Construction of the reference (vertical) hydrographic surface for the bays of Buenaventura and Málaga, Colombian Pacific

Construcción de la superficie hidrográfica de referencia vertical para las bahías de Buenaventura y Málaga, Pacífico colombiano

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Abstract

The present paper defines the methodological path used in the project "Vertical Reference Hydrographic Network for the main Colombian maritime ports", during the generation of reference vertical frame called "Vertical Reference Hydrographic Surface (SHRV2016)" for Buenaventura and Malaga bays in the Colombian Pacific, based on three main components: the mathematical determination of vertical datums associated with historical records of the water level, the establishment of first order geodetic points network, and the measurement of sea surface heights with reference to the WGS84 ellipsoid (World Geodetic System), using GNSS (Global Navigation Satellite System) receivers in differential mode RTK (Real Time Kinematic). The ground reference points were used to have precision vertical control to the datums in the water, and also for the installation of GNSS reference receivers, that were in charge of sending real time differential corrections during the measurement of sea surface heights. These measurements in connection to the calculated vertical datums densification for the area, formed the necessary basis for development the SHRV2016, a model with a spatial resolution of 500 meters, where all water level vertical datums refers to the WGS84 ellipsoid. In addition to standardize measurements made by different users in jurisdictional waters relative to a vertical datum; allowing to take advantage of the benefits of GNSS technology to perform the water level measurement and correction in real-time with the lesser degree of uncertainty during the execution of hydrographic surveying, optimizing time, quality and resources, particularly in places such as Buenaventura and Malaga bays, where the tidal regime makes complex the activity of correction due to the variability in range and phase of the sector, by which makes necessary install multiple tide stations, perform tasks of Surveying and Geodesy in difficult access places, and will wait for include tide gauge records in the final correction of the depths, only until the hydrographic survey will finish. In a medium term, the SHRV will allow the generation of a total tide datums reference model relative to the ellipsoid, covering completely the coastal and island regions of the country, up to the limits of the Territorial Sea, thanks to the combination with satellite altimetry data and observational offshore tools as GPS buoys, which allow the correct fusion with the local models generated in each one of the bays and harbors.

KEYWORDS: Colombian Pacific, Bahia Malaga, Bahia Buenaventura, vertical reference, hydrographic surveys, mean sea level, mean high water springs, mean low water springs, highest astronomical tide, lowest astronomical tide, height reference, vertical datum.

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Resumen

Se define la ruta metodológica usada en el proyecto "Red Hidrográfica de Referencia Vertical para los principales puertos marítimos colombianos", durante la generación del marco vertical de referencia denominado "Superficie Hidrográfica de Referencia Vertical (SHRV2016)" para las bahías de Buenaventura y Málaga en el Pacífico colombiano, a partir de tres componentes principales: la determinación matemática de datums verticales asociados a registros históricos de nivel de agua, el establecimiento de una red de vértices geodésicos de primer orden, y la medición de alturas en la superficie del mar con referencia al elipsoide WGS84 (World Geodetic System), empleando receptores del sistema GNSS (Global Navigation Satellite System) en modo diferencial RTK (Real Time kinematic). Los puntos de referencia en tierra fueron utilizados para dar el control vertical de precisión hacia los datums en el agua, y a su vez para la instalación de receptores base GNSS encargados de enviar las correcciones diferenciales en tiempo real durante la medición de alturas en la superficie del mar. Estas mediciones junto a la densificación de datums verticales calculados para la zona, constituyeron la base en la elaboración de la SHRV2016, modelo que con una resolución espacial de 500 metros, refiere al elipsoide WGS84 los datums verticales de nivel de agua, y que además de estandarizar las mediciones que realizan los diferentes usuarios en las aguas jurisdiccionales relativas a un datum vertical; permite aprovechar las ventajas de la tecnología GNSS para realizar la medición y corrección de nivel de agua en tiempo real con el menor grado de incertidumbre posible durante la ejecución de levantamientos hidrográficos, optimizando tiempo, calidad y recursos, especialmente en lugares como las bahías de Buenaventura y Málaga, donde el régimen de marea hace compleja la actividad de corrección debido a la variabilidad en rango y fase propia del sector, lo cual obliga a instalar múltiples estaciones mareográficas, realizar tareas de topografía y geodesia en lugares de difícil acceso, y esperar al término del levantamiento hidrográfico para incluir los registros de las estaciones en la corrección final de las profundidades. En un mediano plazo, las SHRV permitirán la generación de un modelo completo de referencia de los datums de marea hacia el elipsoide, que abarque completamente los litorales y regiones insulares del país, hasta los límites del mar territorial, gracias a la combinación con datos de altimetría satelital e instrumentos de observación mar adentro como boyas GPS, que permitan la correcta fusión con los modelos generados a nivel local en cada una de las bahías y puertos.

PALABRAS CLAVE: *Pacífico colombiano, bahía Málaga, bahía Buenaventura, referencia vertical, superficie hidrográfica, nivel medio del mar, pleamar media de sicigia, bajamar media de sicigia, marea astronómica más alta, marea astronómica más baja, altura de referencia, datum vertical.*

Introduction

In Colombia, the progress in the determination of reference heights has advanced little by little since the 1940's with the establishment of 35 Laplace stations as a base for the local horizontal reference system, 13 absolute gravity stations and 4 tide gauges installed by the USCGS for the observation and prediction of the sea level with navigation purposes and definition of a vertical reference datum for surveying in the country; two of these were installed in the Caribbean Sea (Cartagena and Riohacha) and two in the Pacific Ocean (Buenaventura and Tumaco).

The records of the tide gauges of the (*Datum* Bogotá, elipsoide de Hayford), implicando que las ondulaciones geoidales fueran relativas y difícilmente comparables con modelos globales (Sánchez, 2003).

It is also noteworthy that the calculation of deflections of the vertical to model an astro-geodesic geoid in 1962, was possible from the Laplace stations mentioned and some complementary astronomical points. Such deflexions complemented with gravimetric and interpolated observations for most of the Colombian territory, reached a precision of ±2" in the mountainous areas and ±6" in the flat areas. These calculations were made on the local datum (Bogotá Datum, Hayford ellipsoid), implying that the geodetic undulations were relative and hardly comparable with global models (Sánchez, 2003).

In 1978, the average sea level calculated for Buenaventura was taken as reference datum, with 18 years of measurements (1951-1968) of 7 tide gauge stations, due it was noted that the level recorded in the Pacific Ocean was approximately 28 cm higher than the one from &sea level obtained from the average of the tide gauge records achieved to eliminate the periodical temporal changes of the sea surface, but the non-periodical, the secular and those generated by the coastal topography were ignored.

The DMA (Defense Mapping Agency) currently known as NGA (National Geospatial-Intelligence Agency), calculated a geoidal model referred to the WGS84 ellipsoid in 1988, with geoidal heights modified to be compatible with the Bogotá Datum. The values of this model resulted somewhat exaggerated, reason why its practical utility was not effective (DMA, 1988).

