Article

ESTABLISHMENT OF THE 2010 VERTICAL DATUM FOR ECUADOR

By Jorge ALAVERA[1] & Jorge NATH[2] (Ecuador)

Abstract

In Ecuador there are two types of official cartography: land mapping and nautical charting developed by the Military Geographic Institute and the Oceanographic Institute of the Navy respectively. This paper aims to describe the methodology established to obtain a vertical datum from the sea level variation records at the Principal Station "La Libertad" (02º13'04"S, 80°54'23"W).

Résumé

En Equateur, il existe deux types de cartographie officielle : la cartographie terrestre et la cartographie marine qui sont développées respectivement par l'Institut géographique militaire et par l'Institut océanographique de la Marine. L'article qui suit a pour objectif de décrire la méthodologie établie pour obtenir un système de référence verticale à partir des enregistrements de la variation du niveau de la mer à la station principale « La Libertad » (02º13'04"S, 80°54'23"O).

Resumen

En Ecuador hay dos tipos de cartografía oficial: la cartografía terrestre y la cartografía náutica, elaboradas por el Instituto Geográfico Militar y el Instituto Oceanográfico de la Marina respectivamente. El objetivo de este artículo es describir la metodología establecida para obtener un dátum vertical a partir de los registros de la variación del nivel del mar en la Estación Patrón de "La Libertad" (02º13'04"S, 80°54'23"O).

[1] Hydrographic Department, Oceanographic Institute of the Navy, Ecuador, levantamiento@inocar.mil.ec

[2] Hydrographic Department, Oceanographic Institute of the Navy, Ecuador, jnath@inocar.mil.ec

** Figure obtained from the electronic address www.danotario.com/articulos/articulo15.php*

INTRODUCTION

No matter its objective, any cartographic process needs both horizontal and vertical references (horizontal and vertical datum respectively). These references provide a starting point to relate field geodetic, topographic and hydrographic measurements to a two dimension surface, such as maps, nautical charts and plans. In general, geodetic reference systems may be classified in two types (i) those that can be described by mathematical models and (ii) those described by physical models. Whilst a mathematical model reference is made to the ellipsoid, the geoid constitutes the reference surface for the physical model.

Land maps and nautical cartography are produced in Ecuador by the Military Geographic Institute (IGM) and the Oceanographic Institute of the Navy (INOCAR) respectively. This paper describes the establishment of a vertical datum based on the sea water level variation records registered at Station "La Libertad". Paredes (2004) describes the development and need to establish an official Vertical Datum and to install a tide gauge station at La Libertad (originally installed in 1948). The determined Datum is then applied and referred to the benchmarks that IGM references to all cities in Ecuador.

Vertical Reference Surface for Land Maps

A reference system seeks to define the shape and dimensions of the earth. The Geoid (Figure 1) is defined as the equipotential surface of the gravity field force and therefore is a function of the mass distribution of the earth. This constitutes an excellent vertical reference surface for planning, execution and control of engineering works, disaster plan management, tsunami modeling as well land cartographic tasks. This Vertical Reference Surface or Vertical Datum can be expressed by the Mean Sea Level and it is important that it is determined through the record of the variation of the sea water level registered during a certain period.

The Oceanographic Institute of the Navy (INOCAR) is the State advisory agency for technical matters related to Nautical Cartography. It has determined the establishment of a permanent National Tide Gauge Network with the objective to continuously monitor the variation of the water level in the coastal zone as well as along the River Guayas. This allows the determination of different vertical reference surfaces, including the oldest station installed being "La Libertad".

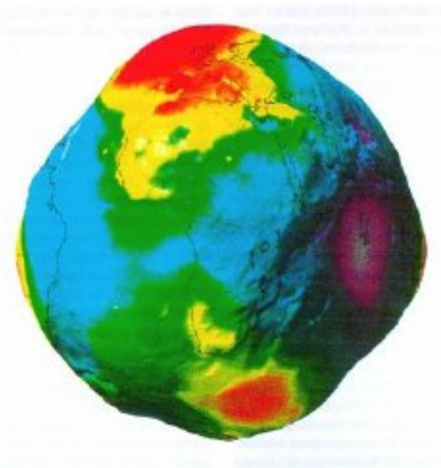

Figure 1. *Shape of the geoid from orbital perturbations of geodetic satellites.**

To establish Mean Sea Level, it is necessary to determine the appropriate time series required for its calculation. However before doing so, it is necessary to understand the tide generation forces. Basically the generation forces are the sun and moon attraction forces. The forces of the moon are 2.5 times bigger than the sun. This is despite the moon having a mass 352 times less. Therefore, the oscillatory movement of the sea is significantly influenced by the moon's movement. The best known moon movements may be described by the cycles of high and low water quadrature, apogee and perigee, declination and the least known, the cycle of Meton or precession movement, the period of which is 18.9 years. This is the reason why several Hydrographic Offices have agreed to adopt 20 years of observation as the ideal period to make any type of tidal height analysis.

