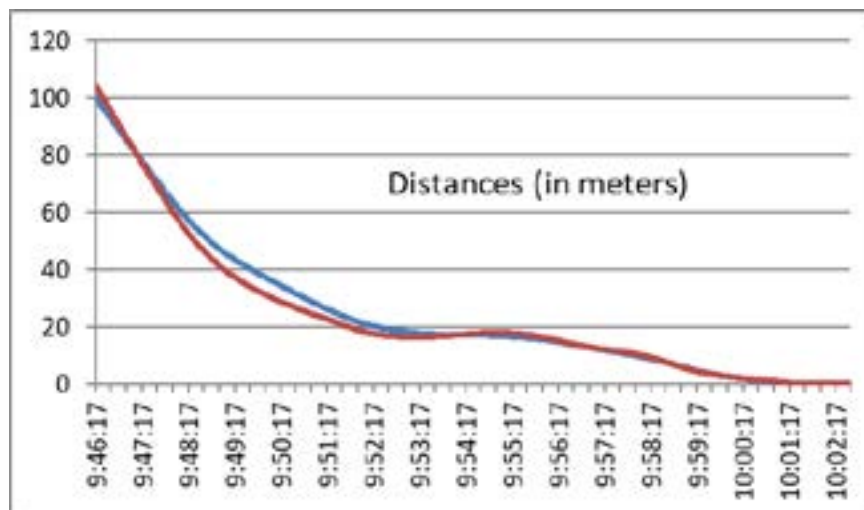


Figure 7 Distances (in meters) measured with A and B total stations

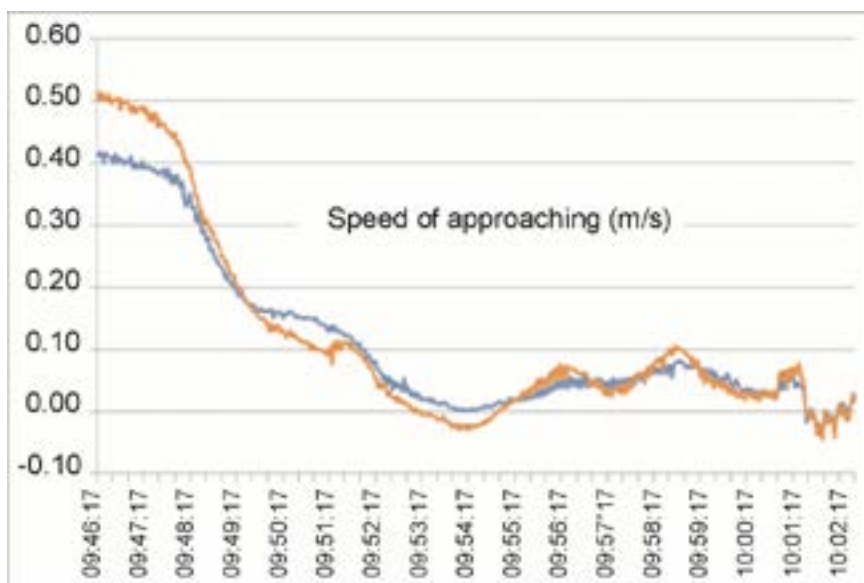


Figure 8 The approaching speed in m/s

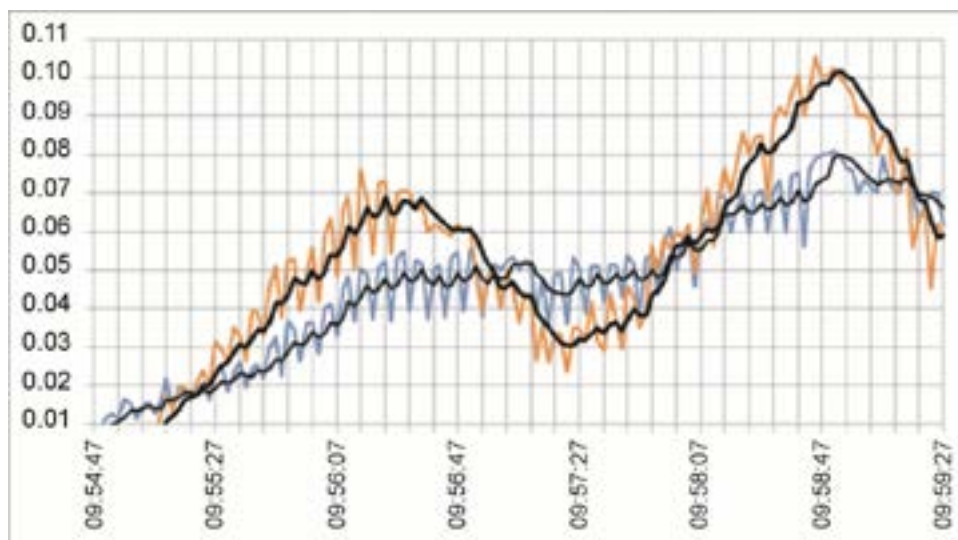


Figure 9 Speeds as a part of Figure 8 compared with the moving average of the adequate speed in m/s