The first geoid calculated for Colombia by the Igac (Geographical Institute Agustín Codazzi), used isostatic anomalies derived from Bouguer anomalies to make the Stokes formulation. However, due to the isostatic anomalies were derived empirically and the gravimetric effect on the topography was omitted, the model errors resulted considerably high (Martínez, Flórez, & Sánchez, 1995).

In 1998, the gravimetric geoidal GEOCOL98 model was obtained, developed from free air anomalies processed by the Stokes formula as a local component and the geopotential EGM96 model (Lemoine *et al.,* 1998) as a global component. Gravimetric information recorded by geophysical vessel was integrated in the marine areas (Sánchez, 2003). This model with relative precision around ±80cm was used in Colombia to derive classical heights referred to the Buenaventura datum from GPS information (Sanchez & Martínez, 2001). Nevertheless, due to discrepancies found in mountainous areas (mainly in the Andes) between the undulations corresponding to GPS heights combined with differential levelling and the derived from the gravimetric model, and in order to reduce these differences and allow the combination of GPS data with existing levelling networks, the quasigeoid GEOCOL2001 model was calculated in 2000 under the Molodensky theory. The interpolation of the gravimetric anomalies was made with total Bouguer anomaly values, this means that the topographic correction calculated with support in the ETOPO5 model was considered (NOAA, 1988). Terrestrial and air gravity data were used with respect to the land, and satellite altimetry was used with respect to the adjacent marine areas to estimate Faye anomalies. The heights obtained in comparison with ellipsoidal GPS heights and levelling heights, resulted in smaller amplitudes in the residuals and a higher precision of the model (Sanchez & Martínez, 2001), however, systematic errors coming from the deficient quality of some of the gravimetric data used still remained (Sánchez, 2003).

As a consequence, a new calculation of the quasigeoid and its geoid (derived from the Helmert’s second method of condensation) in Colombia was carried out in 2004 by the Igac, according to the Molodensky Theory and applying the remove/restore technique. For such purpose, a readjustment of the gravimetric reference networks was carried out and each one of the geophysical projects provided by the Colombian Petroleum Co. Ecopetrol was evaluated and reduced, so they were compatible with the National Gravimetric System SIGNAR. Gravity anomalies derived from satellite altimetry were included in the marine areas. For the analysis of the gravitational effects on the topography, a digital terrain model (30”x30”) with a resolution higher than the previous ones was used (Sánchez, 2003). The result was a 2’x2’model on Colombia and the immediate border areas of its neighbor countries (the islands of San Andrés and Providencia were not included in the process), and although it has a higher resolution and quality than the previous models, its precision is still not sufficient for its direct application in the surveying of the country.

The gravitational EGM2008 model (Pavlis, Holmes, Kenyon, and Factor, 2012) is a combined solution of data derived from the GRACE (Gravity

Recovery and Climate Experiment) satellite and a global gravity anomaly database with a 5´x5´ spatial resolution. This model, when combining the terrestrial, marine and air data with the satellite data, reached a high order of development in spherical harmonics with the highest spatial resolution for a global gravity model so far (Álvarez *et al.,* 2016).

These quasigeoid and geoid models for Colombia and the world, currently serve as reference surface, that linked with physical heights obtained from combining gravimetric data with levelled heights, consistent with geometrical and ellipsoidal heights, define a Vertical System and provide normal (quasigeoid) and orthometric (geoid) heights, used for purposes that involve mainly the practical topography in developments of applied geodesy such as cartography, engineering, implementation of installations, among others. The Vertical Systems in Colombia have been established using MSL (Mean Sea Level) as a reference level, measured by the tide gauge of Buenaventura in the Pacific Ocean. (Sánchez & Martínez, 2001).

The ellipsoidal heights that also serve as "reference heights", are mainly aimed at satisfying the scientific purposes and the requirements of global networks (determination of satellite orbits, correlation between international vertical systems, monitoring of changes in the sea level, control of vertical movements of the crush, etc.) (Sánchez & Martínez, 2001).

Although major steps have been taken in the determination of reference surfaces, the existing vertical datums do not support the requirements of accuracy of the modern geodesy. They are referred at local levels (isolated) and are seasonal (variations in time are not considered) (Sánchez, 2009). With all of these lacks in the formulation of a reliable vertical datum, the General Maritime Directorate (DIMAR) lead by the Oceanographic and Hydrographic Research Center of the Pacific, established the methodology for the implementation of the Vertical Reference Hydrographic Surface (SHRV2016) in the bays of Buenaventura and Málaga in the Colombian Pacific, with a view to extending initially to all the maritime ports of the country, and consequently to the marine areas adjacent to the coastal line.

This methodology began in 2016 with the establishment of the geodesic network composed of 11 first order points, the water level data obtained during one year of continuous registers of 3 permanent tide gauge stations and 3 months of 2 provisional portable stations, and the information of the grid of points resulting from a RTK differential surveying with GNSS technology in the sea surface with total coverage of the bays of Buenaventura and Málaga; information resulting after applying corrections for time and adjustments of the zero of tidal wave to give consistence between the 5 tide gauge stations and from calculating the vertical datums for each station and spread them until every differential surveying point, allowed the obtainment of the HAT[1] (Highest Astronomical Tide), MHWS (Mean High Water Springs), MSL (Mean Sea Level), MLWS (Mean Low Water Springs), and LAT[1] (Lowest Astronomical Tide) reference heights, interpolated through the Kriging method to all the study area and referred to the WGS84 ellipsoid, which finally compose the SHRV2016 with a horizontal precision of ±5cm and a vertical precision of ±6 cm.

At international level, the creation of separation models was initiated by Canada in 1996 by the Canadian Hydrographic Service, using hydrodynamic models and satellite altimetry data to determine the separation between the Chart Datum and the WGS84 Datum. A similar project called Aushydroid (Martin & Broadbent, 2004), was carried out in Australia in 2004, developed through GPS measurements with respect to the ITRF (International Terrestrial Reference Frame), using zonification in open sea and tide gauges in the coast. The United States launched the VDatum separation model in 2002 (Parker, Milbert, Hess, & Gill, 2003), developed by the United States National Oceanic and Atmospheric Administration (NOAA) as a vertical datum transformation tool that allows the transformation of bathymetric and/or topographic elevation data between 28 different orthometric, ellipsoidal/3-D, and tidal datums. VDatum integrates new technologies such as kinematic GPS in real time and LiDAR bathymetry and topography.

1 Contrary to the definition of the tidal datum HAT and LAT that places them essentially as the average of all the water elevations (above or below the mean level) for a period of 18.6 years, the calculation of the HAT and LAT that this article deals with refers to the heights derived from 1 year of real data including the meteorological tide.

