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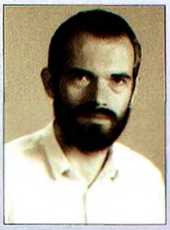

Ship Squat in Hydrography – a Study of the Surveying Vessel *Deneb*

By Alexander Härting, Jörg Reinking, FH Oldenburg/Ostfriesland/Wilhelmshaven, Oldenburg/ Elsfleth, Wilfried Ellmer, Bundesamt für Seeschifffahrt und Hydrographie, Hamburg/ Rostock, Germany

Abstract

In hydrographic observations where the water level is used as a reference plane the knowledge of the surveying vessel's draft is essential. The draft changes dynamically due to the squat effect. A new method called SHIPS was developed for squat estimation of commercial ships and was tested in several experiments on German waterways.

In this paper we present an experiment where SHIPS is used to estimate the squat of the German Federal Maritime and Hydrographic Agency's (BSH) surveying vessel Deneb. The analysis of data results in a description of the squat with an accuracy of 2cm.

Résumé

Dans les observations hydrographiques où le niveau de l'eau sert de plan de référence, la connaissance du tirant d'eau du bâtiment hydrographique est essentielle. Le tirant d'eau change, du point de vue dynamique, en raison de l'effet d'accroupissement. Une nouvelle méthode appelée SHIPS élaborée pour l'estimation de l'accroupissement des navires commerciaux a été testée lors de plusieurs expériences dans les eaux allemandes.

Dans cet article nous présentons une expérience dans laquelle le système SHIPS est utilisé pour estimer l'accroupissement du bâtiment hydrographique Deneb de l'Agence maritime et hydrographique fédérale allemande. L'analyse des données aboutit à la description de l'accroupissement avec une précision de 2cm.

Resumen

En las observaciones hidrográficas en las que se utiliza el nivel del agua como plano de referencia, el conocimiento del calado de un buque hidrográfico es esencial. Los cambios de calado varían dinámicamente debido al efecto de asentamiento. Se ha desarrollado un nuevo método denominado SHIPS, para la estimación de asentamiento de los buques comerciales y ha sido probado en varios experimentos en las vías navegables alemanas.

En este artículo presentamos un experimento donde se usa SHIPS para estimar el asentamiento del buque hidrográfico Deneb de la Agencia Federal Marítima e Hidrográfica Alemana (BSH). El análisis de los datos da como resultado una descripción del asentamiento con una precisión de 2cm.

Background

As a ship moves through the water she creates a system of stream lines around her hull which in turn, according to Bernoulli's equation, changes the distribution of pressure. This simple picture is enough to understand how, in principle, the bow and stern waves and the trough alongside a moving ship are generated. The change of draft and trim of a moving ship with respect to the unperturbed water level is called ship squat.
As the cross section available for the stream lines is reduced in shallow water and narrow channels, the water alongside the ship is accelerated more intensely and the squat effect is more pronounced. Awareness of squat in the shipping community has been aroused in recent decades as more and more large sized ships use restricted waterways to their limits. It is not uncommon in these cases to allow for a squat effect of more than one metre.
Essentially the amount of squat depends on speed-through-water, size and shape of the ship's hull and the cross section of the waterway. Detailed numerical calculations are computationally very intensive and yield a result only for one particular stationary situation at a time. A rather successful analytical approach has been made by Tuck (Tuck E.O.,1966). Yet, for practical purposes, it is customary to use empirical formulae (see e.g. PIANC-IPAH, 1997) that have been developed in the 1970' s from the few experimental data available then. Some of these formulae are only valid for restricted ranges of parameters and in cases where comparisons are possible, results differ substantially.
Since the advent of high-precision satellite navigation the direct measurement of squat has become more promising. In this paper we make use of the SHIPS (SHore Independent Precise Squat observation) method first introduced in 1998 (Härting A.et al, 1999) and improved since (Dunker S. et al, 2002). The principle of the SHIPS method is illustrated in Figure 1.
Three GPS-receivers are operated on the ship such that, apart from the overall vertical movement which will be described by the height change of the Longitudinal Centre of Flotation (LCF), changes in trim and list can also be observed. Another GPS-receiver is installed on a small escort craft travelling ahead, outside the ship's wave system. The purpose of the escort craft is to represent the unperturbed water level at the measurement position. The receiver on the escort craft is used as a mobile reference station and the DGPS solutions for the receivers on the ship is computed directly with respect to the escort craft. Thus, with the SHIPS method, the squat is determined independently of tide gauges and shore-based reference stations assuring a good quality DGPS-solution by a short baseline between receivers, even if the experiment is run over large distances.