METHODOLOGY

Before making the statistical analysis of the sea level variation records, it is necessary to ensure that all data is referred to a common reference level. Each time the sensor is removed for maintenance, a new reference level is created to which the recording is referred (***Figure 2***).

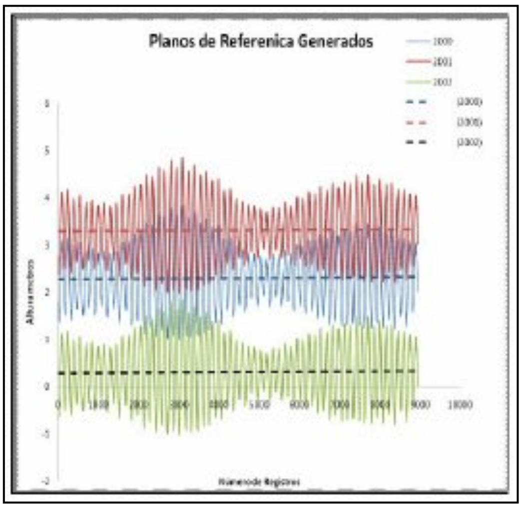

Figure 2. *Records with different reference levels*

As a second step the quality of the data is reviewed using the graphical method (***Figure 3***). Observations seen to be outside the normal patterns are removed.

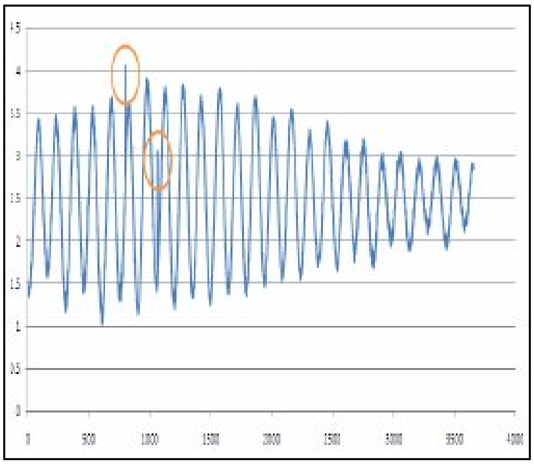

Figure 3. *False records withdrawal*

To determine the difference between the generated reference levels, first select the leveling reference or starting point, and later through direct subtraction, determine the value that shall be added algebraically to the registered data in the series. The difference between the reference levels will be obtained after subtracting from the value adopted as a starting point, the values of the benchmarks calculated referred to that level in each leveling survey executed. It is important that each leveling include the date of execution of the leveling to relate the difference found with the records.

RESULTS

The leveling survey executed between the zero of the tide pole and the tide benchmarks associated to the tide station "La Libertad", concluded that the best benchmark to be selected as reference is the benchmark called BM 48 (02°13'13" S, 80°54' 16"W). This is due to the benchmark having a higher density of leveling data.

In accordance with the proposed methodology, the differences between the various levels, is due to the variation of the location of the sensor's zero over time. These differences are calculated, taking as the starting point the leveling executed in 1952, (***see Table 1***). This methodology was used by Paredes (1986) and Vera (2004).

Once the related differences between the reference levels are calculated, such corrections are applied to the records following the dates in which the leveling was executed. This is followed by the descriptive statistical analysis.

Considering that the average is a statistic result influenced by extreme values, this methodology proposes the elimination of the anomalous values. Vera (2004) states that the withdrawal of the extreme values may not be replaced with mean values. The values in the years when atypical conditions of the sea level exist are included. This includes those influenced by events "El Niño" y "La Niña" that occurred between 1982 - 1983 and 1997 – 1998, thereby avoiding any bias in the overall results.

