HydrOs – An Integrated Hydrographic Positioning System for Surveying Vessels

Annette SCHEIDER, Harry WIRTH, Marc BREITENFELD and Volker SCHWIEGER, Germany

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SUMMARY

Generally, multibeam echo sounders are used for the acquisition of geospatial data such as shape and depth of inland waterways. For safety and ease of navigation these data need to be georeferenced and plotted in accurate and reliable sea charts and maps. Therefore, the positioning of the echo sounder and of the surveying vessel respectively is essential.
Currently, positions of surveying vessels on German federal waterways are determined with GNSS (Global Navigation Satellite Systems) receivers. The project HydrOs (Integrated Hydrographic Positioning System) focuses on the improved estimation of three-dimensional position and the spatial orientation of the vessel in areas with poor GNSS reception. For this purpose the motion of the vessel is predicted by a motion model. In contrast to other prediction models for vessel motion, a three dimensional prediction is realized.
The predicted quantities and measurements from an established multi-sensor system are processed in an Extended Kalman Filter (EKF). Before observations are integrated, their availability and reliability must be checked, especially for GNSS measurements. Therefore, algorithms which detect outliers in the GNSS observations are developed. Other absolute positioning sensors and hydrodynamic models can be added to stabilize the accuracy and integrity of positioning.
The integration of water level from hydrodynamic numerical models as a pseudo-measurement is only possible, if the ship squat is precisely known. In the project a special method to estimate the squat effect of the vessel "Mercator" is developed. Hence, a vessel-specific 3D characteristic model for the squat depending on the under keel clearance and the velocity of the vessel can be estimated.
The final HydrOs system will be able to provide a highly reliable and accurate position of surveying vessels in post-processing and in real-time mode hardly affected by the loss of GNSS signals.

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1. INTRODUCTION

For shipping it is important to know the current position and the water depth and under keel clearance respectively. This knowledge is essential for shipping to plan economically the transportation of goods and also to consider safety aspects. To provide precise water depth to ships, the sea bed or river bed must be surveyed periodically. The German Waterways and Shipping Administration conduct the measurements with specially equipped surveying vessels (WIRTH & BRÜGGEMANN, 2011). Generally, multibeam echo sounders are used for the acquisition of geospatial data such as shape and depth of inland waterways. These data need to be georeferenced and plotted in accurate and reliable charts. Therefore, the positioning of the surveying vessel and the echo sounder transducer respectively is essential. The particular positions must achieve a certain level of availability and accuracy to offer reliable information and maps.
Currently, the positions of surveying vessels on German inland waterways are determined by Global Navigation Satellite Systems (GNSS). Each surveying vessel is equipped at least with one GNSS antenna. Real-time kinematic (RTK) solutions are determined by using a CORS (Continuously Operating Reference Station) network service like **SA*POS*®**. Positioning accuracy of few decimeters or even better can be achieved in areas without any shadowing obstacles. Problems occur in regions with obstacles which interrupt the line of sight between GNSS antenna and satellites. In those cases, the present position is calculated under a bad satellite configuration or positioning is even not possible. To fill the gap between reliably determined positions, it is necessary either to measure the position of the vessel by a total station or to interpolate the position in post-processing mode. Because both methods are personnel- and cost-intensive, an automatic method to get an uninterrupted trajectory is demanded. A convenient additional sensor to improve positioning is an Inertial Measurement Unit (IMU).
Therefore HENTSCHINSKI & WIRTH (2012) investigated the abilities of GNSS-INS coupled systems. Their conclusion is that these commercial products already improve the accuracy of positions, but the required positioning accuracy of 3 dm in the horizontal component and 1 dm in the vertical component cannot be always fulfilled with a level of confidence of 95% in problematic and GNSS shadowed regions. For that purpose a loss of GNSS signals was investigated for a time interval of 60 s.

The Institute of Engineering Geodesy (IIGS, University of Stuttgart) and the department for geodesy of the German Federal Institute of Hydrology (BfG) launched the project HydrOs (Integrated Hydrographic Positioning System). The project focuses on the development of a multi-sensor system which can stabilize the positions and counteract to the drift behavior of the INS in cases if GNSS fails. Next to the hardware system also the HydrOs software is developed which is able to record and process the measured data (SCHEIDER &

SCHWIEGER, 2012). For the optimal processing of the data an adequate filter must be designed.

2. MULTI-SENSOR SYSTEM

To calculate the position and the orientation of the vessel with a higher availability and accuracy, different sensors are installed on the vessel. The measured data can be used to improve the position and the orientation of the vessel and to get information inside regions without GNSS reception. The sensors are connected to a central computer as data processing unit. For this purpose the computer is equipped with 17 serial ports which are sufficient for the task. Some sensors do not have a timing function. Therefore every incoming data package is marked by a time stamp which helps to avoid time offsets caused by different time scales. The consistent time scale is realized by synchronizing the computer clock with the received GNSS time of one receiver. To limit the timing inaccuracy caused by the influence of the drift of the low cost computer clock, the time synchronization must be executed frequently.
In this chapter, sensors which are currently integrated into the system are presented.