Squat of Research and Surveying Vessels

For general shipping the interest in squat is naturally focussed on navigation in shallow waters. However, though less pronounced, squat also exists in unrestricted waters. For any vessel taking measurements based on the local water level it is therefore necessary to account for squat. This situation occurs for example on a surveying ship operating her echo sounders in an environment where only water dependent height information is available.

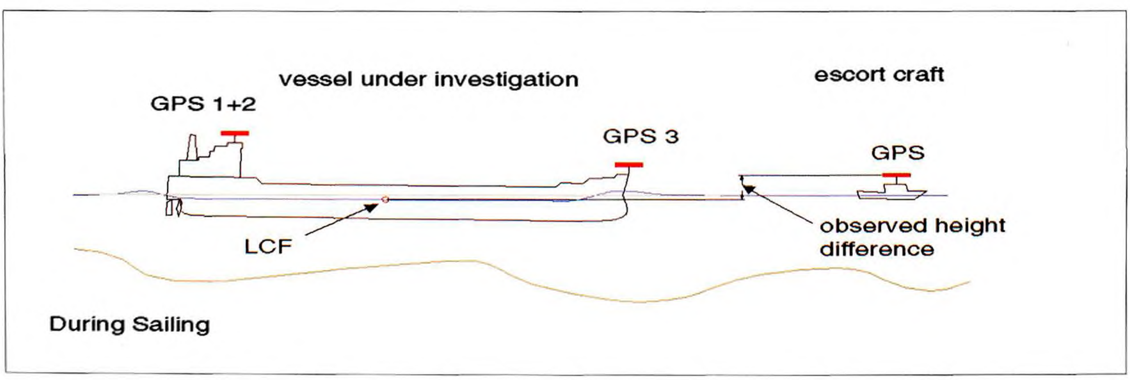

Figure 1: Principle of SHIPS method.

Figure 2: Deneb with GPS antenna positions and escort craft.

On the German Federal Maritime and Hydrographic Agency's (BSH) surveying vessel *Deneb* it was observed by Pohlmann (Pohlmann, 2002) that a non-negligible amount of squat occurs during normal sounding operations. To establish the depth dependence of squat for the *Deneb*, which is assigned to the shallow coastal region of the Baltic Sea, it was therefore decided to carry out a dedicated experiment.

Investigations on the Surveying Vessel *Deneb*

Vessels and Equipment

The *Deneb* is a surveying and research ship that is also used for searching wrecks. Her length, beam and draft are 52m, 11.4m and 3.4m respectively, maximum speed is about 11 knots. To assure good satellite visibility the positions for the GPS-receivers must be selected with care. This turned out to be more difficult on a research ship than on a freighter. One antenna was installed on the top of the foremast, another on the top of a crane shaft on the port side of the superstructure and the third on another crane at the starboard aft end of the working deck. The post-processing of GPS-data revealed that the positions were fortunately chosen.

As an escort craft, one of *Deneb*'s own surveying launches was used. The boat has a length of about 8m, a beam of about 2.5m and a draft of only about 0.7m. It is propelled by an inboard diesel engine with water jet drive and reaches a speed far higher than that of the *Deneb*. Part of the boat's standard equipment is a high-precision GPS whose centrally positioned antenna was used in the experiment.

Location

The experiment was carried out on 14 April 2003 in coastal waters, a few miles east of the entrance channel to the port of Warnemünde. There, the depth of the seabed increases slowly and monotonically with isobaths almost parallel to the shoreline. Since there are uncharted boulders the minimum underkeel clearance kept for safety reasons during the experiment was about 4m.

There was a north-easterly wind of force 3-4 at the beginning, rising to about force 6 towards the end of the experiment. The resulting short-crested wind waves varied from about 0.3 to about 0.6m. Under these conditions the escort craft could still be operated without being adversely affected by roll or pitch motion.

