Hydrographic Surveying without a Tide Gauge

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Depth in hydrographic surveys is measured from the water surface during the survey operation. However, the water surface of oceans, seas and lakes moves as a result of meteorological, oceanographic and tidal effects. Depth values measured at any time and water level should be reduced to a specific vertical datum in order to be used at a different time and different water level. To accomplish that, the changes in water level must be determined. Traditionally, many different types of tide gauges are used for this purpose. The aim of this study is to establish the connection of depth values to a vertical datum without using a tide gauge. For this purpose, an algorithm based on the GPS carrier phase measurement is introduced here. The result shows that, the height of each point at the sea bottom may be obtained without using a tide gauge via the proposed method. Furthermore, if this method is performed, important error sources such as heave, surge, and tides, which affect the sounding, can be eliminated.

Introduction

Water in oceans, seas and lakes moves due to a variety of reasons, a number of them coming into play simultaneously. Movement may be horizontal or vertical, unidirectional or circular, and irregular or periodical (Ingham 1992). Thus, the water level is time and space-dependent. Changes may vary up to several meters and depend on the location and geography. They can be seasonal, monthly or even daily, according to the situation. Meteorological (i.e. pressure, winds) and oceanographic effects, exceptional vertical crust movements and astronomical tides are the main reasons for these effects (Torge 1991). As commonly known, the depth values in hydrographic surveying are measured from the instantaneous sea surface during the survey. If these depths are required at a different time, they should be connected to a specific vertical datum. There are several suitable vertical datums which are available. According to the requirements of the measurement, the measured depths may be reduced to the land-leveling datum or the tidal datum (Bannister and Raymond 1991). Mean Sea Level is often used for the land-leveling datum for a coastal country and is determined by continuous observations of the sea level over a long period of time (18.63 year) (Vanicek and Krakiwsky 1992). This datum is generally used in civil engineering construction, since it enables the levels to be directly related to those of the adjoining shore installations. The second datum is generally used for navigation purposes. The Lowest Astronomical Tide (LAT) is an example of a tidal datum. The latest trend is the use of the LAT as a vertical datum for nautical charts (Kumar 1997). Each country chooses its own vertical datum according to its geographical conditions and circumstances.

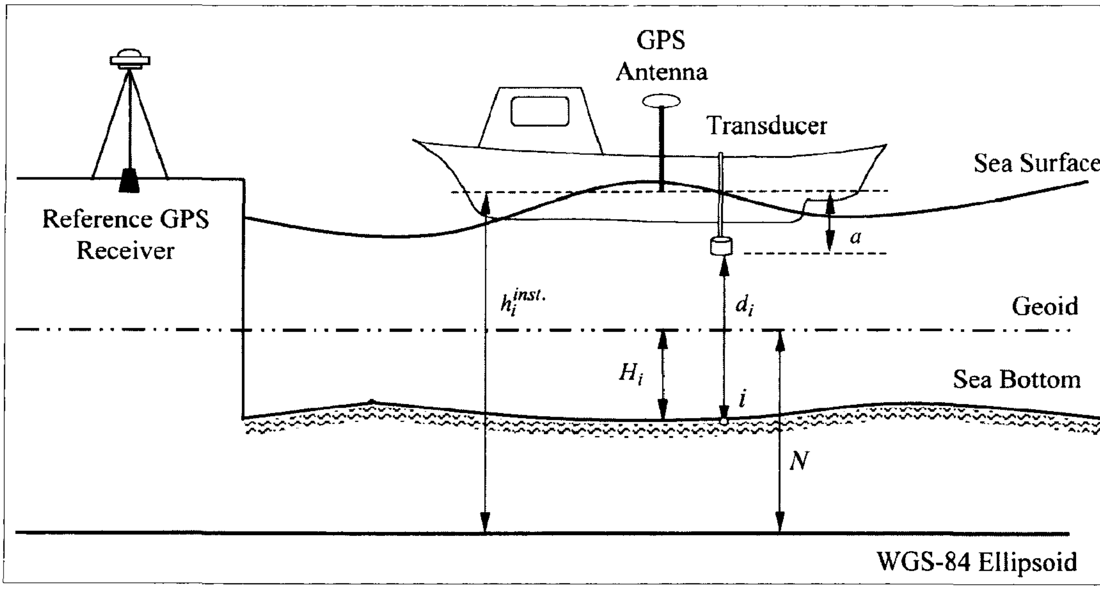

Figure 1: *The Schematic Depiction of the Tiding the Depth to the Vertical Datum without Employing a Tide Gauge*

