SHIPS: A New Method for Efficient Full-Scale Ship Squat Determination

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1 Introduction

Recent full-scale experiments on measuring ship squat are based on differential GPS in kinematic mode where the changes in ellipsoidal height between receivers on the vessel and at shore are observed [1]. In most of these measurements it has been necessary to correct for the change in water level. For this purpose all available tide gauges must be read out and the tide wave must be modelled such that an interpolation in space and time can obtain the water level at the ship. Some authors quote [2] that a precision of about 6 cm can only be achieved if additional tide gauges are deployed for the campaign. Still it must be doubtful whether it is justified to neglect water level topography and wind influence.

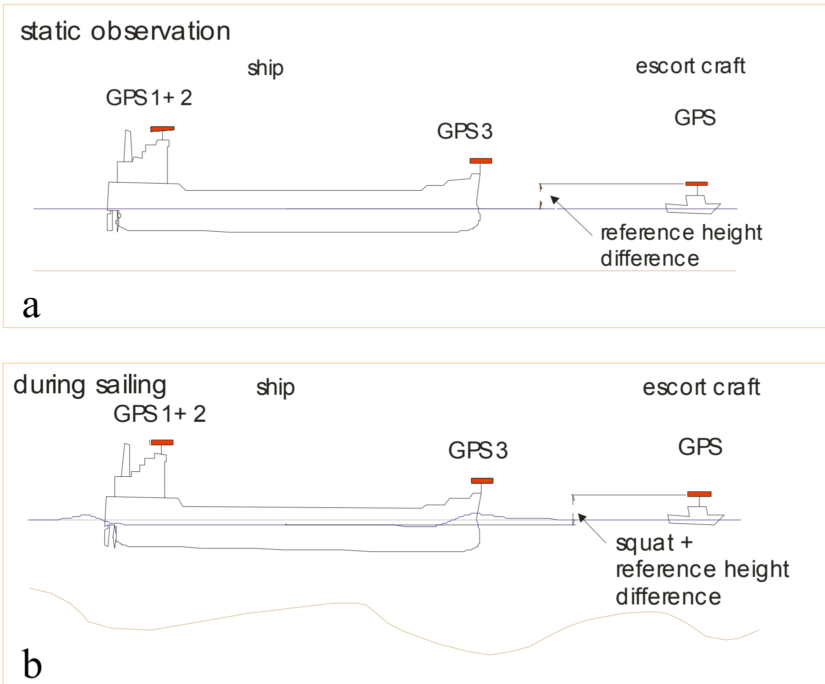
The authors suggest the SHIPS method (SHore Independent Precise Squat observation), in which the disadvantages of the laborious and error-prone use of tide gauges are avoided. Besides this the SHIPS method gives the possibility to observe the squat independently of existing facilities at shore. The concept is also based on GPS and will be explained in this paper in detail. The method has been tested in several experiments on German waterways. The results and experiences of these tests will be presented and discussed.

2 SHIPS method: the principle

The basic idea of the SHIPS method is to represent the water level at the vessel under investigation by a small craft that escorts the ship during the journey instead of using interpolated tide gauge readings (Pic. 1). The concept uses GPS carrier phase observations as the instrument to observe height changes between the vessel for which the squat should be observed and the escort craft. Onboard the ship three high-quality GPS equipments are installed as far apart as possible, however considering a good field of view. On most types of cargo vessels this means that two receivers are set up on the starboard and port sides of the superstructure and one is located on the forecastle. A fourth GPS receiver must be installed on the escort craft. During the experiment the escort craft is travelling 200 – 500 m ahead of the ship and the height differences between the GPS antennas onboard the ship relative to the escort vessel are observed.

The GPS antennas onboard the ship under investigation are connected to the ship's co-ordinate reference frame by standard surveying techniques. For small, quasi-static changes in trim and list it is justified to assume that the rotational axes pass through the longitudinal centre of flotation (LCF), which can be taken from the ship's hydrostatic particulars. From the GPS-derived 3D-co-ordinate differences observed in a local grid system it is then straightforward to compute the height change of a reference point (the LCF) together with roll and pitch angles. To address questions of under-keel-clearance, one is usually interested in the particular point for which the draft increase is greatest. Depending on the shape of the hull and the corresponding trim tendency [3], this point is frequently near the forward perpendicular, the result then being called “bow squat”.