2.1 GNSS

2.1.1 CORS network service

SA*POS*® is a reference service for DGNSS applications and operates under the control of the Working Committee of the Surveying Authorities of the States of the Federal Republic of Germany (AdV). The members of AdV control a network of stable reference stations (**SA*POS*®** network) all over Germany. Some GNSS monitoring stations in neighboring countries are also integrated into the **SA*POS*®** network, allowing the use of combined reference service in areas close to the border of Germany. As a result, the data gathered by the stations can be processed together. SAPOS (2014) describes three kinds of services which are available from the responsible state surveying authorities:

- Real-time Positioning Service **EPS**; accuracy 0.5 – 3 m,
- Highly Precise Real-time Positioning Service **HEPS**; accuracy 1 – 2 cm (horizontal component) and 2 – 6 cm (vertical component),
- Geodetic Precise Positioning Service **GPPS** (Post-processing); accuracy 1 cm.

On surveying vessels, a RTK solution is determined by using HEPS. For precise coordinates in real-time, HEPS service transmits three kinds of correction signals which can be chosen by the user:

- For a Virtual Reference Station (VRS) close to the measurement area,
- Area Correction Parameters (FKP) of the surrounding reference stations and
- Master-Auxiliary Concept (MAC).

Here, correction signals from a virtual reference station are received. Because the vessel is moving all the time, the distances to the VRS may increase too. If the distance exceeds 2 km (SAPOS-BW, 2014) a new VRS is calculated and the system is initialized again. Phase correction data are transmitted in the RTCM (***R**adio **T**echnical **C**ommission for **M**aritime services*) format. RTCM 3.1 transmits not only GPS correction data but also some for GLONASS (SAPOS-BW, 2014).

2.1.2 GNSS receivers

The GNSS antennas on the surveying vessels can process GPS and GLONASS signals and they are able to process two frequencies for a carrier phase solution. As mentioned, positions are determined with Real-Time Kinematic (RTK) mode. This Precise Differential GNSS (PDGNSS) option is realized by using correction signals from **SA*POS***®. Here, one antenna is installed close to the bow and another one close to the stern.
Measured data are transferred via messages in the NMEA-0183 format (DIN, 2011) to a RS232 port of the central processing unit. This format was defined by the ***N**ational **M**arine **E**lectronics **A**ssociation* in 1983. Multiple NMEA-strings are requested and not only ellipsoidal coordinates (*Lon*, *Lat*, h_{ell}) but also information about Speed over Ground (*SOG*), Course over Ground (*COG*) and quality parameters are transmitted.

Some modern surveying vessels are also equipped with integrated GNSS-INS systems (as well loosely as tightly coupled systems), e.g. Seapath 330+ from Kongsberg (KONGSBERG, 2014a). This system consists of two GNSS antennas because it includes a GNSS compass, although only the position of the master antenna is part of the system output. The GNSS position solution is filtered together with measured data from INS and GNSS compass for a higher availability. For this reason, it is possible to calculate coordinates even in areas with poor GNSS reception. According to HENTSCHINSKI & WIRTH (2012) at least four GNSS satellites must be receivable.

GNSS solutions are long-term stable and offer in general a position accuracy of sub-decimeters for RTK solutions.

2.2 Inertial Measurement Unit

Another part of the multi-sensor system is an Inertial Measurement Unit (IMU) which consists generally of three accelerometers and three gyroscopes. IMUs determine relative position changes with a very high accuracy but only with short-time stability. If positions are determined by dead reckoning with IMUs over a longer time, drift effects occur. This is caused by integration of the measured signals whereby small errors are summed up over time (WENDEL, 2007).
Here, a MRU5+ from Kongsberg is installed as an essential part of the Seapath 330+ system. This IMU contains a MEMS gyro (KONGSBERG, 2014b). Next to the angular rates (roll rate, pitch rate, yaw rate) also the orientation angles roll, pitch and heading, the vertical velocity component and the heave (vertical motion) can be transferred. These information are also transmitted in NMEA-0183 format, but in this case two proprietary strings are used.
Another string displays the longitudinal and the transverse velocity components of the vessel in the body coordinate system.

2.3 Compass

FOSSEN (2011) presents magnetic, gyro compass or yaw rate gyroscopes as main components to determine the heading angle on marine crafts. Additionally a GNSS compass can be used if the system is equipped with multiple GNSS antennas. The measurement principles are explained in GROVES (2013). To increase the accuracy of the single

measurements, it is expedient to combine an absolutely measured heading with relative yaw rate measurements. GROVES (2013) describes the advantages of this method: The noise of absolute measurements is reduced by the short-time stable yaw measurements and former ones reduce the drift behavior which is caused by the relatively measuring systems.
It must be taken into account that the different types of compasses are working with different definition of the term 'north': A magnetic compass for example points towards magnetic north pole and the gyro compass to true north. So the measured heading must be corrected to use a unique definition of north direction (GROVES, 2013).
The compass of the Seapath 330+ consists of a GNSS compass with two GNSS antennas, and a yaw rate gyro.

