1. Introduction

It is a well known fact that vessels additionally immerse in restricted waterways due to hydrodynamic effects. Several approaches have been made in the past to study this phenomenon by measuring the variation of the height of a vessel compared to a fixed survey station on shore. However, photogrammetric or nivellitic methods are limited in their applicability to either small sections of a waterway, good visibility or both. Even by using DGPS the accuracy of these observations is limited by the dependence on data from tide gauges to obtain the local water level at the vessel. The poorer accuracy arises from the fact that tide gauges measure the water level in some distance to the vessel. Hence, the data have to be interpolated in time and space for the vessel’s actual position. Such a procedure may be unreliable when local wind or current influences are neglected. Furthermore, each tide gauge has a system error up to 2 cm in relation to its measurement range.

2. Concept for a new Method

The Nautical and the Survey Department of the University of Applied Sciences in Oldenburg (Germany) are developing a new method designed to avoid the influences specified above. The main goal of the project is to develop a powerful product to simplify the determination of the exact squat of a vessel. The GPS-based method is named SHIPS (Shore Independent Precise Squat observation) and has been tested successfully in several experiments on German waterways.
The novelty of this method is the application of GPS carrier phase observations on a small escort craft to represent the local water level at the vessel and avoiding the use of tide gauges. There are three high quality GPS-units on the observed vessel and one on the escort craft to determine the squat (see Fig. 1 and Fig. 2). The GPS-antennas onboard the observed vessel have to be installed as far apart as possible. For an effective measurement it turned out that two GPS-antennas are well located at both wings of the wheel house and the third GPS-antenna on the forecastle. The motions of the vessel around its longitudinal, transverse and vertical axes can be determined by the evaluation of the height differences of the three onboard GPS-antennas. It is assumed that for small, quasi-static changes in trim and list the rotational axes pass through the longitudinal centre of flotation (LCF) of the vessel. The information about its position can be obtained from the ship’s hydrostatic particulars. The change in height of the vessel’s LCF can be determined by measuring the height difference between the three GPS-antennas on the vessel and the GPS-antenna on the escort craft.

3. Evaluation of the GPS-Data

The SHIPS-method uses kinematic GPS carrier phase measurements in differential mode with a moving reference-station, which is, as suggested above, onboard the escort craft. The distance between the vessel and the escort craft usually is about 200-500 metres. Due to the
short baseline the influence of tropospherical effects is strongly reduced. The ionospherical
effects are mostly eliminated by using two-frequency GPS-receivers. We prefer storing the
raw data in the internal memory of the receivers – using sampling rates of up to one second -
rather than using real time options of the receivers because this allows to check for outliers
and data quality and to correct for different effects.
The data analysis is done later in post-processing mode. The non-commercial software
package used for evaluation of the collected data was developed at the University of Applied
Sciences and will constantly be extended and optimised. Tests have shown that the quality of
the derived height differences using this software is approximately 1-2 cm. Considering all
error sources, the expected accuracy of the resulting squat will be better than 3-4 cm.

4. Corrections for the Observed Height Difference

The vertical motion of a vessel can be caused by many reasons. In the procedure of
determining some corrections must be considered. In the following we describe some but not
all influences.

4.1. Squat of the Escort Craft

The behaviour of the escort craft depends on its speed through water. Usually the escort craft
has small dimensions, so its cross sectional area is negligibly compared with that of the
waterway and its draught is insignificant in relation to the water depth. In this manner it is
justified to assume unrestricted condition for the escort craft. Nevertheless the escort craft has
also the tendency to “squat” with increasing velocity, even though the antenna may rise at
reaching planing speed.
The knowledge about the escort craft’s squat is important for the exact determination of
vessel squat, so that the escort craft’s squat has to be measured in a separate calibration
experiment. Preferably this calibration takes place at times of little tidal action. During the
calibration experiment several engine-stop-maneuvers are carried out with different speeds
in the vicinity of a shore based GPS-station. With sufficient calibration data the escort craft’s
squat can be described by an approximation function of speed-through-water.