A gauge, set up on the shore, is used to establish the relation between the depth and land-leveling (vertical) datum. The location of the gauge on the shore is chosen if possible, in an area that is geologically and seismically stable. Commonly used gauge types are: staff tide gauge with an accuracy of ±(1-5) cm, float gauge with an accuracy of ± (0.1-1) cm, recordable tide gauges with an accuracy of ±(0.1-0.5) mm, pressure tide gauge with an accuracy of ± (1-2) cm. Besides this, for monitoring the height changes of the global sea surface with an accuracy of ±(3-4) cm, space-borne satellite altimeters such as TOPEX/Poseidon Follow-On satellites may be used (Chamber *et al.*, 1999, Chen *et al.*, 2000). In most practical hydrographic applications, it is enough to use a staff tide gauge to determine the instantaneous sea water level. The objective of this paper is to introduce a method for transforming the depth to the height, depending upon the GPS carrier phase measurement without employing a tide gauge.

Review of the Coordinate and Depth Determination

Almost all the positioning techniques which have been used in classic land surveying are also used in the hydrographic surveying. However, marine positioning has a different character and special features of the marine environment cause some application problems or restrict their applicability. Generally, the measurement of geographic position is carried out by tachometric, radio positioning and acoustic positioning methods (Napier and Ashkenazi 1987). Recent developments of satellite-based positioning methods have turned to GPS and GLONASS.

GPS and GLONASS methods can be commonly used for a variety of geodetic purposes such as high precision triangulation, tachometric surveys, monitoring crustal movements, determination of the precise orbits and calibration of satellite altimeters (e.g. TOPEX/Poseidon Follow On, ERS-1) (Liu 1998, Asteriadis and Schwan 1998, DeLoach *et al.*, 1995). Satellite measuring technique can be used for both offshore and inshore hydrographic surveying for a variety of reasons, such as being independent of all weather conditions, having no requirement for the inter-visibility of surveying points and being able to conduct surveying during both night and day.

The history of sounding methods can be traced back to the 1750's. Sounding or depth determination corresponds to the leveling in classic land surveying. Sounding has been conducted using a wide range of different methods, from lead line to airborne sounding methods (Wells *et al.*,1991, Koppari *et al.*, 1994, Calkoen *et al.*, 1998). However, today, the most commonly used method is acoustic sounding. It is possible to measure depth from shallow water to the deepest ocean depths with acoustic sounding instruments (echo sounder, fathometer etc.). Ingham (1992) introduces some other depth determination methods. Nowadays, enhanced acoustic sounding systems, such as multi-beam or multi-transducer systems, are in use (Eeg 1999).

Relating the Depth to the Vertical Datum without Employing a Tide Gauge

The height of every measured sea bottom point may be determined without the use of tide gauges. For this purpose an algorithm, which is based on ellipsoidal heights from GPS measurements, depths and the geoid undulation, is introduced here. The schematic depiction of the method is given in Figure 1.