The static height differences between LCF and the GPS antenna onboard the escort craft observed without motion of either vessel - which may be done in a harbour – is used to fix the zero point on the squat scale. Reducing the differences observed during the movements of the vessels by this static height difference gives the values of the draught increase for each observed epoch. Assuming that the escort craft correctly describes the unperturbed water level at the ship, uncertainties and changes of water level during the experiment are thus eliminated.



Pic. 1: Basic concept of the SHIPS method: draught increase is observed between an escort vessel and a ship by height differences derived from GPS carrier phase observation. While observations in a static position gives the reference height difference (a), the draught increase results from the observed height differences during sailing of both vessels reduced by the reference height difference (b).

3 Behaviour of the escort craft

The resulting height differences are strongly influenced by the behaviour of the escort craft. For various reasons the GPS antenna onboard the escort craft does not remain at exactly constant height above the unperturbed water level. Although these height changes are usually small, their knowledge is crucial to obtain accurate ship squat from raw height difference observations.

The height change in dependence of the cruising speed can be observed in a separate calibration experiment. For simplicity we shall call this height change “squat” of the boat, even though, for a small gliding boat, it could also be a height increase and the value is also influenced by systematic pitch and roll depending on the position of the (single) antenna. For calibration purposes the information is sufficient as long as the GPS antenna is mounted at the same position when the boat operates as an escort vessel. With these prerequisites measuring the squat of a small boat with GPS is straightforward. Preferably at high or low tide the boat is operated at various speeds in the vicinity of a shore station and engine stop manoeuvres are carried out several times. Since, on a small boat, this manoeuvre takes only a few seconds, the squat effect can be seen directly from the change in antenna height. If sufficient data are taken, the squat of the boat can be described as a function of speed-through-water by an approximation function. Note that, for the small boat, the waterway can be considered as unrestricted and the calibration function therefore depends on nothing but the speed-through-water.

Whereas the calibration function can correct for the boat squat, during the squat experiment there will also be non-stationary vertical motions by waves and swell. This wave induced heave must be eliminated to avoid misinterpretation of the ship squat. One possibility to derive wave induced heave is to use a heave-roll-pitch sensor, that measures the height change by the use of accelerometers and observations of the rate of rotation. Unfortunately these sensors show a systematic drift over longer time periods so the results must be filtered using digital high-pass filters. An alternative independent observation of heave would be desirable to verify the filtered data. For this purpose the GPS receiver onboard the boat could be used, although no reference station at shore is available and the absolute height of the GPS antenna is unknown. The wave induced height change can be derived from cumulated and filtered epoch-by-epoch GPS phase differences [4].

4 Data quality and additional corrections

After applying the corrections described in chapter 3 for the behaviour of the escort craft, some additional small corrections must be taken into account.

The water density in estuary systems often changes because of tidal change of salinity and temperature. Therefore these parameters should be observed during the experiment. Data from existing observatories like gauges could be compared for this purpose with samples taken form the escort craft. Commonly the correction values for the escort craft are small enough to be neglected but for the ship under investigation they must be considered.

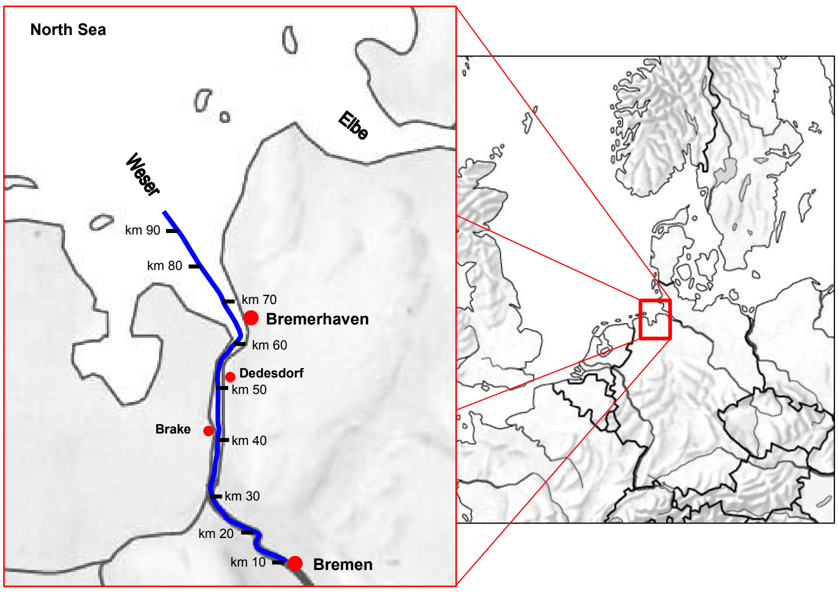
Although small, the water surface gradient between the escort craft and the ship must be regarded. If the distance between the two vessels can be kept small (300-400 m), depending on the tide, the height difference between the water level at both vessels seldom exceeds 1 cm. Such a small correction can probably be derived from the average tide wave with sufficient accuracy. Evaluating the hitherto performed test measurements we have, however, also used interpolated readings from existing tide gauges.

