Comparative methodologies for sounding reduction applied to a bathymetric survey referenced to the WGS-84 ellipsoid, executed in Concepcion Bay and Gulf of Arauco, VIII region, Chile.

Javiera González-Acuña
Hydrographic and Oceanographic Service of the Chilean Navy
Elliot N. Arroyo-Suarez, Naval Oceanographic Office

ABSTRACT

During the months of January and February 2011, a hydrographic survey onboard USNS *Pathfinder*, a ship under technical control of the U.S. Naval Oceanographic Office (NAVOCEANO), and under the assistance of personnel from the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA), was carried out in the areas of Concepción Bay and Gulf of Arauco, VIII Region, Chile.

The main purpose of the survey was to regenerate national nautical charts, which were affected by an earthquake and subsequent tsunami that took place on 28 February 2010.

The hydrographic survey utilized a three-dimensional Global Positioning System (GPS) called Precise Point Positioning (PPP) referenced to the WGS-84 ellipsoid and traditional sounding reduction methods.

The bathymetric data was reduced to a vertical reference plane, which in Chile is called the Sounding Reduction Level (SRL), by using the standard technique of utilizing tidal records from four tide gauges located on the coast (applying observed tides). Also employed was a methodology of GPS Tides, which utilized data recorded by the ship’s GPS system as well as moored GPS buoys. For the GPS Tide application, we developed a Separation Model (SEP) by adjusting the global Earth Geopotential Model of 2008 (EGM-2008) with the mean-sea level (MSL) at six land-based stations, tied to the WGS-84 ellipsoid, and the MSL calculated from the ellipsoidal height of three GPS buoys moored offshore, along with their \( Z_{00} \) values.

Both sounding reduction methodologies were compared on five bathymetric surfaces within the study area, obtaining an average difference of 10 cm between them.

INTRODUCTION

In a typical bathymetric survey, the measured depths must be reduced to a vertical reference plane. This reference plane is known as the chart datum.

The chart datum utilized in Chile is known the SRL, and is determined for the lower low tide in syzygy, when the moon is in perigee (SHOA, 1999). The realization of such a plane is made through the analyses of water level time series.

At the present time, these measurements of sea level records are gathered principally by analog or digital tide gauges installed along the coast.

Chile could benefit by adopting a methodology that consists of carrying out hydrographic surveys with respect to a vertical reference surface that does not vary significantly in time and space. This is achieved through the use of Global Navigation Satellite System (GNSS) Positioning (FIG, 2006).
The benefit of this method is that the acquired bathymetry and the vertical benchmarks are directly referred to the reference ellipsoid.

Although the reference ellipsoids are convenient, they are not physical surfaces that are defined in terms of gravity or mean-sea level, but abstract surfaces defined utilizing mathematical equations (Dodd, 2009). To produce nautical charts, the bathymetric information referenced to the ellipsoid must be transferred to a tidal surface or plane through the use of a SEP.

The SEP is determined utilizing information from the MSL values at the tide gauges, geoid undulation given for the land-based tide benchmark, SRL tied to the MSL, and precise measurements of sea level registered with GPS buoys (FIG, 2006; Oliveira et al., 2010).

To obtain depth relative to an SRL, the generated SEP is applied to the bathymetric measurements that are referenced to the same ellipsoidal surface.

**TRADITIONAL HYDROGRAPHIC SURVEY – SURVEY REFERENCED TO ELLIPSOID**

In traditional hydrographic surveys (Figure 1), two-dimensional positioning (XY) and the sounding reduction are made with the sea level information given by the sensors installed at the coast (tide gauges). For the above, the chart depth:

\[
\text{Chart Depth} = \text{Observed Depth} + \text{Transducer Depth} - \text{Tide} \quad \text{(to SRL)}.
\]

(Eq.1)

In a hydrographic survey referenced to the ellipsoid, the positioning is three-dimensional (XYZ), for which the sounding can be reduced for the tides measured by the ship and the application of the SEP (Figure 2). It does not necessarily need information of the sea level changes provided by tide gauges.

\[
\text{Chart Depth} = \text{Observed Depth} + \text{Transducer Depth} - \text{GPS Tide} \quad \text{(Eq. 2)}.
\]

Where the calculation of the GPS Tide:

\[
\text{GPS Tide} = \text{GPS Height} + \text{Antenna Offset} + \text{Draft} - \text{Heave} - \text{Water Line Offset} - \text{SEP}.
\]

(Eq.3)
Of all values shown in equation 3, the only unknown is SEP, which is determined by:

\[
SEP = Geoid\ Model + Residuals - Z_{00} \\
\text{(Eq.4)}
\]

Where:

Geoid Model: The EGM-2008 model was used for geoid undulation in this study, because Chile does not have a local model.

