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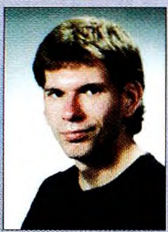

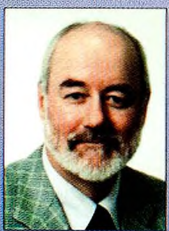

Marine Motion Measurements Using GPS

Heave, Roll and Pitch Determination from GPS Measurements and its Consistency with INS Data

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Geodetic space techniques like the Global Positioning System (GPS) have gained prominent importance for precise global positioning during the last decades. Since the 1990's, GPS measurements have been used increasingly for hydrographic purposes. The variety of applications includes the determination of the orientation of vessels, the measurement of sea-surface heights on floating platforms (e.g. buoys) as well as the determination of height reference systems of islands.

In the present case, five GPS antennas were installed on board a vessel while cruising in the southern Baltic Sea. Based on the observed kinematic GPS data, sea-surface heights as well as the vessel's motion parameters (heave, roll and pitch) have been determined. In addition, the corresponding motion values from the vessel's Inertial Navigation Systems (INS) were available.

This paper describes the realisation

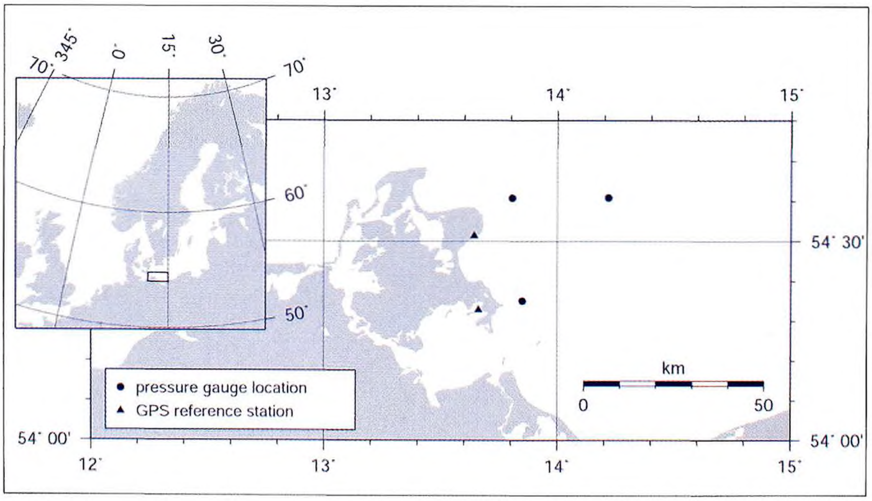

Figure 1: Map of the measurement area in the southern Baltic Sea. The pressure gauge locations and the GPS reference stations are shown

Figure 2: The survey, wreck-search and research vessel DENEB of the Bundesamt für Seeschifffahrt und Hydrographie

and analysis of the GPS measurements. The derived motion parameters are presented and discussed. Special attention is paid to the achieved precision of the results. The comparison of the GPS-derived motion parameters with the independent INS data constitute an essential issue.

The results reveal the capability of GPS measurements to determine both the vessel's motion parameters and precise sea-surface heights under the conditions predominating in the southern Baltic Sea region.

Introduction

Within the scope of the project VEREXT (*Verifizierung ozeanographisch modellierter Meeresspiegelschwankungen der Ostsee mit Hilfe geodätischer Beobachtungen unter besonderer Berücksichtigung von Extremwasser-ständen*), investigations on the sea-level variability of the Baltic Sea have been carried out at the Institut für Planetare Geodäsie of the Technische Universität Dresden (Dietrich et al, 2002). In order to derive sea-level data in the offshore area close to the coast, three pressure gauges were moored on the sea bottom east of Rügen Island (Figure 1). The deployment and recovery of the pressure gauges was accomplished with the aid of the survey vessel *DENEB* (Figure 2) of the Bundesamt für Seeschifffahrt und Hydrographie in May 2000 and May 2001 respectively.

The data of the pressure gauges allow investigations on sea-level variations at their deployment location. Spatial comparisons of sea-level heights derived from pressure gauges require the reference of the measured data to a geodetic height system. The referenced heights of the pressure

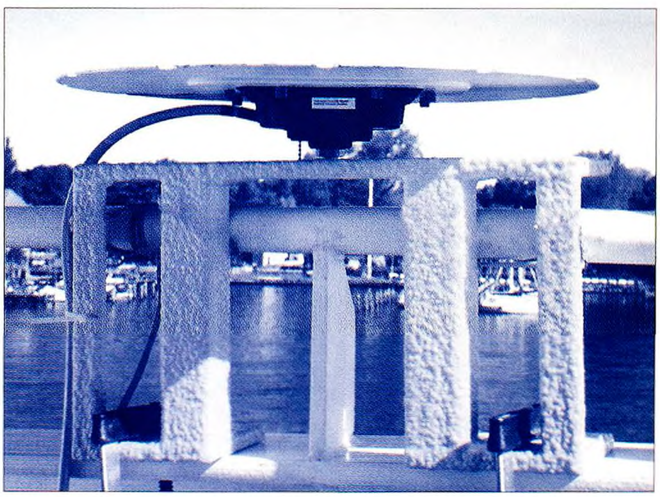

Figure 3: Example of the mounting of a GPS antenna on the DENEB (top deck)