The Vertical Offshore Reference Frame – VORF project (Iliffe, Ziebart, Turner, Oliveira, & Adams, 2006), commissioned by the United Kingdom Hydrographic Office in 2005 and developed by the UCL's Department of Geomatical Engineering, was aimed at modeling the chart datum and other tidal surfaces as a continuous surface with respect to ETRF89 and ITRF2000, additionally determining the average sea surface in the time of reference 2000 with respect to ETRF89. This was made using tide gauge measurements across the coasts and satellite altimetry data in open sea, combined through the interpolation of the Topographic Sea Surface for collocation of least squares.

The SHRV2016 constitutes a vertical separation model intended essentially to be a transformation tool that simulates a vertical reference surface and the differences between this surface and all the vertical datums. For the case, the appropriate reference surface is the WGS84 ellipsoid, which acts as a mean to facilitate the transformation from a vertical datum to another (Davis, Nanlal, Sutherland, and Sutherland, 2011).

Study area

The zone comprehends the bays of Buenaventura and Málaga in Valle del Cauca department, located in the municipality of Buenaventura. The area is covered between the Ladrilleros beach (latitude: 3°56′38,553″ N, longitude: 77°22′3,54″ W) in the north and the sector of Las Palmas (latitude: 3°43′57,312″ N, longitude: 77°11′49,044″ W) in the south on the coast line. From the coast line to the offshore, its extension is around 15 km until the coordinated maritime points latitude: 3°56′35,495″ N and longitude: 77°27′58,174″ W for the north point, latitude: 3°51′42,005″ N and longitude: 77°27′58,174″ W for the middle point, latitude: 3°43′45,083″ N and longitude: 77°21′48,254″ W for the south point. Furthermore, it is extended 500 meters onshore to assure the total coverage of the area (Figure 1).

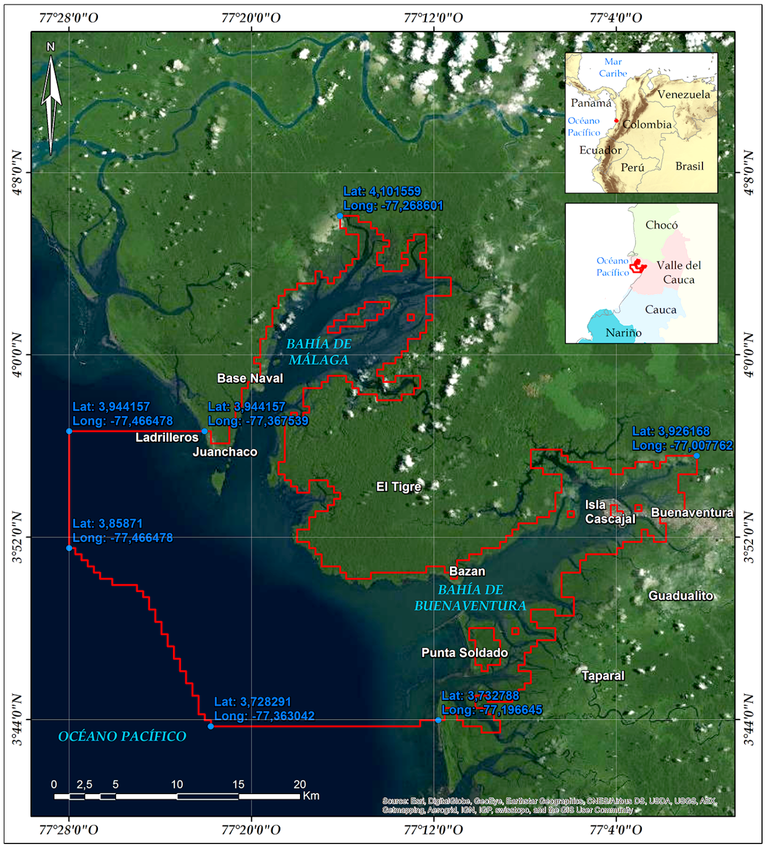

Figure 1. Map of the study area.

Geomorphologically, the area is predominated by hills and hillocks with steep and gentle slopes, characteristic of the bay of Málaga and the north of the bay of Buenaventura. South of the Island of Cascajal, the terrain is characterized for being a deltaic plain with flat to slightly undulated and stable areas that do not receive constant flooding, whose origin is due to the fluvial-marine deposit of sediments. In general, there is a presence of few beaches with fine sand across the bays (Alvarez Machuca, Bermúdez Rivas & Niño Pinzón, 2018).

Methodology

Data

Vertical Reference Hydrographic Surface was calculated from data coming from a tide gauge and a geodesic component; In the tide gauge case, it was provided with the quantification of the vertical datums of LAT (Lowest Astronomical Tide) water level, MLWS (Mean Low Water Springs), MHWS (Mean High Water Springs), HAT (Highest Astronomical Tide) and MSL (Mean Sea Level), from temporary sea level series observed minute by minute for one year in three DIMAR's permanent tide gauges (BV [03°53'29.84"N, 77°04'54.18"W] located in SEMAP quay in Buenaventura, JC [03°54'54.79"N, 77°21'32.70"W] in an islet across from Juanchaco bay of Málaga, and BM [03°58'20.55"N, 77°19'40.41"W] at the naval base of the bay of Málaga) and three months of data from two temporary portable sensors (MB [03°49'57.25"N, 77°10'45.94"W] located in the quay of Bazán Bocana in the bay of Buenaventura and B4 [03°47'34.28"N, 77°18'05.83"W] located in the Buoy No.4 of the access channel to Buenaventura), the latter installed strategically to cover equidistantly the maritime area of the bays that is not observed for the permanent stations.

The geodesic component was provided with the information from the lifting of ellipsoidal heights made on board a hydrographic speedboat on the water surface in RTK differential mode, using GNSS receivers in monitoring of a grid spacing horizontally at 1 kilometer for the internal parts of the bay and at 2 kilometers in the external sector, in which 200 points spatially extended in the 808.05 km^2 (311.99 miles) of the bays were obtained. The reference survey points where the GNSS base receivers for the performance of the RTK surveying were installed, corresponded to the network composed of 11 first order geodesic points materialized in order to support the vertical and horizontal control of the water level datums.

Treatment of the tide signals

The annual observations of the sea level for the DIMAR's tide gauge stations were invaluable to recognize the meteorological and seasonal biases and apply them to the reconstruction of the short-term observations. With respect to the tidal signals, filters were applied to eliminate noise, soften the waves and eliminate atypical data.

The three-month data were reconstructed in one year, basing on the harmonic coefficients resulting from analyzing and treating the wave signals of the genuine data.

With the clean signals, the tidal levels referred to the zero of the permanent tide gauge station were calculated with a higher tide amplitude, corresponding to the MLWS=0.