4.2. Three-Dimensional Motion of the Escort Craft

During the measurement non-stationary motions like waves, swell or steering manoeuvres
affect the escort craft. These motions cause a height change, which can be misunderstood as a
difference in height due to speed-dependent manoeuvres.
One method to eliminate these influences is to install a motion sensor on the escort craft. This heave-roll-pitch sensor measures the height change by the use of accelerometers and observations of the rate of rotation. Because of its tendency to drift over a longer time period the data have to be filtered by an adapted high-pass filter. These filtered data can be verified by a method, which uses the GPS receiver onboard the escort craft, even if no reference station at shore is available and the absolute height of the GPS antenna is unknown. The wave induced height changes can be derived from cumulated and filtered epoch-by-epoch GPS phase differences [1].

4.3. Salinity

In tide affected waterways the salinity and the temperature changes in relation to the tidal conditions and to the distance to the estuary. The brackish water zone is the part of a tidal affected river, where the salinity changes locally and periodically with time. The brackish water border marks the two places where the salinity is still constant. The extension of the brackish water zone essentially depends on geometry and morphology of the estuary, the tidal motion and the upper discharge of the river.

The variation of the vessel's draught due to changing salinity and temperature conditions has to be considered within the brackish water zone. The density-dependent change in height can be calculated on the basis of the changed weight of the displaced water and the hydrostatic tables of the observed vessel. These parameters are observed onboard the escort craft. For the escort craft this correction can normally be neglected due its small displacement.

4.4. Water Level Gradient

The principle of this method is that the escort craft runs at some distance in front of the vessel to avoid any influence by vessel-induced water surface disturbance. Consequently the raw data contain some difference in height due to water surface gradient. If the horizontal distance is not larger than 300 to 400 metres, the height difference is less than a centimetre depending on the steepness of the tide curve. Such a small correction can probably be derived from an average tide with sufficient accuracy. In a tidally unaffected waterway, such as a canal, the correction is in most cases negligible.

4.5. Tidal Currents

The speed over ground determined on the basis of the GPS-data must be corrected with the velocity of the tidal current to get the speed-through-water. The information about the speed-through-water is necessary for analysis as a prime parameter on which the squat depends. The
responsible authorities do not continuously measure the tidal current in the waterways, so that speed-over-ground has been corrected with values from tidal-current-diagrams (see Fig. 3).

Fig. 3  Tidal current diagram of the Weser between ‘Neue Weser’ and Bremen relative to HW at Bremerhaven

5. Presentation and Discussion of Experimental Results

Several experiments have been carried out to test and to improve the efficiency and accuracy of SHIPS. The first experiments took place on the lower Weser, because the Nautical Department of the University is located directly at the bank of the Weser’s tributary Hunte. The Kiel-Canal was selected to avoid tidal effects and influences due to changing waterway geometry.
5.1. Waterway Lower Weser

The Lower Weser is the about 70 km long section between the estuary at km 65 in the north and the weir Bremen-Hemelingen at km -4.5 in the south (see Fig. 4).

The mean high water (MThw 91/2000) is 1.79 m above NN at Bremerhaven (km 66.7) and 2.45 m above NN at Oslebshausen (km 8.4). The mean tidal range (MThb 91/2000) varies between 3.74 m at Bremerhaven and 4.11 m at Oslebshausen (data from WSA Bremen).

The Lower Weser is home to the ports in Bremerhaven, Nordenham, Brake and Bremen and the shipyards and also their gate to the world. The river was deepened in the last 20 years to -11 m below chart datum between Bremerhaven and Nordenham and -9 m below chart datum between Nordenham and Bremen (data from WSA Bremerhaven), so that ships with a draught of max. 10.7 m are able to reach the port of Bremen under utilization of the tide. Vessels with a maximum draught of 12.5 m and 60 - 70,000 tdw are able to reach the port of Nordenham, whereas vessels with the destination Brake are limited to a maximum draught of 11 m and 30 - 40,000 tdw.