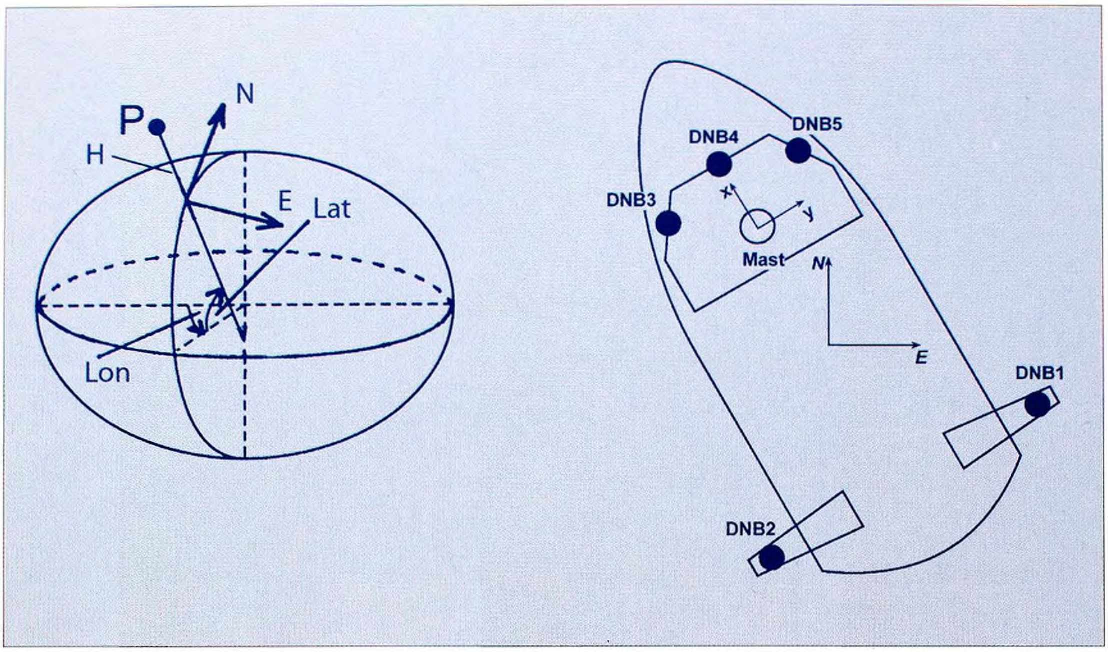

Figure 4.1: Schematical illustration of the used coordinate systems. left: geocentric, ellipsoidal coordinates (Lat, Lon, H) and local topocentric (N. E) coordinates right: local topocentric (N, E) and body-fixed (x,y) coordinates at the example of the DENEB's GPS network The ellipsoidal latitude (Lat) specifies the angle of the point with respect to the equator plane, and the longitude (Lon) that angle with respect to the Greenwich meridian. The ellipsoidal height (H) represents the vertical distance between the surface of the ellipsoid and the point.
The coordinate axes of the local topocentric coordinate system (origin in the balance point of the GPS network) are orientated to the north (N), east (E) and perpendicular to the ellipsoid. The coordinate axes of the body-fixed, vessel-referenced system with the origin in the main mast run along the vessel's longitudinal axis (x), across the vessel's axis (y), and perpendicular to both axes (z). The GPS network consisted of three points on the top deck and one point of each rear arm

gauges' zero points were determined by kinematic GPS measurements during the deployment and recovery cruises. For this purpose, five Trimble GPS antennas were mounted on board the *DENEB* (Figure 3). Kinematic data were logged during stays in the harbour and offshore under different meteorological conditions. In order to provide differential 3D positioning with cm-level accuracy, two GPS stations at Rügen Island (Figure 1) were established for the recording of reference data during the measurement cruises.

For the determination of precise sea-level heights from the vessel-based GPS measurements, the vessel's instantaneous inclinations due to high-frequency, wave-induced sea-level changes have to be considered. On board the *DENEB*, the motion parameters (heading, heave, roll and pitch) are acquired by measurements of an INS in order to correct bathymetric surveys by echo sounding. The motion parameters of the vessel can also be determined using the observations of a multi-antenna GPS network on board. Then the relations between geocentric and local (topocentric and body-fixed) coordinate systems have to be considered.

In past years, the application of GPS measurements for a precise determination of motion parameters and 3D marine positioning has been the subject of a number of studies (Schenke 1992, Griffith et al 1994, Kielland and Hagglund 1995, Lachapelle et al 1996, Boeder and Seeber 1999, Zilkoski et al 1999, Andree et al 2000, Fortes et al 2000, Goffinet 2000, Huff and Remondi 2000, Ueno 2000, Chang et al 2001, Reinking and Härting 2002). Such investigations also have been conducted already on the *DENEB* (Eichhorn 1998). Depending on the focus of the investigations, different measurement configurations were designed, ranging from one antenna (Kielland and Hagglund 1995, Fortes et al 2000, Reinking and Härting 2002) to a four-antenna array on board (Lachapelle et al 1996, Zilkoski et al 2000). Accordingly, the data analysis methods and the accuracies of the obtained results are quite different.

In the following, the concept designed by the *Institut für Planetare Geodäsie* for the determination of instantaneous 3D positions of the vessel-based antennas is described. A particular focus addresses the computation of the motion parameters based on geocentric positions. The precision of the GPS-derived motion parameters is investigated by comparing the relative positions of the antennas. Comparisons with the corresponding INS data prove the plausibility of the results and allow error estimations of both measurement methods under varying conditions. Furthermore, statements about the feasibility of GPS for a precise determination of sea-surface heights under the given configuration and measurement conditions can be derived.

Reference Systems and Motion Parameters

In general, point positions and their changes (velocity) can be described by coordinates referring to a suitable Cartesian coordinate system. A Cartesian coordinate system is defined by the location of its origin, the directions of the axes and a scale factor. For global applications (e.g. the positioning with GPS), geocentric coordinate systems are defined. The origin of a geocentric system is located at the centre of mass of the earth. For the visualisation of a geographic context, geocentric coordinates can be expressed as ellipsoidal latitude, longitude and height, related to a reference ellipsoid centred at the geocentre as shown in Figure 4.1 (left).

Local phenomena can be described by the use of locally-centred Cartesian coordinate systems. A local topocentric system, as shown in Figure 4.1 (left and right), has its origin in a defined local point. The axes of the topocentric system are orientated to the north, to the east and perpendicular to the ellipsoid surface.

The description of the orientation and motion of a body (e.g. a vessel) however requires a local coordinate system, that is fixed to the body (Figure 4.1, right). The origin of a body-fixed system can be defined at an appropriate point of the body. The axes of the system run along and respectively perpendicular to the longitudinal axis of the body.

The position $\underline{x}^2$ of a point in the Cartesian coordinate system 2 can be computed from given coordinates $\underline{x}^1$ of the same point in system 1 by the use of a transformation equation (see also Seeber, 1993). Assuming an identical scale factor in both systems the transformation equation

$$\underline{x}^2 = \underline{d} + \underline{R}(\Psi,\Theta,\Phi) * \underline{x}^1 \quad (1)$$

contains six transformation parameters, which reflect the relation between both coordinate systems:

- $\underline{d}$ = (dx, dy, dz) ... the 3D displacement vector between the origins of both systems and
- $\underline{R}(\Psi,\Theta,\Phi)$ ... the rotation matrix, which contains the sine and cosine values of the orientation angles Ψ, Θ and Φ between the corresponding coordinate axes of both systems

Knowing the coordinates of at least three non-collinear points in both coordinate systems, the transformation parameters dx, dy, dz, Ψ, Θ and Φ can be derived on the basis of equation (1).

In the described case, the balance point of the GPS

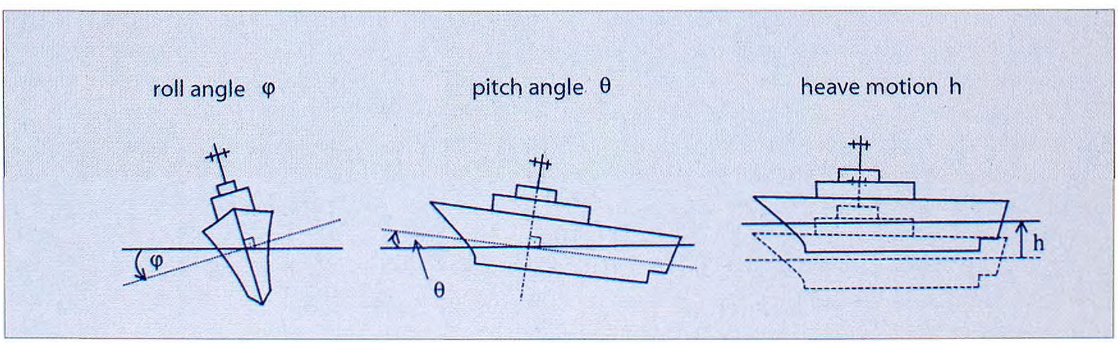

Figure 4.2: Schematical demonstration of marine motions. The definition of the analysed motion parameters roll (left), pitch (middle), and heave (right) are illustrated, the arrows indicate the direction of increasing values

network on board was defined as the origin of the local topocentric system (Figure 4.1, right). The vertical component of the origin was located on the surface of the reference ellipsoid. The origin of the body-fixed coordinate system coincides with the *DENEB*'s main mast (Figure 4.1, right), and the x-y-plane is placed on the water surface. For the realisation of the two coordinate systems, coordinate vectors were assigned to each GPS point as described below.