Calibration of the Escort Craft

For the escort craft to represent the unperturbed water level its own 'squat' must be taken into account. It is surely justified to assume that, for such a small boat, any water in which the *Deneb* can operate is unrestricted. Therefore, the ' squat' of the escort craft will be regarded as depending on speed only. To determine this speed dependence, a calibration experiment was done in Warnemünde harbour near the berthed *Deneb*.

Speed in this paper generally refers to speed-through-water as this is the significant influence parameter for squat. The experiment was done in an area with negligible current. This was corroborated by comparing the GPS-speed of opposite tracks travelled with the same engine setting.

The boat was driven at various speeds, stopping (and turning) in between. Since the manoeuvres of the small boat require only a few seconds, the height differences between stationary speed and

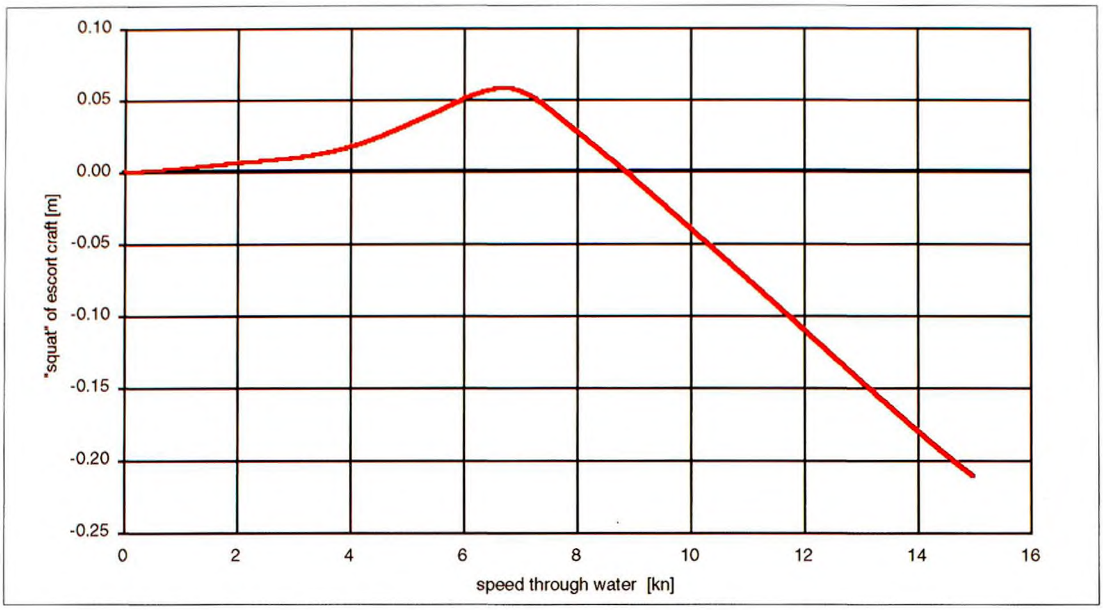

Figure 3: 'Squat' of the escort craft.

drifting can be assigned to the 'squat' at that speed. Results of the calibration are shown in Figure 3.

It can be seen that the boat reaches a maximum squat of 6cm at a speed of about 7 knots. At higher speeds the effect is reversed indicating that a dynamic lift is developing, which is dominating above 9 knots. At the highest speed (about 15 knots) the boat is in planing mode with the antenna more than 20cm higher than in static conditions.

The continuous curve in Figure 3 is determined by thin-plate-spline fitting, according to Harder et al (Harder R.L. et al, 1972). For the evaluation of the *Deneb* experiment, when the boat operates as the escort craft, the curve is entered with the respective speed values to extract the necessary height correction.

Wave Induced Vertical Motion of the Escort Craft and the *Deneb*

Besides the speed-dependent height variation the escort craft's GPS antenna height is also influenced by a wave induced vertical movement. As described above the wave heights varied during the experiment outside of the harbour between 0.3 and 0.6m which is more than the maximum height change due to speed variation. Therefore an additional correction for the wave induced vertical movement had to be applied.