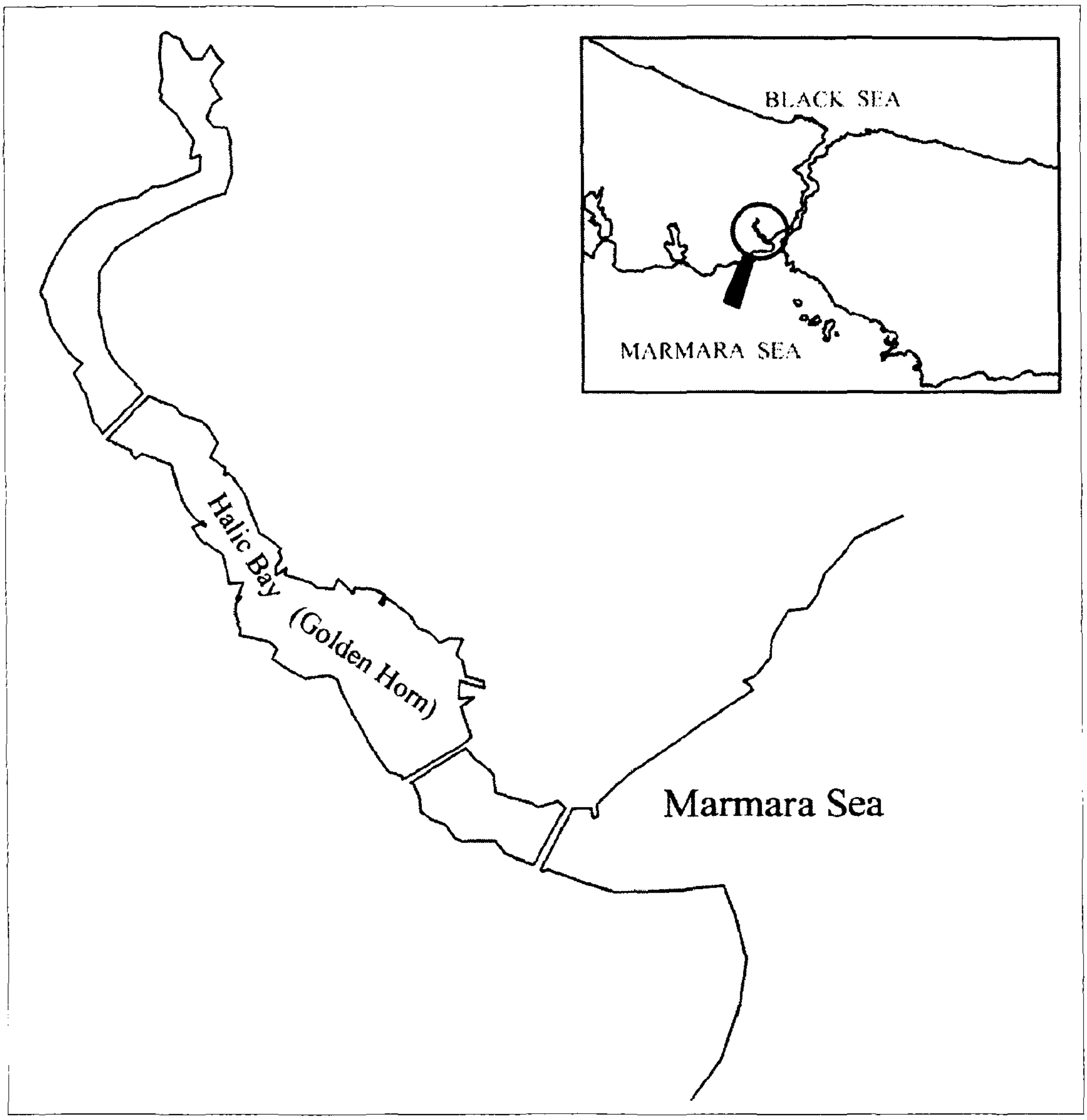

Figure 2: *The Application Area*

The problem is to determine the distance between the geoid and a point on the sea bottom, i.e. orthometric height of each measurement point on the sea bottom. The orthometric height of the i^{th} point can be calculated by (Figure 1)

$$H_i = (h_i^{inst.} - N) - (d_i + a) \tag{1}$$

where, $h_i^{inst.}$ is the instantaneous ellipsoidal height of the i^{th} point (obtained in kinematic mode), N is the geoid undulation, d_i is depth and a is distance between the GPS antenna and the transducer (constant value). This method is valid when the N value is already known. However, if the undulation value is not available for the application area, the problem may also be solved. To do this, a relative geoid undulation could be calculated from the geodetic points' orthometric and ellipsoidal heights. The N value is calculated from the second way in this study. Details of the process are explained in Section 4.