Based on the definition of both local coordinate systems for the present case, the geometrical meaning of the six transformation parameters in equation (1) can be derived. The rotation angles coincide with the instantaneous roll, pitch (see Figure 4.2) and heading of the vessel. Following the definition of the vertical component of the origins, the dz-displacement represents the vertical distance between the sea surface and the reference ellipsoid (i.e. the instantaneous ellipsoidal sea-surface height).

Mathematically defined reference surfaces such as ellipsoids differ from physically modelled reference surfaces like the geoid. A geoid constitutes an equipotential surface of the earth's gravity field, which agrees basically with the mean sea surface, whereas the ellipsoid may deviate spatially from the mean sea level by up to 100m. Hence, for a limited area, the divergence of the geoid from the ellipsoid can be described as a tilted plane in the 3D space by an offset and trend. Accordingly, the time series of ellipsoidal heights measured during a cruise is superposed by various effects:

- Changes of the geoid with respect to the ellipsoid along the track
- Long-periodic, time-dependent sea-level changes caused by tides and meteorological influences (since the astronomic tides reach only small magnitudes in the Baltic Sea, changes are mainly due to varying meteorological conditions)
- High-frequency vertical movement of the sea (heave motion) caused by swell (Figure 4.2)
- Dynamic, speed-dependent changes in the vessel's draft (trim and squat) have also to be considered (Zilkoski et al 1999, Goffinet 2000, Huff and Remondi 2000, Ueno 2000, Chang et al 2001, Reinking and Härting 2002)

For navigational purposes, usually the position (latitude and longitude), the velocity and the heading of a vessel are required. In order to correct hydrographic echo-sounding measurements, moreover the instantaneous heave, roll and pitch motion of the survey vessel have to be known. The determination of sea-level heights can be applied to a range of tasks as e.g. mapping the sea surface (geoid) (Huff and Remondi, 2000). Furthermore it may serve as a tool for the vertical referencing of hydrographic surveys providing either the ellipsoidal height of the echo sounder or the ellipsoidal height of the sea surface (Chang et al 2001).

Measurement Sensors

INS for measurements of the heading, heave, roll and pitch usually consist of a set of accelerometers, rotation rate sensors and a gyro compass (Boeder and Seeber 1999). INS measurements are not affected by satellite signal shadowing (e.g. while passing bridges). Since the INS measures accelerations, the results are affected by drifts and biases due to manoeuvers of the vessel (Andree et al 2000). The measured heave motion contains only information on short-periodic height changes, providing the deflections from 'calm-water conditions' (Kielland and Hagglund, 1995).

The determination of heading, roll and pitch with GPS requires at least three antennas defining a plane in space. The analysis is based on carrier phase observations. GPS-derived motion parameters are not expected to be influenced by bias effects from vessel manoeuvres, because the observations are geometric parameters. Since the carrier phase observations are superposed by random noise, the distances between the GPS antennas on board have to be configured as large as possible in order to improve the precision of the derived motion parameters (Lachapelle et al, 1996). The data quality at the individual points, and thus the availability and accuracy of the derived motion parameters, are constricted by multipath and shadowing effects. A number of GPS multi-antenna systems have already proven to be able to derive motion parameters with accuracies of less than 0.1° under varying conditions (Schenke 1992, Lachapelle et al 1996, Zilkoski et al 1999).

Baseline-wise GPS data processing with respect to a reference station on shore, which is necessary to determine precise sea-level heights, is affected by atmospheric influences depending on the baseline length. Hence, the precision of the obtained results decreases as the distance to the coast increases. Various attempts (Zilkoski et al 1999, Goffinet 2000, Huff and Remondi 2000, Chang et al 2001) have shown that ellipsoidal sea-surface heights can be determined from vessel-based GPS measurements with accuracies of 5-10cm at distances of up to 20-50km, depending on the measurement conditions and the processing software. The use of a network of reference stations (Fortes et al, 2000) as well as special algorithms to treat the carrier phase ambiguities (Huff and Remondi, 2000) can improve the accuracies further to less than 10cm at baselines of up to 100km.

Measurement Configuration and Data Analysis

During the measurement cruises, five geodetic Trimble GPS antennas were mounted at fixed locations on board of the *DENEB* (Figure 3). Their configuration is shown in Figure 4.1 (right). The distances between the antennas amount to 35m along and 12m across the vessel. The data were logged with an output rate of 1Hz using Trimble 4000 receivers. The distance to the GPS reference stations, which were equipped with identical antenna/receivers, reached up to 45km. First the geocentric positions of the reference stations have been determined with respect to the International Terrestrial Reference System ITRF97 (Boucher et al 1999).

The realisation of the body-fixed coordinates was based on measurements carried out in the harbour before and after each measurement cruise under conditions of low dynamics. Whereas the mean internal geometry of the GPS network has been derived directly from the GPS measurements, the orientation of the body-fixed coordinate axes were determined using INS data. The use of additional terrestrial measurements provided the determination of the origin. As a result, each GPS network point has a body-fixed coordinate vector. Since the on-board location did not change, the body-fixed coordinates were valid for the entire measurement cruise.

The kinematic GPS measurements were analysed by post processing with the Trimble GPSurvey software, implying fixed positions for the reference stations and resolving the L1/L2 carrier phase difference ambiguities On The Fly (OTF). As a result of the kinematic GPS processing, time series of 3D geocentric ellipsoidal coordinates (latitude, longitude and height) of each GPS network point on board have been calculated. The geocentric coordinates for each measurement epoch were transformed into local topocentric coordinates related to the ellipsoid as described above.

The motion parameters of the *DENEB* during the observation sessions have been determined for each epoch by the six-parameter transformation between the topocentric and the body-fixed coordinates as denoted in equation (1). The transformation equation has been applied in a least-square adjustment algorithm, similar to that used by Lachapelle et al (1996). Since three points are necessary for the non-ambiguous parameter determination, the used network consisting of five antennas produced a redundancy. This was used to detect outliers and thus to improve the precision of the solutions. Apart from the required motion parameters (heave, roll and pitch), the adjustment procedure also yielded estimations of the rms errors of each parameter. The rms errors represent the deviation of the solutions for each epoch from the mean network geometry (given by the body-fixed coordinates), and are consequently a significant indicator to assess the precision of the GPS-derived motion parameters. According to the observation frequency, the computed motion parameters and rms errors were derived as time series with an output rate of 1Hz.

