Sea Surface Mapping with GNSS

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SUMMARY

Nowadays, monitoring and measuring sea surface heights are primary conducted by mareographs and satellite altimetry. Each one of those methods produces good results but at the same time each has its disadvantages - Mareographs provide only local information while satellite altimetry gives data with poor temporal resolution and eventually provides results with reduced quality in coastal areas. In this paper a ship-based method for monitoring and measuring sea surface heights by means of GNSS is presented. The method is capable of spatial and temporal coverage also in coastal areas. The paper reviews the main principals of the method and calculations required in order to obtain the sea surface height.

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1. INTRODUCTION

Sea surface height is constantly changing. Throughout earth's history the sea surface height varied drastically and this ongoing process has a significant impact on life in coastal areas. Therefore, there is a need for constant monitoring of those fluctuations. Nowadays there are primary two approaches for monitoring and measuring sea surface height, mareographs and satellite altimetry. There are many forms of mareographs: floating mareographs, acoustic mareographs, radar mareographs and pressure based systems, each of these systems carries out the measuring process in a slightly different manner. The mareographs provide data with high accuracy though they suffer from the disadvantage that the local measurements do only allow drawing conclusions about the sea surface height in the vicinity of the mareograph. Satellite altimetry is a method developed to overcome this problem. The results show an almost perfect spatial coverage of up to 95% of oceans surfaces. However, satellite altimetry has its own disadvantage in terms of quality performance. It fails to produce accurate measurements of the sea surface height in shallow and coastal areas (Vignudelli et al. 2008).

In the paper we present a different approach for sea surface height measuring with emphasis on spatial coverage and good performance in coastal areas. In this method GNSS receivers mounted on a vessel are used for sea surface mapping. In order to perform these measurements it is necessary to be able to handle some key parameters: ships attitude in the water (pitch/roll), influence of the squat effect on the antenna height above the water (squat is a hydrodynamic phenomenon in which a moving ship creates an area of lowered pressure that changes the structure of the surrounding water surface and hence, leads to a change of the GNSS antenna’s reference point with respect to the undisturbed water surface), finding the antenna's phase center relative to the longitudinal center of floatation (LCF) of the ship and the heave, the wave and swell-induced height changes of the ship. Other parameters like static draft and dynamic trim were not considered. In recent years, several projects (see below) that involved measuring of sea surface height in a similar manner were conducted, but not in all of them all relevant parameters were treated at once.

In an experiment which took place in an archipelago north-east of Australia, sea surface height measurements were made in a similar manner using a vessel with a GNSS antenna. No accurate modeling of the speed effect on the antennas height was made (Bouin et al. 2008).

In a project conducted in the Baltic Sea, GNSS measurements were made from a sailing ship in order to examine the quality of the undulation model in the sea. During the processing no corrections were made for the height differences resulting from ships attitude and sailing speed (Jürgenson et al. 2008).

In Taiwan, sea surface height measurements were made using an on board GNSS antenna with ships attitude taken into account. Final results showed significant improvement between heights that were processed with a correction due to the ships attitude and the heights that were processed with no correction (Chia-Chyang and Hsing-Wei. 2002).

A series of experiments conducted in Germany for modeling the squat effect of small boats and sea-going vessels has yielded fine results, which allows estimating the squat and dynamic trim change of the ships depending on the sailing speed with good accuracy (Härting and Reinking. 2002; Härting et al. 2007).
The latest experiment was carried out on a cruises vessel in the Atlantic Ocean (Reinking et al. 2012) showing that ship-based GNSS observation can give excellent results for sea surface monitoring if all relevant effects are considered.
The purpose of this study is to present results from a survey of sea surface height in which the processing combines the most relevant effects of the various components affecting ship-based measurements and give an accuracy assessment.