It is important to state that, all the collected $h_i^{inst.}$ and d_i values were corrected for pitch and roll effects. For removing the pitch and roll errors from the measurement, first of all a coordinate system needs to be defined. The centre of gravity of the vessel was defined as the origin of the body frame (vessel-fixed coordinate system). For the determination of the centre of gravity of the vessel, the boat was first of all, lifted from the water to the shore and mapped three-dimensionally by an electronic tachometer, with all the measuring equipment in place i.e. GPS antenna, transducer and inclinometer which is used for the measurement of pitch and roll angles (note that, the value of a was determined during that survey). The constituted coordinate system was a right-handed system. The body longitudinal axis coincided with the x-axis. The attitude of a ship is described by the roll and pitch angles. Here, the roll angle (R) was defined as the angle between the y-axis and the horizontal plane, and the pitch angle (P) was defined as the angle between x and the horizontal plane. The transformation from the body frame to the local level (navigation frame) can be expressed by

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{LL} = \underline{\Phi} \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{BF} \tag{2}$$

where, the subscript LL and BF are the local level and body frame respectively, and Φ is the total transformation matrix and can be expressed in the following form

$$\underline{\Phi} = \begin{bmatrix} CosBCosP & SinBCosR + CosBSinPSinR & SinBSinR - CosBSinPCosR \\ -SinBCosP & CosBCosR - SinBSinPSinR & CosBSinR + SinBSinPCosR \\ SinP & -CosPSinR & CosPCosR \end{bmatrix} \tag{3}$$

where, B is the bearing angle of the heading (clockwise horizontal angle from the true north). All the collected data were corrected for the pitch and roll effects by the above equation. In this way, the reduction of coordinates from the ship's antenna to the transducer was also carried out. Further information is given about this subject in (Hare, 1995) and (Luscombe, 1994).

Data Acquisition Methodology

Halic Bay, widely known as Golden Horn, was chosen as a test area (Figure 2). The fieldwork was performed in August 1999. The following steps were realized under the scope of the study.

Pre-studies

A sufficient number of geodetic points was set up in the test area. The spirit leveling, reciprocal leveling and valley crossing leveling methods were performed for measuring the height differences. These points were tied to the National Vertical Control Network benchmarks around the test area. Furthermore, the geodetic points were coordinated by static GPS carrier phase measurements. At the end of the pre-study, adjusted cartesian coordinates and orthometric heights were available for each geodetic point.

The geoid undulation in the working area was derived from the orthometric and ellipsoidal heights of the geodetic points by the following formula:

$$N_i = h_{GP_i} - H_{GP_i} \tag{4}$$

where, h_{GP_i} and H_{GP_i} are the ellipsoidal and orthometric heights of the geodetic points, respectively, i denotes the geodetic point number. The calculated undulation was not absolute but relative because the coordinates of the geodetic points were not absolute (pertain to a local reference system). This did not create any problem because the adjusted ellipsoidal coordinates were used for all the subsequent measurements. In this way, all measurements were carried out in the same datum, even though they were performed at different times. The average value of every undulation value calculated from (4) was taken as a current geoid undulation, N.

Hydrographic Surveying

The hydrographic surveying was carried out along the previously defined parallel survey profiles. The coordinates and depths were measured simultaneously at 1 Hz rate interval. The data collection was performed using the Profimap Software. The Profimap is a hydrographic software and is used for acquiring, matching and logging both position and depth data at the same time. In general, survey preparation and on-line/off-line processing could be performed by this software (Alkan and Kalkan 1999).

The positioning was performed with GPS carrier phase measurement in the marine environment. The kinematic surveying method was applied because a moving object had to be considered. The initial integer ambiguity was determined by the On The Fly (OTF) method. The ambiguity was resolved with the OTF method while the object was moving.

An Atlas Deso-15 two-channel echo sounder, with frequencies of 33 kHz and 210 kHz, was used for measuring the depths. The stated accuracy of results from this instrument is given as ±10 cm and ±1 cm at 33 kHz and 210 kHz, respectively (Atlas Elektronik 1994). The current sound velocity of the working area was determined by the bar check method before starting the hydrographic surveying. The recorded depths were between 3 and 38 m.

While the hydrographic surveying was continuing, readings were observed every 15 minutes from a staff tide gauge established on the shore. The staff was an enameled ruler with dimensions of 90 cm length and 12 cm width. The zero point height of the staff was determined with geodetic spirit leveling and the orthometric heights of the seabed were calculated once again in this way.