The corresponding INS data of the *DENEB* were available with an output rate of 0.1Hz and resolutions of 0.1° for the roll and pitch angles and 0.1m for the heave motion. The time offset of the INS data with respect to the GPS time, which has to be considered for precise comparisons, was determined by a cross-correlation analysis between the corresponding records. The motion parameters resulting from GPS and INS have been compared with each other to assess their quality. In the following, the results in heave, roll and pitch components are presented and discussed exemplarily for one measurement session of about 2 hours of duration. The session was observed at open sea 20-40km off the coast, under rough meteorological conditions reflected in large variations in the motion parameters (see Figure 5).

Results of Roll and Pitch Motions

The comparison of the GPS-derived roll angles with the INS data is displayed in Figure 6 (top). During the present session, the meteorological conditions (wind-stress) in conjunction with the vessel's heading caused a permanent inclination in the roll com-

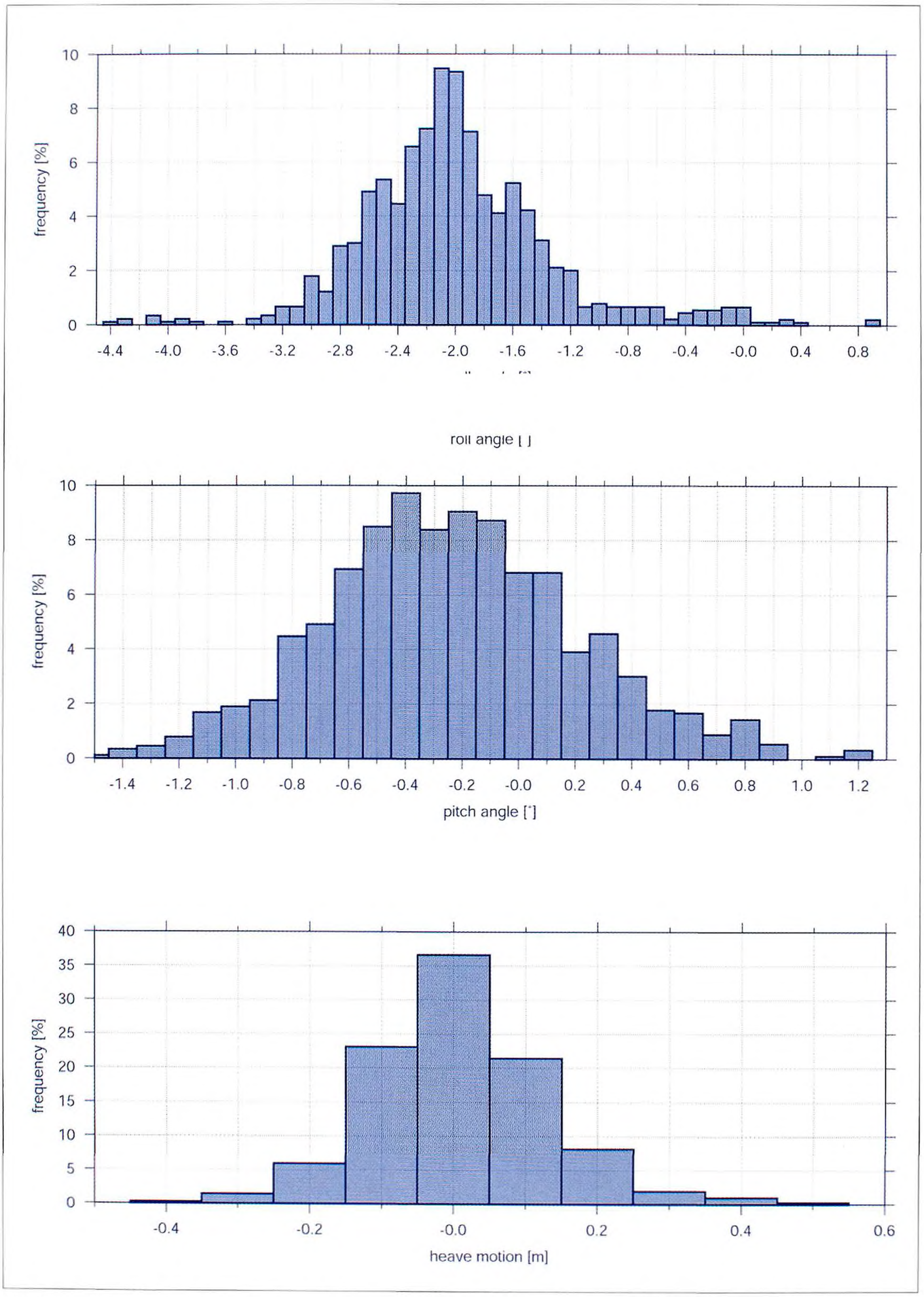

Figure 5: Frequency distribution of the motion parameters. For the studied period of about 2 hours, the relative frequencies of appeared motion values for roll (top), pitch (centre) and heave (bottom) components are illustrated