Installation of the first order geodesic network

The survey point network materialized through 11 points type pilaster and embedment, was distributed homogeneously in the study area on places that met favorable conditions in the following aspects: stability and firmness of the terrain, easy access, safety, separation of possible obstacles that interfere with the correct acquisition of GPS data close to the coast line, seeking that the leveling does not overcome 500 meters in its overall distances and sufficient height for installation of base stations in RTK works. The final solution of coordinates assigned to each one of these points was based on the static surveying method, making post-processing for raw data collected by GNSS TOPCON GR3 receivers that offer a horizontal precision of 3 mm + 0.5 ppm, and a vertical precision of 5 mm + 0.5 ppm for this type of surveying.

The reference stations used as control points during the processing, generation of base lines and triangulations that allowed to guarantee the quality of the finales data corresponded to the Colombian Geological Service's GPS Satellite Geodesic Stations Network– GEORED.

For the calculation of the fiducial coordinates from the reference time to the observation time, the coordinates associated with the reference time for Colombia were transferred from 1995 to the day when the GNSS surveying, 2016 was made for Buenaventura and Málaga, with help of the VEMOS2009 speed model (Drewes and Heidbach, 2009).

Obtainment of ellipsoidal heights from the tidal surface

The RTK (Real Time Kinematic) differential surveying from ellipsoidal heights at sea level was made in a grid of points distributed across the study area, establishing as a limit, the scope in a straight line (12 km in average) of the differential RTK signal transmitted from each control point using double frequency GNSS Leica GX1230 receivers, until the mobile receiver located in the vessel where the height surveying was carried out. The points were distributed with spacing between 1 and 2 km, however, the excessive waving in shallow waters did not allow a suitable record in these sectors (Figure 2).

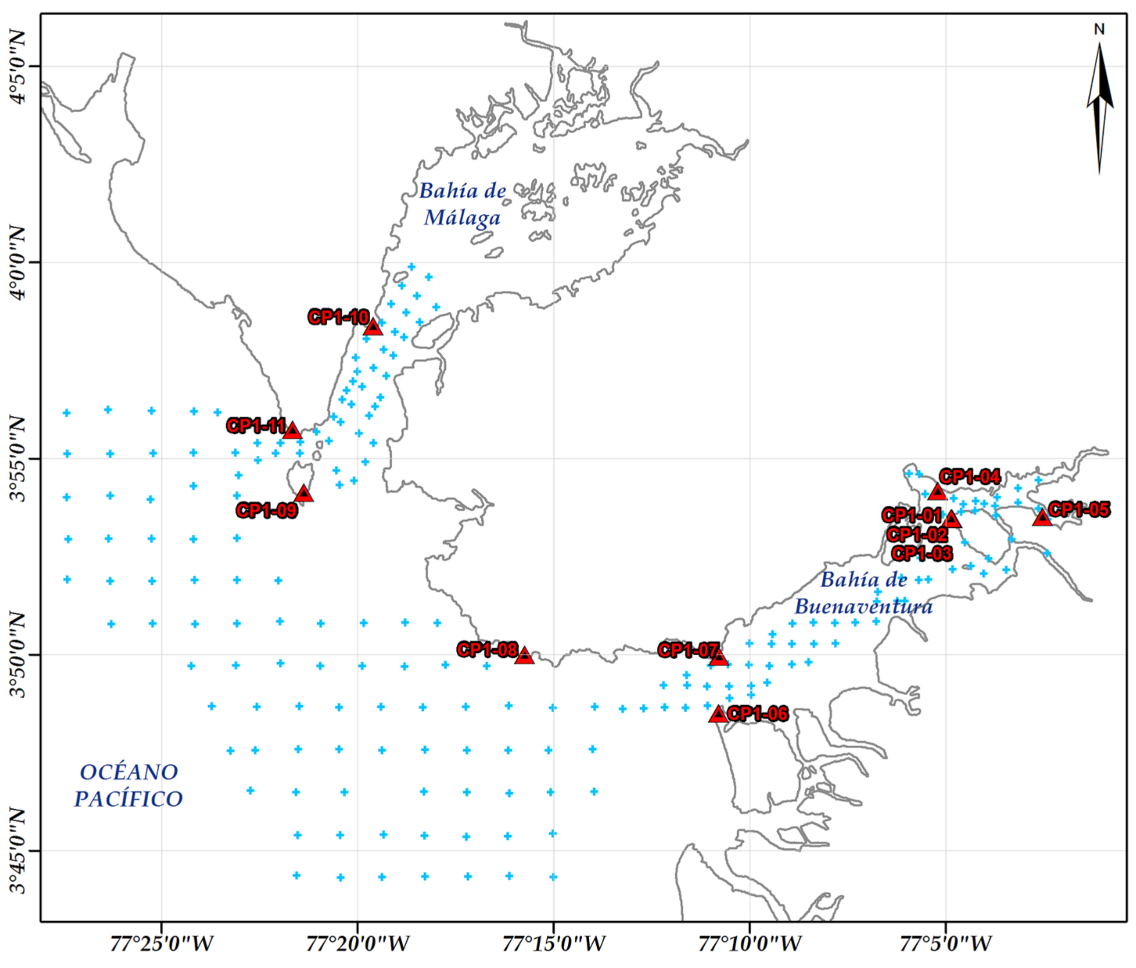

Figure 2. Point cloud for the GNSS surveying. Points of survey in the coast.

Once finished the ellipsoidal height surveying from the sea surface, the data that overcome a total combined uncertainty (horizontal error in X and Y combined with the vertical error in Z) of 0.1 m were eliminated. These ellipsoidal heights taken in different occurrence times and alternatively, in different water level heights were corrected and taken to the same reference zero through the closest tide gauge records, to consequently add the corresponding vertical datum values for each location.

Generation of the SHRV2016

In Colombia, the Pacific Coast has macro-tides that evidence tidal ranks that exceed 4m and where the tide currents dominate the active processes, the Caribbean coast, on the contrary, shows micro-tides with tidal ranks lesser than 2m, where the wave action dominates the active processes. According to the frequency, the Pacific coast shows semidiurnal tides, that is, produces two high tides and two low tides, whereas the Caribbean coast shows mixed tides, with an evident diurnal inequality in the elevation of the high tides and low tides between successive tide cycles (NOAA, 2017).

The presence of ranks of upper tides in the Pacific coast, required the estimation of the tide variations across the bays of Málaga and Buenaventura, having not only tides processed for the 5 gauges (discrete data), but also with the interpolation surfaces of the datum of each tide gauge (continuous data), all of these being tide data relative to zero of the tide gauge with a greater tidal amplitude, which for the bays were BV [03°53’29.84”N, 77°04’54.18”W] in the island of Cascajal of the bay of Buenaventura.

The tides processed for each tide gauge station, referred to the MLWS=0 of BV (Table 1), showed a greater tidal amplitude in BV with 5.64 m, followed by BM with 5 m, MB with 4.91 m, JC with 4.80 m and finally, B4 with 4.54 m. The relative MSL value on.

Table 1. Datums relative to MLWS=0 of the BV tide gauge.