Digital Terrain Model

In this section of the study, both sea surface and sea bottom are modeled by Digital Terrain Model (DTM) using ellipsoidal heights and depths, respectively. The DTM can be defined as digital representation of the terrain and it is based on measurements of some measurement points that are called control or reference points. The depth and orthometric height of any desired point of sea bottom could be calculated using the modeled surface. This is basically an interpolation procedure. There are a number of methods which have been successfully applied to hydrographic or similar applications.

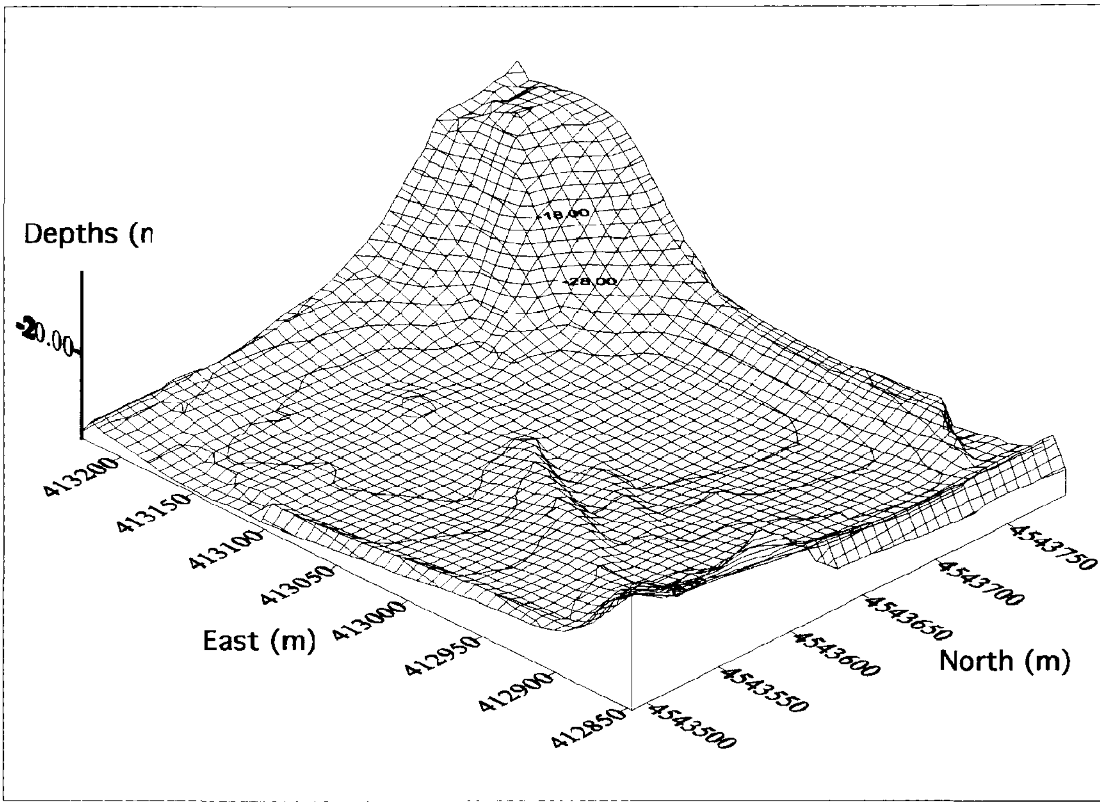

Figure 3: *3-D Surface Visualisation of Sea Bottom Topography*

The DTM has been discussed extensively in the literature (Hardy 1971, MatZin *et al.*, 1994, Petrie and Kennie 1987, Schut 1976, Watson and Philip 1984). Therefore, it will not be repeated here. One must keep in mind that, whichever interpolation method is used, the derived information cannot produce more accurate measurements than direct measurement.

At the end of the study, $e_i(east)$; $n_i(north)$; $h_i^{inst.}$ *(ellipsoidal)* and d_i *(depth)* values of the every measurement point were obtained. If the $h_i^{inst.}$ and the d_i values are put into equation (1), the depth values can be transformed to the orthometric heights. Determination of the other necessary parameters for the equation, i.e. N and a, are explained in previous sections. When the sounding is measured with single beam or single transducer systems, data is gathered only along one surveying profile. Thus, there is no information between the surveying profiles. Information about the whole sea bottom could be obtained by applying the DTM. By the use of DTM, the sea bottom and sea surface are modeled by using the measurements, and in this way, depth and orthometric height of any desired point of the sea bottom may be predicted (calculated) according to the modeled surface.

