Ship-based Oceanwide Observation of Sea Surface Heights in Consideration of Hydrodynamic Corrections

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Key words: GNSS,Oceanwide,Sea Surface Heights,Ship-based, Hydrodynamic

SUMMARY

The latest development in GNSS PPP processing allows observing the heights of moving antennas aboard seagoing vessels with accuracies up to 5 cm and it is foreseeable that the quality will be improved in the future. Consideration ofsome essential hydrostatic and hydrodynamic corrections makes it possible to use these antenna heights as a good basis to derive ocean wide precise in-situ data of sea surface heights (SSH).

If only a small portion of the more than 60.000 ships that sail the ocean at any time can be used for the determination of SSH a significant amount of additional ocean wide data could be obtained independently from remote sensing techniques. These data sets would have a very high resolution along the track of the ship and might be used to increase the sensitivity of satellite altimetry over short wavelengths in a combined analysis. Additionally, thesedata would provide a continuous validation of altimeter biases over vast areas in almost all oceans.

The results of two experiments in the Atlantic and Pacific Oceans will be presented. The first one shows in a case study on a cruise vessel the necessary methods to correctly determine and consider the squat of a moving ship and to derive the correct GNSS antenna height above the water level.

The second one presents an ocean wide determination of SSH from measurements on a cargo ship. The results from this experiment were compared with those from the Jason-2 altimeter and an altimeter bias was calculated from cross-over points with the ship track. Additionally, the quality of the spatial resolution is shown for the crossing of the Hawaiian–Emperor seamount chain.

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1. INTRODUCTION

The monitoring of sea surface heights (SSH) and its changes became more and more important during the last decades since it is of major interest for progress in environmental studies. Satellite altimetry is nowadays the standard tool to observe the height of the oceans and its variability. This method offers an excellent spatial coverage with an impressive quality but is not very sensitive to local features at short time scales due to the limited spatial and temporal resolution.

Apart from conventional stationary observation methods using tide gauges, pressure or GNSS buoys,kinematic GNSS observations aboard ships can be used to derive precise data of sea surface heights. Different groups used ship-borne measurements in the past e.g. to calibrate radar altimeters (e.g. Bonnefond et al. 2003, Melachroinos et al. 2009, Crétaux et al. 2011, Mertikas et al. 2012) or to map a local geoid or the local mean sea level (MSL) (Rocken et al. 2005, Müller et al. 2006, Bouin et al. 2009, Foster et. al. 2009, Pineau-Guillou and Dorst 2011). An ocean wide trial was conducted by DTU (Danish Technical University) aboard a research vessel on her way from Perth to Copenhagen (Andersen et al. 2010).

The latest development in GNSS PPP processing allows observing the heights of moving antennas aboard seagoing vessels with accuracies up to 5 cm and it is foreseeable that the quality will be improved in the future. It is important to mention that these antenna heights are only a good basis to derive ocean wide precise in-situ SSH data if some essential hydrostatic and hydrodynamic corrections are considered correctly.

Provided a sophisticated consideration of all corrections observations on only a small portion of the more than 60.000 ships that sail the ocean at any time can be used to derive a significant amount ofindependentlymeasured SSH data. These data sets would have a very high resolution along the track of the ship and might be used to increase the sensitivity of satellite altimetry over short wavelengths in a combined analysis. Additionally, thesedata would provide a continuous validation of altimeter biases over vast areas in almost all oceans.Chapter 2 gives a summary of how SSH can be derived from observed GNSS antenna heights under consideration of essential corrections.

The observation and analysis of the hydrodynamic behavior and mainly the squat of merchant ships, particularly in restricted waters, have been investigated for more than a decade at the Jade University of Applied Sciences, Germany. We carried outtwo experiments in the Atlantic and the Pacific Ocean. The first one shows in a case study on a cruise vessel the necessary methods to correctly determine and consider the squat of a moving ship and to derive the correct GNSS antenna height above the water level. The results are presented in chapter 3.

Chapter 4 will discuss the second experiment. We will present an ocean wide determination of SSH from measurements on a cargo ship. In this experiment all hydrostatic and hydrodynamic corrections are applied to derive SSH which can be compared with those from the Jason-2 altimeter. Based on this comparison an altimeter bias was calculated from cross-over points with the ship track. Additionally, the quality of the spatial resolution will be shown for the crossing of the Hawaiian–Emperor seamount chain.

2. SSH FROMOBSERVED GNSS ANTENNA HEIGHTS

We assume that at least three GNSS antennas are installed aboard a ship to allow for the observation of the rotational movements of the ship. It may also be possible to use a lower number of antennas but in this case additional sensors to measure roll and pitch must be used. Further we suppose that the heights of at least one antenna in a global frame are available from either relative or PPP processing of the GNSS data.
While a ship is stationary the height of a GNSS antenna aboard the ship above the water surface depends on the static draft of the ship and the height of the antenna above the keel.
Hence, the positions of the GNSS antennas in the body frame of the ship (SRF – ship reference frame) must be derived from static measurements.
The longitudinal center of floatation (LCF), which is the center of the waterline area, is the intersection of the axes of small, quasi-static roll and pitch motions and can be calculated from the ship's hydrostatic data. Therefore the LCF is an ideal point to be used for height referencing. Since the coordinates of the LCF and the GNSS antennas are both known in the ship's body frame, the height of the LCF in a global frame can be obtained easily by a 3D transformation.
As long as the ship is not moving only the fixed antenna height and the hydrostatic correction due to draft changes have to be accounted for. If the ship starts to sail it is influenced by hydrodynamics. The water flow around the hull generates a wave system. To maintain the hydrostatic equilibrium the ship settles in a lower position at the center and the trim may be changed additionally. The resulting vertical movement is called "squat" and influences the antenna heights above the water level, too. Oscillatory antenna height changes are due to roll and pitch, while heave due to waves and swell will produce additional vertical translations of the antenna.The squat effect is commonly described as a lowering of the LCF together with the additional trim change.
The resulting instantaneous heights of the LCF are influenced by ocean tides and tidal loading as well as by atmospheric loading. Hence, additional geophysical corrections must be applied to derive SSH.

2.1 Hydrostatic Corrections

The static vertical position of the LCF is influenced by changes in loading, fuel and ballast water. The calculation of the positions is mandatory for merchant ships and is done daily by the loading computer of the ship. Although all relevant changes of the ship's displacement are recorded and considered in its calculation, the resulting draft at the LCF might differ from the actual draft because the water density is an estimated value in most cases. As long as the calculated draft is recorded together with the assumed water density, the draft can later be corrected if the actual water density is available.
The draft correction due to a difference in water density can either be calculated using a 3D model of the ship's hull or, simpler, by taking the TPC value (Tonnes per centimeter, mass

required to increase or decrease a ship's mean draft by 1 cm) from the loading computer data.

2.2 Hydrodynamic Corrections

2.2.1 Heave correction

The wave induced height variations can be determined using precise onboard GNSS receivers (Reinking and Härting 2002, Reinking 2010) with the advantage that the heave of the antenna is determined exactly for the observation epoch and position of the measurement. This becomes more important for a large vessel which cannot be treated as a rigid body due to possible bending of the ship's hull.

For the GNSS-based approach double-differences of carrier phases between consecutive epochs are used to derive 3D coordinate differences between the epochs. The coordinate differences and hence the antenna height changes are influenced by pitch and roll. To eliminate this influence, the changes of the pitch and roll angles between the epochs must be known either from an attitude sensor or from a network of at least three GNSS receivers aboard the ship.

Afterwards, the differences are integrated and high-pass filtered to reduce long-term systematic effects not modelled properly. The result is the heave for a single GNSS antenna. Assuming no significant deformation of the ship's hull, the heave of all GNSS receivers aboard the ship must be equal since they should describe the vertical translation of the whole ship. Therefore the single heave values are averaged for every distinct epoch to derive the heave of the ship's LCF.