To analyse the velocity dependence of squat, the speed-through-water is the relevant parameter. What is obtained from GPS observations with good accuracy is, however, the speed-over-ground. Thus far, we used calibration values derived from some 180° turns of the escort boat with constant r.p.m. of the engine together with the tidal current profile taken from the pilot book for interpolation of current values to correct the GPS-derived speed-over-ground. It would be desirable to obtain independent measurements of the current conditions, at least by an accurate speed log on the boat. Further investigations have to be carried out depending on available equipment.

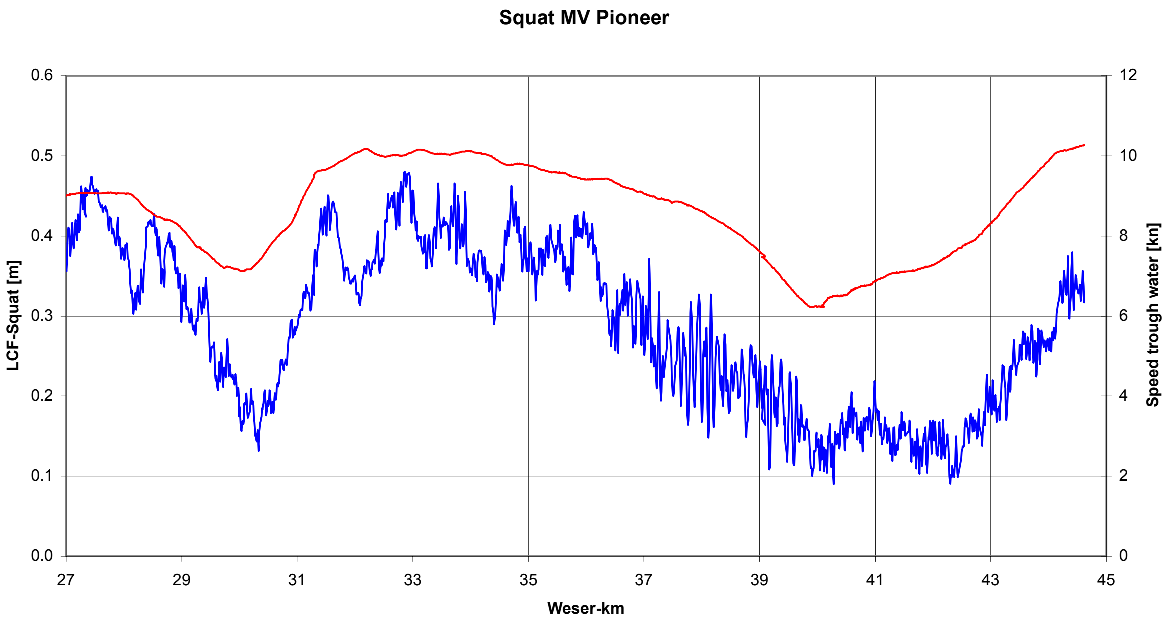
The method presented in this paper does not rely on GPS receivers in RTK mode, because stored raw phase data allow to check for outliers and data quality and to correct for different effects. In addition, wave induced heave data could only be correctly calculated from GPS in post-processing mode. The sampling rate of the data should be high but depends on the memory capacity of the receivers. Commonly we choose a sampling interval of one second. When the idea for the SHIPS method first came up, there was no commercial GPS post-processing software available, which had the option to process GPS carrier phase data using a moving reference station. Therefore we developed our own software package, which uses the moving GPS receiver of the escort craft as a reference station. Due to the short baseline between the receivers onboard the ship and the moving reference receiver, the influence of tropospheric effects is strongly reduced. Ionospheric effects are mostly eliminated using two-frequencies receivers. Tests have shown that the quality of the derived height differences using this software package is approximately 1 cm. Taking into account all error sources, the expected accuracy of the resulting squat will be better than 3-4 cm.