Tide gauge station	LAT	MLWS	MSL	MHWS	HAT
BV	-0.41	0	2.41	4.73	5.23
JC	0.07	0.42	2.41	4.4	4.87
BM	0.02	0.33	2.41	4.52	5.02
MB	-0.13	0.32	2.41	4.51	4.78
B4	0.13	0.49	2.41	4.33	4.67

With the relative levels of the 5 tide gauges, the area was interpolated to generate more approximate values of the tidal variations across the area. The spatial interpolation was made on each tidal datum, obtaining 5 surfaces of relative datums. In Figure 3, the MLWS datum surface illustrates the constant change that the rank of the tide is presenting, showing lower magnitudes in the external areas of the bays of Málaga and Buenaventura, and increasing this value as it advances to their more internal sectors.

Considering that during the surveying of ellipsoidal heights for water level, the tide gauge stations were recording simultaneously the information referred to the relative datums of the mentioned surfaces, the final ellipsoidal height value referred to the WGS84 ellipsoid was obtained in each one of the surveyed points (K), through equation 1.

$$K = [(A_t - B) - (W_t - D)] \quad \textbf{(1)}$$

Where:

A_t: Ellipsoidal height of the antenna of the mobile receiver at the moment of the observation T1.

B: Height of the antenna of the mobile receiver with respect to the water line (fixed value).

W_t: Height of the water surface recorded by tide gauge sensor with respect to its zero of measurements at the moment of the observation T1.

D: Datum value selected with respect to the zero of measurements of the tide gauge station (fixed value since vertical datums are determined).

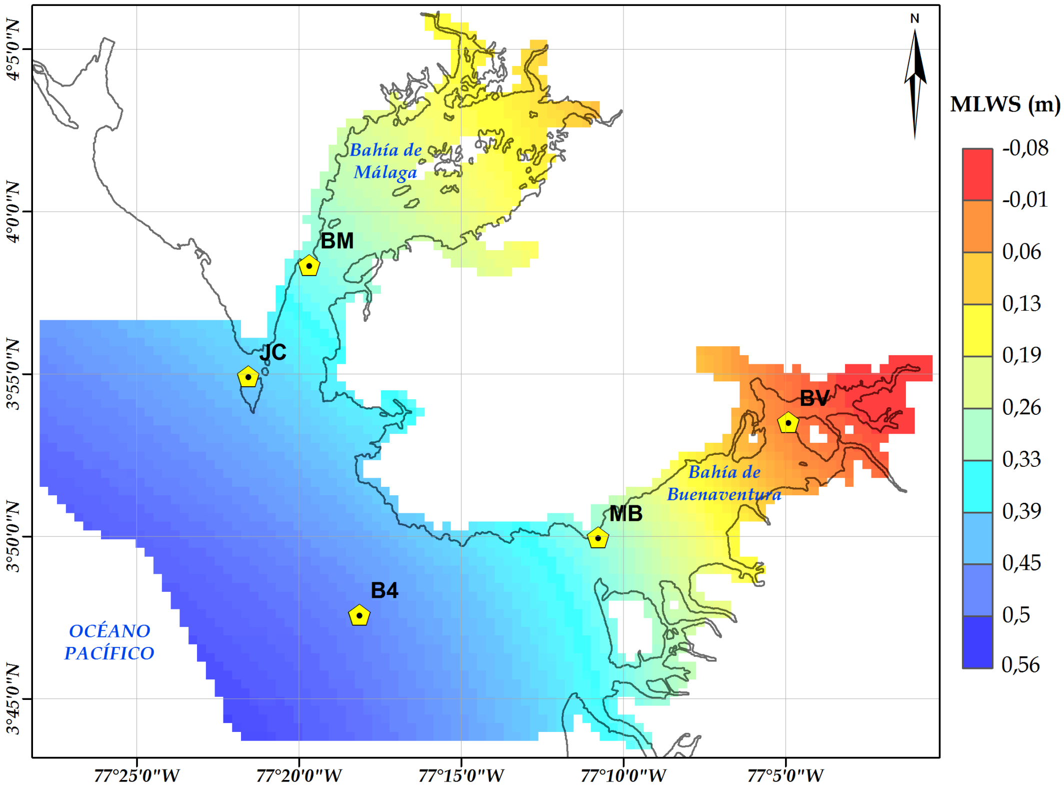

Figure 3. Tide gauge stations. Surface with relative heights referred to the MLWS=0 of the BV station in the Island of Cascajal in Buenaventura.

To achieve a 500 m spatial cell resolution, it was necessary to represent each tidal reference framework as a continuous surface with respect to the WGS84 ellipsoid, using the empirical Bayesian Kriging interpolation method, based on a set of functions responsible for quantifying the local contribution of each point. For the shallow zones of the bays, or with wild waters, where the RTK GNSS surveying was not viable due to the difficulty in the measurement of water levels, new heights were generated through the measurement of the separation between the datum and the geoid that was better adjusted to the zone, that was the IGAC's GEOCOL2004 model (Laura Sánchez, 2003) for the case of the bays, extrapolating the data with the same spatial interpolation technique to achieve a total coverage of the area.

Nautical chart datum

Whereas the MLWS is used as chart datum in Colombia, the International Hydrographic Organization (IHO) recommends the adoption of the Lowest Astronomical Tide (LAT) by the hydrographic services as chart datum. However, in specific areas where low tide levels se deviate frequently from the LAT, another similar may be used alternatively (IHO, 2017).

The chart datum heights modeled with respect to the WGS84 ellipsoid, were calculated to allow a variety of performances, highlighting the generation of hydrographic applications, observations and tide predictions, and nautical charts.

Sea surface technology

The difference between the geoid and the tidely derived MSL, due to the permanent currents and average meteorological effects, called Sea Surface Topography (SST), allowed to evaluate the precision of the SHRV2016 with existing geoidal models. For this case, the SST was generated for the GEOCOL2004 and EGM2008 geoidal models, that have different resolution and precision (Table 2), but that allowed to confirm the tendency of the SHRV2016.

Table 2. Spatial resolution and precision. GEOCOL and EGM Vs SHRV2016.

	GEOCOL 2004	EGM 2008	SHRV 2016
Spatial resolution	3600 m (2′x2′)	9000 m (5′x5′)	500 m (18″x18″)
Precision	±0.80 m	±0.15 m	±0.06 m

Results

The SHRV represents a key development in the assimilation and use of provided data in vertical reference frameworks different from the chart datum generally used. It also favors the high precision topography with GPS and Lidar to determine tidely defined coast lines storm waving modelling, studies on increase in sea level, eco-systemic studies, management of coastal areas and planning for the mitigation of proactive disasters. In addition, any maritime activity that involves measurements referred at a determined level or tide datum, such as hydrographic surveying, nautical cartographic production, maritime navigation, maritime works (dredging, recleans, waterway design, maneuvering areas, anchoring, quays, bridges, coastal protection, among others), management of maritime signaling, generation of tidal forecast, definition of maritime borders, among others.