The quality of the correction thus obtained is in most cases excellent. However, a pronounced ocean swell of very long period would be problematic, demanding an impracticably low cut-off in the high-pass filter.

2.2.2 Squat correction

Squat can be explained by the fundamental physical law of energy conservation. With negligible viscous friction it is governed by Bernoulli's principle which states for an incompressible fluid that the sum of dynamic and hydrostatic pressures is constant along a streamline. Bernoulli's equation implies that the squat is approximately a quadratic function of the velocity of flow.

Whereas the principle can be understood with Bernoulli's equation, a computation of the amount of squat requires the knowledge of the velocity field in a volume around the ship's hull. Numerical calculations are usually done by solving a three-dimensional partial differential Laplace-equation. Although this computational fluid dynamics (CFD) approach neglects friction, the squat is derived in good approximation. In particular in restricted coastal waters, dredged river sections or approach channels additional experimental validation is advisable.

Information about ship's squat can be derived from full-scale experiments, too. Today, all reliable methods of measuring squat are based on GNSS equipment aboard the investigated vessel. While traditionalmethods use land-based reference stations and tide gauge readings, the authors developed the SHIPS-method, in which the unperturbed water level is represented

by an escort craft equipped with a single GNSS-receiver for which the squat behaviour is known from a calibration experiment. The method eliminates the need for fixed reference stations, tide gauges and a perfect knowledge of the geoid and was successfully used in restricted waters as in the open ocean (Reinking et al. 2012).
As mentioned before the squat is in first approximation a quadratic function of the speed of the ship trough water (STW). GNSS observations allow deriving speed-over-ground (SOG) only. Hence STW must either be derived from SOG and information about currents or from other reliable sources such as a Doppler log on the ship.
In restricted waters the squat at the LCF can reach values of 1.5 m and more while in the open ocean it will rarely extend values of 0.5 m even for the biggest ships. In the open ocean it can be expected to derive the squat with a quality of 5-10 cm using CFD methods and of 3-6 cm using calibration results.

2.3 Geophysical Corrections

2.3.1 Corrections for ocean tides and tidal loading

Instantaneous LCF heights must be corrected for ocean tides and tidal loading. The corrections can be calculated using the SPOTL software package (Agnew 2012). To keep the resulting data consistent with that derived from other sources it is important to select the tidal model correctly.

2.3.2 Atmospheric loading

Atmospheric loading influences the sea surface and must be also corrected for. Commonly, this is done by calculating and applying the inverse barometer (IB) effect. The instantaneous IB effect on sea surface height can be computed from the atmospheric pressure at the sea surface.
The atmospheric pressure at the ship can be derived from log book recordings or additional readings of the ship's barometer. Before this data can be used for the calculation of IB corrections, a calibration is recommended. Since the barometer is commonly installed a the ship's wheelhouse deck the pressure readings from large ships should be corrected for the deck's height above the sea surface.

3. CASE STUDY: ATLANTIC OCEAN

To validate the possibilities and to check the limits of ship-based SSH observation an experiment was carried out on a vessel that sailed from St. Cruz de Tenerife to Funchal, Madeira (Fig. 1a) on March 19th and 20th 2011. The main purpose was to test the applicability of the SHIPS-method in unrestricted waters and to estimate the quality of the resulting heights (Reinking et al. 2012).
The ship used in this case study was the AIDAblu, a cruise vessel with an over-all-length of 252 m and a width of 32 m (Fig. 1b). According to the SHIPS method an escort craft was used to determine the squat of the AIDAblu during her approach to Funchal. For this purpose a fast but open boat was chartered (Fig. 1c).

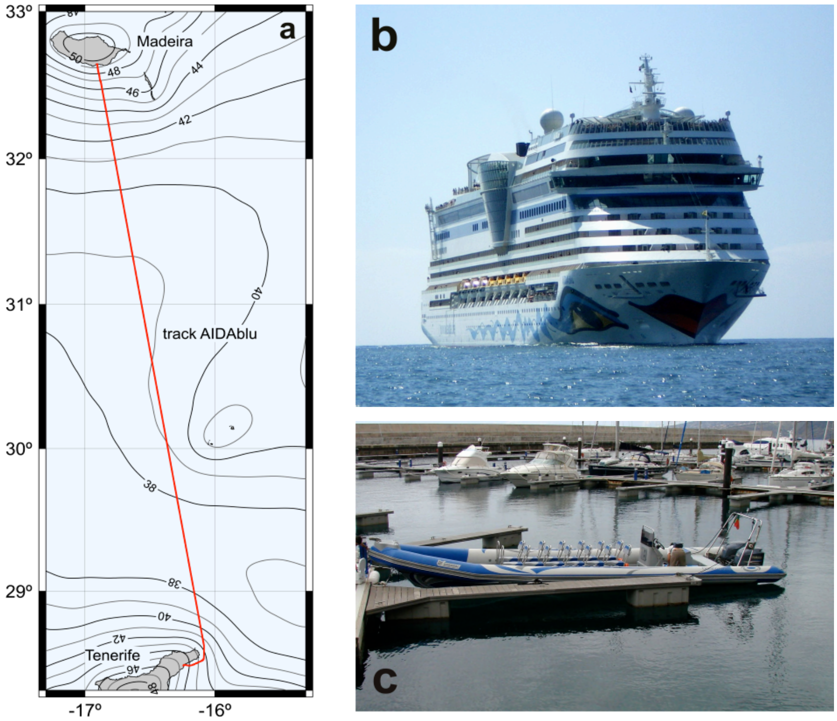

Fig. 1: Measured track between Tenerife and Madeira in the Atlantic Ocean, contour lines of EIGEN-6C geoid (a), cruise vessel AIDAblu used in this study (b), escort craft Oceanodroma used for calibration of cruise vessel's squat (c)

Three dual-frequency Trimble 4700 GPS receivers and Compact L1/L2 antennas without ground plane were installed aboard the cruise vessel, one at the foremast and two at the starboard and port sides close to the stern leading to a distance between the aft receivers and the one installed at the foremast of 188 m and between the starboard and port side receivers of 32 m. Another receiver and antenna of the same type was used aboard the escort craft.
The coordinates of the LCF in the ship's reference frame (SRF) were taken from the loading computer of the vessel and additional manual draft readings in both ports were used to verify particularly the vertical component of the LCF position. To derive the LCF position in a global reference frame later on, the GNSS antenna positions in SRF were taken from the general arrangement plan of the vessel and calibrated by GNSS-derived static coordinate differences and draft readings at the berth in Funchal.

3.1 GNSS Data Processing

The GNSS data processing was carried out using three software packages:

1. Self-developed software using an epoch-to-epoch carrier phase double difference approach yielding position changes in time. From the resulting data the course and speed over ground as well as the heave of the ships can be derived.
2. Self-developed dual-frequency carrier phase double difference in a moving-baseline mode to calculate kinematic coordinate differences between the ARPs of the receivers.

3. Bernese software 5.0 (BSW) (Hugentobler et al. 2006, Teferle et al. 2007, Geng et al. 2010) was used to derive he coordinates of the ARPs in IGS08 reference frame from PPP processing.

The results of all three processing modes were used to computethe ship's attitude and the relative position of the LCF, the heave of the escort craft and the cruise vessel and the final coordinates of the LCF in IGS08 reference frame.
To derive the 3D Cartesian coordinates of the LCF,to evaluate the quality of the results from the PPP processing and to detect and eliminate gross errors,the 3D coordinate differences of the antenna's ARPs and LCF from the moving baseline solution were transformed to the PPP solution. We eliminated all epochs showing a standard deviation of the translational transformation larger than a threshold of 7.5 cm for north and east directions and 10 cm for the upward component.A histogram of the standard deviations is presented in Fig. 2.The average standard deviation of the remaining epochs is 2.1 cm for the north, 1.8 cm for the east and 3.7 cm for the up component.