The channel width on the Lower Weser amounts to 200 m in the section between Bremerhaven and Brake and to 150 m between Brake and Bremen.

5.2. Experimental Results

The results of the measuring campaigns are plotted for a short section of the Lower Weser. The authors have chosen for presentation the section between km 38 and km 30 (see Fig. 5)
for three inbound passages. The bottom of the Weser shows here ripples with an altitude of 1 - 2 m and a wave length of 50 – 100 m. The results are compared with theoretical squat values calculated by the formula of ICORELS (International Commission for the Reception of Large Ships [3]).

\[ S_h = 2.4 \cdot \frac{\nabla}{L_{pp}^2} \cdot \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} \ [m] \]

\( \nabla \): volume of displacement \([m^3]\),

\( L_{pp} \): length of ship between perpendiculares \([m]\) and

\( F_{nh} \): Froude Depth Number \( F_{nh} = \frac{\nabla}{\sqrt{g \cdot h}} \ [-] \).

Fig. 5 Map of the regarded section of the Lower Weser-km 38 – km 30

5.2.1. 1st Measurement With the MV Pioneer

A first test measurement was accomplished on the lower Weser from Weser-km 45 to Weser-km 24 at the end of Oct. 1998 [2]. The observed vessel was the 50,000 t bulk carrier MV Pioneer with a length between perpendiculars of 217.5 m, a ship’s breadth of 23.15 m and a draught in fresh water of 10.7 m. This is as mentioned above the maximal permissible draught for the lower Weser and the necessary water depth can only be obtained during the flood. The escort craft was the launch Alk from the Schulschiffverein Großerzogin Elisabeth (association of the sail training ship ‘Grand Duchess Elisabeth’) in Elsfleth.
Fig. 6 Measured and calculated bow squat of the Pioneer from Weser-km 38 to km 30

Fig. 6 depicts that the curve of the measured squat follows roughly the curve of the speed through water, but with variations that the curve of the calculated squat does not show. Obviously there are some interactions between the squat and the speed without any influence by manoeuvre of the vessel. For example the squat decreases near the mouth of the Hunte river (km 32.2) due to a change in water depth and channel width, so that the speed of the vessel increases by about 0.4 kn. The variations of the ICORELS squat are caused by ripples in this sections. The Pioneer acts in this case as a filter, so that the measured squat does not show this variations.

5.2.2. 2nd Measurement With the Maersk Taian

The second measurement has also been performed on the lower Weser in July 1999. Due to its length of 215 m and its breadth of 32.2 m the Maersk Taian belongs to the category of the PANMAX bulk carrier. The Maersk Taian was accompanied by the general purpose boat Geestemuende of the WSA Bremerhaven from Weser-km 96.9 to Weser-km 10.3.
Fig. 7 Measured and calculated bow squat of the *Maersk Taian* from Weser-km 38 to km 30

Fig. 7 depicts very well the phenomenon that the vessel speed can be influenced by squat. The *Maersk Taian* was cruising at a mean speed of about 10.2 kn. The variations of the speed were not caused by active manoeuvres as the bridge protocol shows. Furthermore, the curve of the ICORELS squat shows an increase of the squat due to the variation of the water depth, whereas the curve of the measured values demonstrates the opposite (for example at km 31.6).

5.2.3. 3rd Measurement With the *Weser Stahl*

Our latest experiment was carried out on the lower Weser on May 1st 2002. For this measurement the bulk carrier *Weser Stahl* was accompanied from Weser-km 66 to the

![Escort craft Marvin](image_url)
port of the steel plants in Bremen at Weser-km 10.3. The *Weser Stahl* is used to transport iron ore in shuttle traffic between the ports of Rotterdam (NL) and Bremen as well between the ports of Narwick (N) and Bremen. The 185 m long and 32.26 m wide *Weser Stahl* was on an inbound journey coming from Rotterdam. On this day the *Weser Stahl* had a displacement of nearly 56,500 t with a fresh water draught of about 10.50 m. The escort craft was the *Marvin* (see Fig. 8), a former surveying boat, which is now in the possession of the Nautical Department of the Oldenburg University of Applied Sciences in Elsfleth.