5 Test results

Several experiments were carried out to check the practicability of the SHIPS method and the quality of resulting squat data. The first test of the proposed method has been done on Oct.30 and Nov.1, 1998 on the lower Weser river between Bremerhaven and Bremen [5]. The investigated vessel was the "MV Pioneer", a 50.000 t bulk carrier of 10,7 m fresh water draught – which is the max. draught allowed for the lower Weser river up to Bremen - with a cargo of ore for the Bremen steel works. Escort craft was the 12m-launch "Alk" of the "Schulschiffverein Großherzogin Elisabeth". The boarding party carrying all equipment entered the “Pioneer” at Geestemünde (Bremerhaven) when pilots were changed on the inbound journey. After installing all receivers observations were done between Weser-km 45 (Dedesdorf) and 10 (Bremen steel works) (Pic. 2). Due to technical problems on the escort craft nominal data taking could only be achieved up to Weser-km 24. Pic. 3 shows the resulting squat for the section between km 45 and km 27. The squat is obviously depending on the speed-trough-water, as expected, but also some other effects can clearly be identified. Between Weser-km 41 and 37 the bottom of the river shows ripples with an amplitude of 1-2 m and a wave length of 50-100 m. In connection with this phenomenon the squat in this section shows a variation of 10-15 cm. On the other hand there are some squat variations between km 35 and 31 that cannot be explained by a simple relation between squat, speed and depth. In this section a negative correlation between small speed changes and squat changes can be found. The question was whether this effect did really exist or whether it was induced by observation errors inherent to the method.