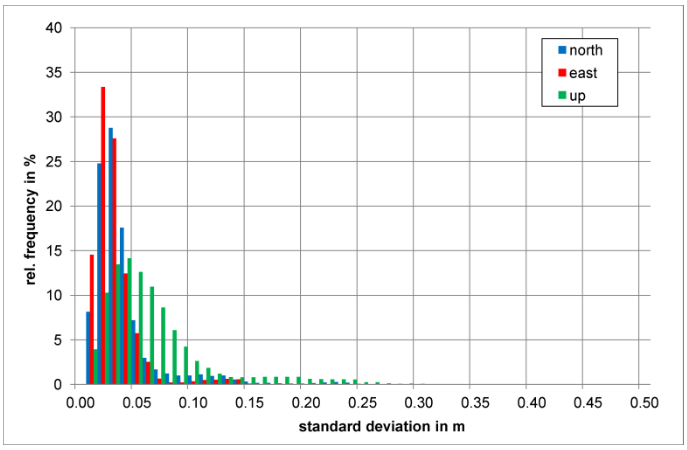

Fig. 2: Histogram of standard deviation of north, east and up component from translational transformation of relative coordinates of GNSS antennas to the PPP-derived absolute coordinates

The GNSS data of the beginning and end of the journey was also processed up to a distance of about 25 km from the shore lines of the islands with respect to the fixed reference stations in St. Cruz de Tenerife and Funchal in relative kinematic double-difference mode. Thus, for these sections, the LCF coordinates are derived independently and can be used to compare with the results from PPP processing.
The resulting differences for north, east and up components are shown in Fig.3. Taking into account the quality of the relative kinematic solution it seems permissible to assume a quality of the PPP result for the LCF coordinates of 2-3 cm for the horizontal and 4-6 cm for the upward component.

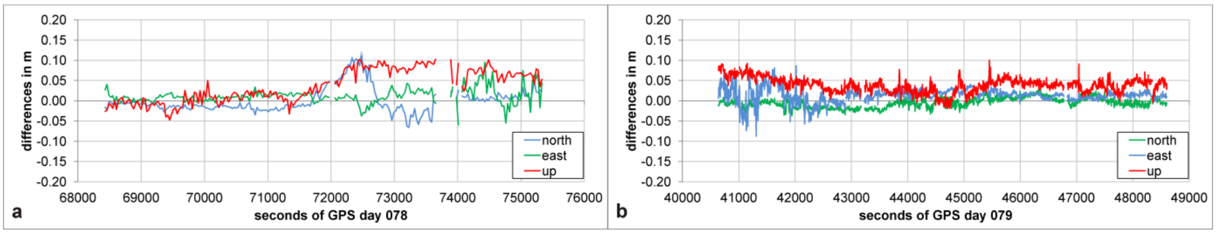

Fig. 3: Differences of LCF coordinates from PPP solution and relative kinematic processing for departure (a) and arrival (b)

3.2 Hydrostatic Corrections

Data from the vessel's voyage data recorder (VDR) for the whole cruise in conjunction with data from the loading computer were used to estimate draft changes due to fuel consumption or variation of water density. The values of water density show no variation, hence no correction was applied. As mentioned before additional manual draft readings in both ports were used to verify particularly the vertical component of the LCF position.
The antenna coordinates in SRF were derived from readings of the general arrangement plan which gives in this case a quality not better than 0.5 m. To ensure high-quality coordinates, particularly in the height components, we processed the GNSS data from the receivers aboard the cruise vessel relative to the one on the escort craft in the port of Funchal without motion of both platforms and derived the coordinate differences of the ARPs. The height of the ARP on the escort craft above the water level was measured by tape. Since the LCF at berth represents the water level and its height in SRF is well-known from draft readings, the heights of the ARPs of the receivers aboard the cruise vessel relative to SRF could be adjusted to derive the correct height difference to the water level later on.

3.3 Hydrodynamic Corrections

3.3.1 <u>Heave correction</u>

Double-differences of carrier phase between consecutive epochs were used to obtain 3D coordinate differences between epochs. These coordinate differences were corrected for the changes of the pitch and roll angles between the epochs using the GNSS-derived ship's attitude data.
The vertical components of the cumulated coordinate differences of a GNSS antenna were high-pass filteredto reduce the influence of systematic effects and a random walk. In this investigation we used a 6th order Butterworth digital high-pass filter (Parks and Burrus 1987) with 0.025 Hz cut-off in a forward-backward application. The selected cut-off reduces effects with a period longer than about 40 s and seems to be adequate since we assume that waves show only shorter periods in moderate sea conditions (Van Dorn 1993).
The results for all antennas aboard the same ship must be equal since they should describe the vertical movement of the whole ship. Therefore the single heave values are averaged for every distinct epoch to derive the heave of the ship's LCF. The average standard deviation for the heave is 0.007 m, the histogram of the standard deviations for all epochs is shown in Fig. 4.

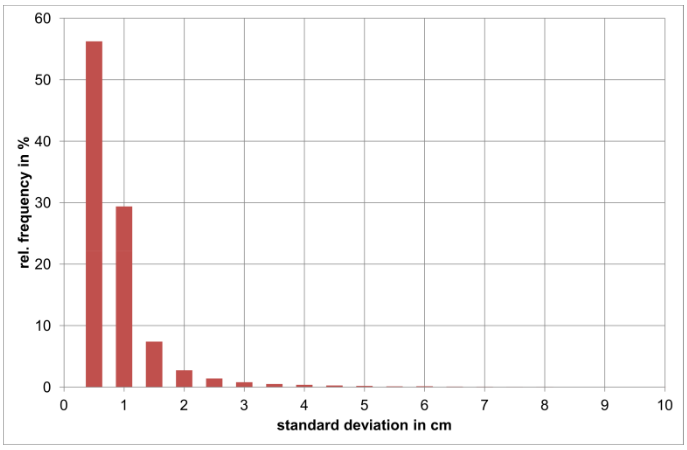

Fig. 4: Histogram of standard deviations of heave determination for the cruise vessel for all epochs.

3.3.2 Squat correction

Since we used an escort craft during this experiment, a squat function of the cruise vessel can be derived in from a calibration according to the SHIPS method. The escort craft sailed ahead the cruise vessel during the approach to Funchal and represents the undisturbed water level. The escort craft itself is influenced by its own squat, too. Hence, a calibration of the escort craft is likewise necessary.

To describe and apply the squat correctly the speed through water (STW) of the vessel must be known.The STW from the Doppler log was not recorded in the VDR data, so we recorded it manually for the major part of the journey while the vessel sailed in deep water. The relation between STW and GNSS-derived SOG was found to be linear with a constant factor of 0.99. Therefore, we assume no hydrodynamically relevant current in this area during the experiment and will use the SOG as STW. A comparisonof the SOG of thevessel and the revolution-per-minute data (RPM) of the ship's propeller from the VDR in conjunction with the recorded headwind shows discrepancies of less than 0.3 m/s and the average absolute value was0.07 m/s.

Calibration of escort craft:

The calibration experiment was carried out at the port of Funchal in an "inverted" mode of the SHIPS method: the cruise vessel was used after berthing as a floating platform to represent the water level and the coordinate differences between the LCF of the cruise vessel and the ARP of the escort craft was calculated from the GNSS relative kinematic processing using self-developed software.