Estacion	FECHA	14/07/1952	20/11/1952	20/08/1953	15/01/1955	16/07/1955	17/04/1956	30/03/1957	20/11/1957	19/11/1958	06/07/1967	25/02/1970	18/02/1971	24/10/1971
BM 8	1948	14.717	14.717	14.717	14.628	14.731	14.732	14.732	14.747	14.256	14.261	14.358	14.166	14.180
DIF 52	BM 48	0.000	0.000	0.000	0.089	-0.014	-0.015	-0.015	-0.030	0.461	0.456	0.359	0.551	0.537

Estacion	FECHA	29/11/1972	10/06/1973	24/09/1975	18/10/1977	24/04/1983	01/01/1984	18/03/1985	04/09/1986	31/08/1987	02/08/1988	29/09/1989	28/04/1990	02/10/1990
BM 8	1948	14.178	14.183	14.176	14.195	14.317	14.411	14.411	14.412	14.415	14.413	14.418	14.478	14.490
DIF 52	BM 48	0.539	0.534	0.541	0.522	0.400	0.306	0.306	0.305	0.302	0.304	0.299	0.239	0.227

Estacion	FECHA	14/02/1991	04/05/1991	03/05/1992	27/03/1993	15/03/1995	27/03/1998	29/03/1999	16/02/2000	08/04/2002	06/04/2003	21/05/2004	01/11/2006	02/05/2008	02/05/2009
BM 8	1948	14.557	14.623	14.476	14.476	14.496	14.503	14.506	14.495	14.477	14.515	14.525	14.548	14.553	14.575
DIF 52	BM 48	0.160	0.094	0.241	0.242	0.221	0.214	0.211	0.223	0.240	0.202	0.192	0.170	0.164	0.146

Table 1. *Historical leveling surveys at "La Libertad" station*

ANALYSIS

Until 1999, only hourly records of the variation of the sea level were kept. The uncertainty associated in determining the average is larger than using more frequent recorded data (5 minute intervals) and therefore it is necessary to determine this difference comparing the averages obtained using both the hourly and 5 minute interval data during 2002-2007 period. (***See Table 2***).

año	2000		2001		2002		2003		2004		2005		2006		2007	
mes	min	Hr	min	Hr	min	Hr	min	Hr	min	Hr	min	Hr	min	Hr.	min	Hr.
Enero			2.59	2.58	2.53	2.52	2.59	2.57	2.58	2.60	2.55	2.54			2.61	2.60
Febrero	2.48	2.48	2.58	2.58	2.63	2.62	2.55	2.53	2.59	2.61	2.57	2.59	2.68	2.68	2.54	2.53
Marzo	2.55	2.55	2.53	-	-	2.61	2.59	2.57	2.56	2.58	2.72	2.74	2.60	2.60	2.54	2.53
Abril	2.62	2.62	2.49	2.49	2.60	2.60	2.56	2.57	2.56	2.57	2.80	2.83	2.61	2.61	2.55	2.54
Mayo	2.65	2.65	2.49	2.48	2.63	2.61	2.60	2.61	2.66	2.66	2.74	2.73	2.66	2.66	2.62	2.61
Junio	2.64	2.63	2.48	-	-	2.60	2.53	2.55	2.72	2.72	2.69	2.72	2.61	2.61	2.60	2.59
Julio	2.53	2.54	2.48	2.49	2.56	2.55	2.57	2.60	2.51	2.51	-	-	2.61	2.60	2.59	2.58
Agosto	-	-	2.47	2.47	2.51	2.49	2.58	2.59	2.54	2.54	2.65	2.68	2.60	2.60	2.57	2.56
Septiembre	2.53	2.53	2.50	2.50	2.56	2.53	2.54	2.54	2.53	2.56	2.68	2.72	2.62	2.62	2.56	2.55
Octubre	2.55	2.54	2.56	2.56	2.60	2.58	2.60	2.61	2.58	2.61	2.68	2.71	2.64	2.64	2.57	2.55
Noviembre	2.50	2.50	2.55	2.54	2.68	2.66	2.61	2.63	2.54	2.57	2.73	2.76	2.60	2.60	2.62	2.61
Diciembre	2.54	2.54	2.54	2.53	2.67	2.65	2.65	2.67	2.54	2.56	2.64	2.68	2.60	2.60	2.61	2.61