Nowadays, there is an algorithm which is extensively used in hydrographic applications apart from the methods which are introduced in the above literature such as weighted arithmetical mean, polynomial regression, minimum curvature, nearest neighbor, multiquadric surface and triangulation. This method is called Kriging. The Kriging method has been developed by the Centre de Morphologie Mathematique as a method of optimum estimation which permits the best possible representation of a terrain from available data (Chiles and Chauvet 1975). The Kriging method takes into account the structure of the phenomenon by employing a structural function and is very similar to Least Squares prediction. The main difference being that the Kriging uses the morphological structures for interpolation and for this reason is the best technique that can be used for marine cartography (Schenke 1989).

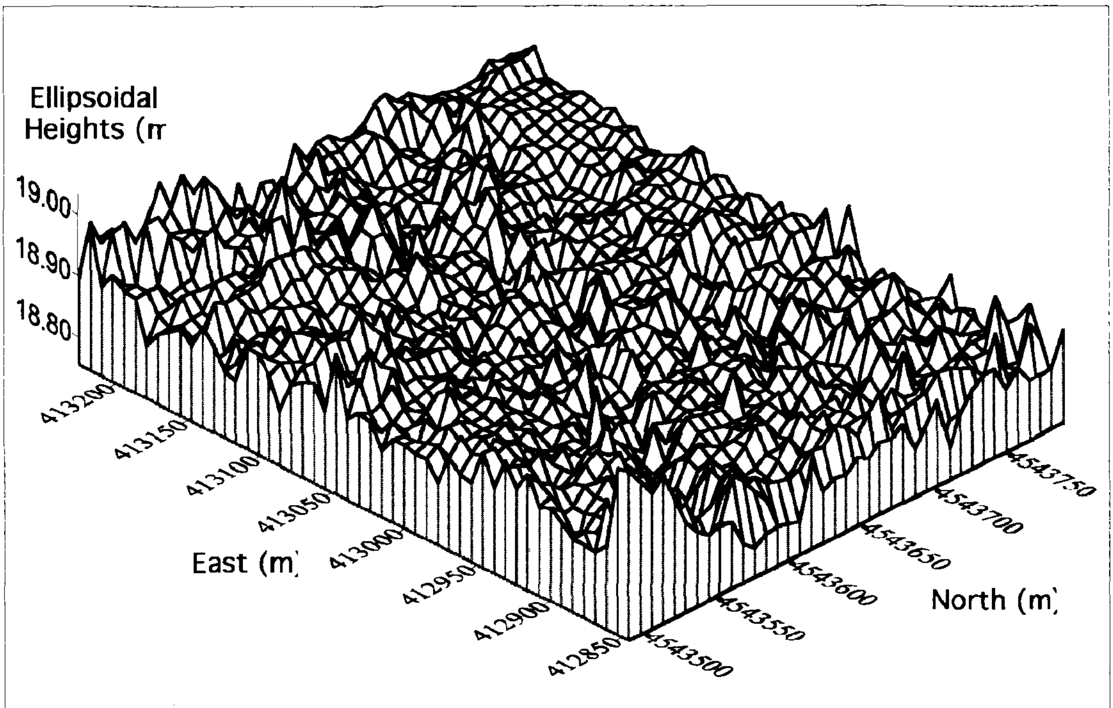

Figure 4: *3-D Surface Visualisation of Sea Surface Topography*

The process steps are given below:

i-) The depths are modeled by the Kriging method utilizing the coordinates and depths (e_i, n_i, d_i) (*Surface-I*) (Figure 3).

ii-) The sea surface is modeled utilizing the $e_i, n_i, h_i^{inst.}$ values which were obtained from GPS carrier phase measurements (*Surface-II*) (Figure 4).

iii-) Preparing the interpolation file which consists of coordinates (e_j, n_j) belonging to the unmeasured area. Then the depths (d_j) corresponding to coordinates are calculated on the first surface by interpolation.

iv-) Again, the ellipsoidal heights of the same points are calculated on the second surface by the interpolation.

v-) The orthometric height of the measurement point (H_i) or interpolation point (H_j) is calculated by means of eq. (1).

vii-) Finally, a text file is produced, which consists of (e_i, n_i, H_i) or (e_j, n_j, H_j).