The escort craft was operated at various speeds in the vicinity of the cruise vessel and engine stop maneuvers were carried out several times. Since, on a small boat, this maneuver takes only a few seconds, the squat effect can be seen directly from the change in height differences between the LCF and the ARP onthe escort craft after the heave for both ships has been applied. Fig. 5 shows the height differences corrected for heave and the related speed of the escort craft. The height differences were reduced by the height of the ARP aboard the escort craft above water level.

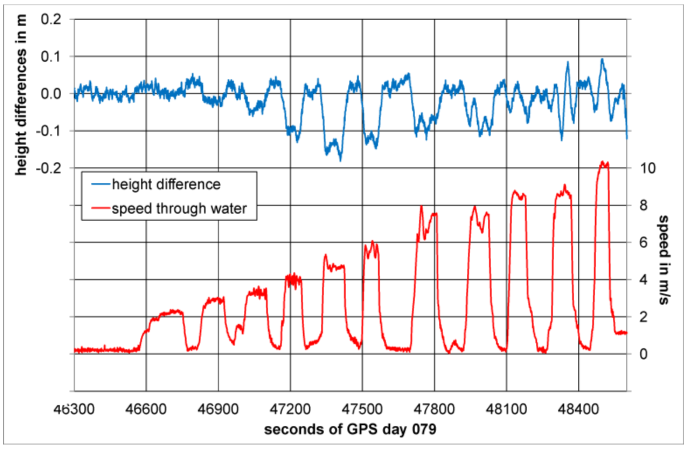

Fig. 5: Heave corrected height difference between LCF and escort craft's ARP and speed through water of the escort craft in the port of Funchal.

After cleaning the data for segments with acceleration and turns a thin-plate spline least squares approach (Franke et al. 1994) was used to derive a functional fit based on the remaining 644 data points (Fig. 6). The resulting function describes a typical hydrodynamic behavior of a small but fast boat (Härting et al. 2007).

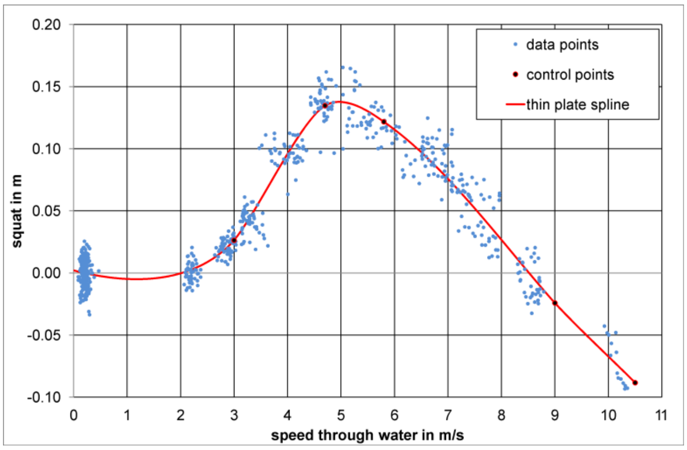

Fig. 6: Speed-depending height variation of the ARP aboard the escort craft. Used data points and control points of least squares thin-plate spline adjustment and resulting thin-plate spline function.

Calibration of cruise vessel:

The heights of LCF from relative kinematic processing of the departure from Tenerife and arrival in Madeira together with the heights of the ARP of the escort craft, likewise derived from relative kinematic processing and corrected for squat and heave, were used to estimate the squat of the cruise vessel. The data of the departure was restricted to a segment of distance between 5 km and 25 km from the port of St. Cruz de Tenerife to eliminate data containing maneuverings at the beginning of the journey. The arrival data were reduced by a segment when the cruise vessel was travelling astern during the approach of her berth in the port of

Funchal. Fig. 7 shows the used tracks and contour lines of geoid heightsfrom EIGEN-6C.

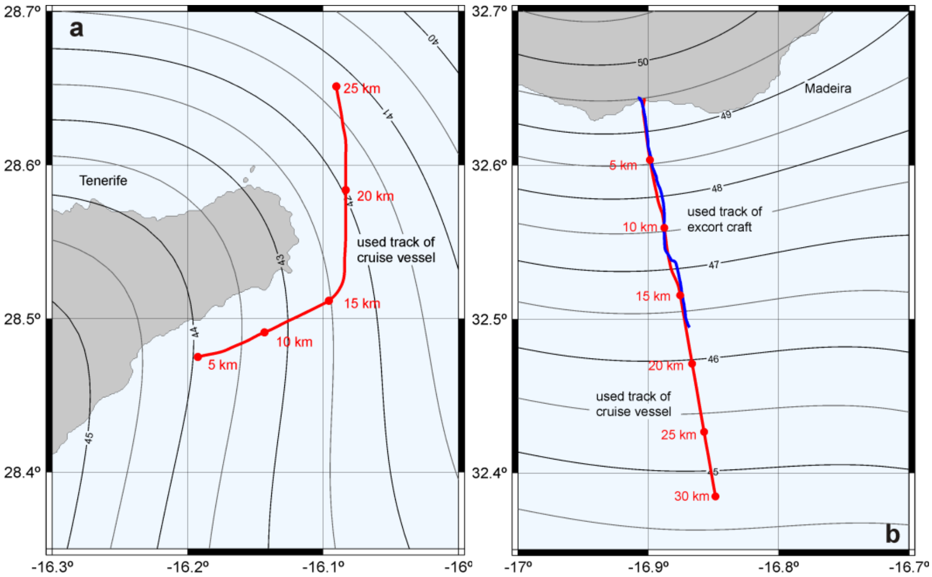

Fig. 7: Tracks of cruise vessel and escort craft during departure (a) and arrival (b) used to derive a squat function for the cruise vessel. Sailed distance along the track (a) and distance from shore line (b) in km.

All observed data were introduced into a least squares adjustment in which some additional systematic effects were considered.Fig. 8 presents the adjusted LCF heights for Madeira and Tenerife and the resulting squat function. A confidence interval was created by doubling the standard deviation of 0.8 cm at the maximum speed of 9.5 m/s and applied for all speeds. The squat of the cruise vessel reaches a value of 29.6 cm for the maximum speed of 9.5 m/s. If a maximum error in the speed through water of 0.3 m/s is assumed, the error in the squat value will still be less than 2 cm and therefore in the range of the measurement quality.

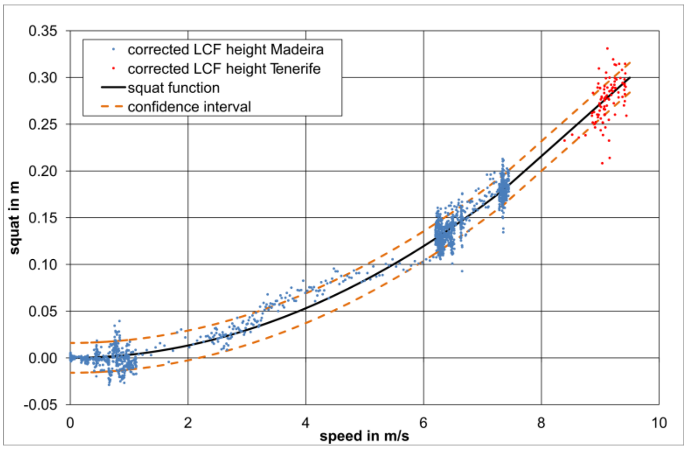

Fig. 8: Adjusted heights of LCF with respect to static heights, resulting quadratic squat function and related confidence interval.

To double-check the resulting squat, additional CFD calculations can be used. As theexact hull form of the cruise ship was not available for this investigation, calculations for different ship types with hull forms and block coefficient C_b (quotient of the vessel's displacement and the surrounding cuboid calculated from ship's length, width and the static draft)known from former projects were used for comparison. CFD calculations were performed at different speeds for ships with diverseC_b. For every ship a quadratic function was derivedand plotted in Fig. 9 together with the squat function of the cruise vessel from this investigation. The squat of the cruise vessels fits very well to the data from CFD calculations.