2.4 Doppler Velocity Log

Doppler velocity logs are a type of Acoustic Doppler Current Profiler (ADCP). Here an instrument Workhorse Navigator Doppler Velocity Log (DVL) from Teledyne RD Instruments is in use (RD INSTRUMENTS, 2014). Four sending/receiving units are assembled to determine the three dimensional velocity components in water by measuring the Doppler shift of the emitted signal frequencies. There are two options to measure velocities: The velocity components over ground or relative to defined water layers can be determined. Besides, the water depth is measured.
In this case the DVL is fixed in front of the vessel with a constructed adapter. The axes of the platform coordinate system must be aligned to the vessel coordinate system and the remaining orientation deviation must be determined. In this case, the measured data can be transferred directly to the vessel coordinate system.

2.5 Ship Propulsion

The ship propulsion is realized by a Schottel rudder propeller which is propulsion and steering unit in one part (SCHOTTEL, 2014). Each propeller can be rotated by 360° and pulls the vessel in the regulated direction. Some modern surveying vessels have even two rudder propellers, so a resulting pull direction must be determined.
Information about the direction and the relative speed of the vessel caused by propulsion cannot be taken from a given interface, so special devices had to be installed. Here ampere meters are installed. There is one ampere meter to get the direction compared to the longitudinal axis of the vessel and another to capture the revolution speed of a propeller. For two propellers, all in all four ampere meters are required. A calibration function to transform the measured amperage to propeller direction and revolution speed respectively was developed.

2.6 Hydrodynamic Models

General information about water level and flow velocity can be extracted from hydrodynamic models. They are available for multiple pre-defined scenarios concerning discrete discharge intensities. The modeled water levels are based on the assumption of steady flow between two succeeding gauges. So local effects e.g. flood waves, transversal gradients in river bends or turbulences are not taken into account. In a one-dimensional hydrodynamic model, the given velocity components are also one-dimensional and referred to the centerline of the river. These information can be integrated to the HydrOs system as pseudo-observations but it is also possible that the results of HydrOs can validate and even improve the hydrodynamic models. Because of their low level of accuracy, the values can only be integrated to the system as observations with low weight. It is only advisable to integrate the modelled current if no other measurements are available.

If the virtual observation water level is included in the system, a transfer between the defined discharge scenario and the predicted state variables of the system must be defined. In addition, some more information is required: Heave, load of the vessel and the resulting squat effect (chapter 4).

3. DATA PROCESSING

The sensors of the system work with different measurement frequencies. Therefore the data must be interpolated or in real time even extrapolated to instants of time on the consistent time scale. For the HydrOs system, a data frequency of 10 Hz was chosen, according to the measurement frequency of GNSS input.

If the measured observations and predicted variables are available at the point of time, they can be combined in a filter to improve the accuracy and the availability of position information. The motion behavior can be predicted with a prediction model, which estimates at least twelve state variables. The observations and the predicted values are combined in the measurement equation of a filter. Here an Extended Kalman Filter was chosen, to overcome the non-linear model.

3.1 Motion Model

Most of the models used in literature to predict the turning rates, the velocities, the position and the orientation of a vessel only consider a horizontal and thereby two dimensional motion. They are used for steering and course keeping maneuvers. Basis for most of the currently used models is the First Order Nomoto Model (NOMOTO ET AL., 1957 and FOSSEN, 2011) which can be classified as a yaw subsystem (FOSSEN, 2011). It predicts the second derivation of the yaw angle based on the rudder angle and the first derivation of yaw angle. This derivation corresponds to the turning rate around the z-axis of the local coordinate system (ω_z). ZIMMERMANN (2000) extends the model by a drift angle. So the transversal motion between longitudinal axes and driving directing is also taken into account. Another approach is the motion model according to DAVIDSON & SCHIFF (1946). Next to the turning rate ω_z, the transversal velocity component v_y is predicted directly.

Table 1: State variables and regulating variables of the HydrOs prediction model

	Variables	Representation	Coordinate System
State	Turning rates	$\omega_x, \omega_y, \omega_z$	Vessel
State	Velocity components	v_x, v_y, v_z	Vessel
State	Orientation angles: *Roll, Pitch, Heading*	φ, θ, ψ	Vessel → Global
State	Coordinates: *East, North, Upwards*	E, N, U	Global
Reg.	Resulting Propeller angle	δ_{res}	Vessel

For the HydrOs project, the height component is even more important than the horizontal coordinates, so a three dimensional prediction model is required. Therefore the mentioned models are extended. Multiple approaches of the motion model have been developed. Here the linear and the spherical approach with one regulating variable are considered. The state variables (see Table 1) are predicted for a user-defined reference point whose coordinates must be given in the local vessel coordinate system. The state vector can be extended by the state variable water level U_{WL}.