The vertical separation model generated from the measurements in land and open sea, implementing modeling and interpolation techniques to relate the vertical datums with the ellipsoidal reference surface (WGS84), was composed of five hydrographic surfaces representing each vertical datum, as shown in Figure 4.

With respect to the chart datum currently used in Colombia (MLWS), it represents heights of approximately 13 m in the separation of the ellipsoid and the datum, with variations between 11.28 m, west of Juanchaco and Ladrilleros, and 15.59 m, within the bay of Buenaventura.

Different comparisons were made to evaluate the results of the SHRV2016. The first method consisted on contrasting the ellipsoidal height of the sea level closest to each point of survey given by the trigonometric levelling with Leica Viva TS15 total station with horizontal and vertical precision of ±4 mm, and the heights given by the spatial interpolation as a product of the GNSS RTK surveying, obtaining discrepancies equal or lesser than 9 cm, as shown in Table 3. The second method involved the comparison of the common area of the SHRV with the GEOCOL2004 and EGM2008 models.

The comparisons of the mean sea level (MSL) heights with the geoidal undulations (N) of the GEOCOL2004 and EGM2008 models adjusted quite well for the zone in general. The differences showed a higher fit between the MSL and the GEOCOL2004 model calculated for Colombia, this correlation (differences under 50 cm) was due to the fact that the generation of GEOCOL, the mean sea level calculated in Buenaventura was taken as reference datum. In Table 4, the tide gauge stations served as points to compare the separations between the geoids and the MSL (Topographic Sea Surface).

The generation of profiles allowed to verify graphically and quantitatively the existing correlation between the geoidal models (EGM2008 and GEOCOL 2004) and the MSL datum, as well as the existing variability for the separation ellipsoid-datums across the study area, confirming that with respect to this latter variable, for the general area of the bays of Buenaventura and Málaga, it is impossible to assume a single separation value as a source for the development of projects and works that involve fusion between terrestrial and bathymetric

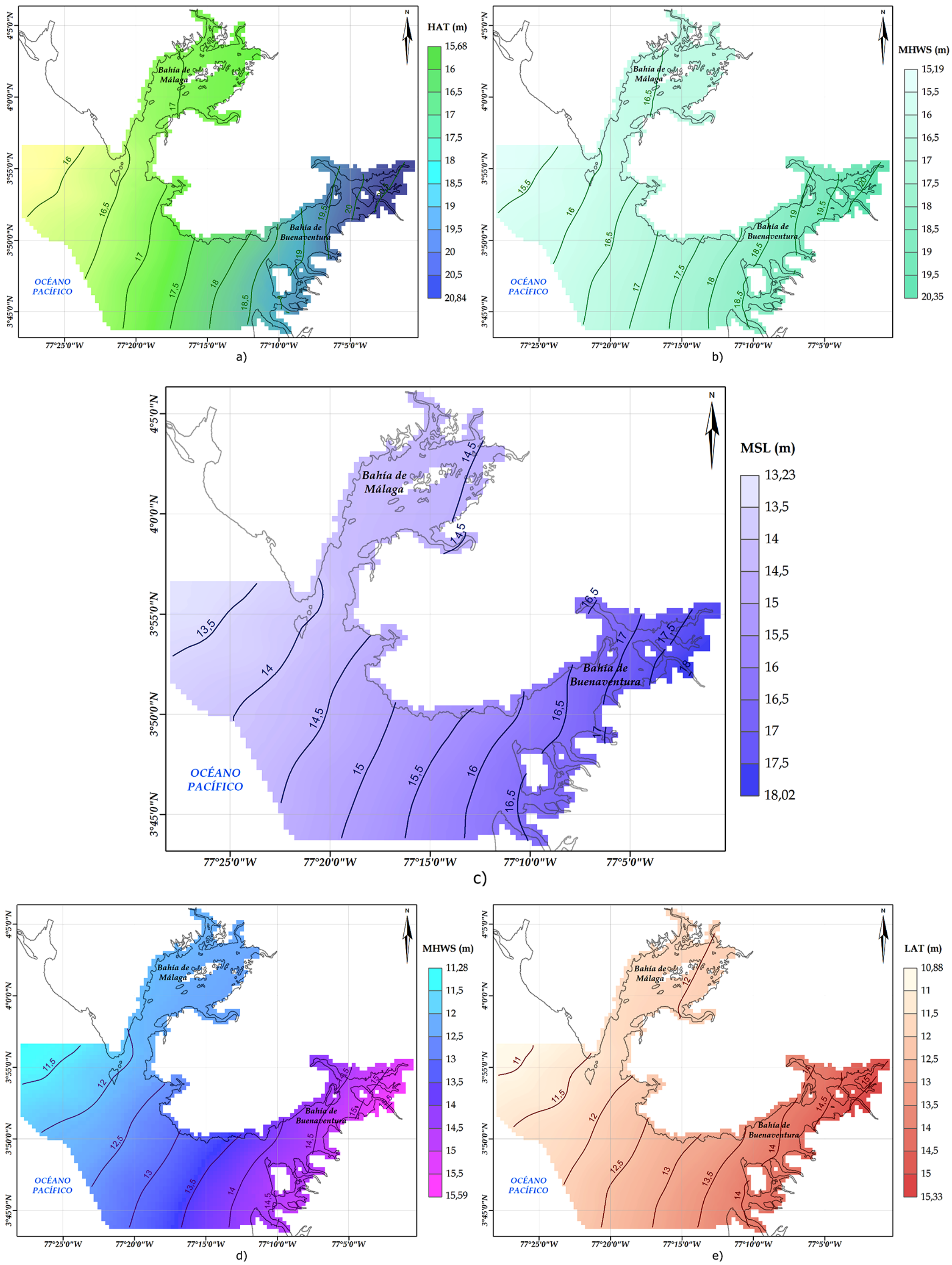

Figure 4. Surfaces of vertical datums referred to the WGS84 ellipsoid: a). Surface of the highest astronomic high tide. b). Surface of the average high syzygy tides. c). Surface of the average sea level. d). Surface of the average low syzygy tides. e). Surface of the lowest astronomic low tide.

Table 3. Vertical control applied on the water mirror closest to each point of survey.