2. EXPERIMENT AND DATA COLLECTION

An experiment was performed in the Mediterranean Sea close to the city of Tel-Aviv. The vessel chosen to carry out the experiment was the "Etziona", which belongs to the Israel Institute of Oceanographic and Limnological Research (fig. 1). Four antennas were placed on the ship; two of them were positioned along the longitudinal axis, one at the stern and one at the bow, the other two were positioned perpendicular to the longitudinal axis. The antennas were placed as far as possible from each other. The use of several antennas allows calculating ships attitude (pitch/roll) which is necessary to calculate the position of antenna's phase center above the sea surface. Sea surface height is calculated based on data collected from all four antennas. The accuracy of the resulting height can be assessed by comparison of the results from all antennas since the measured sea surface height from all antennas is assumed to be identical. One antenna was of the AeroAntenna AT2775 type and the other three were of the Leica AS10 type. The receiver used to collect the GNSS data was of the JAVAD SIGMAQ type.
A dynamic reference station was set up in the form of a GNSS buoy. An antenna was mounted on a wide, flat based buoy (fig. 2) so that the antenna phase center is as close to the water as possible. Hence, the influence of inclination due to waves on the measured height was negligible. The buoy was placed in a still water anchorage within the breakwater. Another AeroAntenna AT2775 type in conjunction with an Ashtech Z-surveyor was used at the buoy. The buoy served mainly during the calibration phase as a dynamic reference station for the observation of tidal changes.

Fig. 1 – The "Etziona"

Fig. 2 – The GNSS buoy that was used during the experiment

The experiment was divided into two phases; the first phase served as a calibration survey for the Squat effect modeling, while the measurements from the second phase were used for sea surface height calculation. In both phases GNSS data was collected every second.

3. DATA PROCESSING

It is possible to calculate relative heights of the antennas' phase center from the GNSS measurements in an ellipsoidal reference frame with respect to a reference station. These relative heights have to be corrected in order to acquire the sea surface height. During the first phase (calibration survey) all processing were made relative to the dynamic reference station (buoy) by "moving base" approach. The vector between the ship and the buoy can also be processed in regular kinematic solution relative to land-based permanent reference station. In that way we calculate two vectors one between the land-based station and the ship and another one between the land-based station and the buoy. Reduction between the two results provides indirectly the ship-buoy vector. During the second phase (measurements for sea surface height calculation) GNSS data was processed relative to a land-based permanent reference station, TELA, which is located close to the area under investigation. The relative phase center heights of all four antennas on board the ship and the one on the buoy were calculated relative to TELA in a post-processing using the Trimble Total Control (TTC) software. In the next step all required corrections were calculated.

3.1 Finding the antennas' position in the ships reference frame

Even though the centre of rotation is changing dynamically, the longitudinal center of floatation (LCF) can be used as a good approximation of the ship's spatial movement in the water. It is the center of the waterline area of the ship. In order to correct the measured height for ship's attitude (pitch/roll) it is mandatory to obtain the antenna's phase center position with reference to the LCF, which is used herein as the center of a ship's reference frame system.

Obtaining the antenna's position in this ship’s reference frame system was divided into two steps; in the first step all four antennas, together with two additional points on the ship’s hull, were measured with a Total Station (TS) while the latter served as the center of a local coordinate system. The positions of the two additional points in the ship's reference frame are known from previous measurement made on the ship several years ago. Then the parameters of a 2D transformation between the two systems were calculated based on the additional points since only these two points were known in both systems. By using these parameters the antennas' position in the ship's reference frame were obtained. Two sets of measurements were taken and a total of six points were measured.

The angle α is denoted as a horizontal direction measured relative to a fixed reference point which is set as the north of the TS local coordinates system, H as an elevation angle relative to the TS horizon and L_H as the slope distance. Therefore, the antenna's phase center coordinates in a local coordinates system $(X, Y, Z)_{\mathrm{TS}}$ is determined by:

$$\begin{aligned} X_{TS} &= L_H \cdot \sin(\alpha) \\ Y_{TS} &= L_H \cdot \cos(\alpha) \\ Z_{TS} &= L_H \cdot \tan(H) \end{aligned} \tag{1}$$