All these processes are performed by the Golden Software Surfer program.

The values, which are obtained from eq. (1) compare with the results of the staff tide gauge. To do that, orthometric heights of the each i^{th} point are calculated by using the gauge reading by (Figure 5)

$$H_i = H_{MSSL}^{inst.} - (d_i + t) \quad \textbf{(5)}$$

where, $H_{MSSL}^{inst.}$ is the orthometric height of the mean sea surface level during the survey (the orthometric height of the instantaneous sea surface level), d_i is depth and t is the difference between the sea level and the transducer, i.e. transducer draft. The transducer draft, which was measured accurately in the calm water, has to be added to the reported depth to determine the actual depth. As known, the transducer of the echo sounder is located beneath the vessel because the propellor of the vessel may create

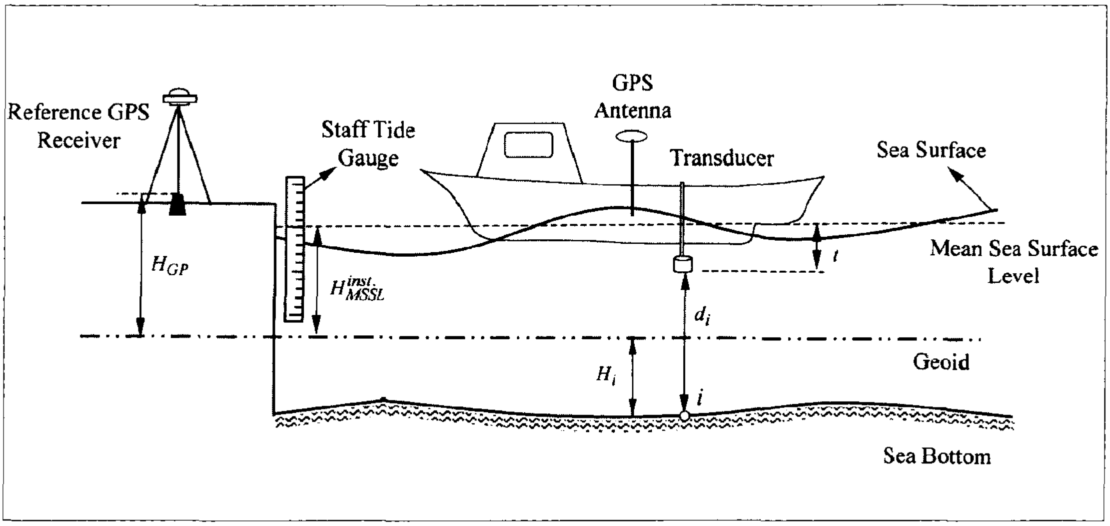

Figure 5: *The Schematic Depiction of the Tiding the Depth to the Vertical Datum with Employing a Tide Gauge*

aeration and this may damage the characteristic shape of the acoustic waves on the transducer surface especially when the vessel is underway.

The differences between the orthometric heights which are obtained from equation (5) and the method introduced here are given in Figure 6. It is clearly seen from the figure that, there are significant differences between the results. The magnitude of these errors can reach up to several decimeters. The differences in the figure show the presence of the errors (signals and noises) for long and short periods, such as heave, surge and tides. On the other hand, one should keep in mind that the long and short period effects also affect the tide gauge readings. Disturbing factors of the water surface were grouped in