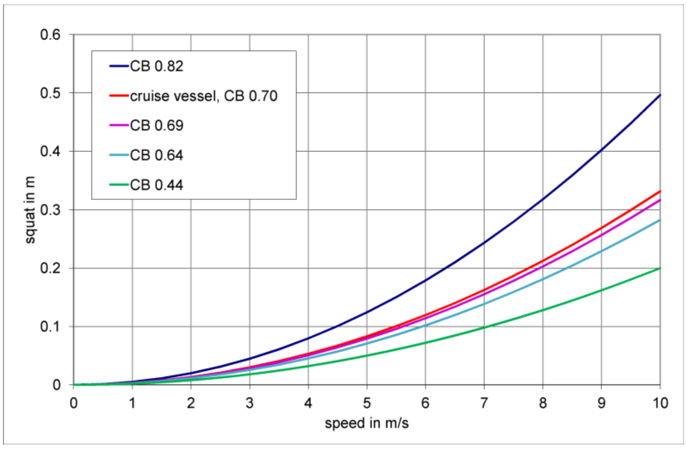

Fig. 9: Squat functions for the cruise vessel derived from this experiment and for ships with different block coefficients CB calculated by means of CFD

3.4 Geophysical Corrections

The purpose of this experiment was to test the applicability of the SHIPS-method in unrestricted waters and to estimate the quality of the resulting LCF heights. Although it is necessary to apply geophysical corrections if SSH is to be derived, it is sufficient for the present purpose to analyze the corrected LCF heights. Hence, there was no need to apply geophysical correctionsin this test experiment.

3.5 Resulting LCF Heights and Their Quality

The resulting height of the LCF obtained from the PPP solution and reduced for gross errors and outliers can be interpreted as the instantaneous SSH including tidal variations, ocean and atmospheric loading and changes of geoid heights along the track of the cruise vessel. Fig. 10 shows the uncorrected LCF height in IGS08.It is clear that this result is influenced by a heave of the ship of up to 1 m. The heave-corrected LCF height shows a much lower dispersion but it is still influenced by the squat of the ship. This was corrected for by the derived squat function. The fully corrected LCF height represents the instantaneous SSH.

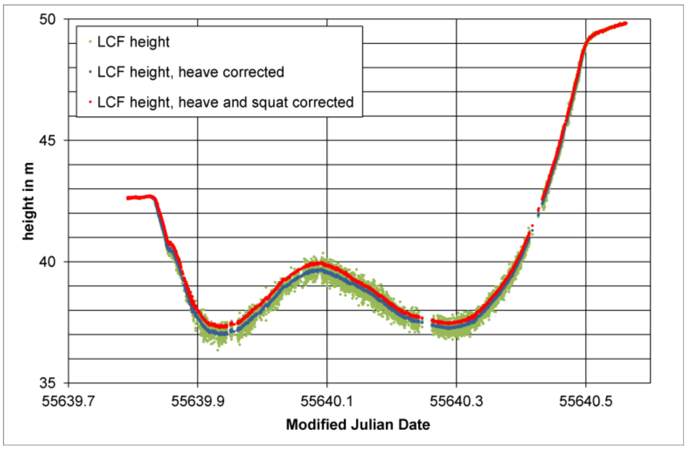

Fig. 10: LCF height between Tenerife and Madeira along the track of the cruise vessel. The fully corrected LCF height represents the instantaneous SHH.

Assuming that these influences are governed by a long-periodic variation, a short-period precision (SSP) can be calculated in analogy to Bouin et al. (2009).We computed the standard deviation of the mean value of the derived SSH over an interval with a length of 500 m. Although the correct elimination of the ship's squat cannot be controlled by SPP, since it is a long-periodic systematic effect itself, this value gives an acceptable indicator for the noise level of the data. The histogram of the SPP values is shown in Fig. 11, where the average SPP is 1.9 cm with a maximum value of 8.1 cm.

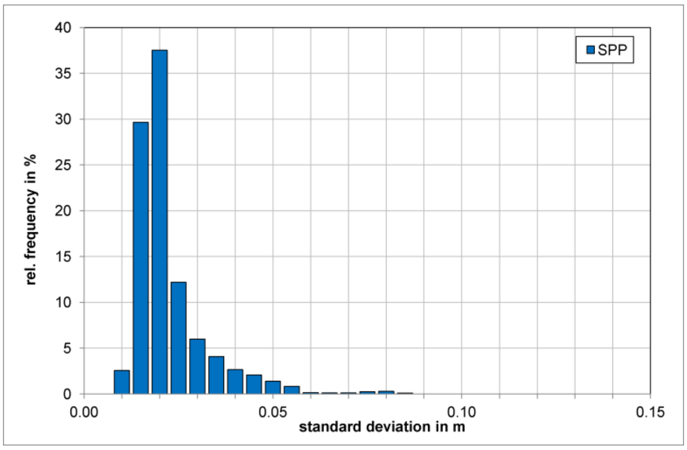

Fig. 11: Histogram of short period precision (SPP) of LCF height calculated over intervals of length 500 m along the track of the cruise vessel.

4. OCEAN WIDE DETERMINATION OF SSH

To test the methods also over a largerdistance and a longer period under more practical and routine conditions we decided to carry out an observation aboard a container ship that frequently sails between Asia and Middle and South America (Roggenbuck et al. 2014).
The vessel used in this experiment was the Monte Verde of Hamburg Süd Group, a 5500 TEU container vessel with an over-all-length of 272 m, a width of 40 m and a maximum draft of

12.5 m. The experiment was carried out on her journey from Hong Kong via Busan, South Korea, to Manzanillo, Mexico, crossing a wide part of the Pacific Ocean over a distance of about 12000 km between April 5th and May 1st 2012. Because the ship called at some other ports between Hong Kong and Busan and often sailed along the coast in shallow waters only the section from Busan to Manzanillo was used for SSH determination (Fig. 12).

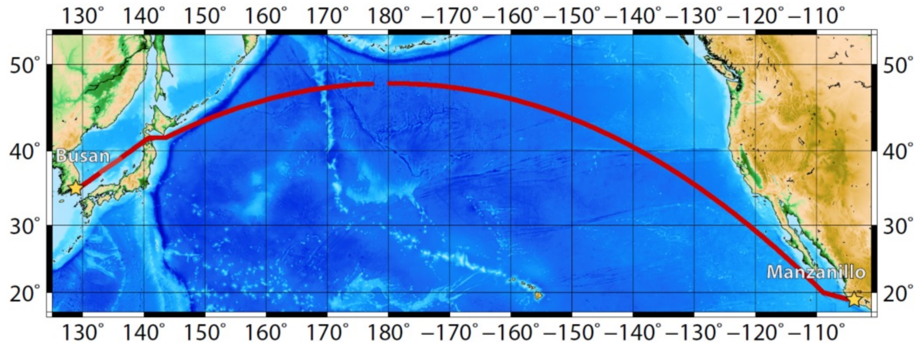

Fig. 12: Track of the cargo ship used to derive sea surface heights in the Pacific Ocean.

The ship was equipped with two single-frequency RCB-LJ u-blox GNSS receiver boards with AT575-70 antennas installed on top of the fore and aft masts. To allow for a later PPP processing and to derive the ship's attitude from GNSS observations, two additional dual-frequency Hemipshere mini-Eclipse receivers with Hemisphere A52 antennas were mounted at the port and starboard bridge wings. GNSS data of all receivers were collected with 1 Hz sample frequency.

Unfortunately, we did not get access to the vessel's voyage data recorder (VDR) due to a hardware problem. Hence, some relevant data had to be recorded manually and completed by information from the logbook.