![Graph](image)

**Fig. 9** Measured and calculated bow squat of the *Weser Stahl* from Weser-km 38 to km 30

The measurement depicted in Fig. 9 shows first of all the effects of unfavourable satellite constellations, because some data are missing within some ranges. The measured and the calculated squat have nearly the same magnitude of value, but they show a different trend. Whereas the formula uses the information about water depth in a direct manner, i.e. the water depth at the position of one point (e.g. LCF), the vessels acts as a filter due to its length and breadth, i.e. the water depth under the whole hull.
The comparison of the three inbound passages on the lower Weser in Fig. 10 demonstrates, that three different vessels observed many months apart with different escort craft show very similar details in the squat behaviour within the same section of a waterway.

The *Pioneer* and the *Maersk Taian* cruised nearly at the same speed in the section of km 34.5 to km 32.3. The mean difference of speed is 0.10 kn and the mean difference of squat is 0.07 m, whereas the maximum difference is 0.20 kn and 0.13 m. Both Vessels have nearly the same length, but the *Pioneer* is smaller and had more draught during the measurement. Even the water level was about 0.4 m lower, i.e. the underkeel clearance (UKC) of the Pioneer was about 0.8 m lower in relation to the *Maersk Taian*. This comparison shows in this case, that the ratio ship breadth to waterway width is more important to the magnitude of the squat than the water depth and / or UKC for constant speed.

The comparison of the *Pioneer* and the *Weser Stahl* shows for the same section a mean speed difference of about 1.56 kn and a mean squat difference of about 0.07 m. The water level of the measurement of the *Weser Stahl* was about 0.87 m higher than the water level for the *Pioneer*. In this case several parameters can be responsible for the higher squat of the *Pioneer*, such as the higher speed, the lower water level and the greater draught. The greater cross section area of the *Weser Stahl* (338 m² compared to 248 m² of the *Pioneer*) does not affect the magnitude of the squat in this manner as the other parameters do.
The *Maersk Taian* and the *Weser Stahl* have nearly the same midship section area of about 332 to 338 m² for a statical draught of 10.3 to 10.5 m, but they cruised at different speeds, displacement and the water depth was about 0.47 m higher in this section for the measurement of the *Weser Stahl*. A comparison of the measured data shows a mean speed difference of about 1.70 kn and a mean squat difference of about 0.11 m within the section of km 37.0 and km 32.2. The different behaviour is caused by a lower water level and a higher speed at the measurement of the *Maersk Taian*.

![Fig. 11 LCF squat of three inbound passages and morphologic data](image)

Fig. 11 shows a tendency how a change in bed level and / or in width affects the squat behaviour of a vessel. Within some sections, such as km 34 – 32.3, it is obvious that the squat is directly affected by bed structures with wave lengths longer than about 700 m (km 33.9 – km 33.2). Whereas the squat is more influenced by a greater width than by the bed level, such as in section km 38 – km 35.5.

Although the width at water level within the section of km 32.0 decreases for a constant bed level, the squat of all vessels is reduced at the mouth of the Hunte. Therefore it can be assumed that not only the relatively small mouth of the Hunte means a lateral width expansion of the Weser, but a part of the tributary.
5.3. Waterway Kiel-Canal

Fig. 12. Overview map of the Kiel-Canal

Additional to the experiments on the lower Weser some investigations were carried out on the Kiel-Canal in the north of Germany (see Fig. 12). Approximately 250 nautical miles are saved by using this waterway instead of the way around Skaw. The 100 km long Kiel-Canal connects the Baltic Sea at Kiel with the North Sea at Brunsbüttel and it is the most frequented artificial waterway in the world. About 38,400 vessels with 62.5 millions of cargo tons passed through the Kiel-canal in 2001 (data from the Canal authority WSD Nord). At both ends of the Canal are locks with an usable length of 310 m and an usable width of 42.2 m. Vessels with a maximum draught of 9.5 m, a maximum length of 160 m and 27 m width, or 193 m length and 20 m width are allowed to use the Kiel-Canal. If the draught does not exceed 7 m, vessels with a maximum length of 235 m and 23.5 m width are able to use this waterway. The permitted maximum speed for vessels varies due to their hull dimensions, for those with more than 8.5 m draught the maximum speed is about 6.5 kn, for all others it is about 8.1 kn.