Turning rates and velocity components are considered as dependent quantities. They depend to each other by factors a_{ij}, like it is described in the model of Davidson & Schiff for the horizontal components (ZIMMERMANN, 2000). The resulting direction of pull of the rudder propellers δ_{res} also affects the angular and the linear velocity components with factor $a_{i\delta}$. In contrast to the mentioned models, longitudinal velocity v_x is not assumed to be constant ($\dot{v}_x \neq 0$). In the following the relations are described:

$$\begin{bmatrix} \Delta\overline{\omega}_{x,k+1} \\ \Delta\overline{\omega}_{y,k+1} \\ \Delta\overline{\omega}_{z,k+1} \\ \Delta\overline{v}_{x,k+1} \\ \Delta\overline{v}_{y,k+1} \\ \Delta\overline{v}_{z,k+1} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \cdot \begin{bmatrix} \hat{\omega}_{x,k} \\ \hat{\omega}_{y,k} \\ \hat{\omega}_{z,k} \\ \hat{v}_{x,k} \\ \hat{v}_{y,k} \\ \hat{v}_{z,k} \end{bmatrix} + \begin{bmatrix} a_{1\delta} \\ a_{1\delta} \\ a_{1\delta} \\ a_{1\delta} \\ a_{1\delta} \\ a_{1\delta} \end{bmatrix} \delta_{res,k+1} \quad (3.1)$$

These parameters must be determined by parameter estimation, e.g. adjustment methods.
The orientation and the coordinate changes in the local vessel coordinate system caused by the velocity components must be transformed to a motion independent coordinate system (FOSSEN, 2011). Here, another definition of local level coordinate system is used with x-axis pointing toward east direction (*E*), y-axis toward north direction (*N*) and z-axis upwards (*U*).

$$\begin{bmatrix} \Delta\overline{\varphi}_{k+1} \\ \Delta\overline{\theta}_{k+1} \\ \Delta\overline{\psi}_{k+1} \end{bmatrix} = T\left(\hat{\varphi}_k, \hat{\theta}_k, \hat{\psi}_k\right) \cdot \begin{bmatrix} \hat{\omega}_{x,k} \\ \hat{\omega}_{y,k} \\ \hat{\omega}_{z,k} \end{bmatrix} \cdot \Delta t, \quad (3.2)$$

$$\begin{bmatrix} \Delta\overline{E}_{k+1} \\ \Delta\overline{N}_{k+1} \\ \Delta\overline{U}_{k+1} \end{bmatrix} = R_z\left(\hat{\psi}_k\right) R_y\left(\hat{\theta}_k\right) R_x\left(\hat{\varphi}_k\right) \cdot \begin{bmatrix} \Delta L \\ \Delta Q \\ \Delta H \end{bmatrix}. \quad (3.3)$$

Position changes ΔL, ΔQ and ΔH can be predicted with two alternative model approaches: The linear prediction approach determines the coordinate changes along the coordinate axes of the vessel coordinate system (Figure 1):

$$\begin{bmatrix} \Delta L \\ \Delta Q \\ \Delta H \end{bmatrix} = \begin{bmatrix} \hat{v}_{x,k} \\ \hat{v}_{y,k} \\ \hat{v}_{z,k} \end{bmatrix} \cdot \Delta t. \quad (3.4)$$

EICHHORN (2005), RAMM (2007) and BEETZ (2012) developed a prediction model which describes a curve drive of vehicles. Here, the two dimensional model is extended to the third dimension by rotating the curved trajectory around the y-axis of the vessel coordinate system for angle α (Figure 2). This approach expresses the position change along a great circle with spherical radius R and apex angle ζ:

$$\begin{bmatrix} \Delta L \\ \Delta Q \\ \Delta H \end{bmatrix} = R_y(\alpha') \cdot \begin{bmatrix} R \cdot \sin\varsigma \\ R \cdot (1 - \cos\varsigma) \\ 0 \end{bmatrix}. \tag{3.5}$$