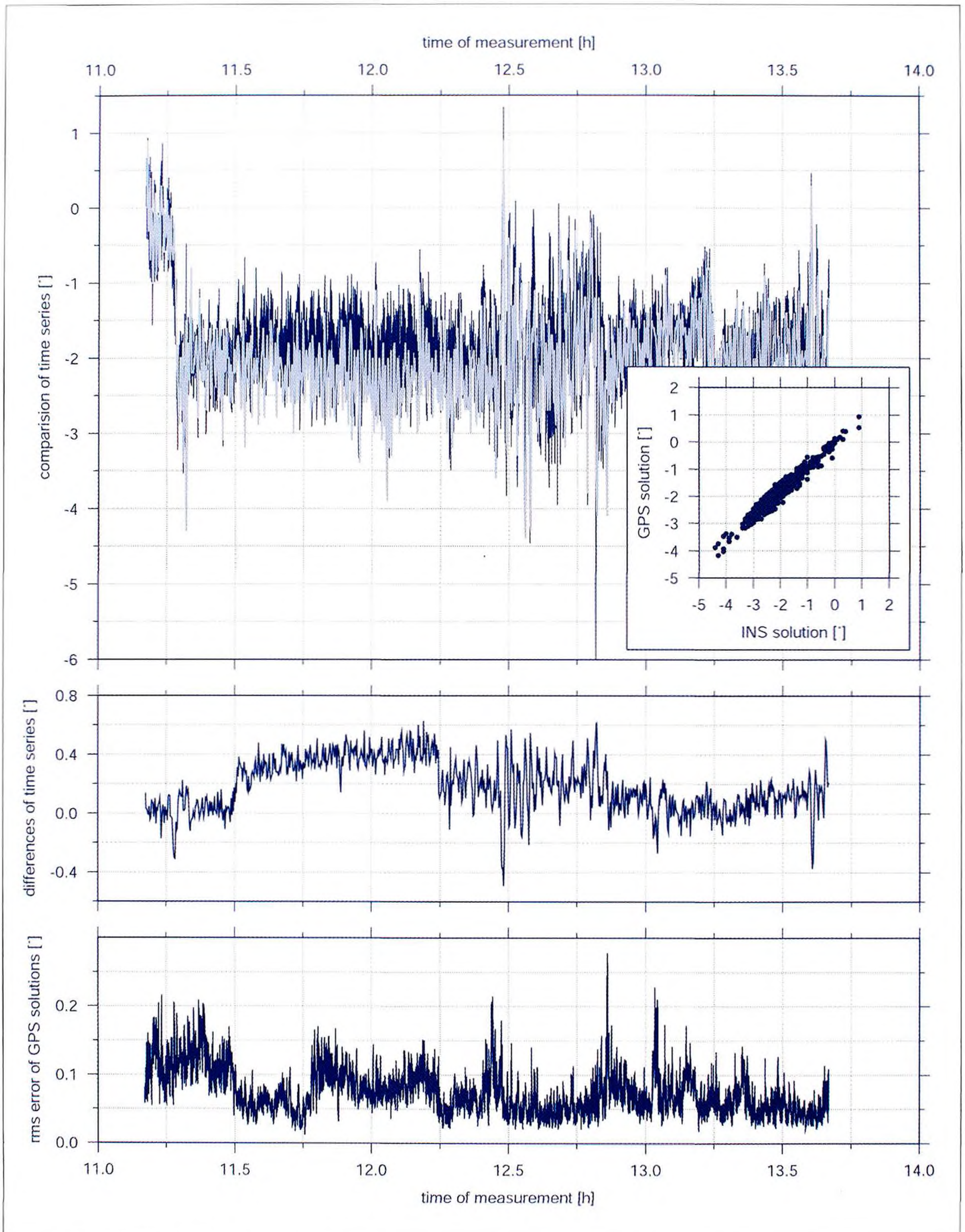

Figure 6: Comparison of the roll-motion results

top: The solutions from GPS measurements (black line) and the INS (grey line) of the DENEB. The agreement of the corresponding results is shown in the correlogram. The two time series are correlated with a coefficient of 0.97.

centre: Differences of the time series GPS minus INS. The average of the differences amounts to 0.19°±0.17° for the investigated session.

bottom: rms errors indicating the precision of the GPS solutions. The rms averages to 0.07°

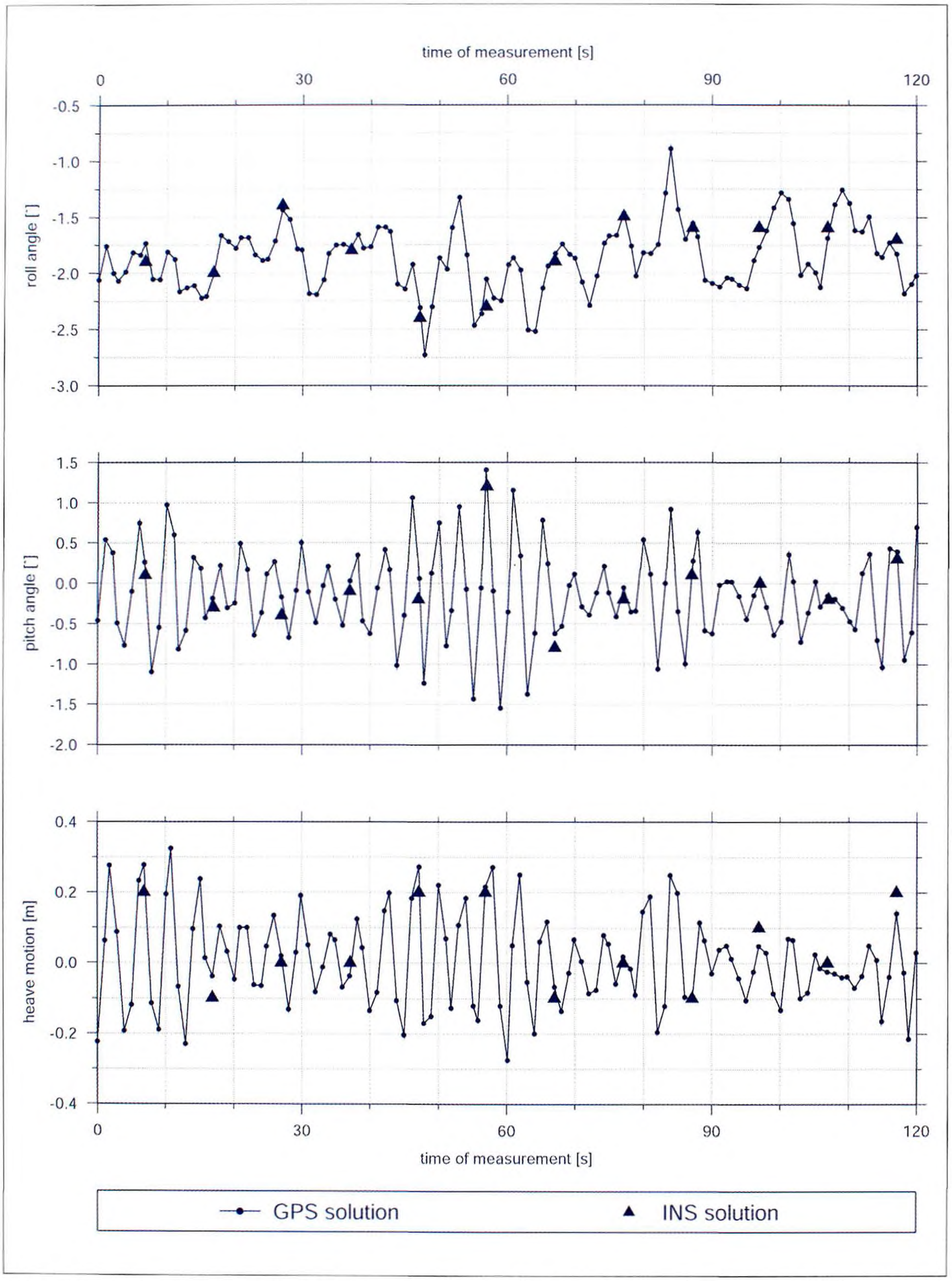

Figure 7: Comparisons of the motion parameters during selected time sections. The results are demonstrated exemplarily for a period of two minutes. Circles and triangles represent individual solutions from GPS and INS respectively. top: roll angle; centre: pitch angle; bottom: heave (with geoid heights removed and GPS solutions high pass filtered)