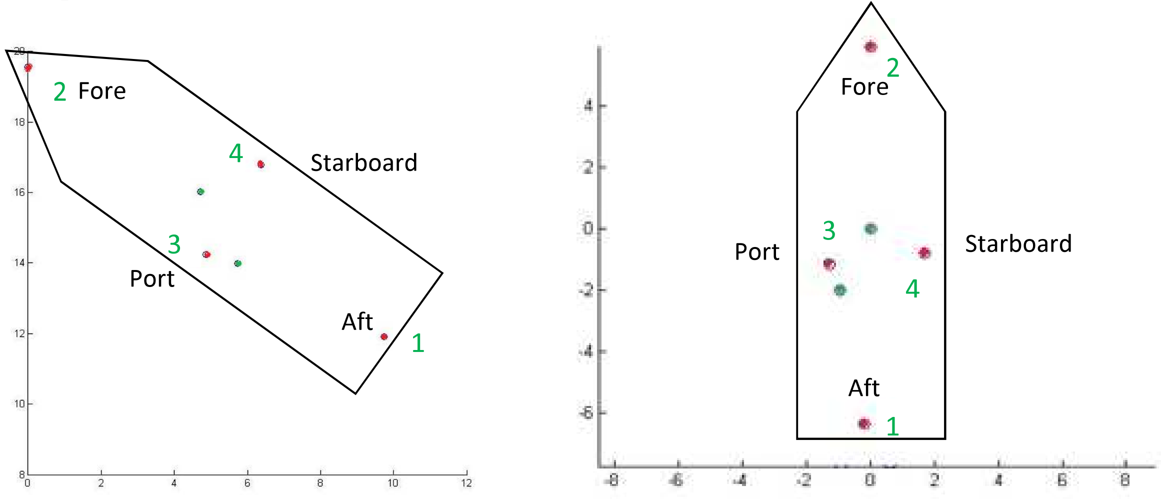
Transformation of the antenna's position to the ship's reference frame is performed using (2), where θ defines the angle of rotation between the two systems and the parameters d_x and d_y define the shifting vector.

$$\begin{bmatrix} X_{ship} \\ Y_{ship} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} X_{TS} \\ Y_{TS} \end{bmatrix} + \begin{bmatrix} dx \\ dy \end{bmatrix} \tag{2}$$

X_{ship} and Y_{ship} refer to the position of the measured point in the ship's reference frame. The scale factor was kept constant in this transformation to prevent distortions of the high-quality relative positions of all points measured by TS. Z values of the measured point underwent only an approximate shifting transformation between the two systems, the shifting value calculated as the average difference between Z positions for known points in both coordinate systems. The results of the measurements and the transformation are shown in fig. 3. The conditions in which the measurements were carried out were far from being ideal. Even thought the ship was in still water she kept moving which significantly affected the accuracy of the measured points. Because only two points were known in both coordinate systems it was not reasonable to assess the accuracy of the transformation. Therefore, the accuracy of the measured point was calculated from both measurement sets as a standard deviation of the measurements:

$$\sigma_x = 0.039_{[m]} \ , \ \sigma_y = 0.039_{[m]} \ , \ \sigma_z = 0.017_{[m]}$$

To improve the accuracy, measurements should be made while the ship is placed out of the water. Also at least three points, whose positions are already known in the ship's reference frame, should be measured to allow calculation of spatial transformation parameters. It should also be considered to carry out GNSS observations of the reference (additional) points while the ship is in the water.



(a) (b)

Fig. 3 – (a) Points in the TS reference frame, (b) Points after transformation to ships reference frame. Antennas and their numbers placed on the ship marked in red and two known points in the ships reference frame marked in green.

3.2 Extraction of pitch and roll angles

One of the elements affecting the measured height is ship's attitude in the water. During sailing ship's attitude is not constant, hence the obtained height from the GNSS measurements does not represent the sea surface height. After the height of antenna's phase center is calculated it is necessary to extract inclination angles in order to calculate the correction for height variations due to changes of ship's attitude. Inclination angles refer to pitch and roll. When the ship is pitching her bow rises up or goes down. On the other hand when the ship is rolling she tends to the port or starboard (fig. 4).

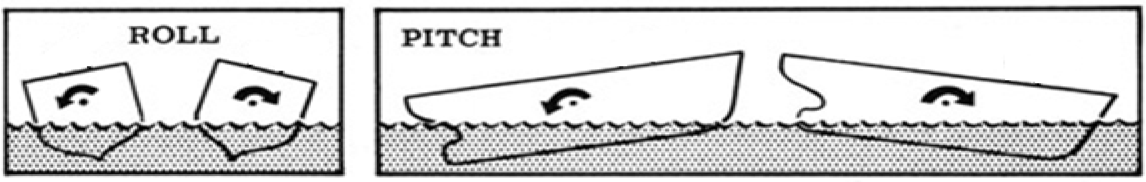


Fig. 4 – Illustration of pitch and roll

During the survey, data regarding inclination angles and their accuracies were collected directly from the SIGMAQ receiver. In the case of using a receiver which does not have this capability, inclination angles can be calculated through a spatial transformation (3). A transformation should be calculated for each measuring epoch.