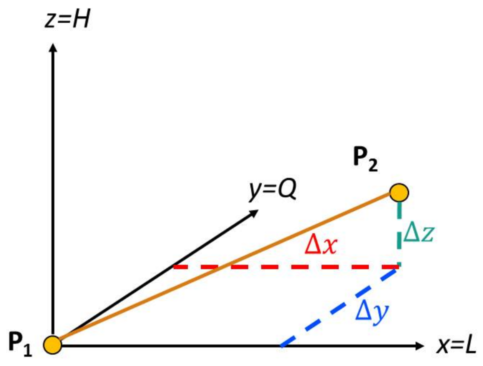

Figure 1: Linear prediction approach

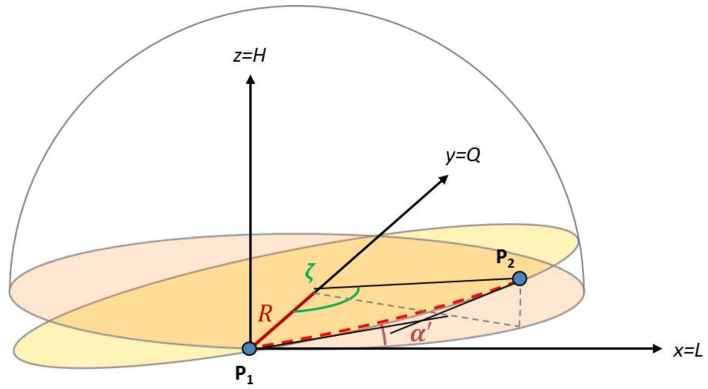

Figure 2: Spherical prediction approach

3.2 Filter

Not only the prediction model but also the measurement equations are non-linear. Since the filter should be able to run in real-time mode, the computational costs should be minimal. Therefore an Extended Kalman Filter (EKF) was chosen to estimate the state variables. The basic facts of the Kalman Filter method are described in GELB (1974). EICHHORN (2005) and RAMM (2007) adapted the EKF to estimate the orientation and the coordinates for driving vehicle in a horizontal plane. For the HydrOs model angular accelerations and linear accelerations respectively in three dimensions are assumed as disturbing variables. These disturbing variables are not considered in the prediction model itself, but only stochastically.
Before observations are integrated into the measurement equations, it must be checked if each of them is available at a particular time. It must be differentiated carefully between missing observations and gaps which are caused by a low measuring frequency and which can be closed by an adequate interpolation method. If particular measuring data are not available the measurement equation system must be reduced. If the observation quantity is again available with a certain reliability, the corresponding measurement equation is activated too. Especially GNSS observations must always be validated carefully. One approach to check their applicability is described in chapter 3.3.
For the transfer between state variables and observations, the different locations of the sensors have to be considered: State variables can be predicted for any defined point on the vessel, but observations are conducted on the position of the particular sensor. Therefore the state variables are transformed to the location of the individual sensors using the measurement

equations.

3.3 Detection of Unreliable GNSS Measurements

If the GNSS signals have been lost for 60s, it is not advisable to integrate all GNSS measurement in the proximity of the gap to the filter. Partly shadowing already reduces the accuracy of GNSS measurements because of a possibly bad satellite configuration. Obstacles may also provoke multipath effects or signal diffraction. Therefore it is necessary to check carefully whether the kinematic GNSS measurements are still reliable. Often it is difficult to judge the status with only one parameter, so a combination of several criteria is used.
Multiple GNSS antennas are fixed on the majority of surveying vessels in Germany; hence their measurements can be analyzed isolated from each other but also by comparing them. One option to recognize shadowed antennas is to examine the Dilution of Precision (DOP) values, which represent the current satellite geometry. KAUKER (2014) shows, that DOP values seem to be a good indicator for a following loss of one or more satellites, especially for the used Seapath 330+ system.
If only two GNSS antennas are installed on the vessel, the measured base length between those two might be compared to the known distance. For this purpose, the coordinates of the antennas in the vessel coordinate system and the base length between them respectively must be known with high precision. A differing base length is a sign of disturbed GNSS positions. In combination with the DOP values from multiple measurement epochs, the shadowed antenna may be detected.
KAUKER (2014) suggests comparing the measured speed over ground for each antenna instead of using the base length. If the difference between the single measured *SOG*s exceeds a defined threshold, one of the antennas is probably affected by shadowing effects. For this purpose not the directly measured values can be considered. They must be corrected by the apparent change of velocity caused by turns of the vessel. Therefore measurements from IMU and compass respectively must also be used.
With more than two installed antennas it is easier to detect unreliable measurements. KAUKER (2014) considers a vessel with three given positions: GNSS receivers close to bow and close to stern and the Seapath 330+ system in the middle position. In this case, KAUKER (2014) suggests considering the DOP values of the middle position in a first step. If it is shown that these two antennas or the calculated position respectively is not affected by shadowing, the *SOG* from the Seapath system is compared to the *SOG* from bow antenna (if the ship is driving forwards). Large differences between the corrected velocities indicate that the bow antenna seems to be affected by disturbances and the observation is no more integrated to the system. Now, the corrected *SOG*s of middle and stern position are considered. If the middle position is identified to be shaded, it can be calculated according to the current velocity how long the stern antenna might be used until it is also unreliable.
The currently used algorithm classifies GNSS measurements as available after a shadowed region if the bow and the two antennas on middle position deliver reliable positions again.

4. SQUAT DETERMINATION

To determine a relation between the measured heights of the GNSS antennas on the vessel and the water level, the subsidence of the vessel caused by the squat effect must be known.

BRIGGS (2006) describes squat as "the reduction in under keel clearance between a vessel at-rest and due to the increased flow of water past the moving body." The velocity in forwards direction causes a suction of the ship into the water. The influence of the squat at the bow can be appraised by a large variety of predefined equations (see BRIGGS, 2006 and BRIGGS, 2009). It must be considered that they are used for safety aspects, so many of them predict the squat effect pessimistically (BRIGGS, 2006). The comparison between the equations quickly shows differences of several centimeters or decimeters. Many of the mentioned equations are only suitable for specified types of ships (mainly large sea-adapted ships) or channel configurations. The equations are not designed for surveying vessels with twin hull. The modeling of the catamaran squat behavior is expected to be different. So the idea was born to determine the squat influence for each ship or class of survey vessel individually.