ponent of approximately -2°, which is evident in both solutions. The good general agreement between both solutions is also proved by a cross-correlation coefficient of 0.97. Furthermore, both solutions agree well in the high-frequency variations of the roll angle as shown in Figure 7 (top).
The differences between both solutions, that may indicate systematic biases exceeding the precision and resolution of the compared solutions, averaged to +0.2° (Figure 6 centre and Figure 8 top right). While the differences remain close to zero most of the time, variations of up to 0.5° occur during particular periods. Similar differences between GPS and INS solutions were also detected by former investigations on the *DENEB* (Eichhorn, 1998).
The precision of the roll angles determined by GPS measurements are shown in Figure 6 (bottom) as a time series and in Figure 8 (top left) as a frequency distribution. The values, consisting of the rms errors of the six-parameter transformation, reflect the capability to reproduce the internal network geometry (given by the body-fixed coordinates) at each observation epoch and the propagation of the deviations into the roll angle. The mean precision over the entire session amounts to less than 0.1°. The precision values vary within 0.2°-0.3° due to changing measurement conditions, exceeding occasionally the resolution of the INS data of 0.1° slightly.
In general, the differences correspond to the resolution of the INS data of 0.1° and to the precision of the GPS solutions of 0.1°-0.3°. Since the relevant errors of the GPS solution are basically reproduced by the rms value (except remaining uncertainties in the body-fixed coordinates of the GPS antennas), the exceeding differences may reflect inertia effects on the INS data during strong dynamic motions caused by swell or turning manoeuvres. A further reason may be residual shifts in the time synchronisation of INS and GPS data.
The solutions for the pitch component show an agreement similar to the roll solutions. The GPS and INS time series are again correlated by a coefficient of 0.97. The high-frequency variations in both time series (Figure 7, centre) show a good agreement, too.
The derived precision of the GPS-determined pitch angles (Figure 8, centre left) averages to better than 0.05°, which is slightly less than the resolution of the INS data of 0.1°. At any measurement epoch, the precision remains below 0.15°. That means, the GPS solution of the pitch motion is 2-3 times more accurate than that for the roll component. This can be explained by the described on-board antenna configuration, which allows a more accurate tilt determination along the vessel's longitudinal axis than across this axis. On the other hand it can be concluded, that the accuracy of GPS-determined motion parameters improves with increasing distances between the antennas.
An average of approximately 0.1° has been achieved for the difference between both solutions in the pitch component (Figure 8, centre right) over the entire session, which is equivalent to the resolution of the INS-derived pitch data. In particular cases, the differences reach 0.4°, which again agrees with the comparisons of Eichhorn (1998). The reasons may be the same as for the roll component (remaining uncertainties in the body-fixed coordinates of the GPS antennas, effects of inertia in the INS data due to strong manoeuvres or uncertainties in time synchronisation).
From the spectral analysis of the GPS solutions it can be seen that the roll motion of the *DENEB* has a cycle duration of about 12sec (Figure 10, top). A similar roll motion period of 11.4sec was ascertained by Eichhorn (1998) for this vessel.
For the pitch component the analysis revealed a typical motion period of about 4sec (Figure 10, centre). This means that the inclination of the *DENEB* along the longitudinal axis changes by factor 3 faster than the inclination across this direction.

Comparison of Heave Motions

In Figure 9.1, the results of the vertical motion derived from GPS and INS measurements are illustrated. Whereas the INS reveals solely high-frequency movements, the GPS-derived solution shows a clear trend of about 1 metre. This is primarily caused by the influence of the spatial change of the geoid height above the ellipsoid along the sailed track of about 50km length (Figure 9.2). In order to facilitate the comparison of the two solutions, the long-periodic variations of the GPS results were eliminated by reduction of the geoid heights. In addition, a subsequently applied high-pass filter (window width 100sec according to investigations of Kielland and Hagglund, 1995) removed remaining long-periodic signals of sea-level changes caused by meteorological influences. In analogy to the roll and pitch components, the

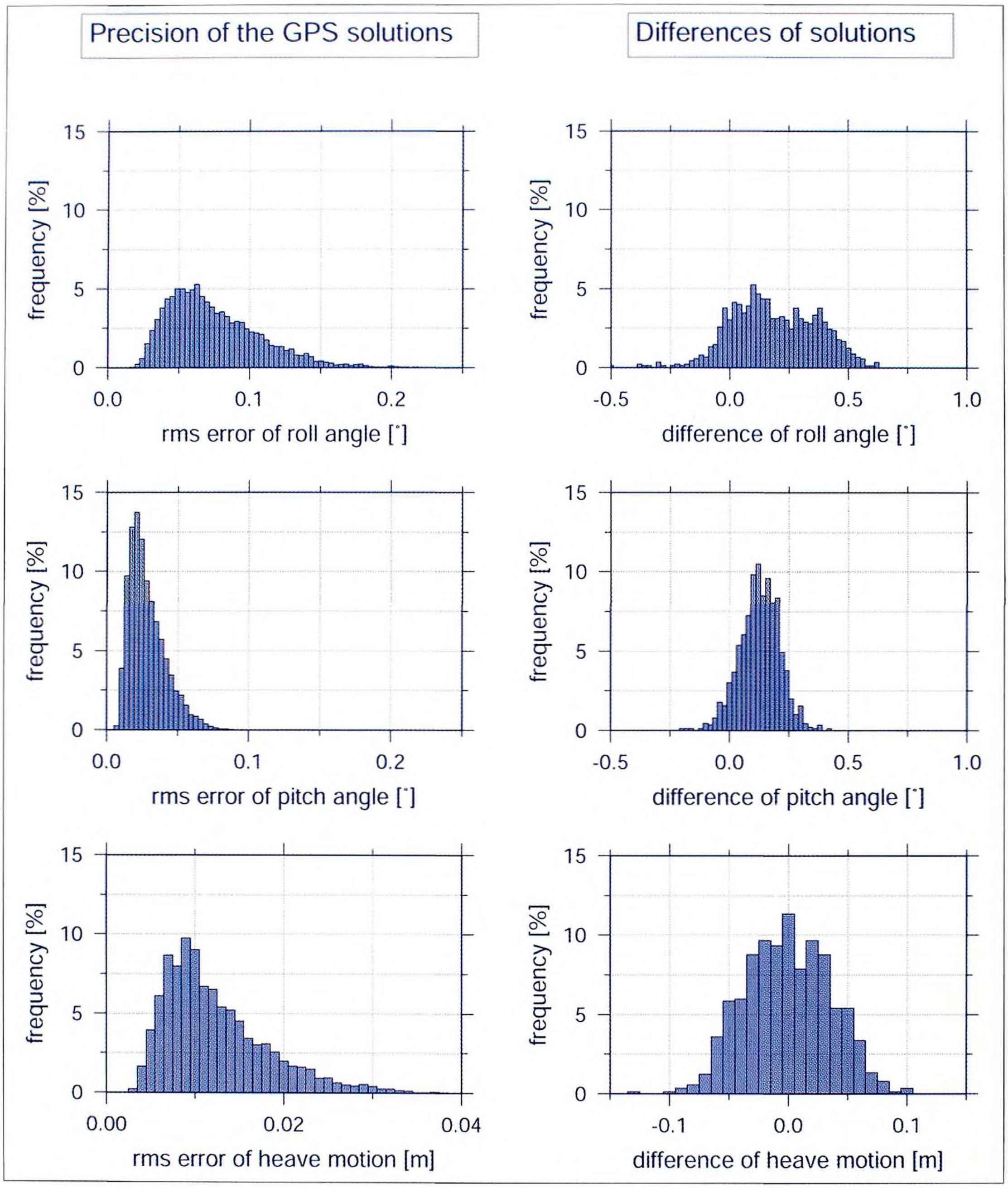

Figure 8: Frequency distribution of the determined motion parameters. In the left column, the relative frequencies of the rms errors of the GPS-derived motion parameters as indication of the precision of the GPS solutions are presented. For a comparison, the relative frequencies of the differences of GPS solution minus INS solution of the investigated session are shown in the right column.