ranging from 70 to 20 meters from the quay. This is absolutely the influence of the accuracy of the distance measurements.

An example of these oscillations is presented in Figure 9 (this is a part of a graph from Figure 8). Suggestions that the speed calculated based on the laser measurements of the distance should be filtered, can be seen, for example in [20]. In Figure 9 additionally smoothed data (which are counted as the moving average) is introduced. This is the part of the experiment when the vessel was not more than 20 meters to quay. The method of estimating the more integrated data is not a goal at the moment, so as an example the moving average is calculated as average for each last 5 values:

$$\Delta V_i = \left| V_i - \frac{1}{5} \sum_{j=1}^5 V_i \right|, \quad (2)$$

where:

V_i - is the consecutive measurement,

ΔV_i - deviations of consecutive measurements from the moving average value.

The experience proves that the accelerations occurring at this stage of mooring process do not cause essential changes of the speed of approaches and in the time of 10 sec this movement can be treated as stable. Assuming that such a value is the reference value, one can appraise that each value is different from the true one for not more than 10 mm/s. and mean value of such differences for all period of the experiment is 0.05 mm/s. In such a case and remembering that the cycle of measurement is 2 s, the error of measurements of the distance can be estimated as 10mm (0.005 m/s error in the window of 2 s.). The conclusion from the analysis of the distance measurements is that accuracy of the distance to the vessel in motion measurements with the total station in reflectorless mode can be evaluated as 10mm.

Besides the laser imperfection one can assume other sources of these errors. It is doubtful that this would have to be due to the hull accelerations, which is unlikely

with such a huge mass of the vessel. This issue requires deeper analysis; however, the following hypothetical reasons for this phenomenon can be indicated:

- imperfection of the surface of the ship's side: dents, welds, rust, etc.;
- vibrations of the metal plane due to the operation of the engine and other ship mechanisms;
- changes in distance to the point of sighting on the side caused by the oblique shape and slight hinges of the hull;
- painting of the hull, especially presence of black or very dark elements which did not have reflection at greater distances resulting in a lack of reading.

Occasionally irregular, but significant differences between successive measurements (even 100 mm, especially at longer distances) were found, which requires further analysis. Such differences occurred during daytime measurements and they did not occur at night. This may suggest that such systems operate in a more stable manner after dark. It is possible that this phenomenon was affected by the solar reflections during the day coming from other elements (moving) nearby.

5 Conclusions

Laser measuring technology is undoubtedly a great solution for mooring support systems. However, one should be aware of several limitations associated with a certain solutions causing erroneous judgments, if general information on laser distance meter capacity is relied on. The most important conclusion is that, in the systems currently used, the measurement is taken using the reflectorless method, which means that the accuracy of distance measurement is much worse than what could be assumed based on the commonly accessible materials. The most often suggested few millimeters accuracy of distance measurement is unattainable in these particular conditions.

The method of many measurements and averaging measured values in 1 or 2 - second cycles is easily accessible with commonly used devices. In such cases, the indicated value refers to the center of the measurement interval. Thus, the accuracy of the result is determined by the speed of the vessel movement and not by the accuracy of the laser since the latter value is many times lower.

An important issue in this type of measurement systems may be a problem of disturbances, primarily resulting from environmental conditions, especially accidental reflections and light reflections at greater distances from the quay. These systems are definitely better at night than during the day, assuming, of course, that no other artificial sources of light are present on site.

Application of lasers in the considered solutions has been known for many years, however it seems that development of technology still leaves a space for proposing several improvements. Development of the robotic total stations commonly used in surveying allows to suggest that similar measurements could be made, which seems possible providing that these devices are installed on the quay. Installation of the two total stations on the wharf is not a troublesome task and gives a chance to create a more elastic solution, especially in the places where such laser-system is indispensable once in a while.

Acknowledgements

Author acknowledges to Mr. Ireneusz Bojarowski for the help in making measurements for this article.

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