Table 2. Average comparison - hourly versus 5 minutes interval

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
ENERO	2.470	2.480	2.590	2.690	2.580	2.520	2.610	2.610	2.690	2.600	2.610	2.650	2.530
FEBRERO	2.530	2.510	2.490	2.770	2.580	2.550	2.570	2.640	2.780	2.620	2.570	2.640	2.550
MARZO	2.560	2.520	2.550	2.610	2.610	2.590	2.560	2.590	2.780	2.580	2.540	2.540	2.510
ABRIL	2.540	2.530	2.570	2.660	2.550	2.610	2.570	2.580	2.740	2.650	2.570	2.520	2.510
MAYO	2.570	2.550	2.570	2.690	2.550	2.610	2.540	2.620	2.610	2.680	2.620	2.530	2.540
JUNIO	2.560	2.590	2.600	2.620	2.580	2.600	2.520	2.610	2.630	2.640	2.640	2.560	2.520
JULIO	2.550	2.510	2.620	2.590	2.570	2.550	2.510	2.590	2.570	2.580	2.570	2.560	2.520
AGOSTO	2.570	2.540	2.570	2.620	2.540	2.550	2.530	2.590	2.560	2.550	2.350	2.500	2.500
SEPTIEMBRE	2.550	2.540	2.550	2.620	2.540	2.560	2.570	2.540	2.530	2.550	2.350	2.510	2.520
OCTUBRE	2.540	2.540	2.630	2.630	2.520	2.600	2.570	2.600	2.550	2.580	2.650	2.520	2.500
NOVIEMBRE	2.540	2.510	2.650	2.610	2.500	2.610	2.550	2.660	2.570	2.680	2.670	2.500	2.510
DICIEMBRE	2.560	2.550	2.590	2.570	2.520	2.600	2.550	2.630	2.650	2.670	2.680	2.490	2.510
PROMEDIO	2.550	2.530	2.580	2.640	2.550	2.580	2.550	2.610	2.640	2.620	2.570	2.540	2.520

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
ENERO	2.540		2.586	2.532	2.594	2.581	2.545	2.654	2.606	2.655	2.595
FEBRERO	2.520	2.483	2.584	2.633	2.551	2.588	2.565	2.675	2.538	2.641	2.618
MARZO	2.570	2.552	2.530	2.605	2.592	2.562	2.715	2.600	2.540	2.652	2.640
ABRIL	2.530	2.624	2.493	2.602	2.563	2.557	2.803	2.607	2.553	2.715	2.686
MAYO	2.620	2.652	2.485	2.627	2.598	2.661	2.737	2.655	2.617	2.769	2.776
JUNIO	2.550	2.635	2.483	-	2.531	2.719	2.694	2.613	2.596	2.741	2.746
JULIO	2.520	2.525	2.481	2.561	2.573	2.510	-	2.605	2.586	2.540	2.730
AGOSTO	2.450	2.501	2.467	2.514	2.581	2.542	2.649	2.599	2.566	2.514	2.728
SEPTIEMBRE	2.460	2.530	2.503	2.555	2.543	2.532	2.684	2.619	2.561	2.627	2.710
OCTUBRE	2.490	2.547	2.559	2.598	2.599	2.583	2.675	2.641	2.566	2.601	2.706
NOVIEMBRE	2.480	2.499	2.545	2.679	2.608	2.543	2.728	2.603	2.623	2.603	2.757
DICIEMBRE	2.480	2.543	2.535	2.670	2.647	2.535	2.642	2.603	2.610	2.615	2.853
PROMEDIO	2.520	2.550	2.520	2.600	2.580	2.580	2.680	2.620	2.580	2.640	2.710

Table 3. *Monthly average of sea level variation at "La Libertad" station*

The descriptive analytical analysis applied to the difference between the averages obtained show that the monthly averages from hourly records have an uncertainty of +/- 1.5 cm at a 95% confidence level with respect to the more frequent records. We can infer the results by comparison that the averages obtained until 1999 have the same uncertainty as those found. It is worth mentioning that this uncertainty is increased by the precision of the sensor used to measure, and therefore it is very difficult to determine any trend.

Considering the above-mentioned factors, ***Table 3*** provides details of the monthly averages of the sea level variation between 2000 and 2009. These values are from records gathered at 5 minute intervals, while up to 1999, values are obtained from hourly records.

The compiled averages in Table 3 and shown in Figures 4 and 5, suggest that the mean sea level has an oscillatory performance over the last 20 years. Nevertheless starting in 2000, it can be seen that a positive tendency in the data exists without losing the aforementioned behavior.

The positive tendency shown in the annual data of the mean sea level in the last decade may be better observed in ***Figure 4*** and expressed with the equation $y = 0.014x + 2.518$ thus indicating that the mean sea level has been increasing at an annual rate of 1.2 cm approximately during this study period.

The 1952 Leveling was used as the commencement for the information process. Considering that the present tide pole is generating another reference level, it is necessary to refer the calculated mean sea level to the zero of the actual tide pole.