Point	Ellipsoidal height Trigonometric levelling					Ellipsoidal height SHRV Interpolatin					Difference between ellipsoidal heights (Uncertainty of the model)				
	MSL	MLWS	MHWS	HAT	LAT	MSL	MLWS	MHWS	HAT	LAT	DIF. MSL	DIF. MLWS	DIF. MHWS	DIF. HAT	DIF. LAT
CP1-01	17,11	14,70	19.43	19.92	14.36	17.04	14.64	19.35	19.85	14.31	0.07	0.06	0.08	0.07	0.05
CP1-02	17,11	14,70	19.43	19.92	14.36	17.04	14.64	19.35	19.85	14.31	0.07	0.06	0.08	0.07	0.05
CP1-03	17.13	14.72	19.45	19.94	14.38	17.04	14.64	19.35	19.85	14.31	0.08	0.07	0.09	0.08	0.06
CP1-04	16.98	14.57	19.30	19.80	14.26	16.90	14.50	19.22	19.71	14.18	0.08	0.07	0.08	0.09	0.08
CP1-05	17.57	15.16	19.92	20.42	14.86	17.60	15.16	19.95	20.46	14.90	-0.03	0.00	-0.03	-0.04	-0.04
CP1-06	16.17	14.09	18.25	18.52	13.70	16.21	14.14	18.29	18.57	13.74	-0.04	-0.05	-0.04	-0.05	-0.04
CP1-07	15.96	13.87	18.06	18.34	13.47	15.91	13.82	18.02	18.30	13.44	0.05	0.05	0.04	0.04	0.03
CP1-08	15.15	13.15	17.15	17.49	12.77	15.20	13.20	17.20	17.54	12.82	-0.05	-0.05	-0.05	-0.05	-0.05
CP1-09	14.04	12.06	16.02	16.48	11.70	14.06	12.07	16.05	16.50	11.72	-0.02	-0.01	-0.03	-0.02	-0.02
CP1-10	14.19	12.11	16.30	16.80	11.79	14.17	12.09	16.28	16.78	11.77	0.02	0.02	0.02	0.02	0.02
CP1-11	13.78	11.78	15.79	16.27	11.43	13.84	11.84	15.85	16.33	11.49	-0.06	-0.06	-0.06	-0.06	-0.06

Table 4. Topographic sea heights in the tide gauge stations of the bays.

Tide gauge station	MSL	NGEOCOL 2004	NEGM2008	NGEOCOL 2004 - MSL	NEGM 2008 - MSL
BV	17.04	17.48	15.91	0.44	-1.13
JC	13.92	14.39	13.11	0.47	-0.81
BM	14.14	14.41	13.15	0.27	-0.99
MB	15.91	16.61	15.10	0.7	-0.81
B4	14.97	15.56	14.14	0.59	-0.83

surveyings, as well as correction of water level in hydrographic surveyings for GPS tide method among others. In Figure 5, the profile 1 projected in the external area of the bays, shows that the MSL maintains a behavior trend similar to the geoidal models, however, the undulation magnitudes (separation to the ellipsoid) differ in -0.5 metros in average with respect to GEOCOL 2004 and +1 meter with respect to EGM2008; the general separation variability ellipsoid-datums for this 40-kilometer long profile in direction south-east is of approximately 3.5 m the above due to its perpendicularity with respect to the geoidal undulation isolines. Profile 2 projected in direction northeast from the external part, access and internal sector of the bay of Málaga, maintains the general behavior tend similar to the geoidal models and the undulation magnitude differences in the order of -0.5 meters with respect to GEOCOL 2004 and +1 meter with respect to EGM2008; The general separation variability ellipsoid-datums for this 35-kilometer long profile is approximately 0.4 meters, indicating us that in this profile orientation, there is a very adjusted coincidence to the geoidal undulation isolines. Finally profile 3, across the bay of Buenaventura in direction east with an approximate longitude of 40 kilometers, maintains the trend between the MSL and the geoidal models across its route, improving its adjustment in the port area of Buenaventura, with respect to GEOCOL 2004; The separation variability ellipsoid-datums for this profile due to its perpendicularity with the geoidal undulation isolines is of approximately 4 meters.

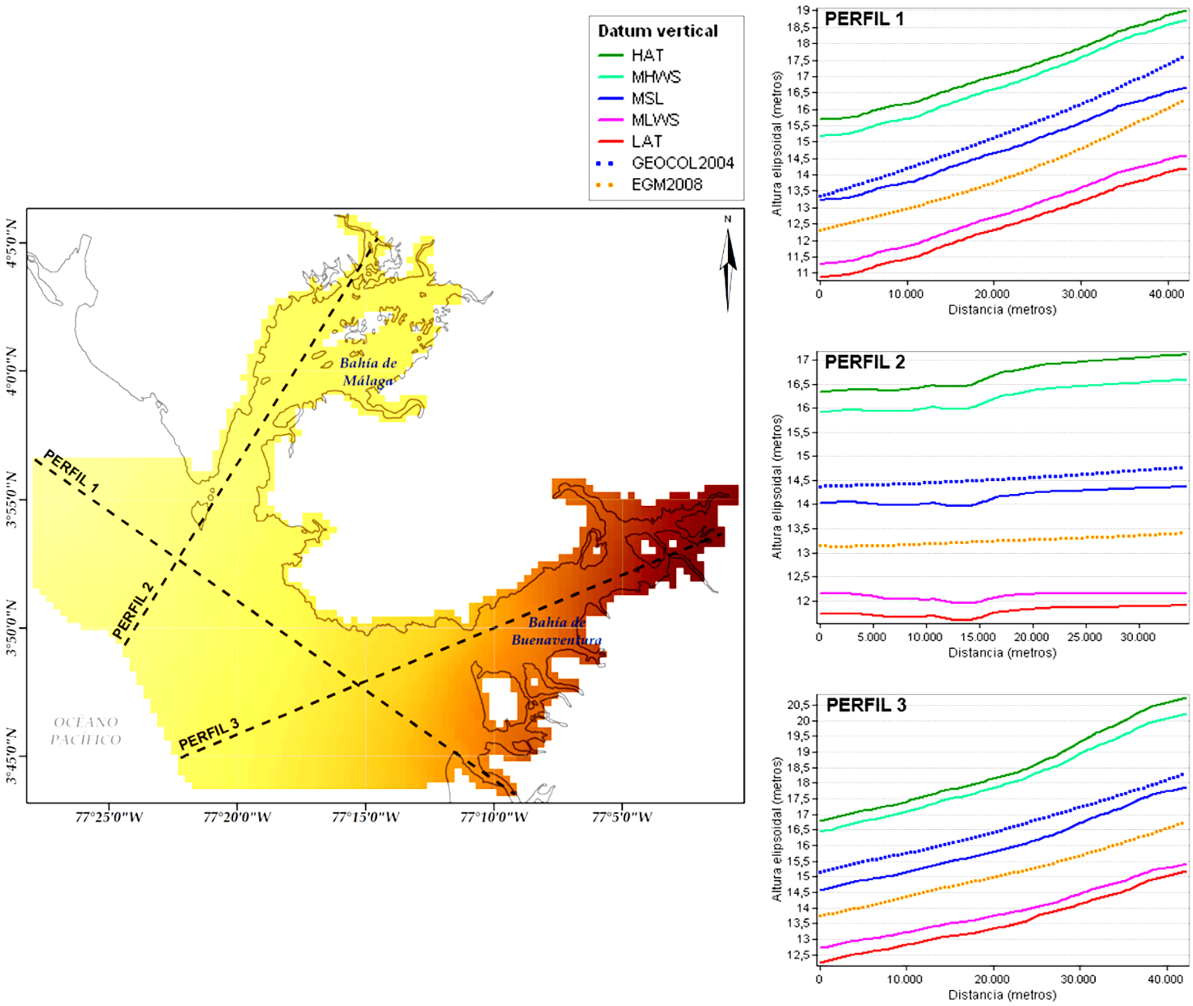

Figure 5. Datum variations in different profile lines.