The 11 m deep Kiel-Canal has a width at water level of 160 m (partly 102.5 m) and a width at the bottom of about 90 m (partly 40 m).

This waterway was chosen because of its advantages like an almost constant water level, no tidal motion, small current, constant waterway dimension over longer distances and smaller cross section areas compared to the lower Weser.
5.4. Experimental Results

Two campaigns were carried out for the same vessel passing the Kiel-Canal in different directions. The results of the campaigns are plotted for a short section of the Kiel-Canal. The measured bow squat is compared with values calculated by the empirical formula of Barrass. The range of validity of this formula is for vessels with a block coefficient from 0.5 to 0.9 on waterways with a water depth/draught ratio from 1.1 to 1.5 [4].

\[ S_b = \frac{c_b \cdot S_2^2 \cdot V_{k}^{2.08}}{30} \text{ [m]} \]

- \( c_b \) : block coefficient
- \( S_2 \) : midship section area
- \( V_k \) : ship’s speed through the water [kn]
- \( \cdot \) : wetted cross-section area of waterway
- \( L_{pp} \) : [ship’s beam/draught]
- \( [-] \) : [-]

The authors have chosen the section between km 80 and km 90 (see Fig. 14) for the presentation of both passages. In this section the Canal has still its old cross section of 90 m at water level and 40 m at the bottom. In the middle of this section is a siding area, which serves as a waiting area for passages of bigger vessels.

5.4.1. 1st Measurement With the Polaris (Eastbound)

The first squat measurement on the Kiel-Canal was a west-east passage of the general purpose carrier Polaris. The Polaris has a length between perpendiculars of 115.23 m and a breadth of 20.2 m. The midship’s draught amounted to 6.3 m on this day, but the Polaris was trimmed by the head to increase the squat effect. The displacement added up to about 10,700 t. This campaign was escorted by the general purpose boat Friedrich Voss of the WSA Kiel – Holtenau.

Fig. 13  Map of the regarded section of the Kiel-Canal (km 90 – km 80)
Calculated and measured bow squat are in good agreement, although the use of this formula exceeds the range of validity because of a water depth/draught-ratio greater than 1.5 in the Canal. The measured bow squat is lower than the calculated one, when the Polaris is lowering her speed while entering the siding area (km 81.5 – km 85.3). The increase of the measured squat is more intense than the calculated one as the Polaris began to accelerate at the end of the siding area.

Fig. 14 Measured and calculated bow squat of the Polaris from Kiel-Canal km 80 to km 90 on a west-east-passage (1st trip)

5.4.2 2nd Measurement With the Polaris (Westbound)

The second measurement on the Kiel-Canal was performed on Dec. 10th/11th 2001. This time the Polaris was escorted on an east-west passage through the canal again by the Friedrich Voss. The midship’s draught was less than previously.
The more interesting range of this section is between Canal-km 86.5 and 84.0. The Canal profile expands from about 100 m to 300 m width at water level. Strong punctual changes of the squat were measured at Canal-km 89.4, within the section of the ferry at Landwehr, at Canal-km 81.5 and at Canal-km 80.3, which cannot be explained simply with the vessel's actual speed.

Within the section of Canal-km 89.4 the squat decreases by about 0.15 m despite an increase of speed. On the basis of morphologic data it is evident that in this section the canal bottom is a little bit deeper.