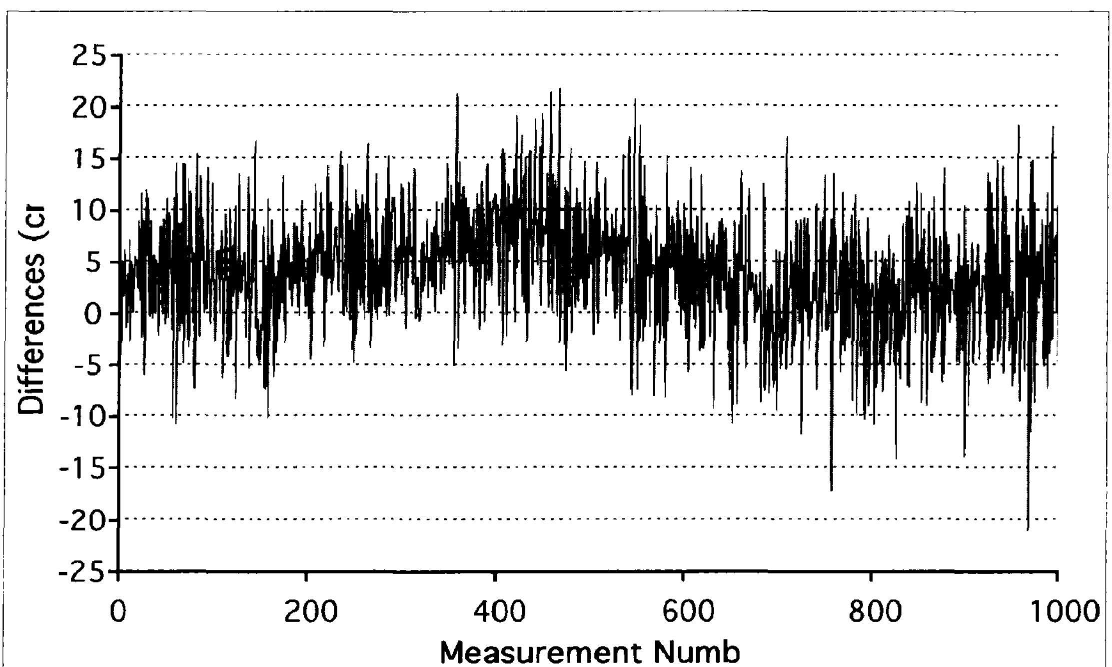

Figure 6: *The Comparison of the Orthometric Heights obtained from eq. (1) and eq. (5)*

some parts in the previous section. However, the most important effects among them that change the water surface are tides and winds. The astronomical tide can reach up to only a few centimeters in the survey area (Alpar, 1993). To avoid the external effects of wind or other marine vessels, etc. the tide gauge was established in a relatively undisturbed part of the study area. In this way, it was tried to eliminate the disturbing factors affecting the tide gauge readings.

Conclusions and Suggestions

The algorithm presented in this paper successfully achieves the transformation of the depth values to the orthometric heights by the GPS carrier phase measurement without the need of a tide gauge readings. If the aim of the hydrographic surveying is only charting the sea bottom three dimensionally and the information about the sea surface is not considered, the charting procedure can be performed without tide gauges by using this method. The introduced method is very useful, especially for hydrographic surveying which is being carried out for engineering projects. The most serious drawback of the method is the necessity of knowing precisely the geoid undulation. This problem has been solved by most of the countries which have defined their N values and made them available for practical use. If the N value is unavailable, the previously mentioned approach and (4) could be used to calculate it.

The working area is modeled by using the DTM utilizing both coordinate and depth measurements. In this way, it has been possible to derive depths and their orthometric heights belonging to the unmeasured area via modeled surface.

The survey vessel moves irregularly as a result of wave action, both the in horizontal and vertical planes and as a result of this movement heave, pitch and roll errors may occur. The heave can be defined as the vertical motion of the vessel. Waves produced as a result of environmental effects such as wind and tides (if present) causes the heave motion. It is a very important error source in hydrographic surveying and can reach up to significant values depending upon the measurement conditions. The result shows that, when the algorithm introduced here is carried out, the errors, which have resulted from the irregular vertical motion of the vessel, such as heave, surge, etc. could be eliminated without the need of extra study. This result is valid, if the reduction from antenna to transducer is carried out without error and if the GPS measurements and survey soundings are synchronized.

Acknowledgements

The author wishes to thank O. Baykal for his valuable comments and suggestions, and F. Akbulut and S. Alkan for their assistance in data collection.

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Biography

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