$$\begin{bmatrix} X_{ship} \\ Y_{ship} \\ Z_{ship} \end{bmatrix} = \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} + k \cdot R \cdot \begin{bmatrix} X_{sail} \\ Y_{sail} \\ Z_{sail} \end{bmatrix} \tag{3}$$

During calculation seven parameters need to be adjusted; three shifting parameters (d_x, d_y, d_z), one scale parameter k and three rotation angles that form the rotation matrix R. Therefore, in order to reach a solution it is necessary to use at least three antennas. The transformation performed between a set of constant coordinates $(X, Y, Z)_{\text{ship}}$ which remains constant throughout the calculation process and a set of variable coordinates which changes in each epoch $(X, Y, Z)_{\text{sail}}$. Antennas' coordinates in each epoch should be placed in the variable coordinates set while in the constant set antennas' coordinates in the ship's reference frame should be placed. Figure 5 shows pitch values obtained directly from the GNSS receiver during sailing while figure 6 shows pitch values calculated through the spatial transformation. It can be seen that the values vary from minus to plus 40 cm, fairly large pitching for a 14.4 m long ship.

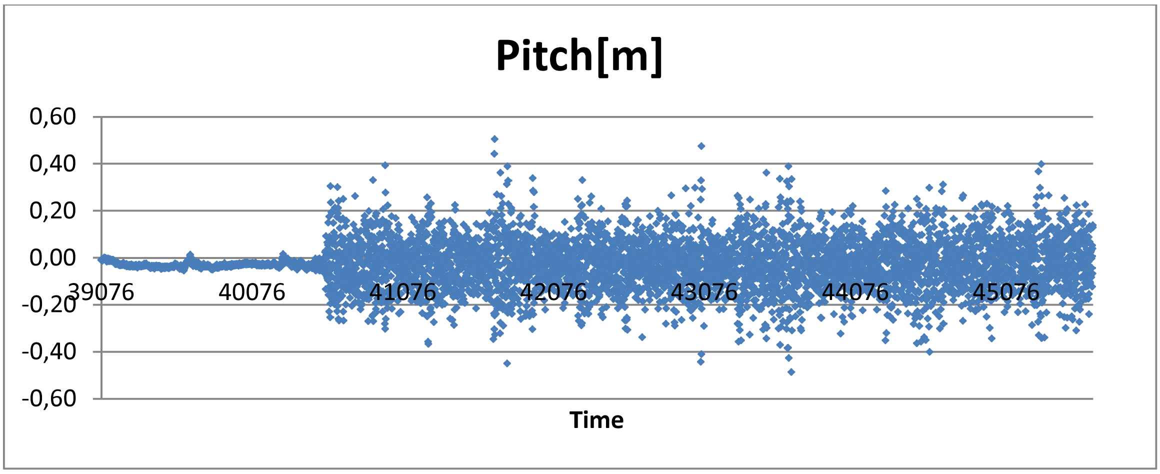


Fig. 5 – Pitch values in meters obtained directly from the receiver

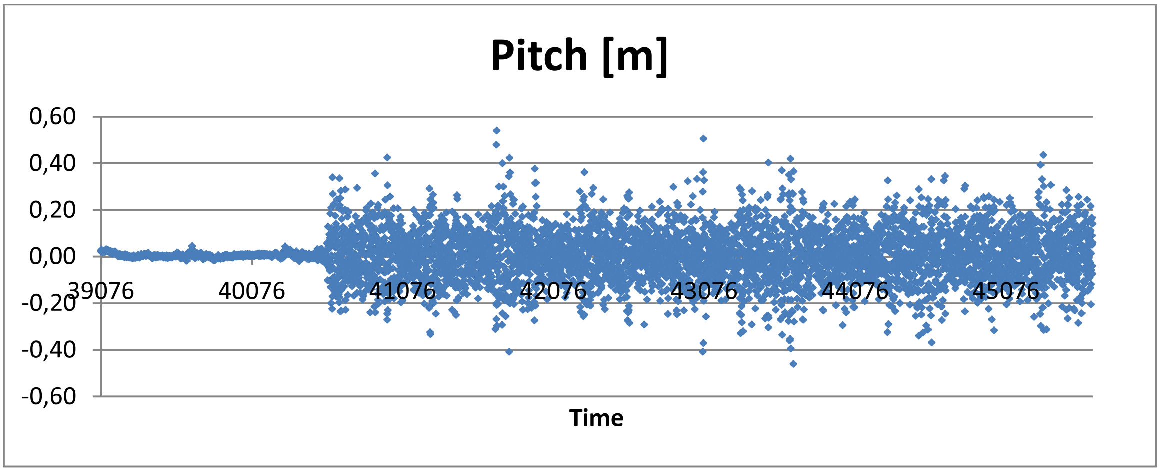


Fig. 6 – Pitch values in meters calculated through 3D transformation

After obtaining pitch and roll values the required height corrections are calculate from a 3D rotation of antenna coordinates in ship reference frame using