Considering that the horizontal component of the SHRV manages a 500-meter resolution, the combined total uncertainty was only determined in the vertical component as a critical variable in the object and surface scope; This total uncertainty in the vertical was given by the summation of the uncertainties contributed separately in the different technical processes carried out; The grid of surveying for ellipsoidal heights in the water surface, the materialization of the geodesic network, and the vertical control through trigonometric levelling; estimating a final value of ±6cm.

Discussion

The official height system in Colombia allows with a minimum degree of uncertainty, the performance of projects and activities that involve measurements in land, making them compatible among themselves thanks to the support of the national reference geodesic framework, which is defined by a network of materialized marks for the vertical and horizontal control, active GPS observation stations and the GEOCOL 2004 geoidal model, being finally the average sea level, the vertical reference plane.

However, the current height system becomes insufficient when its use is required in the development of activities that involve measurement in water bodies influenced by the dynamic of the tide, mainly in hydrographic surveyings and their derived activities, where it is requested that the depths are referred to a specific water level datum, preferably one coincident with low tide levels, as the lowest astronomic tide LAT or the mean low water springs MLWS, datums different from the means sea level on which the official height system is referred.

Parallel to the above, in places with macro-tidal regime as in the case of the Colombian Pacific, where tide ranks over 4 meters with its variations due to the morphology of the seabed and the coastline are presented, make inaccurate to assume a single datum value for areas considered as a complete navigation unit, it is the case of the bay of Buenaventura, where the difference in rank between the sector of the external bay and the port complexes may reach 1.2 meters (Oceanographic and Hydrographic Research Center of the Pacific, 2016).

The uncertainty generated when not having water level datums determined and densified within each of the bays and main ports, associated with a geodesic reference framework, triggers inconsistencies in the final hydrographic data produced by different entities; In the same way, it makes that the fusion with data from surveyings in land is complicated and technically opts for making arbitrary vertical corrections in order to achieve a correct adjustment.

At global level, this type of problems and inconsistencies has been solved thanks to the generation of separation models between reference ellipsoid and water level datum, which cover a geographic maritime area of interest and are constructed under the fusion of permanent tide gauge observation, generation of vertical control networks with fixed marks in land, permanent GNSS observation, satellite altimetry and GNSS buoys as in the case of the Vertical Offshore Reference Frame VORF project (Iliffe, Ziebart & Turner, 2007) developed in the United Kingdom.

The Vertical Reference Hydrographic Surface SHRV2016 for the bays of Buenaventura and Málaga unlike VORF, was constructed through GNSS observation in RTK mode on the water surface, but maintaining the determination of water level datums based on the historical observation and rank variability and present phase analysis (Oceanographic and Hydrographic Research Center of the Pacific, 2016). The network of 11 high precision control points materialized and distributed in land across the study area, allowed to carry out the verification of the model and its values, through the result of the precision levelings made from each point to the datum of interest.

The SHRV 2016 is compatible with the current National Geodesic Reference Framework and its correspondence with the International Reference Terrestrial Framework, its applicability as well as VORF, will be in function of the standardization, development of hydrographic surveyings optimizing times and resources when using correction methods per tide using GNSS equipment in RTK mode, the tide forecasting tools and the correct fusion with data from surveyings in land.

Conclusions

- The SHRV2016 becomes the first separation model between the ellipsoid and the different vertical reference hydrographic datums in Colombia, through a 500-meter spatial resolution surface and a estimation of total uncertainty in the vertical component of ± 6cm, guaranteeing the best adjustment to the local tide gauge conditions of the study area, which benefits the quality of the activities that involve measurements referred to a vertical datum in the water, such as dredgings, hydrographic surveyings, generation of terrain models with bathymetric data and land data among others.

- The use of GNSS receivers in RTK mode, have become a more used tool for the observation of heights. With state of the ark precision, its application in the measurement of points on the water surface, allowed to associate the tide gauge registers and consequently, the vertical datums derived from these ones, with the WGS84 reference ellipsoid. The above establishes the possibility of creating tide gauge stations in offshore locations, using floating elements such as the buoys that indicate the navigable channel for entrance to the bay, where a permanent GNSS functioning receiver in RTK differential correlation reception mode may be installed from a reference base in land, obtaining water level time series referred to the ellipsoid.

- The correlation of the SHRV's MSL with the EGM2008 and GEOCOL 2004 geoidal models allowed to identify a very coincident trend across the covered area, where the differences in the separation or undulation values with respect to the ellipsoid were maintained in the approximate order of 0.5 meters with respect to GEOCOL 2004 and 1 meter with respect to EGM2008. The above establishes the possibility of making local adjustments to the mentioned geoidal models thanks to variables that have been quantified locally for the study area, mainly the variability of rank and phase presented by the tide, and it is represented in the vertical datums defined and tied ellipsoidally.

- The SHRV will allow to carry out hydrographic surveyings in the study area applying the tide correction method in real time with GNSS equipment, thanks to the ellipsoid-datum separation value delivered by the SHRV, finding the variable pending to be known in a hydrographic surveying, where the antenna of the GNSS receiver is responsible for measuring all the movements in the vertical suffered by the vessel. This methodology supposes a significant saving in time, resources, and infrastructure that is demanded when the corrections for water level are made in post-process, resorting to the records taken from one or several tide gauge observation stations.

- The analysis of the consistency between the ellipsoidal heights of the water level datums derived from trigonometric levelings and those obtained from the GNSS RTK surveying, provides an important redundancy and verification parameter to assure the quality of the information. In the area of the bays studied, the average discrepancy between the two analyzed heights is of ±5 cm, varying between -6 cm and 9 cm.

- The construction of the SHRV locally for the bays of Buenaventura and Málaga and its replication in the main ports of the country, will allow to establish the future development of a total ellipsoid-datums separation model that covers the Pacific and Caribbean coastlines, as well as the insular region, extending until the maritime borders, thanks to the inclusion of data from satellite altimetry, GPS buoys and others, migrating finally to the creation of the vertical reference oceanic framework for Colombia.

- In order to optimize the Vertical Reference Hydrographic Surface year by year, updates to the fixed mark framework in land should be made through precision levelings, verification of coordinates, application of speed model for corrections for displacement xyz, and incorporation of the adjustments made in the calculation of vertical datums as a product of the historical increase in water level data.

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