WIRTH ET AL. (1996) were the first to measure the squat and attitude of Panmax-class container-vessels (ships capable of passing through the lock chambers of the Panama Canal) on the river Elbe by installing three GNSS-Receivers on each ship, and a consecution of GNSS reference stations along the coastline. The undisturbed water level was modeled by gauges linked together by a time-variant parameter estimation. At that time the low availability of GNSS was a drawback as well as the fact that the equipment and personnel had to leave the ship over rope ladders on tour.
DUNKER ET AL. (2002) developed a less sumptuous method to determine the squat effect of large vessels relative to a small escorting craft. Here, as a precondition the undisturbed water level is derived from the squat effect of the small vessel itself. This method needs no gauges, and no reference-stations. The raw relative heights are corrected for longitudinal inclination of the water level and speed through water. The speed through water is computed by adding current velocities published in manuals for pilots. All measurements are carried out with precise differential GPS (PDGPS) receivers. The uncertainty of the difference vector is in the range of 1-2 cm (DUNKER ET AL., 2002). So the overall uncertainty is mainly influenced by the accuracy of the squat function for the small vessel and the measured heave. The heave has a typical accuracy of 5 cm or 5% of heave whichever is highest (KONGSBERG, 2014a).

The HydrOs software shall compute the height of the undisturbed local water level. This can be solved by combining the squat, heave, the raw water level heights of the hydrodynamic model and the estimated model error. The model error may be estimated in the EKF. Therefore the HydrOs project aims at an accuracy of less than 2 cm for squat correction. For that purpose a characteristic squat diagram is needed which shall be used to calculate the squat in real time. The squat is assumed to

- be a function of size and shape of the ship hull,
- increase linearly with decreasing water depth respectively under keel clearance,
- increase quadratically with increasing speed through water.

To determine the squat effect three GNSS receivers being installed on a vessel are used. If the heights of GNSS receiver are transformed to a reference point, the squat is the difference between the height of the reference point with undisturbed water level at rest and the reference point height while moving with various speeds through water. The orientation angles of the vessel are considered in the transformation.
Caused by the developments of the last years, the **SA*POS*®** reference service can be used for

the desired PDGNSS methods. Other locally installed reference stations should prove the suitability of **SA*POS*®** and in second place reduce the influence of troposphere.

According to the measuring program, first the ship drifts downstream along a straight line with engine idle, which avoids any squat effect. Simultaneously the longitudinal inclination of the undisturbed water level is measured by GNSS as a function of the station. After a U-turn the vessel drives the same trajectory with different velocities. In post-processing the height differences for positions with equivalent station and under keel clearances (h_{ukc}) were computed. Speed through water (v_{rel}) completes the coordinate-triples. This procedure was repeated several times for trajectories with different water depths (resp. under keel clearances) and velocities. The pitch and heave induced by waves were not modeled for data processing, because they were small and they change periodically. Hence it is assumed that the influence of pitch, heave and multipath effects are zero in average.

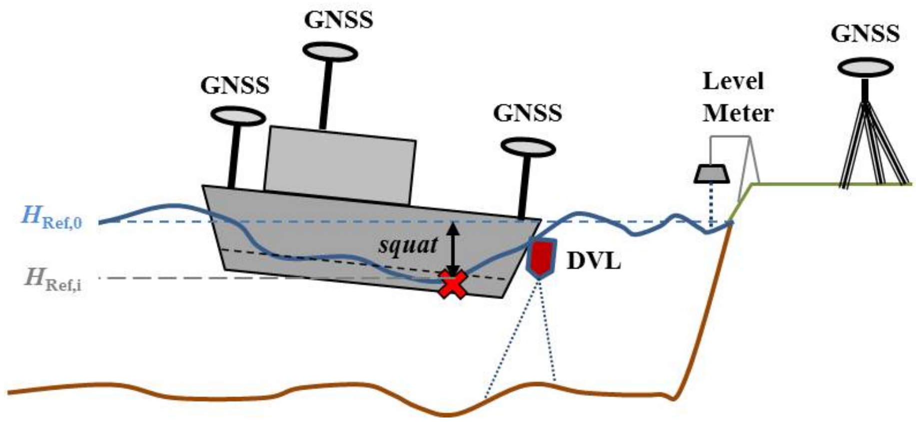

Figure 3: Principle of squat determination

$$squat_i = H_{\mathrm{Ref},0} - H_{\mathrm{Ref},i}\left(v_{rel}, h_{ukc}\right) \tag{4.1}$$

squat: height change caused by squat effect
$H_{\mathrm{Ref},0}$: height of the reference point on the vessel for zero position
$H_{\mathrm{Ref},i}$: height of the reference point on the vessel at epoch *i*
v_{rel}: relative speed of the vessel compared to the water
h_{ukc}: under keel clearance

Measurements could only be conducted without any disturbances by other ships. For the detection of disturbances of the water level from traffic three measures were taken:

- On the downstream border of the survey area a water level gauge was installed on the riverside,
- Upstream a ship equipped with PDGPS measured the local water level,
- Personnel had to record the traffic and to take pictures of the passing ships.