Before reaching the landing ramp of the ferry at Landwehr the squat decreases with the reduction of the speed and a small expansion of the Canal profile. Then the squat is reduced to almost zero at Canal-km 86.9 despite constant speed and an approximately constant Canal profile. On the position of the landing ramp the squat of the Polaris increases to a value of about 0.25 m. Briefly after passing the ferry the squat drops again on about 0.10 m. The empirical formula computes for this area a reduction of the bow squat according to the speed decrease and to the depth of water.

A satellite image from this section demonstrates the locally limited expansion of the Canal profile near to the landing ramp. Consequently this among other things could be responsible for the decrease of the squat. A further point could be a propulsion induced erosion when the ferries have to push against the landing ramp to keep their position.
Further the satellite image shows that the landing ramp of the southern embankment projects into the canal and this means a cross-section contraction, which could have caused the short term rise of the squat. The squat rises at Canal-km 81.5 more strongly than within the siding area due to the narrower cross section and the route near to the embankment. Within the section of Canal-km 80.3 the squat rises abruptly about 0.30 m. For this section no measured data were available for the height of the canal bottom.

It is only remarkable that on both banks a road ends, an auxiliary transition or NATO ramp. And indeed, exactly here is a NATO ramp, that locally decreases the Canal profile.

6. Further Possibilities

The final goal of this project is to create an efficient method to determine the exact vessel squat as quickly and reliably as possible. For a faster analysis the data flow has to be accelerated efficiently.

According to that it must be analysed which kind of data can be replaced by standardized information and its effect on the accuracy of the result. Most of all it is important to become independent of external sources, such as tide gauges, wind gauges and current gauges.

The following enumeration shows some conceivable possibilities to reduce time for the analysis:

(1) Measuring the water depth with an echo sounder on board
(2) Measuring the currents with a ADCP
(3) Determination of the salinity by an measuring instrument on board

There are still remaining tasks which need to be accomplished as there are comparing standardized values (currents, gradients of tide curves ) with actually measured values and the loss of accuracy using them, creating a database of the waterway (bathymetry, geometry, tidal information) with the possibility of updates and at the end adaptation of the empirical formulae with the measured values, experiments on other waterways like the Elbe.

7. Conclusion

The SHIPS method is a powerful instrument to determine the exact squat of a vessel. The data captured by SHIPS contain all available information for the exact determination. Its efficiency

---

1 Acoustic Doppler Current Profiler
and accuracy were demonstrated in several experiments on German waterways. The authors have compared the results of measured vessel squat with results from empirical squat formulae (ICORELS and Barrass) and have expounded the reasons for differences in the results. For some special conditions these formulae calculate the squat nearly accurately, but in most of the tested waterway sections the measured squat is significantly different. It shows both, the good quality of the experimental data and the limited validity and parameter range of the empirical formulae.

The importance of a well determined vessel squat is obvious, because an over-estimation of squat means that part of a vessel’s loading capacity remains unused with a consequent loss of money. On the other hand under-estimated squat might cause a damage or even the loss of a vessel under unfavourable circumstances. A good measured and analysed squat means optimal freight conditions for the ship’s owner, the safety and ease of shipping and less dredging for the waterway authorities.

8. References


9. The Authors

Dipl.-Ing. Sven Dunker, Prof. Dr. Alexander Härting
FH Oldenburg/Ostfriesland/Wilhelmshaven
Institut für Maritime Studien
An der Kaje 4
26931 Elsfleth
+49 (0)4404 9288 4257/ 4261
Sven.Dunker@els.fh-oldenburg.de, haerting@els.fh-oldenburg.de

Dipl.-Ing. Andreas Gollenstede, Prof. Dr.-Ing. Jörg Reinking
FH Oldenburg/Ostfriesland/Wilhelmshaven
Institut für Mess- und Auswertetechnik
Ofener Str. 16
26121 Oldenburg
+49 (0)441 7708 3324/ 3350
Andreas.Gollenstede@fh-oldenburg.de, reinking@fh-oldenburg.de