$$\Delta H = Z_{ship} - (X_{ship}\sin(pitch) + Y_{ship}\sin(roll)\cos(pitch) + Z_{ship}\cos(roll)\cos(pitch)) \qquad (4)$$

Height correction is performed by adding the calculated values to the original heights obtained by GNSS measurements. Positive pitch refers to a raised bow; positive roll refers to a hell to port. The angular accuracy is influenced by the number of antennas on which the transformation process was based and the sea state during sailing. Inclination angles accuracies could be obtained through adjustment calculation for the transformation process. Relatively rough sea conditions during sailing had great effect on the accuracy of the inclination angles; pitch accuracy averaged about 0.3 degrees while roll accuracy averaged approximately 1.1 degrees. The accuracy of the sea surface height is obtained from error propagation process and therefore it is affected by the accuracy of the measured inclination angles, higher accuracy of the angles means more accurate final results of sea surface height.

3.3 Squat effect modeling

For squat modeling a calibration survey is required. Calibration survey is conducted as follows: at first the ship sails in a certain default direction (choosing the direction is arbitrary; we decided to sail along the coast) for approximately two minutes while maintaining a constant revolutions per minute (*RPM*) during this period, then making a 180 degrees turn and sailing in the opposite direction for another two minutes while maintaining the same *RPM* as before. The idea behind this act is to isolate the effect of the currents velocity on ship's speed. This process was repeated several times, each time increasing the *RPM* by 100. Calibration survey started with 1000 *RPM* and finished with 1800 in order to obtain a fairly wide sample range at the end.

The purpose of squat effect modeling is to find a mathematical function which allows correcting for the ship’s apparent draft change with respect to the undisturbed water surface relative to the sailing speed. Ship's speed could be obtained from differences in antennas position between any two consecutive measuring epochs, but this yields the speed over ground (*SOG*) while squat depends on the speed through water (*STW*). For solving this problem the *SOG* was modeled as a combined function of *STW* as a quadratic polynomial of *RPM* and current as a linear polynomial of time in seconds of day (*SOD*). All tracks were sailed twice in opposite directions. Hence, an angle α was introduced to describe whether the ship sailed in the default direction (α=0°) or opposite direction (α=180°)

$$SOG = a_1 \cdot RPM + a_2 \cdot RPM^2 + (b_1 + b_2 \cdot SOD)\cos(\alpha) \tag{5}$$

From (5) ship's STW can be deduced and calculated (for the default sailing direction),

$$\begin{aligned} STW &= a_1 \cdot RPM + a_2 \cdot RPM^2 \\ STW &= SOG - (b_1 + b_2 \cdot SOD) \end{aligned} \tag{6}$$

meaning, calculation of *STW* could be made in two different ways depending on the parameters at hand; a direct calculation of *STW* using the *RPM* or an indirect calculation in which the *STW* is obtained by subtracting the current's speed from the *SOG*. At the end of the modeling process two functions for squat calculation can be derived, one is based on the *RPM* and the other based on the *SOG* and current speed.

The ship's squat is calculated for each epoch relative to the initial height differences between the antennas on the ship and the buoy which is the averaged height difference observed during mooring while the distance between the ship and the buoy was not more than 250 meters. For each two minute time period several average values must be calculated: squat, *SOG* and *SOD*. Using equation (5) we then calculate and adjust the parameters a_1, a_2, b_1, b_2. After the adjustment process is finished it is possible to present a scatter of points which describes the dependence between squat and *STW* while the latter is calculated twice using both equations (6) (fig. 7 - 8). For each set of samples a curve needs to be fitted which will describe the phenomenon best. It is important to emphasize that the squat is defined as the apparent draft change at LCF and the additional dynamic trim change which leads to height changes at a certain point depending on the position of this point in the ship’s reference frame. Therefore for every antenna placed on the ship a different curve is fitted that describes the squat at this position relative to the *STW*.