The coordinates of the LCF in the ship's reference frame (SRF) were taken from the loading computer of the vessel. GNSS data from Hong Kong's SatRef network were processed together with the data from the GNSS receivers aboard the ship to find the coordinates of the GNSS antennas in the ship's reference frame.

4.1 GNSS Data Processing

To derive the epoch-to-epoch coordinate differences and thekinematic coordinate differences between the ARPs of the receivers aboard the vessel the above described self-developed software for GNSS data processing was used likewise.

The coordinates of the antennas in IGS08 reference frame were derived from PPP processing using the Online Global GPS Processing Service (CSRS-PPP) of Natural Resources Canada (NRCAN). The data of the two dual-frequency receivers at the port and starboard side were smoothed and reduced from 1 s to a 5 s data rate. It must be kept in mind that the resulting data are related to conventional tide-free crust and ocean loading was not considered.

The coordinate differences in a local horizontal system for both receivers together with those of the LCF were transformed to the absolute coordinates of the antennas. Since the local plane coordinate differences are superior in quality only a translational transformation was applied.

Again, the residuals of this transformation were used as a quality criterion for the PPP results and to detect and eliminate gross errors. We eliminated all epochs showing a standard deviation larger than a threshold of 5 cm. Fig. 13 presents the histogram of the absolute residuals of the remaining epochs. The average residual is 0.7 cm for the north and east and 1.7 cm for the up components.

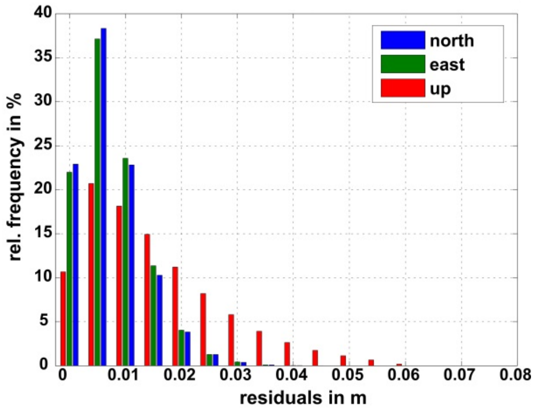

Fig. 13: Histogram of the absolute residuals of a translational transformation of the coordinate differences in a local tangent plane to the absolute coordinates from PPP solution.

4.2 Hydrostatic Corrections

The positions of theGNSS antennas in the ship's reference frame (SRF) were obtained from a calibration observation in the port of Hong Kong after loading was finished. The vessel's GNSS data were processed together with data from a reference station of Hong Kong's SatRef. The resulting ellipsoidal height differences were corrected for the differences of the geoid heights to relate them to the Hong Kong Principal Datum (HKPD) and finally to the Chart Datum.
The antenna heights above the water level were determined from the comparison of the readings of the nearby tide gauge, likewise related to the Chart Datum.In conjunction with draft readings at the fore and aft perpendiculars and the LCF height in SRF from the loading computer, the antenna heights in the SRF were calculated with a quality of better than 2 cm.
During the voyage the vertical position of the LCF was taken from the loading computer of the ship, which recorded and considered all relevant changes of the ship's displacement in its calculation. Nevertheless, the resulting draft at the LCF might differ from the actual draft because the water density is an estimated value only. A correction must be calculated based on actual water temperature and salinity.
The water temperature observed aboard the ship and salinity data from the Aquarius satellite were interpolated to the epochs and sites of observation.The draft correction was calculated using a 3D model of the ship's hull which was available from earlier investigations of this ship. The difference of the reciprocal densities was multiplied by the mass of the ship to derive the change in volume. To derive the draft correction the volume change must be divided by the waterline area calculated from the 3D hull model at the LCF draft. The calculated corrections are presented in Fig. 14. The absolute value do not exceed 1.5 cm.

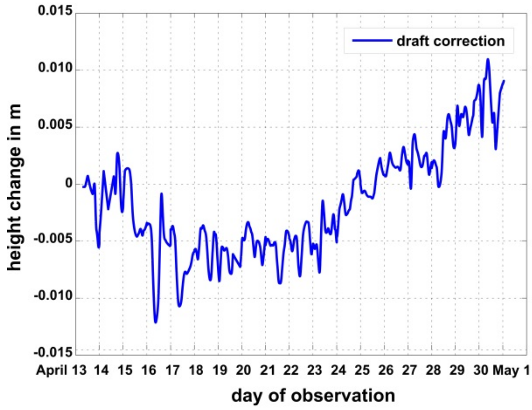

Fig. 14: Draft correction due to water density differences between actual data and values used by the loading computer of the vessel.

4.3 Hydrodynamic Corrections

4.3.1 Heave correction

The epoch-to-epoch height differences, obtained with self-developed software, were corrected for epoch-to-epoch pitch and roll changes. The heave of all four receivers aboard the vessel was derived again from these cumulated and high-pass filtered differences. The data, recorded in a moderate sea state, was filtered using a 6th order Butterworth digital high-pass filter with 0.025 Hz cut-off in a forward-backward application. Fig. 5 shows a 3 min section of the data for GPS day 4 of GPS week 1685. The heave for all four antennas was averaged to calculate the heave at LCF. About 90% of the rms from all epochs shows a value below 1.5 cm.

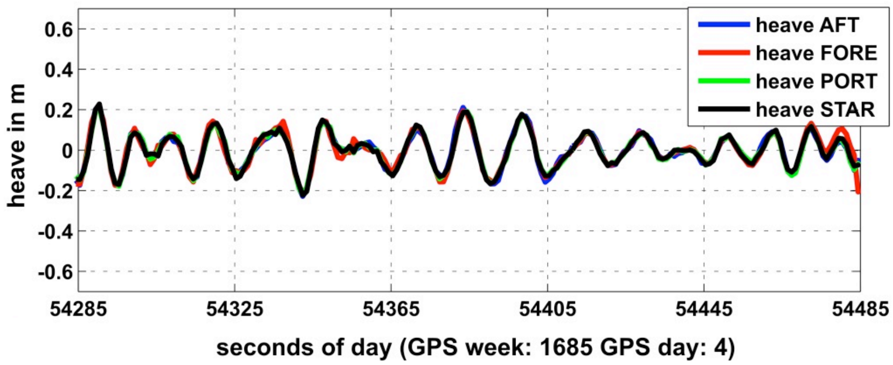

Fig. 15: Heave at the antenna positions of the four GNSS antennas aboard the vessel for a 3 min section of GPS day 4, GPS week 1685, roll and pitch corrected.

4.3.2 Squat correction

Since no data from the ship's VDR was available STW was manually recorded from the Doppler log every 20 minutes (daytime only) as an average over 20-30 s. Speed over ground (SOG) was derived from GNSS observations and compared to STW. The differences were

filtered, interpolated and later used to calculate the STW from GNSS-derived SOG. The uncertainty of the calculated STW can be estimated as less than 0.15 m/s.
As the 3D model of the ship's hull was available the squat at LCF was calculated from CFD for a series of different drafts. For a draft variation from 12.8 m to 13.2 m the squat changes by about 9 mm at a speed of 10 m/s. To double-check the CFD results two stop maneuvers of the vessel for engine maintenance during the voyage couldbe used. The period of speed reduction for both events is presented in Fig. 16. Because the events extend over a distance of about 15 km and 25 km respectively the PPP-derived LCF heights were corrected for geoid height change from EGM2008 (Pavlis et al. 2012) and tide influence as well as heave. Height differences were determined with respect to an average LCF height at minimal STW.