top: roll angle (averaged rms error of the GPS solutions 0.07°, averaged difference +0.19°±0.17°, correlation of time series 0.97)

centre: pitch angle (averaged rms error of the GPS solutions 0.03°, averaged difference +0.12°±0.12°, correlation of time series 0.97)

bottom: heave (averaged rms error of the GPS solutions 11mm, correlation of time series 0.94), the GPS solutions were reduced by the geoid's impact and high pass filtered

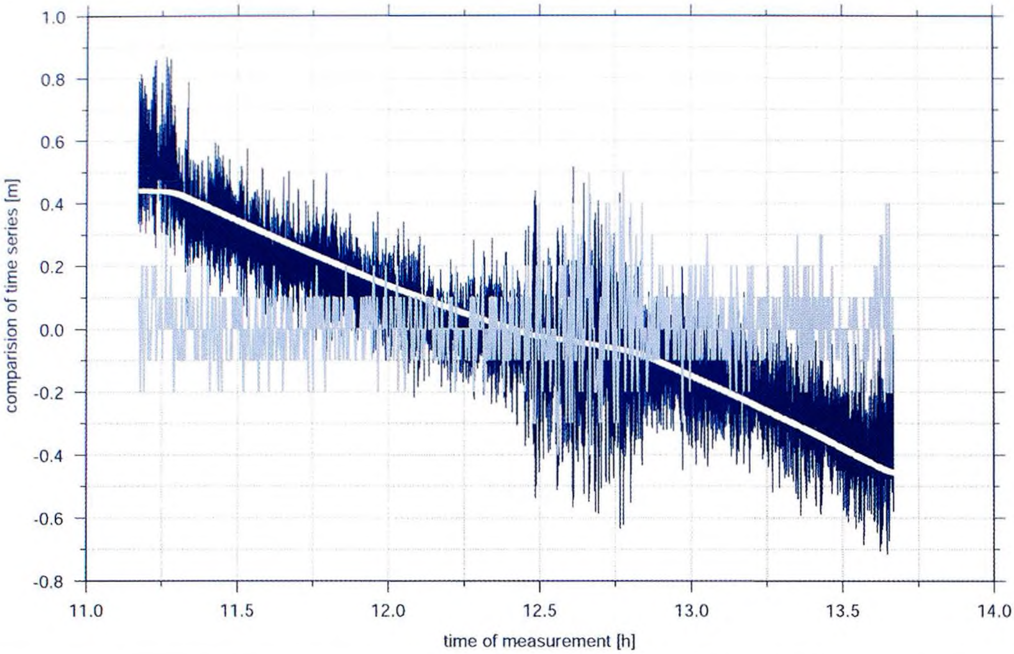

Figure 9.1: Results of the vertical motion in comparison. The GPS solution (black line) and the heave recorded by the INS sensor (grey line) are shown for the same time section. The GPS-derived heights are centred to the averaged INS value. The impact of the geoid height on the GPS solutions (white line) is centred to the mean value, too

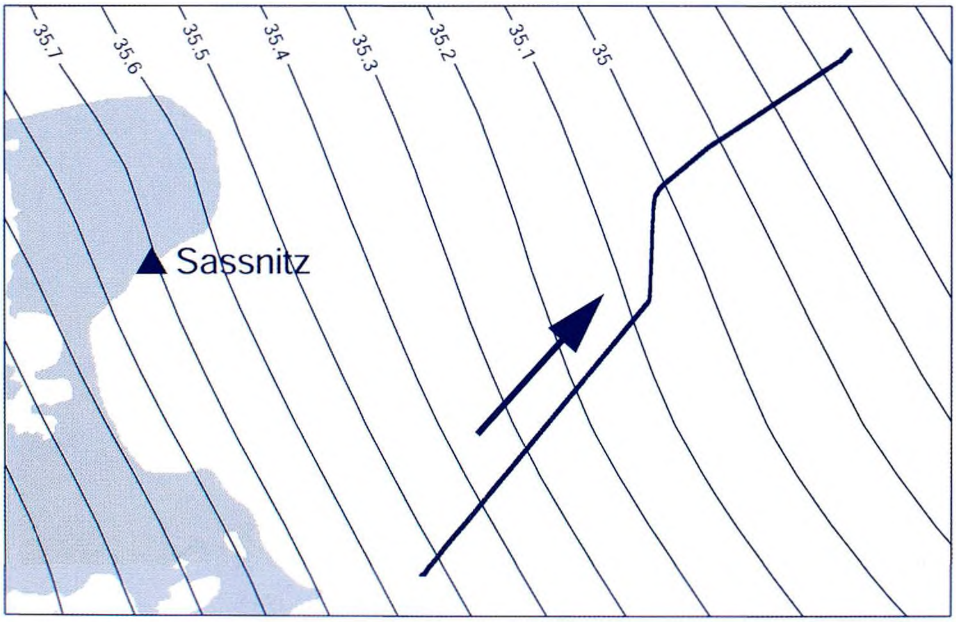

Figure 9.2: Effects of spatial height changes. In the figure, the course track of the DENEB during the examined time section is displayed to the east of Rügen Island. The drive direction is given by the arrow. For the computation of the geoid heights, the model European Gravimetric Geoid EGG97 (Denker and Torge 1997) was used, which is depicted in the figure by isolines of the geoid heights in meters. A height change of about 90 cm that is also shown in Figure 9.1 can be recognised along the sailed track