Residual (R): Is the difference between the geoidal undulations and the measured ellipsoid to local MSL. This is done by leveling the field benchmark to the referenced ellipsoid, and by calculating the MSL at the buoy location.

\[Z_{00}\]: Is the distance between the MSL and SRL in tide benchmark and GPS buoys.

With the values of the SEP model (Figure 6), it is possible to compute GPS Tide using equation 3 and apply the correction at a later time to obtain the charted depth.

**METHODOLOGY**

The data utilized in this work was acquired between January and February 2011, during the hydrographic survey in the areas of Concepcion Bay and Arauco Gulf (Figure 5), aboard the hydrographic and oceanographic ship USNS Pathfinder (T-AGS 60). This was a joint effort between NAVOCEANO and SHOA.

The available information corresponds to bathymetric data acquired with multibeam echosounders, data of GPS positioning, data of variation of sea level in four tide gauges (red symbols), information of six vertical control benchmarks located on the coast (purple symbols), and three GPS buoys (blue triangles) spread out in the survey area.
The vertical benchmark used in the study corresponds to those located in Naval Base Talcahuano, Quiriquina Island, Port of San Vicente, Tome, Lirquen, and Coronel. These vertical benchmarks provided information of MSL, SRL, and precise ellipsoidal height.

The values of MSL and SRL\(_B\) were obtained directly from the benchmark sheets. Twenty-four hour observations of GPS data provided the precise ellipsoidal height (h\(_B\)) at each location. From these ellipsoidal height values (h\(_B\)), the height of local MSL referred to the reference ellipsoid (h\(_{MSL}\)). The residual (R) is obtained from differencing the EGM-2008 model (N\(_{EGM-2008}\)) and h\(_{MSL}\). In addition, the Z\(_{00}\) value is obtained from the subtraction of the MSL\(_B\) and SRL\(_B\). In figure 6, we can observe all of the parameters utilized at the vertical benchmark.

Three GPS buoys were deployed in the survey area in order to get the best accuracy for the SEP model. They were deployed in the center of Arauco Gulf, west of San Vicente Bay, and west of Santa Maria Island.

The buoys were the 0.9 m model of the Axys HydroLevel\textsuperscript{TM}, which registers and logs variations in sea level using GPS positioning. The buoy also logs and compensates for the angular motion using a motion sensor, which is used to calculate the precise position of the waterline on a time-series. The time-series is utilized to compute a MSL and the chart datum (SRL) referenced to the ellipsoid. The positioning and motion sensor data were collected at 1Hz.

The calculation of the SRL from the GPS buoys was accomplished by Tidal Analysis Harmonics (Methods of Least Squares) (Foreman, 1977), using the methodology indicated in Hydrographic Instruction Eq.5 of the SHOA (2003). This method assumes that vertical variations in sea level can be expressed mathematically like the sum of a series of harmonic terms that have a direct relation with astronomic conditions. The given information is enough for a complete description of the tide and future predictions. A more exact value of the SRL comes from 19 years of observations (Meton’s cycle), although for semi-diurnal tidal regimen, with 30
days of observations is enough (Parada et al., 2001), (SHOA, 2003).

The tide’s principal harmonics that correspond to diurnal and semi-diurnal components are determined by:

\[ SRL = MSL - (M_2 + N_2 + S_2 + K_1 + O_1) \]  
(Eq. 5)

The positioning of buoys was in absolute mode. In order to obtain better positioning accuracy, the GPS data were post-processed using the Precise Point Positioning (PPP) technique. The PPP processing utilizes information from precise clocks and orbits of satellites (Huber et al., 2010).

One of the grid surfaces corresponds to the EGM-2008 geopotential model, at a resolution of 1’ x 1’. We have used the method of Natural Neighbor, based on the concept of Thiessen polygons, where the interpolator utilizes a weighted average of nearby observations. This method of interpolation maintains the original values of the equidistant EGM-2008 points.

The residual surface (R) represents the difference of the EGM-2008 model and the observed MSL (MSL_{bu}) at each of the buoy location, and the local MSL at the benchmark locations (h_MSL). The method of interpolation (and extrapolation) must represent the real tendency of this surface in this area. To construct this grid, we utilized the linear regression method, which defines tendencies and patterns in data on a large scale. This method is not really an interpolator since it does not try to predict the unknown values of the surface; rather it assumes the values delivered by the benchmark and buoys.

For the grid surface Z_{00}, which represents the distance between the MSL and the SRL, we utilized the method of interpolation linear kriging. Basically, it is a statistical method that generates a grid of data from a set of observations, assuming that the distance and/or the direction among points of sampling are an expression of spatial correlation among themselves.