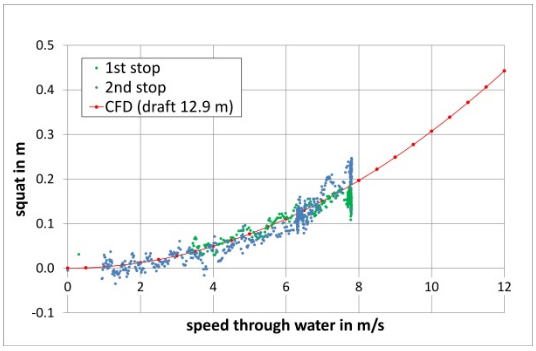

Fig. 16: Variation of LCF heights (left axis) and speed through water (right axis) during the two periods of stop maneuvers of the vessel.

The results for both stop maneuvers are presented in Fig. 16 together with the CFD-derived squat at a draft of 12.9 m. Although the quality of the observed values is limited it is reasonable to assume that the CFD results have a quality of better than 1 cm. Taking additionally into account the above mentioned uncertainty in the STW of 0.15 m/s, which will result in a squat discrepancy of 9 mm at a STW of 10 m/s, the overall quality of the squat can be assumed as 1.5 cm.

4.4 Geophysical Corrections

4.4.1 Corrections for ocean tides and tidal loading

The corrections for ocean tides and tidal loading were calculated using the SPOTL software package (Agnew 2012). To reduce the computation time only 144 instants per day with an interval of 10 min were processed and later interpolated to the time of measurement. We checked for one day that the differences between modelled and interpolated data for 1 min intervals are less than 0.5 mm.
Although the predominant part of the voyage was in the open ocean we decided to use the DTU10 model (Cheng and Anderson 2010) since it is a shallow-water extension and adjustment of the FES2004 which will later be used with altimetry data.

4.4.2 Atmospheric loading

The atmospheric pressure from the ship's barometer was recorded every 20 minutes during day time and taken from log book entries at night time. Before this data has been used for the calculation of IB corrections, a calibration was carried out using barometer readings over a period of 3.5 h at the port of Busan and official pressure data from the airport of Busan which is located in a distance of about 15 km from the ship's berth. The rms of this comparison is about 0.3 mbar yielding an uncertainty of the IB correction of less than 3 mm.
During her voyage the ship passed an anticyclone with a maximum pressure of about 1038 mbar resulting in an IB correction of about -25 cm.

4.5 Resulting Heights and Their Quality

For this experiment sea surface heights are derived after applying all necessary corrections to the LCF heights. A large portion of the data was eliminated during the processing because it did not pass the threshold tests explained in section 3.3, for instance during the transformation of local tangent plane coordinate differences, for both receivers together, to the PPP-derived coordinates of the antennas. In total 46% of all observed 5 sec-data can be used for further investigations of the SSH.
The short period precision (SPP) was calculated for the SSH, for which we computed the standard deviation of the mean value of the derived SSH over an interval of 500 m. The histogram of the SPP values is shown in Fig. 17, where the average SPP is 1.2 cm with a maximum value of 19 cm.

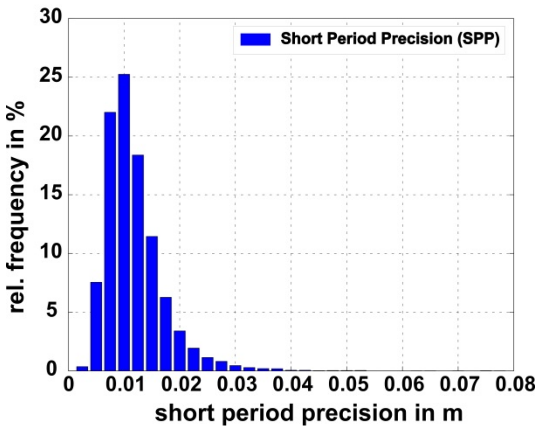

Fig. 17: Histogram of the short period precision over an interval of 500 m.

4.6 Comparison with SSH from Altimetry

The GNSS-derived SHH from this experiment can be compared with data from satellite altimetry. From the five missions in space in April 2012 only Jason-2 was usable during the period of the ship's journey. Unfortunately, Envisat seized communicating on April 8th and Jason-1 did not send data in April because it was moved to another orbit in March. The SSH data from Cryosat-2 did not reach the quality level of other missions and data from the Chinese HY-2 mission were only accessible with permission of the Chinese spaceauthorities.

4.6.1 Data sources and corrections

We accessed the final 1 Hz geophysical data records (GDR, Version "D") for cycle 135 to 145 of Jason-2 from the NODC server (National Oceanographic Data Center) of NOAA (National Oceanic and Atmospheric Administration). Editing and processing of the data was carried out using the Basic Radar Altimetry Toolbox (BRAT, Rosmorduc et al. 2011) using the BRAT standard formula for SSH determination SSH_Jason2. To keep the SSH data consistent with that derived from ship-based measurements we replaced the standard ocean tide values of model GOT4.7 with FES2004 using parameter ocean_tide_sol1 instead of ocean_tide_sol2.
The LCF heights were transformed form WGS84 ellipsoid to the Topex/Poseidon reference ellipsoid to conduct the comparison in the reference frame of the Jason-2 altimetry data. The GNSS-derived heights are given in a conventional tide free reference systems and were converted to the mean tide system using IERS formulae (Petit and Luzum 2010).

4.6.2 Cross-over points

Every Jason-2 GDR set represents one site of observation that extends over the area of the altimeter footprint which can cover several km^2. For the definition of a cross-over point of the altimeter's and ship's tracks we set a maximum distance of 5 km. Hence, all footprints which are closer than 5 km to at least one point of the ship's track were defined as cross-over points. In total 1342 altimeter footprints fulfilled this condition.
To reduce influences from the geoid's structure we corrected all ship-derived SSH for the difference of the geoid heights at the footprint centre and the corresponding LCF positions derived from EGM2008. All corrected ship-derived SHH at the LCF positions had to be averaged. Since the Jason-2 tracks of all cycles form a regular pattern that crosses the ship's track, the cross-over points form groups at almost the same longitudes. The cross-over points in each group were used to calculate an average for the longitude group.
Fig. 18 presents the differences and the mean of the groups. It can clearly be seen that the first group at a longitude of about 129° shows a much stronger dispersion than the other groups. All cross-over points of this group are observed close to the coast at the beginning of the voyage in Busan. At that position larger differences may be a result of short-wavelength geoid changes not present in the global EGM2008 geoid model, or systematic effects in altimeter data. The average standard deviation of the other groups is 4.1 cm.At a longitude of about 184° an outlier in the LCF heights was detected that was not identified and eliminated by the various thresholds used in the processing. After removing these blunders the average of the differences is -75.1 mm, calculated with a standard deviation of 5.8 mm and an rms of 42.5 mm.

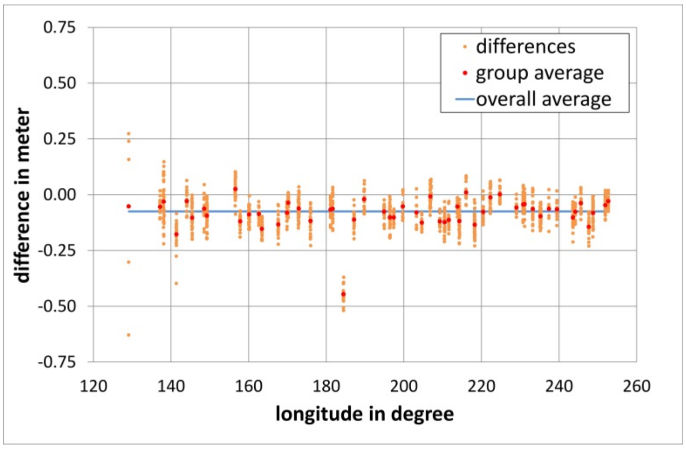

Fig. 18:SSH differences between ship-derived and Jason-2 measurements and their mean values for the latitude groups as well as the overall average of all differences.