With this information all contaminated data could be erased.
The water depth as well as the velocity components over ground and the current components have been measured by DVL. The survey area stretched on a straight river section between km 779 and km 780 on the river Rhine near Duisburg. The data was captured in June 2013.

In a least squares adjustment a mathematical function for the squat was estimated. For that purpose the parameters *a*, *b*, *c* and *d* in equation (4.2) have been determined by inserting the coordinate-triples in

$$squat_i = a + b \cdot v_{rel,i} + c \cdot h_{ukc,i} + d \cdot v_{rel,i}^2 . \qquad (4.2)$$

In Figure 4 the characteristic squat diagram for the bow position of the vessel "Mercator" is shown. The standard deviation of the adjustment was about 1.8 cm which shows that the desired accuracy was met. By knowing the trim, the squat can be transformed to every position of the vessel. In the diagram it can be seen, that the squat does not depend much on under keel clearance. The reason is that the under keel clearance was relative large so the influence of varying depth is very small. But the diagram shows one basic fact: The squat basically increases with increasing water depth.

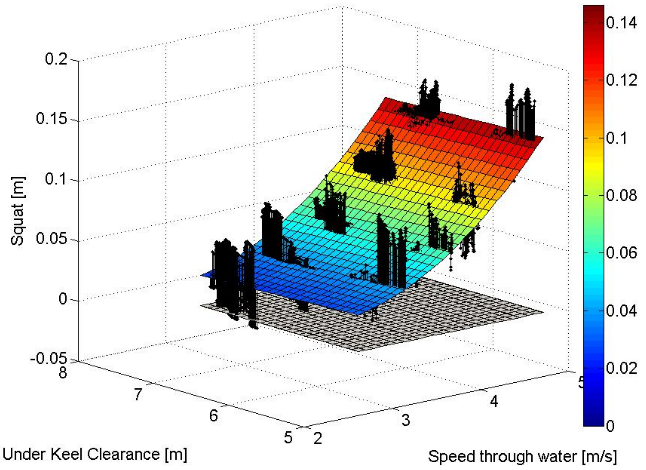

Figure 4: Squat characteristic diagram

Due to the fact that the measurements were taken within a high water period, the characteristic diagram currently is not complete. The shallow water area is still undetermined.

It might be of some interest to compare our individual squat function appropriate for a dual hull vessel to the standard equations which are widespread in use. Some of the equations, mentioned in BRIGGS (2006), are not valid for the measured scenarios. The squat, computed with the equations of *Barras*, *Norrbin* and the *Japanese equation* (see BRIGGS, 2006) bore no resemblance with the others, so they were excluded. In Figure 5, the results of the BfG-equation (black bold line) are shown in comparison with the equations of *Hooft* and *ICORELS* (BRIGGS, 2006) for unrestricted channels. The equations for the mono-hull ships seem to be much more sensitive against variation of under keel clearance than our individual equation for dual-hull vessels.

5. CONCLUSION AND OUTLOOK

The objective of the HydrOs project is to determine the vessel position and orientation without gaps and with a high accuracy. Even if the GNSS signal is lost, the position should be determined with an accuracy of a few decimeters in height and in horizontal components. For that purpose a multi-sensor system is designed consisting of different position, orientation and velocity sensors. All these sensors send their measured data to the HydrOs software which is able to record and process them. Processing can be performed in real-time mode as well as in post-processing mode. A three dimensional motion model was developed to predict the state variables. Predicted state variables and observations are filtered within an Extended Kalman Filter and the estimated state variables for each epoch are calculated. The output data rate will have a frequency of 10 Hz. In future, an output NMEA-0183 string will be created which can be utilized by other sensors or systems, e.g. to georeference data form the multibeam echo sounders. In future, the measured swathes of the multibeam echo sounders will achieve a higher accuracy in areas with poor GNSS reception without any additional land-based measurements.