Once the three grids were computed, we then applied equation 4 to each of the grid nodes in order to construct the SEP model.

The generated SEP model was valid only for the area of bathymetric coverage, whose limits correspond to buoys offshore and the benchmark at the coast.

Values of MSL_{bu} and SRL_{bu} are obtained from the time series collected by the buoy.

The undulation residual (R_{bu}) is obtained by subtracting the EGM-2008 (N_{EGM-2008}) geoidal undulation model and the observed MSL (MSL_{bu}). Z_{00} values are obtained through the subtraction of the MSL_{bu} and SRL_{bu} (figure 7).

The SEP is constructed using the parameters delivered by the vertical benchmark and the GPS buoys, which implies the development of three surface grids.
The soundings were collected by a system of integrated measurements with multibeam echosounders, SIMRAD models EM-710 and EM-122. The motion and positioning sensor was the Position and Orientation System for Marine Vessel (POS-MV), augmented by the NavCom SF-2050G receivers operating in Real-Time GIPSY (RTG) mode. All NavCom 2050G data were collected in raw format and post-processed utilizing the PPP technique. Bathymetric data were processed by the CARIS HIPS and SIPS 7.1 software.

Bathymetry Associated with Statistical Error (BASE) surfaces were created at a resolution of 2 and 5 meters (figure 8). One set of BASE grids we reduced using the traditional tide, while the other sets of BASE grids over the same area were reduced by the GPS tide method.

Quality control (QC) was performed to validate the bathymetric data, where the sounding’s records were compared statistically to a line of verification (transversal to sounding). This QC determines the percentage of soundings that fall within the standard minimum established for hydrographic surveys by the International Hydrographic Organization (IHO) Special Publication 44 (S-44). In this study we will focus on Order 1A (IHO, 2008).

Comparisons between the bathymetric surfaces were performed by subtracting a surface which the traditional tide (observed tides) has been applied from a surface which the GPS tide had been applied.

If the surface difference is positive, it indicates that the bathymetry to which the GPS tide had been applied was shallower.

RESULTS

The time series of the four tide gauges are consistent in phase and amplitude. The tide gauge located in Port Talcahuano presented greater height (1.24 m), followed by Port Tomé (1.11 m), while the tide gauges located in San Vicente and Puerto Coronel registered a lower average of 1.07 m and 1.05 m, respectively.
The difference when subtracting the EGM-2008 undulation model from \( h_{\text{MSL}} \) is negative in five of the six sites, which implies the EGM-2008 model is, on average, 10.3 cm above the measured MSL, except in San Vicente where it is located 2.4 cm below.

The Z\(_{00}\) values show a smaller difference than those shown on the benchmarks, with a minimum of 0.884 m at buoy No. 2, located in the northwest Gulf of Arauco, and a maximum of 0.924 m at buoy No.1 located in the center of the Gulf (Table 4).

The uncertainty of the PPP of the GPS buoys on the horizontal component was, on average, 0.092 m standard deviation, while vertical is a little higher, with an average of 0.124 m.
Figure 10 shows that the geoid undulation is greater closer to the coast and decreases as we move seaward.

With the \( Z_{00} \) (Figure 11) surface, the distance of separation between MSL and the SRL is greater on coast, with the exception of the benchmark localized on Quiriquina Island, where the distance is less (0.931 m) compared with the average. Offshore values tend to be smaller, averaging 0.908 m at the buoys.

With the sum of the surfaces of EGM-2008, \( Z_{00} \) and residual (R) using the expression on Eq.4, the SEP model was calculated (Figure 13). This model represents the separation distance between the reference ellipsoid and the tidal datum (SRL).
COMPARISONS BETWEEN BATHYMETRIC SURFACES WITH DIFFERENT SOUNDING REDUCTION METHODS.

The bathymetric survey area corresponds to more than 2000 km²; because of this, and to make comparisons between sounding reduction methods, we selected five representative zones located in (Figure 14):

1. San Vicente Bay
2. Northwest Conception Bay
3. Northwest of the Gulf of Arauco (Biobío Canyon)
4. Centre of the Gulf of Arauco
5. West Santa Maria Island

Surface No.1 is located in the vicinity of San Vicente Bay. The difference between soundings reduced using by comparing the GPS tide to the traditional tide was 7.9 cm with 96.1% positive values (table 5), which indicates that the bathymetry is shallower with the GPS tide.

The second area was located northwest of Conception Bay, which is considered to be under the influence of the tide gauge of Tomé. The difference between the two surfaces was 12.5 cm with 99.9% negative values; the height of the tide recorded by the sensor located on the coast was greater than that recorded by the vessel.