This result fits well to the findings from in-situ calibration at Kerguelen Island (Testut et al. 2012) which shows a mean difference of -77 mm with an rms of 48 mm.It should be emphasized here that these results were not derived at one particular site but on a campaign covering the width of the Pacific Ocean over a longitude sector of about 132° and a distance of 12000 km. The stability of the differences over the whole area is impressive and underlines the applicability of ship-based GNSS observation for SSH determination.

4.6.3 Spatial Resolution

The ship crossed the Hawaiian–Emperor seamount chain and the altimeter data was interpolated in this area to allow for a comparison with ship-derived SSH.Although it is clear that satellite altimetry is not very sensitive over short wavelengths, this comparison shows the potential of a possible combination of both data sources. Fig. 19 shows the ship track and the color-coded SSH interpolated by thin-plate-spline of Jason-2 data. Fig. 20 presents the ship track projected onto the sea floor and the ship-derived SSH.

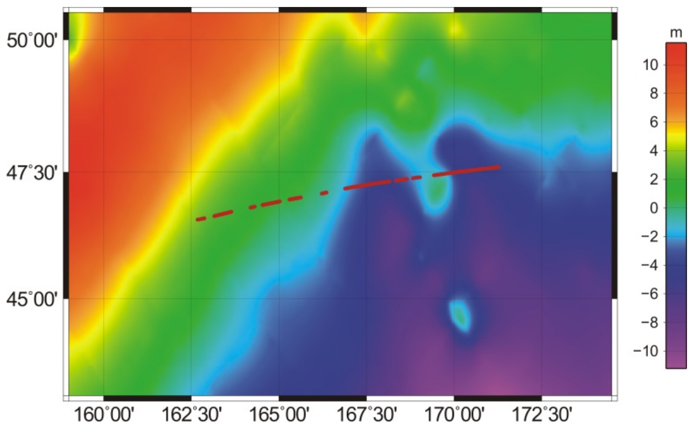

Fig. 19: Spatial interpolated and color-coded SSH from Jason-2 and the ship track.

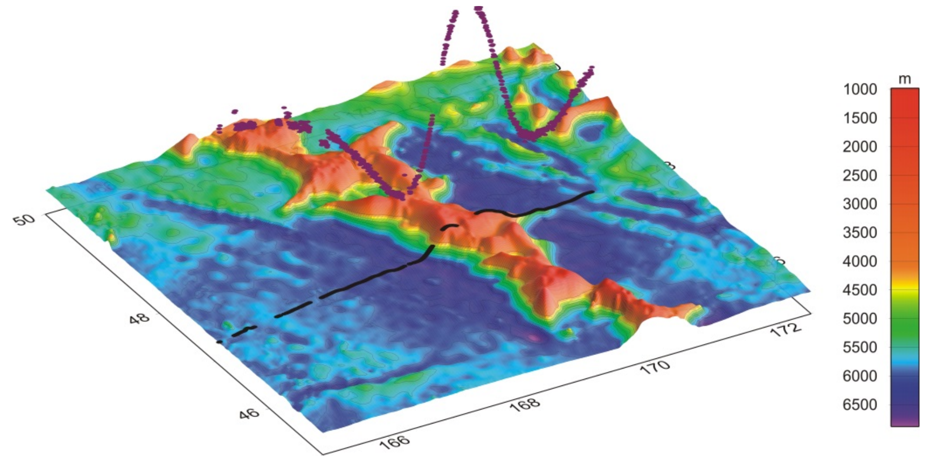

Fig. 20: Projected ship track crossing the Hawaiian–Emperor seamount chain and the ship-derived SSH.

Even though the basic formation of the sea floor is distinguishable in Fig 19, it cannot be expected that the interpolated SSH from Jason-2 will reflect the detailed structure that results from variations of geoid undulation. Fig. 20 shows that SSH from ship-based observations is suitable to also investigate short wavelength variations of the sea surface. While this is only true in along-track direction, it indicates that it would be worth to combine satellite altimetry data with a larger number of ship-based measurements.

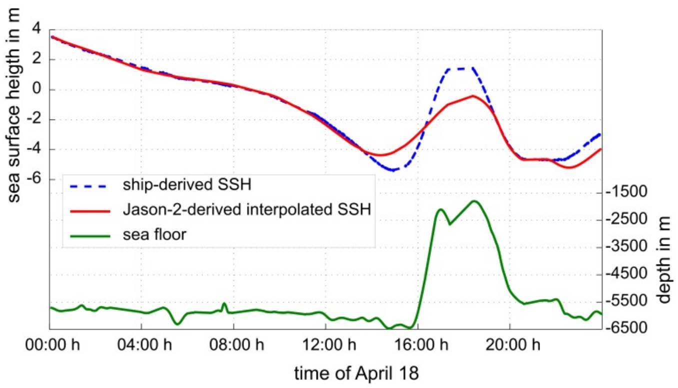

Fig. 21: Sea floor heights (right axis); ship-derived (red) and Jason-2-derived interpolated (blue) SSH (left axis).

5. CONCLUSION

We demonstrated that ship-based GNSS measurements can be used for precise observation of SSH if appropriate corrections are taken into account. Apart from static corrections, which directly influence the draft of a vessel and hence the antenna height above the sea level, additional hydrodynamic and geophysical corrections must be considered. Provided the relevant side data are recorded, such measurements can be done on almost any kind of ship.

Using merchant vessels would open up a new, continuous data source in addition to existing programs.
The determination of antenna heights from GNSS observations limits the precision of ship-based SSH measurements. In coastal waters fixed reference stations can be used to derive relative coordinates with the typical precision of kinematic GNSS processing. Nowadays, PPP processing offersgood possibilities to derive absolute heights in the open ocean with a quality of better than 5 cm, also for kinematic applications. It has proven reasonable to use multiple GNSS receivers aboard a ship to derive highly precise relative coordinate differences, which can be used for blunder detection and the elimination of gross errors.
The hydrodynamic corrections can be determined with high precision for small craft as well as for seagoing ships from calibration experiments using the SHIPS method. For observations in unrestricted waters were the squat is a function of STW only calculations from CFD can be used alternatively if a 3D model of the ship's hull is available.
The experiment in the Pacific Ocean has shown that the quality of results from ship-borne SSH determination is consistent with the one achieved in satellite altimetry, thus allowing a cross-wise validation over large areas. Feeding ship-based data into a combined analysis with satellite altimetry seems attractive, because the excellent along-track resolution could serve to improve the spatial resolution of global SSH models.

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BIOGRAPHICAL NOTES

Prof. Dr. Jörg Reinking studied geodetic engineering at the Technical University (TU) Berlin, Germany and received his diploma in 1988. Since 1988 he has worked as a research associate at TU Berlin and Technical University (TU) Braunschweig, Germany. He obtained his doctorate from TU Braunschweig in 1993 and worked as a scientist at the GeoForschungsZentrum (GFZ) Potsdam from 1993 to 1997. Since 1997 he has been a Professor of geodesy, adjustment techniques and hydrographic surveying at the Jade University of Applied Sciences in Oldenburg, Germany. During the last decade he was engaged in the development of geodetic observation and analysis strategies for ship dynamic analysis (squat, trim and roll) and founded the Institute of Metrology and Analysis Techniques and is a member of the Institute of Maritime Studies in Elsfleth, Germany.

Prof. Dr. Alexander Härting is a physicist who received his doctorate from the University of Regensburg, Germany, in 1984. He held positions as an orbital mechanics contractor at the German Space Operations Centre and as a scientist at the GeoForschungsZentrum (GFZ) Potsdam. Since 1995 he has been a professor of physics and navigation at the Jade University of Applied Sciences in Elsfleth, Germany. As a member of the local Institute of Maritime Studies his main field of research is ship dynamics.

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