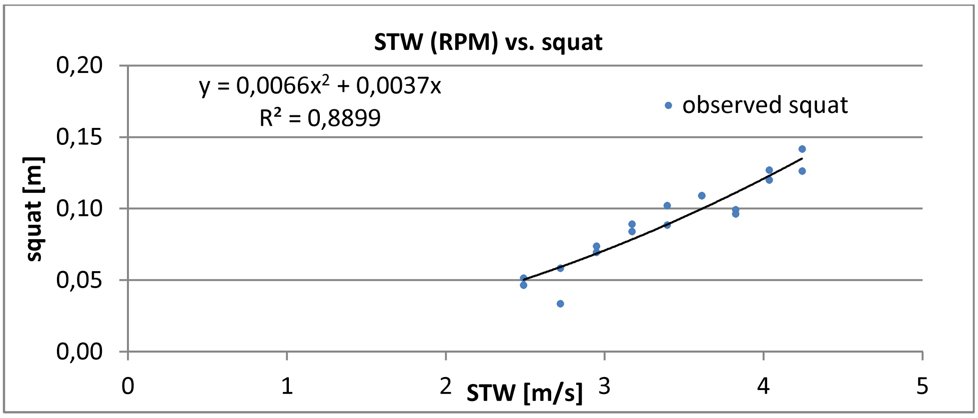


Fig. 7 – Example of curve fitting for antenna #1 based on *RPM*

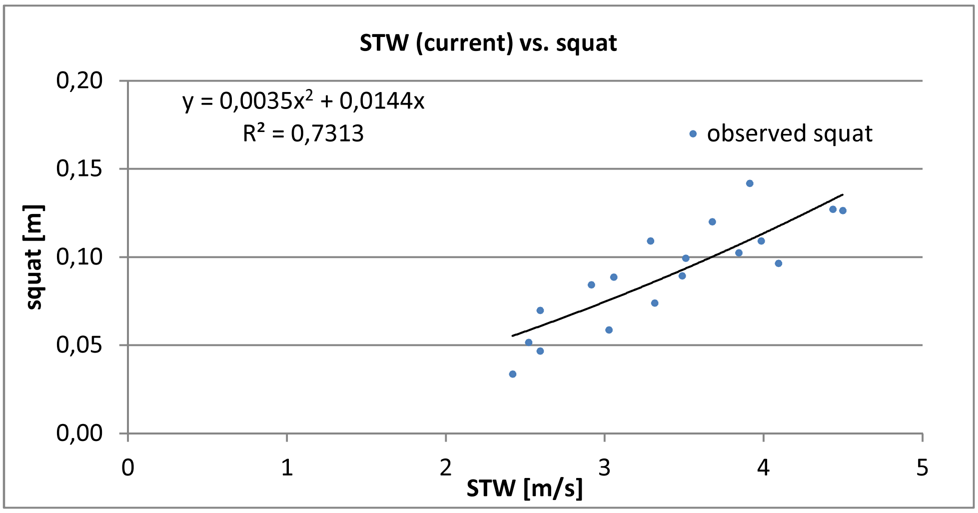


Fig. 8 – Example of curve fitting for antenna #1 based on *SOD* and current speed

It seems, only by examining the square of the correlation coefficient (R^2), that curve fitting for *STW*-squat relation based on *RPM* values is much better. Still, height correction during post processing of data from the second phase (measurements for sea surface height calculation) of the survey was made using the curve based on current as a function of *SOD* because there is no record of *RPM* values throughout the survey available. However, data for speed calculation based on current and *SOG* are more accessible and could be obtained from the GNSS data. Using equations (6) and b_1 and b_2 parameters it is possible to calculate the *STW* based on current and *SOD* in every two consecutive epochs. Using the fitted curve we obtain the corresponding squat which then needs to be accounted as a correction to the measured height.

Accuracy of the fitted curve is a direct result of the sea state during the calibration survey. In rough conditions the measurements will be much less accurate and much more scattered, this will cause to a poor fitting of the curve to the data. Accuracy achieved for all four antennas ranged from 1.7 to 2.3 cm.

3.4 Heave effect filtering

While sailing a ship is influenced by wave and swell-induced heave which has a substantial impact on the measured height. One way of dealing with this problem is by filtering the data.