Table 4 shows the resulting statistical analysis of the annual averages between 1984 and 2009. The calculated mean sea level is located 2.585 meters above the zero of the 1952 tide pole. In order to refer the calculated mean sea level of "La Libertad" station to the zero of the actual tide pole, subtract the difference found after comparing the level value of the benchmarks BM48 in 1952 and in 2009. A difference of 0.16 meters exists as seen in ***Table 1***. This results in the mean sea level being 2.441 meters above the zero of the tide pole.

	84-89	90-99	00-09	84-09	88-09
Enero	2.560	2.610	2.590	2.590	2.590
Febrero	2.570	2.610	2.590	2.590	2.590
Marzo	2.570	2.590	2.600	2.590	2.590
Abril	2.580	2.580	2.620	2.600	2.600
Mayo	2.590	2.600	2.660	2.620	2.620
Junio	2.590	2.580	2.640	2.610	2.610
Julio	2.570	2.550	2.570	2.560	2.560
Agosto	2.570	2.500	2.570	2.550	2.540
Septiembre	2.560	2.500	2.590	2.550	2.550
Octubre	2.580	2.560	2.610	2.580	2.580
Noviembre	2.570	2.580	2.620	2.590	2.600
Diciembre	2.570	2.580	2.630	2.600	2.600
Promedio	2.570	2.570	2.610	2.585	2.588

Table 4. *Resume table of mean sea levels*

Figure 4. *1984-2007 Mean Sea Level at "La Libertad"*

Figure 5. *1999-2009 Mean Sea Level at "La Libertad"*

CONCLUSION

The tide benchmark level BM 3 (02°13'10"S, 80°54'19"W) is considered as a starting point for the progression of the leveling of the National Vertical Basic Control network executed by IGM. Therefore the value of the leveling calculated in 2010 is 8.7122 meters referred to the zero of the tide pole. Considering that the value of 2.441 metres is the mean sea level referred to the zero of the tide pole, the height of the benchmark BM3 above mean sea level, is 6.2707 meters for the study period.

BIBLIOGRAPHY

- Paredes N., Determinación del Datum Vertical en la Libertad, Ecuador, Acta Oceanográfica del Pacifico, Vol 3(1), 1986.

- Vera L. Estudio del Nivel Medio del Mar en Puerto Bolívar, Acta Oceanográfica del Pacifico, Vol 12(1), 2003-2004.

- Pugh, David T., Tide, Surges and Mean Sea Level, John Wiley & Sons, Chichester: Bath Press, Avon 1987.

- OHI, Manual de Hidrografía (IHO M-13), Mónaco, 2005, pp. 313-368.
- Doodson A.; The Harmonic Development of Tide Generating Potential, Proc. R Soc, 1921.
- Boon, John D.; Secrets of the Tide Horwood Publishing, Chichester, U. K., 2004.
- Harris, Pt., Manual de Marea, Washington DC, 1895.
- Marner, H.A., Tidal Datum Plane, Washington: U.S. Government Printing Office, 1951.
- Comité Permanente de Mareas y del Nivel del Mar, Comité Intergubernamental para Levantamiento y Mapeo, Australian Tide Manual (Publicación Especial S-9), Wollongong, 2004.
- NOAA; Special Publication, Tidal Datum and their Applications, febrero 2001, extraído http://tidesandcurrents.noaa.gov/publications/
- IOC, Manual on Sea – Level measurement and interpretation vol. III, UNESCO 2002.

BIOGRAPHIES OF THE AUTHORS

Jorge Ariel ALAVERA ALVARADO obtained a Bachelor's degree in Naval Science from the Naval School of Ecuador. He is a qualified Naval Hydrographer and Oceanographer and has a Master (MSc.) in Earth Sciences, with a specialization in Ocean Mapping. He graduated with honours from the Naval School, the Naval Polytechnic Academy in Chile, the Naval Warfare Academy and from the University of New Hampshire (USA). He has taught Naval Communications at the Surface Warfare School, as well as Hydrography. He is currently the Head of the Hydrographic Department at the *Instituto Oceanográfico de la Armada* (INOCAR) and has held this post since 2012

Jorge Guillermo NATH NIETO is an Oceanographer and holds a Master in Business Administration. He has given a number of courses in tides as part of a specialized course in Hydrography, as well as Financial Mathematics, Applied Statistics in business and Calculus 1 at the University of *Espíritu Santo* (Ecuador). He has also participated in various programmes and scientific projects. He is currently a research oceanographer (Hydrographic Department) at the *Instituto Oceanográfico de la Armada* (INOCAR).

Page intentionally left blank