The wave induced vertical movement is a result of roll and pitch as well as heave of the boat. In the presented experiment the roll amplitude of less than 5 deg caused a contribution to the vertical motion of less than 5mm. The full vertical motion is interpreted as heave with negligible error.

The wave induced height variations in hydrographical measurements are frequently corrected for by using heave-roll-pitch sensors. However, such a sensor was not installed on the escort craft but height variations can also be determined using precise on-board GPS-receivers (Reinking J et al, 2002).

The height changes between successive epochs are computed by epoch-to-epoch GPS phase differences. This is easily done under the assumption that atmospheric effects can be neglected if the time difference between the epochs is short. The vertical movement can be calculated by accumulating the height changes but unfortunately the neglected atmospheric effects are leading to artificial long-term variations. Tests have shown that the application of a 6th order high-pass Butterworth filter with 20 s cut off period reduces or eliminates these long-term variations without spoiling the information about the vertical movement induced by short-period waves. In this experiment the dominant wave period was about 4 s. The result is a high quality wave correction that fits exactly to GPS observation epochs and positions.

Although the vertical movement of the *Deneb* is

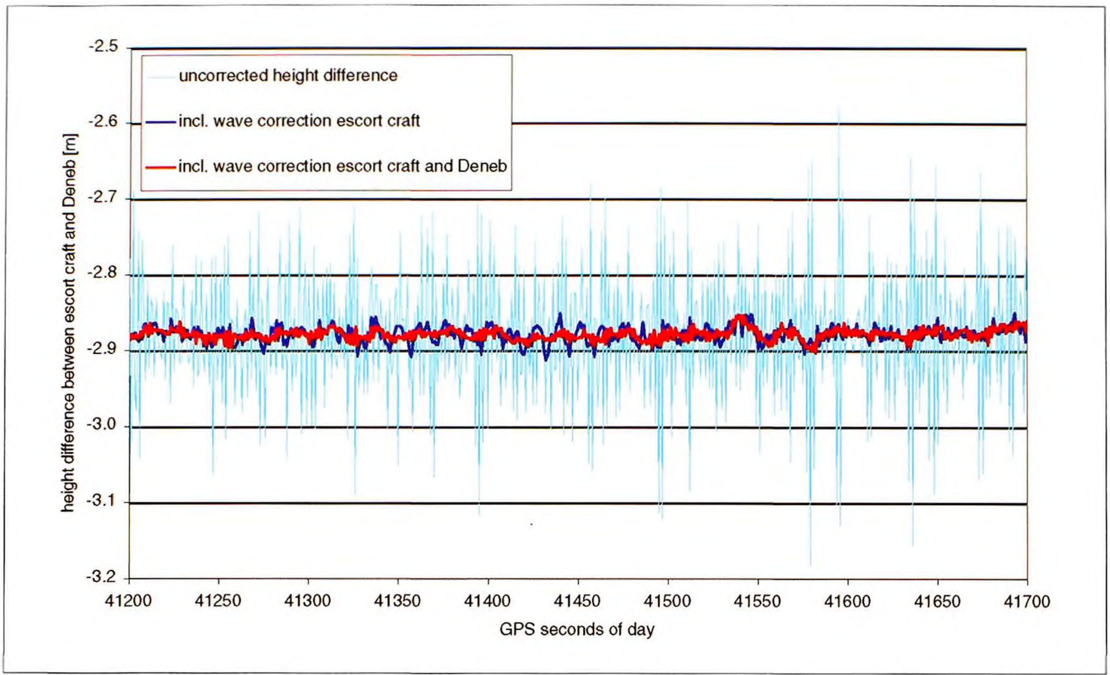

Figure 4: Height differences between escort craft and Deneb.

much smaller than that of the escort craft, a similar GPS derived wave correction must also be applied to all observations of the GPS receivers onboard the *Deneb*. Figure 4 shows an example of the uncorrected as well as the corrected height differences between the escort craft and the *Deneb*. It is obvious that further analysis of the squat behaviour should reasonably be done using the data adjusted by the wave correction of both vessels.