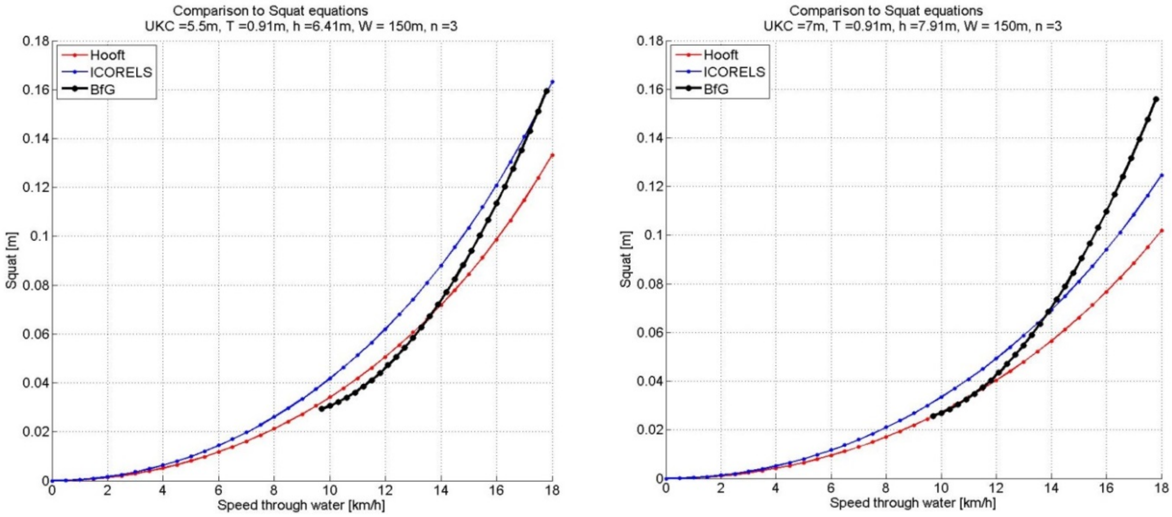

Figure 5: Comparison of SQUAT- formulas to BfG-Squat characteristic diagram for depth 5.5 and 7.0 m

To distinguish reliably between measurements captured in areas without any surrounding obstacles and (partly) shadowed areas which affect the reliability and accuracy of GNSS measurements, suitable algorithms and thresholds must be defined. The current approach deals with the DOP values and the comparison of the corrected *SOG* from the single GNSS receivers. The reliability might increase if additional data are intgrated, e.g. measurements from DVL.

Besides the motion state of the vessel additional information can be presented to the users: Current components can be measured with DVL. In further steps they will be filtered and issued by the HydrOs system. Reliable water level information can be provided by considering real measured heights and estimating the squat effect. Additionally data from hydrodynamic models can be integrated as pseudo-observations, if the offset between water level scenario and the real water level is constant. For this reason a new approach for squat determination was implemented. The squat can be determined with a characteristic diagram for particular vessels. Therefore a measurement campaign must be conducted with this vessel, equipped with PDGNSS receivers. Hence, HydrOs software can be utilized to validate and improve hydrodynamic models.

This means that the shipping profits twice of the new system: One the one hand, more precise maps will be offered and on the other hand, they can use improved hydrodynamic models.

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BIOGRAPHICAL NOTES

Dipl.-Ing. **Annette Scheider**

2004 – 2010	Studies of Geodesy and Geoinformatics in Stuttgart (University of Stuttgart)
2010	Dipl.-Ing. Geodesy and Geoinformatics (University of Stuttgart)
2010	Research Associate at Institute of Engineering Geodesy, University of Stuttgart

Dipl.-Ing., Vermessungsoberrat **Harry Wirth**

1980 – 1986	Studies of geodesy, Friedrichs Wilhelms University of Bonn
1986	Dipl.-Ing. Degree at Friedrichs Wilhelms University of Bonn
1986	Research Assistant at the Friedrich Wilhelms University of Bonn, Institute for Applied Geodesy
1986 – 1988	Trainee for Public Service in the field of Cadastrial Surveying and Mapping Authorities in Germany
1988 – 1991	Research Associate at the Federal Institute of Hydrology (BfG), Koblenz
1991	Head of the team for Surveying Techniques and Hydrographic Survey Systems

M.Sc. **Marc Breitenfeld**

2008 – 2012	Studies of Geodesy and Geoinformation, Friedrich Wilhelms University of Bonn
2012	M.Sc. at Friedrich Wilhelms University of Bonn
2013	Research Associate at the Federal Institute of Hydrology (BfG), Koblenz

Prof. Dr.-Ing. habil. **Volker Schwieger**

1983 – 1989	Studies of Geodesy in Hannover
1989	Dipl.-Ing. Geodesy (University of Hannover)
1998	Dr.-Ing. Geodesy (University of Hannover)
2004	Habilitation (University of Stuttgart)

2010 Professor and Head of Institute of Engineering Geodesy, University of Stuttgart

CONTACTS

Dipl.-Ing. Annette Scheider / Prof. Dr.-Ing. habil. Volker Schwieger
Institute of Engineering Geodesy, University of Stuttgart
Geschwister-Scholl-Str. 24D
70174 Stuttgart
GERMANY
Tel. + 49 711 68584057 / + 49 711 68584040
Fax + 49 711 68584044
Email: annette.scheider@ingeo.uni-stuttgart.de / volker.schwieger@ingeo.uni-stuttgart.de
Web site: www.uni-stuttgart.de/ingeo

Dipl.-Ing. Harry Wirth / M.Sc. Marc Breitenfeld
Bundesanstalt für Gewässerkunde
Am Mainzer Tor 1
56068 Koblenz
GERMANY
Tel. +49 711 13065232 / +49 711 13065285
Fax +49 711 13065280
Email: wirth@bafg.de / breitenfeld@bafg.de
Web site: http://www.bafg.de