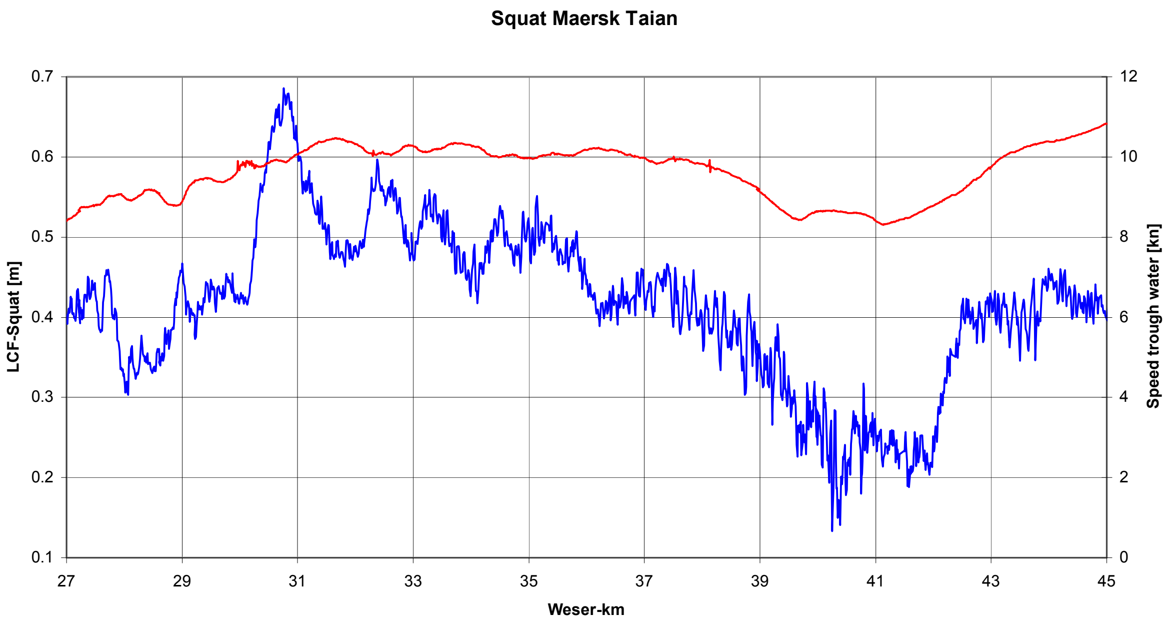


Pic. 2: Map of lower Weser river



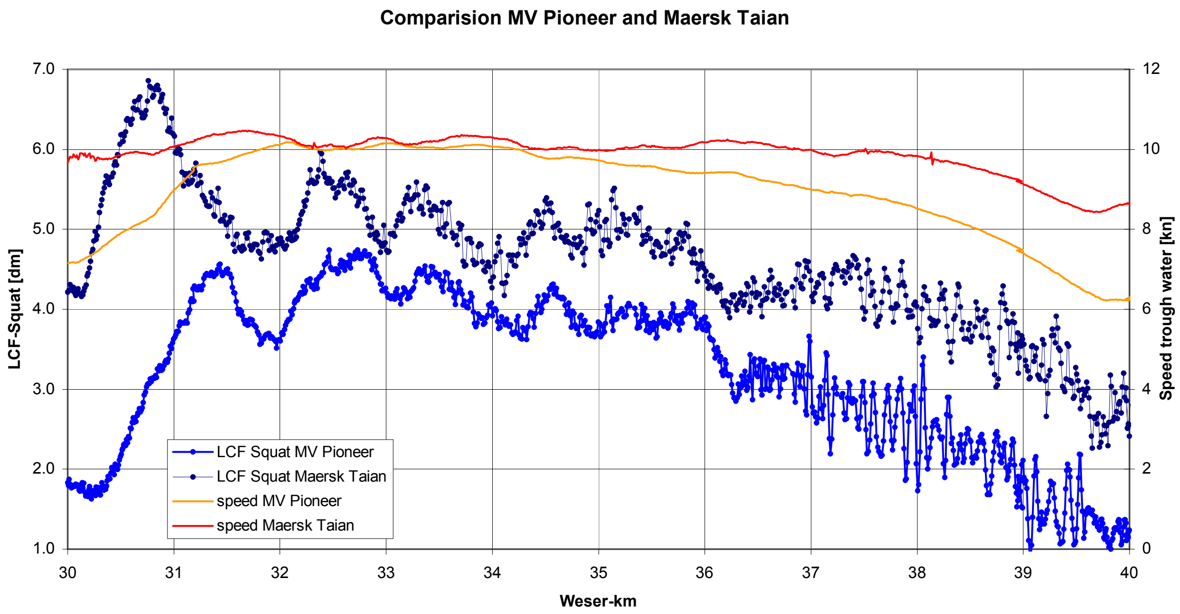
Pic. 3: Squat results (blue) and speed (red) of first experiment with MV Pioneer

A second experiment was carried out on July, 14th 1999 on the lower Weser river again. The ship under investigation was the PANAMAX bulk carrier "Maersk Taian" on the inbound journey to Bremen steel works with a draught of 10,3 m. The staff and equipment were able to board at the Weser pilot position and observations were done between Weser-km 96,9 and 10,3. Escort craft was the "Geestemünde", a general purpose boat of the shipping authorities at Bremerhaven.



<Pic. 4: Squat results (blue) and speed (red) of the experiment with Maersk Taian

Plotting the results of this experiment for the same section as for the MV Pioneer test (Pic. 4), again the dependence of squat of the speed can be seen. Also the influence of the rippled Weser bottom between Weser-km 41 and 37 can be found. And again, this independent test with completely different parameters (weather, escort craft etc.) shows a negative correlation of squat and speed between Weser-km 31 and 35. A detailed direct comparison between the results of these test is shown in Pic. 5.