Figure 9 presents height measurements made using antenna number 1. It is possible to recognize a primary trend which dictates the overall behavior with addition of sharp variations in the measured height. These variations are caused mainly by the heave effect and could be treated as a part of a signal that needs to be filtered. Data was filtered using a low pass filter (LPF) which is designed to filter out high frequencies. We chose to filter out height variations caused by waves with a period shorter than 20 seconds, assuming that wave periods during the measurements were shorter than 20 seconds. Selection of this cut-off period is a result of trial and error and consultation with professionals from the signal processing field.

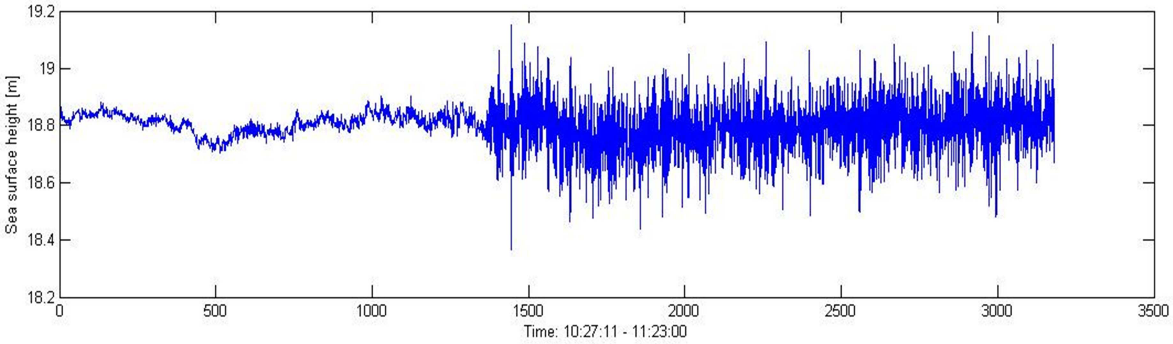


Fig. 9 – Height obtained from GNSS measurement from antenna #1

4. ERROR BUDGET

The accuracy of resulting sea surface height in each epoch can be calculated through error propagation, each height correction component contributes its error to the final result. If *f* is defined as the function of sea surface height calculation the accuracy m_f is calculated using simple error propagation neglecting possible but unknown correlations:

$$m_f^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \right)^2 \cdot m_i^2 \qquad (7)$$

Error sources x_i and their accuracies m_i are locations of antenna's phase center, pitch and roll extraction, curve fitting for the squat effect, heave and GNSS measurements. Estimated accuracy for GNSS height measurements can be set as 2 cm. Another error is the position of the LCF which serves as the center of the ship's reference frame. Note that the only accuracy values changing with each epoch are the ones regarding pitch and roll angles, therefore a conclusion can be made that epochs with low accuracy represent a time in which the ship was rolling and pitching more aggressively. Resulting accuracies were about 5 cm.

5. RESULTS AND CONCLUSIONS

Sea surface height was calculated during mooring and along a sailing profile that lasted about 40 minutes. Due to frequent connection loss between antenna number 4 the satellites, sea surface height was calculated based only on the other three antennas. The average number of satellites per epoch for this antenna was 3.7 while for the other antennas it was between 4.8 to 5.7 satellites per epoch. One would expect that at any given point in time results from all three antennas will be the same, but that was not the case (fig. 10 – 11) due to multipath effect on GNSS measurements, concealments and other factors. Therefore it is necessary to examine whether differences in height measurements between the antennas are within the estimated accuracy. During mooring height measured by the GNSS buoy was considered as the correct sea surface height and height differences between each antenna and the buoy were examined. Note that during mooring, obtained accuracies are much better because pitch and roll are negligible and the squat effect is insignificant. During sailing height differences between antennas and the average sea surface height based on all three antennas were examined. It would be expected to achieve better results during mooring because during sailing there are much more disruptions throughout the measuring process. During mooring a standard deviation not exceeding 1.8 cm was obtained for height differences between the buoy and antennas on the ship. During sailing a standard deviation not exceeding 3.2 cm was obtained for height differences between the average height and antennas on the ship.

Table 1 presents results of standard deviation of sea surface height measurements for each antenna. Final results are acceptable because obtained standard deviations are within the estimated accuracies of about 5 cm.