Squat of the *Deneb*

Squat is mainly dependent on the speed through water and the under-keel clearance of the ship with respect to the water depth. Lateral restrictions that have to be considered for merchant ships sailing in confined waterways could be neglected because the *Deneb* commonly operates in laterally unrestricted waters. Therefore four different tracks were selected to observe the squat of the *Deneb* in variation of both parameters to cover the operational range of speed and depth. Two of the tracks were designed parallel to the shoreline and two more were selected perpendicular to the coast.

Since the isobaths are almost parallel to the shoreline the parallel tracks show almost constant depths below transducer of approx. 4 and 8m. These lines were sailed several times while the speed-through-water was increased from the lowest possible speed for safe manoeuvrability (approx. 2-3kn) up to the maximum speed of the *Deneb* (approx. 10kn). The lines that were designed perpendicular to the coast were sailed with constant speeds of approx. 6,5 and 9,5 knots because the seafloor shows a uniform decrease the depth varies between approx. 4 and 15m during these passages. Due to the weather and wave conditions it was not possible to sail out to the area with greater depth with lower speed.

The GPS raw data were computed with a self developed 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-frequency receivers. Tests have shown that the quality of the derived height differences using this software package is approximately 1cm. Taking into account all corrections described above, the expected accuracy of the resulting squat will be better than 2-3cm.

In total approximately 7,500 observations were analysed. The resulting squat is presented in Figure 5 plotted as red dots over depth (below transducer) and speed. The squat shows the highest peaks at maximal speed and minimal depth and reaches values of about 32cm. At higher depths and high speeds, the squat decreases to 10cm. The data shows a strongly pronounced quadratic dependence on speed, which is expected from Bernoulli's equation as well as from most empirical formulae. The dependence on depth can roughly be described as linear but for this ship and its specific hull form there is also a small significant quadratic contribution that should not be neglected.

The data were therefore fitted by a bi-quadratic surface function using least squares estimation. The resulting surface is plotted as a grey mesh in Figure 5. The residuals of the original squat data are plotted in the histogram of Figure 6. More than 95% of all residuals lie between –4 and +4 cm leading to a standard deviation of 2,0cm. This fits very well to the proposed quality.

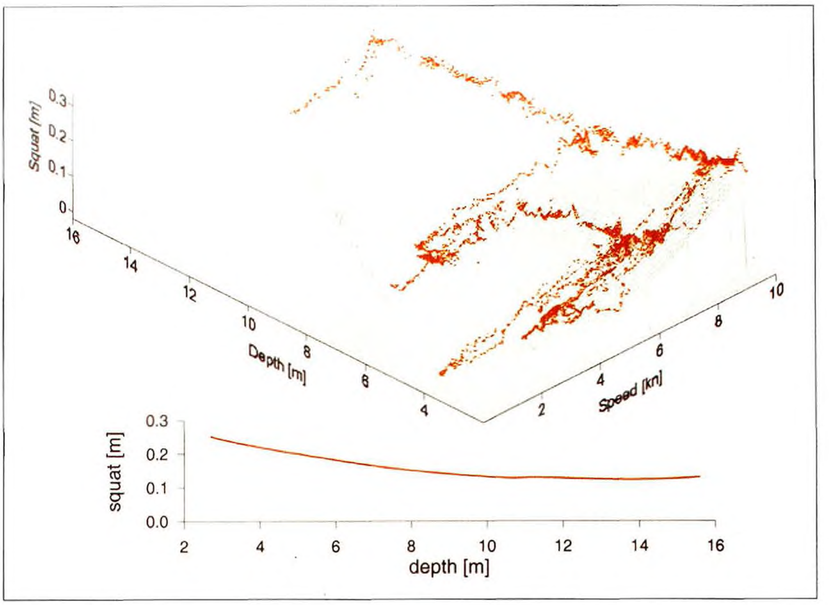

Figure 5: Original squat data (red dots) with estimated surface function (grey mesh) and cross section of the mesh at constant speed of 9kn.

The resulting quadratic surface can be used to interpolate the squat of the *Deneb* within the limits of depth and speed values of the experiment. Obviously extrapolation should be avoided. In the case of *Deneb*, a correction table is calculated that is used by the hydrographic software package to compute squat-corrected depth observations from echo soundings. For observations taken at lower speeds in deeper waters (see missing data in left corner of Figure 5) the correction is set to zero without decreasing the accuracy.