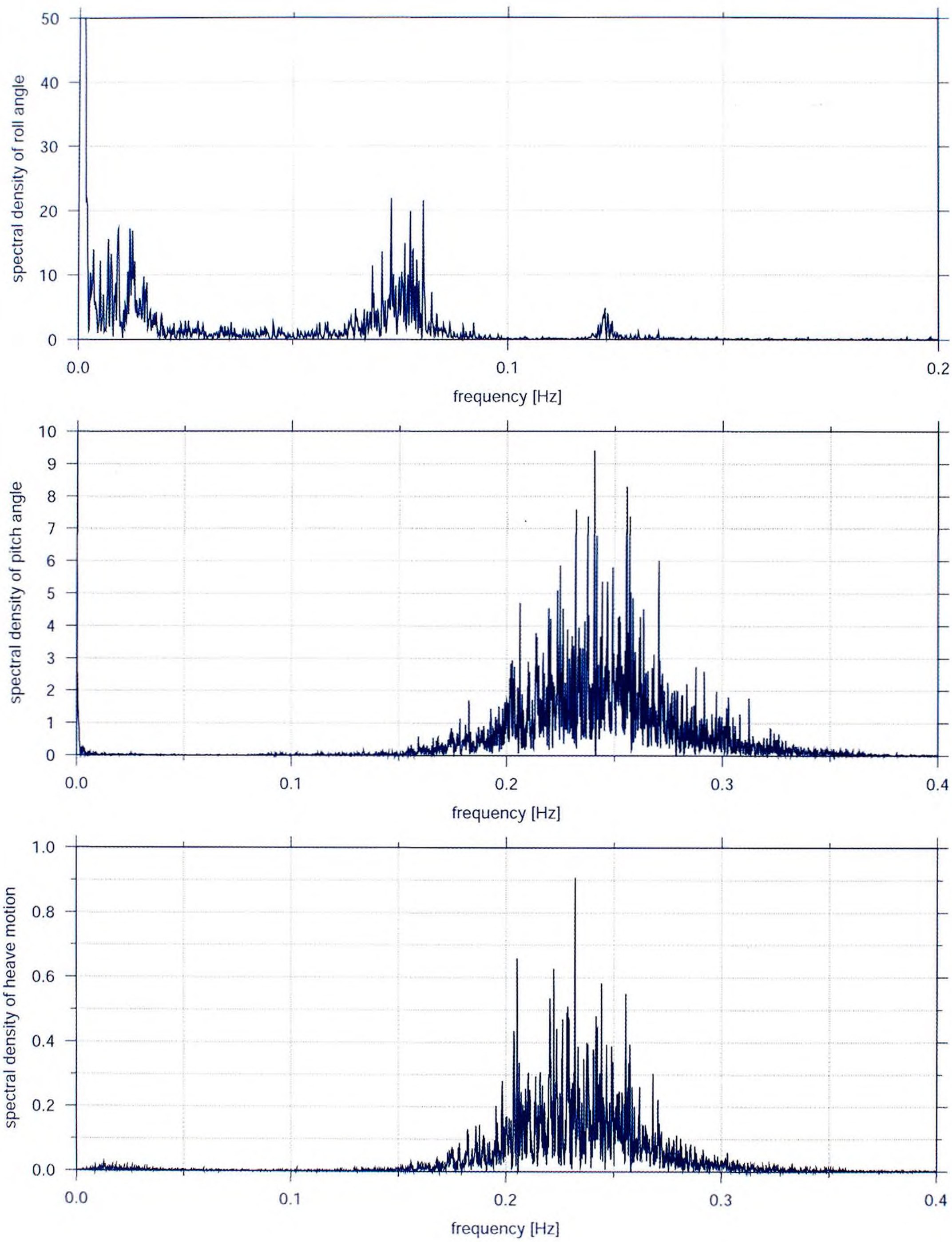

Figure 10: Results of the spectral analysis of the motion parameters. The spectral densities of the GPS-derived motion parameters are displayed as function of the frequency. top: roll; centre: pitch; bottom: heave (geoid removed and filtered)

precision of the GPS-determined heave motion is described by the rms error calculated from the deviations at each epoch from the mean network geometry. Figure 8 (bottom left) shows the frequency distribution of the values for the investigated session. The precision of the heave motion averaged over the entire session amounts to 10-15mm. Depending on varying measurement conditions, the value can increase to up to 4cm (Figure 8, bottom left), but remains in any case below the resolution of the INS data of 0.1m.

A coefficient of 0.94 proves a similarly high correlation between the GPS and the INS heave solutions as for the other motion components. The accordance of the two solutions can also be seen from the comparison of a selected time cut displayed in Figure 7 (bottom).

The differences between the GPS and INS-derived heave motion over the entire session (Figure 8) average to zero, according of the high-pass response of both solutions. The rms error of the difference amounts to 3cm, confirming the precision of the GPS-derived heave motion. In none of the cases, the difference reaches the resolution of the INS data of 10cm. Similar findings for the heave motion were obtained by Kielland and Hagglund (1995).

A variable cycle duration around 4sec results from the spectral analysis of the GPS-derived heave motion (Figure 10, bottom). The same period has been determined for the pitch motion.

The determination of the high-frequency vertical movement (heave) of the *DENEB* with GPS measurements was performed with an accuracy of 1-2cm over the largest part of the investigated session. The results of the described method show that, in principle, absolute i.e. ellipsoidal sea-surface heights can be ascertained with accuracies in the cm-level. This suggests the possibility to apply this approach as a tool for the vertical referencing of hydrographic surveys providing the deviation of the instantaneous sea-level height from the equipotential surface (geoid) at the measurement location. The ellipsoidal sea-level heights determined by GPS can be reduced onto the equipotential surface with the aid of a geoid model. For the region of the southern Baltic Sea, there exist spatially high-resolving geoid models with an accuracy of a few centimetres, thus the described method makes in principle a precise vertical referencing in the coastal area offshore Mecklenburg-Vorpommern possible.

Conclusions

In the context of the VEREXT project, a conception for the determination of sea-level heights in the open sea has been successfully implemented. The measurement concept based on GPS observations facilitates also the determination of marine motions (heave, roll, pitch) on board the *DENEB* vessel. For this purpose, coordinates with respect to the geocentric as well as local topocentric and vessel-fixed coordinate systems were determined. The data analysis yielded precise results for both measurements in the harbour and up to 45km offshore. From the GPS measurements, the motion parameters have been determined with mean precisions of:

- Better than 0.1° for the roll component
- Better than 0.05° for the pitch component
- Better than 2cm in the heave component

Hence the GPS-derived results are equivalent compared to the resolution of the vessel's INS data in the roll component, and remain below the INS resolution in the pitch and heave components.

The better precision in the pitch component compared to the roll component coincides with longer distances between the GPS antennas in the vessel's longitudinal direction. Consequently the results emphasise that GPS-derived motion parameters will be more accurate on larger ships, where longer baselines are available, than on small ships.

The motion parameters derived from GPS have been compared with the corresponding results of the vessel's INS. The independent solutions show a good consistency in the reproduction of high-frequency changes of the motion parameters, which is reflected by high correlation coefficients of around 0.95.

The agreement between the solutions of GPS and INS averaged over longer time spans may be influenced by uncertainties, the resolutions and possible biases of both methods. It was found to be:

- Better than 0.2° for the roll component
- Better than 0.1° degrees for the pitch component
- Better than 5cm in the heave component

It was noticed, that the quality of the results is subject to temporal variations due to varying measurement conditions. In the limits of the accuracies of both techniques, the comparison with the measurements of the vessel's INS sensors revealed good agreements. Based on the obtained results, the ability of GPS measurements for the determination of marine motions has been confirmed. Furthermore, the results prove the capability for a precise survey of the sea-surface height relative to a reference ellipsoid in the southern Baltic Sea.

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