Antenna	**Standard deviation [m]**	
	Sailing	Mooring
a1	0.027	0.015
a2	0.024	0.018
a3	0.032	0.017

Table 1 – Standard deviation of sea surface height measurements

Despite the harsh sea conditions for this boat during sailing we were able to achieve good results. Final results could be improved if slight changes were to be made during the working process and several parameters calculations. For instance, the antenna's location in the ships reference frame has great influence on the final results and their accuracies. Therefore, TS measurements should be made while the ship is placed out of the water on a dock or alternatively using GNSS to observe known points in ship’s reference. Rough sea state has significant effect on the squat modeling therefore performing the calibration survey in better conditions (calm to moderate sea) or using a larger vessel will improve the accuracy of the fitted curve for the squat effect. Another problem we encountered was the attachment of antennas to the ship; due to logistical problems it was not possible to attach the antennas to places designed especially for that purpose which made them unstable and affected measuring quality. Performing another experiment while taking into account all those factors will certainly yield better results and better accuracies.

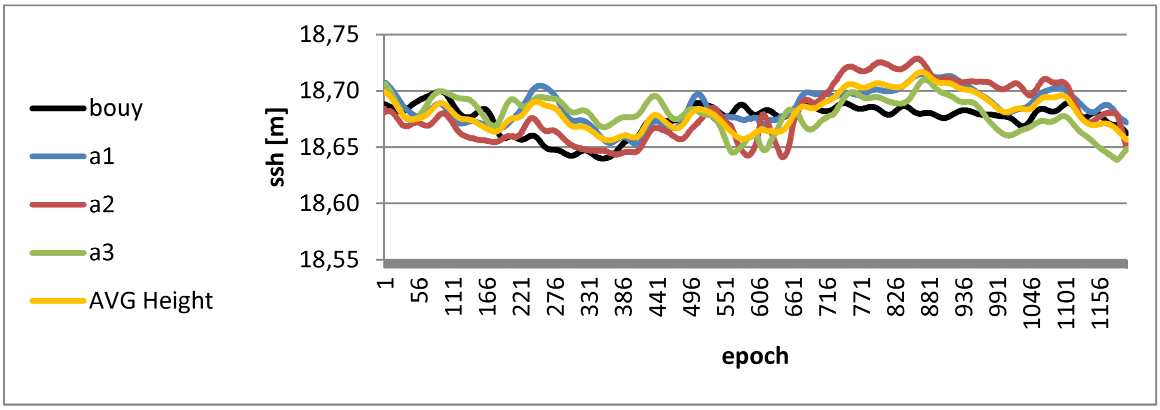


Fig. 10 – Final sea surface heights during mooring

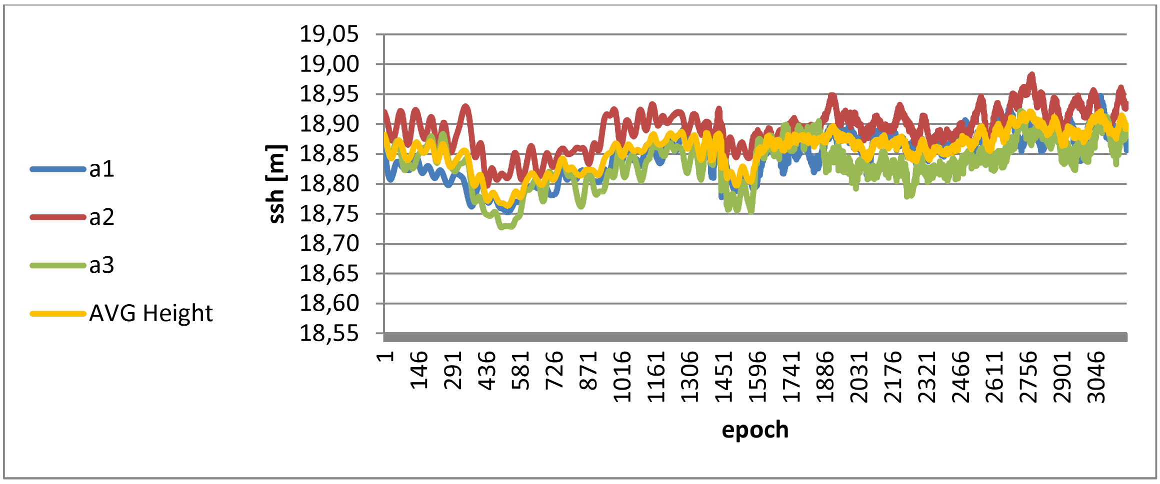


Fig. 11 – Final sea surface heights during sailing

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