The third area was located to the northwest of the Gulf of Arauco; this area is the deepest, reaching 1100 m. The surface difference gave 94.5% positive data with an average of 5.9 cm, which indicates that the reduced depth by GPS tide is shallower than the depths reduced with observed tide.

The center of the Gulf of Arauco was represented by surface No.4. The surface difference gave 72.1% positive data with an average of 3.5 cm, and 27.9% negative data with an average of 3.3 cm.

Surface No.5 was located to the west of the Santa Maria Island. This area of difference showed greater variation between both methodologies, obtaining 100% positive data with an average of 19.3 cm. This suggests that GPS tide recorded by the vessel presented greater height than that recorded by the sensor installed on the coast.

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Tide Gauge Distance (km)</th>
<th>Depth Average (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1</td>
<td>San Vicente</td>
<td>3.2</td>
</tr>
<tr>
<td>2 11.5</td>
<td>Tomé</td>
<td>23</td>
</tr>
<tr>
<td>3 30</td>
<td>San Vicente/Coronel</td>
<td>46/51</td>
</tr>
<tr>
<td>4 20</td>
<td>Coronel</td>
<td>24</td>
</tr>
<tr>
<td>5 7</td>
<td>Coronel</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 5. Surface area differences.

<table>
<thead>
<tr>
<th>Dif min (m)</th>
<th>Dif max (m)</th>
<th>% (+)</th>
<th>Ave (+) cm</th>
<th>%(-)</th>
<th>Ave (-) cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 -0.16</td>
<td>0.15</td>
<td>96.12</td>
<td>7.9</td>
<td>3.88</td>
<td>-2.3</td>
</tr>
<tr>
<td>2 -0.45</td>
<td>0.19</td>
<td>0.01</td>
<td>7.3</td>
<td>99.9</td>
<td>-12.5</td>
</tr>
<tr>
<td>3 -0.86</td>
<td>2.39</td>
<td>94.47</td>
<td>5.9</td>
<td>5.53</td>
<td>-1.1</td>
</tr>
<tr>
<td>4 -0.41</td>
<td>0.55</td>
<td>72.09</td>
<td>3.5</td>
<td>27.9</td>
<td>-3.3</td>
</tr>
<tr>
<td>5 0.005</td>
<td>0.44</td>
<td>100</td>
<td>19.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Bathymetric surface comparison, results.
DISCUSSION

The geopotential model must be adjusted vertically when surveying over large areas when using GPS tide methods. Therefore the construction of a SEP model for the sounding reduction is essential.

Chile does not have a local geopotential model, so we used the EGM-2008 global model that present errors estimated between 0 and 0.45 m (Pavlis et al., 2008). Ellipsoid-to-MSL values observed on some control points showed a maximum difference between the geoid undulations obtained from the EGM-2008 model of 0.177 m at elevation of Tomé. The GPS buoy was 0.212 m in buoy No. 2.

Four bathymetric surfaces reduced by the GPS tide were shallower than the surfaces reduced using observed tides (Table 6), indicating an average difference of 10 cm with a standard deviation of 4.3 cm (1σ). These values are similar to those obtained by Riley (et al. 2003) in Delaware Bay (USA), Dodd (2010) in Bay Fundy (Canada), and Oliveira (et al. 2010) in Guanabara Bay, Brazil.

The surfaces located west of Island of Santa Maria had the largest difference, which presented 19 cm on average and a maximum of 44 cm. A possible reason for this difference could be the distance between the tide instrument of Coronel (table 5) and the GPS tide. If we analyze the tide record retrieved by the buoy No.3 and compare it with the tide instrument of Coronel, we obtained an average difference between both series of (17.3 cm), which could explain the difference between the tide of the ship and the tide gauge.

CONCLUSIONS

The average difference between both methods of sounding reduction was 10 cm. That difference is affected directly by the model SEP. The results obtained in the present work show that the GPS tides can reliably meet the requirements of an Order 1A survey.

For surveys that require higher order of uncertainty, like a Special Order or dredging, a more accurate positioning method will be required, such as Real-Time Kinematic (RTK) or Post-Processed Kinematic (PPK) positioning.

The most critical point in the implementation of this type of survey is the development of the model of separation SEP, which includes a combination of the uncertainties of all surfaces.

The use of GPS buoys helps in the definition of the SEP over large areas. They should be deployed for a period of at least 29 days to obtain a more accurate derived tidal datum.

Chile must continue with the development of this new form of hydrographic survey mainly focusing on obtaining more accurate SEP's.

ACKNOWLEDGMENTS

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