Although the results show a high accuracy level, the data distribution in the speed-depth-plane is not fully satisfying because the data is poor for greater depth and lower speeds. It is therefore recommended for future squat estimations to observe especially in deeper water also on lower speed levels to avoid an error-prone extrapolation of data.

Summary and Consequences

A new method of squat observation called SHIPS was used to estimate the squat behaviour of the German federal hydrographic agency's (BSH) surveying vessel *Deneb* in an experiment in the Baltic Sea. Using GPS onboard the *Deneb* and an escort craft the squat was observed without the use of tide gauges or shore-based GPS reference stations. The data were taken so that the operational range of speed and depth of the *Deneb* is widely covered. The computation of GPS data was done using a self developed software package. The resulting height differences between the escort craft and the longitudinal centre of floatation are corrected by the squat of the escort craft and the wave induced vertical movement.

The squat data could be described by a simple bi-quadratic function where the squat is quadratically dependent on speed and depth. This description has an overall standard deviation of 2,0cm and can be used to correct echo soundings in the future. This accuracy underlines that the SHIPS method is a powerful instrument to determine the exact squat of a vessel.

Acknowledgements

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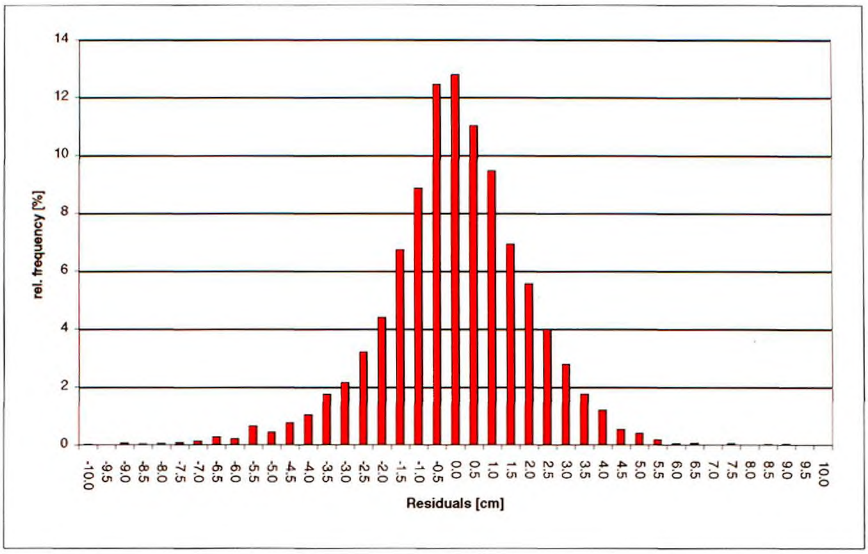

Figure 6: Histogram of the residuals.

iments of Ship Squat). Our special thanks are due to the captain, officers and crew of *Deneb* for their perfect support of the experiment.

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Biographies

Prof. Dr Alexander Härting is teaching Navigation and Physics at the University of Applied Sciences Oldenburg/Ostfriesland/Wilhelmshaven, Department of Marine Studies in Elsfleth. His main tasks in research are GPS-based squat determination, attitude determination with GPS and inertial sensors as well as the application of hydroacoustic sensors.

Prof. Dr Jörg Reinking is teaching Surveying and Geodesy at the University of Applied Sciences Oldenburg/Ostfriesland/Wilhelmshaven, Department of Building and Civil Engineering and Geoinformation in Oldenburg. His main tasks are GPS-based squat determination, attitude determination with stand-alone-GPS-receivers, and the use of low-cost-GPS receivers for the estimation of dynamic parameters in rowing.

Dr Wilfried Ellmer is head of the section Marine Geodesy, Automation, and Bathymetry at the German Federal Maritime and Hydrographic Agency, where he has been working since 1990. The focus of his work is on procedures and equipment of hydrographic surveying, quality management, and reference systems. Before 1990, he worked on satellite geodesy and plate tectonics at the German Geodetic Research Institute in Munich.

E-mail: hearting@fh-oldenburg.de