Pic. 5: Comparison of the results of first two experiments

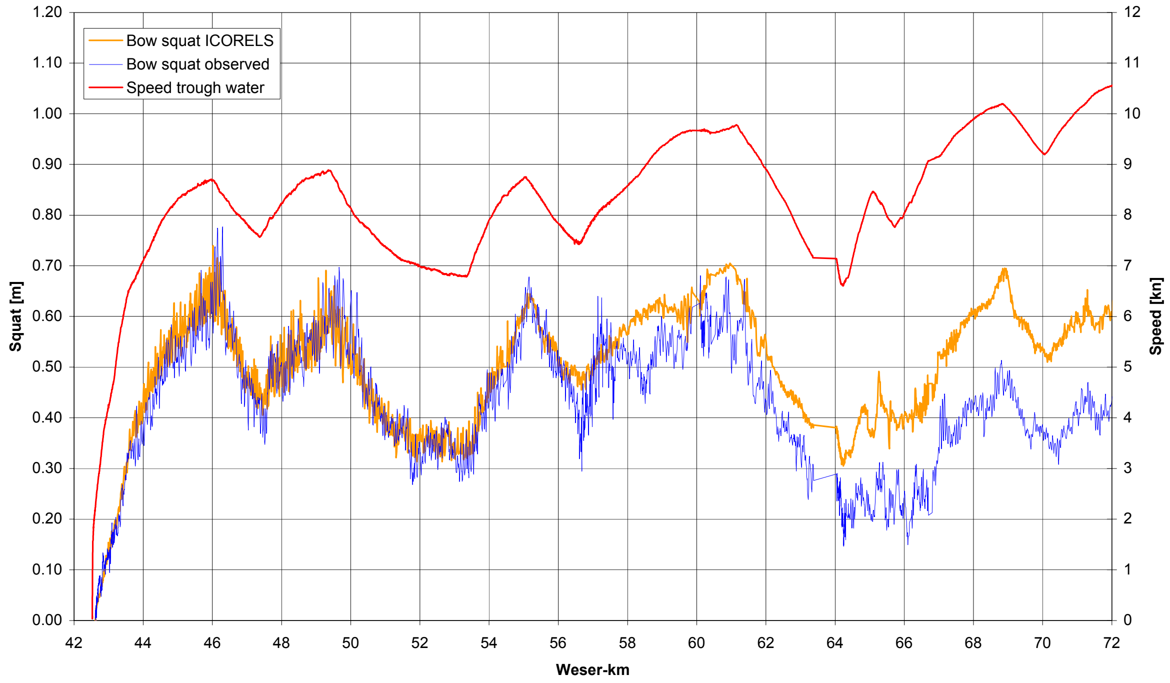
The speed of both vessels show a similar characteristic behaviour between Weser-km 36 and 31,5. Both squat data also show the same negative correlation with the small speed changes at the same position. Although this behaviour is not yet cleared up in detail, the comparison of the two independent data sets demonstrates the impressive quality of the data derived from the SHIPS method. Apparently the expected accuracy of better than 3-4 cm is achievable using the new concept and regarding all necessary corrections.

A third experiment was carried out on Dec. 22nd 2000 again on the lower Weser river. The Sanko Summit, a bulk carrier with a length of 190 m and a beam of 32,2 m, left the port of Brake (km 40) on an outbound journey with a fresh water draught of 11,3 m. The escort craft – again the "Geestemünde" - accompanied the Sanko Summit up to the port of Bremerhaven (km 72). Pic. 6 shows the resulting bow squat and the speed trough water. In addition, we plotted the bow squat calculated from ICORELS [3] approximation function:

$$s_b = 2.4 \cdot \frac{\nabla}{L_{pp}^2} \cdot \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} \cdot K_s$$

Depth and channel width were taken from official hydrographic information. Between Weser-km 42 and 56 the ICORELS-squat fits the observed squat with a sufficient quality, the rms derived from the differences between these values is 4,3 cm. Taking into account that ICORELS is not able to describe the whole squat behaviour of a ship exactly due to the approximative character of the formula, and regarding that the observed squat also includes small scale effects we can state that at first, the accuracy of the observed squat is obviously as good as expected and , second, ICORELS formula as used in the mentioned form is an adequate fit of the reality for these set of parameters (ship, tide, channel structure etc.). From

Weser-km 56 up to km 72 the width of the channel continuously increases up to values which could not be covered by the correction factor K_s. For this part of the river an adjustment of the conservative factor of 2,4 will lead to a better fit.



Pic. 6: Squat results (blue) and speed (red) of the experiment with Sanko Summit. Squat calculated from ICORELS formula is plotted in orange.

6 Further possibilities

During all of our first test campaigns some makeshift improvisations have been necessary. For efficient measurements in the future the logistic preparations, the use of equipment and the data flow must be optimised. The excellent quality of data shows that there is much more information than could be presented in section 5. Analysis must be carried further towards an understanding of all significant parameters.

Once the proposed method will be established, full scale measurements of the squat effect can be done with much smaller effort than before. From a larger series of measurements, apart from the individual results, the following substantial questions may be addressed:

- Is it possible to extract, for a particular ship and river, a prediction of the squat effect depending on speed, position and state of the tide? How accurate is such a prediction? Ideally, the experimental results should be presented in a form that can be used similar to manoeuvreing tables.
- Is it possible to "calibrate" existing empirical formulae for a particular ship based on the individual measurements?
- Is it possible to generalise the observed systematic behaviour and perhaps reach a product that can replace existing empirical formulae? Such a product should be tailored for a standard personal computer and partly rely on analytical expressions, while partly using a suitable interpolation technique accessing a data base with experimental results.

A sufficient number of high-quality experimental data allows to investigate whether there is a dynamic effect in the squat behaviour of a ship, i.e. a dependence on the fluctuation of parameters. To learn about such a behaviour would be important because such fluctuations are typical for a realistic situation, whereas all theoretical approaches assume stationary conditions.

7 References

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