

Absolute Comparison of Satellite Altimetry and Tide Gauge Registrations in Venezuela

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Abstract. Relative comparisons of satellite altimeter observations and sea level registrations at tide gauges have been particularly important to evaluate the long-term stability of satellite altimetry. Here, absolute comparisons between both time series are used to estimate the displacement between the geoid and the conventional height system, initially defined without any knowledge about the sea surface topography. The method is applied to the La Guaira tide gauge used to define the origin of the height system of Venezuela. The absolute comparison includes the determination of a local high resolution gravimetric geoid, the processing of the tide gauge time series with hourly sampling rate, the extrapolation of multi-mission altimeter data towards the tide gauge location and the geocentric positioning of the tide gauge bench mark by GPS. For the period 1992-2000, the altimetric time series and the tide gauge time series show a correlation of 0.85, a mean absolute offset of 3 cm and differences with ± 5 cm RMS. Taking into account the secular rate of mean sea level change, the Venezuelan height system is estimated to be -10 cm below the local geoid. This value agrees with the -8 cm displacement between the geoid and the national vertical datum referred to the geocentric system by GPS and leveling measurements. The investigations are a step towards the unification of national height systems in South America.

Keywords. Altimetry, Tide Gauge, Sea Level Time-Series, Geoid

1 Introduction

Direct intercomparisons of altimetric heights with *in situ* sea level data from tide gauges have been reported, for example, by Christensen et al. (1994), Mitchum (1998), Chambers et al. (1998) and others. These investigations were able to access and validate the long-term stability of altimeter data.

Here it is shown that such comparisons can also be useful to estimate the displacement between the global height reference surface (geoid) and the local realization of mean sea level used to establish the reference surface (vertical datum) of a national height system.

The difference between the local mean sea level and the geoid is called sea surface topography (SSTop). The SSTop depends on oceanographic and meteorological factors (salinity, temperature, pressure, wind etc.). Its magnitude is about ± 2 m. Due to changes in water density and meteorological conditions the SSTop also shows temporal variations with long and short periods on different spatial scales.

In general, the SSTop is not considered in the definition of the conventional vertical datum because realization of mean sea level is assumed to coincide with the geoid. This introduces a systematic displacement of national height systems relative to the geoid.

If the geoid is known with sufficient accuracy and resolution, the SSTop can be estimated in the tide gauge area by means of satellite altimetry and compared with the local definition of the vertical datum to determine the magnitude of the displacement. Such an absolute comparison requires that the tide gauge zero point (P_0) has been linked to a geocentric system by GPS positioning.

The paper presents a method for the absolute comparison of sea level time series obtained by multi-mission altimetry and tide gauge registrations. The method is applied to the La Guaira tide gauge in Venezuela. The results are used to estimate the displacement between a high resolution gravimetric geoid model and the Venezuelan vertical datum defined by a long-term average of tide gauge registrations at La Guaira.

2 Location and Data

The tide gauge is located at the central coast of Venezuela, in the port of La Guaira (Fig. 1a). Here, the continental shelf extends only 20 km into the Caribbean Sea. This situation is convenient because sea level registrations are not disturbed by shallow water effects. In addition, this facilitates the monitoring of pronounced spatial and temporal variability known for the semi-enclosed basins like the Caribbean Sea (Carton and Chao, 1999).

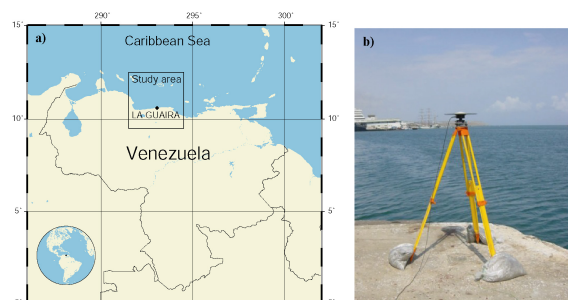


Fig. 1 Location of La Guaira tide gauge and GPS measurements at GUA2 TGBM.

There are two subsatellite tracks from both, TOPEX/Poseidon and the ERS-1/2 satellites that are nearly coinciding with the La Guaira tide gauge (Fig. 2). The orthogonal distance from the tide gauge to the tracks is about 5 km. This makes the tide gauge an ideal location for the comparison with sea level time series from satellite altimetry.

2.1 Tide Gauge Registrations

La Guaira is the principal tide gauge in Venezuela. It was installed in February 1948 and worked with an analog registration system until October 1998. Since then it operates with a digital instrument. The mean sea level (MSL) in La Guaira, based on averaging 19 years of observations during the period 1953-1971, defines the origin of the present height system of Venezuela.

For this investigation, hourly tide gauge registrations for the period 1992-2000 were used. They were provided by the IGVS (Instituto Geográfico de Venezuela Simón Bolívar).

Unfortunately, the time series is not continuous. The change of the recording device in 1998 caused data losses and reference level offsets that are handled by a careful reconstruction process (see Section 3.3).

2.2 Altimeter Data

For the generation of the altimetric time series the corrected sea surface heights CORSSHs from AVISO (1998) were used for TOPEX/Poseidon (T/P), ERS-1 and ERS-2 during the period of the tide gauge registrations (Fig. 2). The altimeter data were corrected not only for geophysical effects, atmospheric propagation delays and instrumental errors, but also orbital errors and, therefore, refer to a consistent vertical system which allows their combined use in sea level analysis.

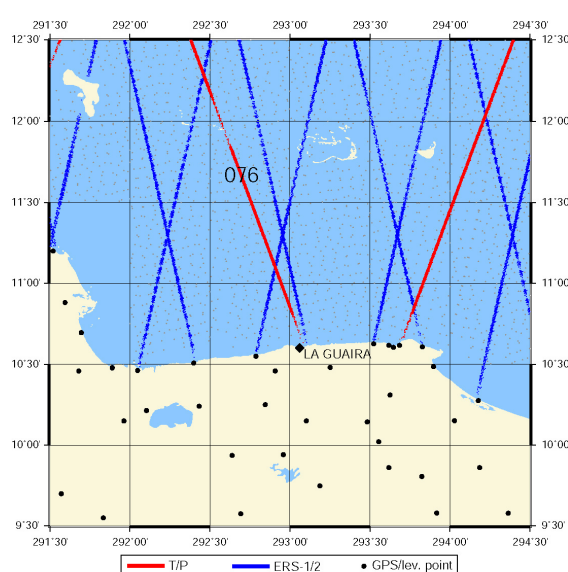


Fig. 2 Geographical study region. TOPEX/Poseidon and ERS-1/2 trajectories as well as GPS/leveling stations near the La Guaira tide gauge.

2.3 GPS Measurements

In order to link the tide gauge zero point to the geocentric system, double frequency GPS measurements were performed on a benchmark (BM) of the tide gauge vertical control net (Fig. 1b). The measurements were carried out in three 12 hour-sessions with an ASHTECH Z-Surveyor equipment in April 2002. Geodetic leveling between the BM and the P_0 in La Guaira complete the link (see Fig. 3).

3 Processing and Analysis

3.1 Survey on the Applied Methods

The most critical issue for the absolute comparison of altimeter time series and tide gauge registrations is the fact that direct altimeter observations at the tide gauge location itself are not available. This is

because the radar echo of the altimeter is in general corrupted as soon (or as long) as the footprint (the reflecting area) includes land surface. This implies a necessary extrapolation of the altimeter measurements towards the tide gauge position (Fig. 3). This extrapolation is here performed by means of a local high resolution geoid, specifically generated for this study. Details for the geoid determination are described in section 3.2.

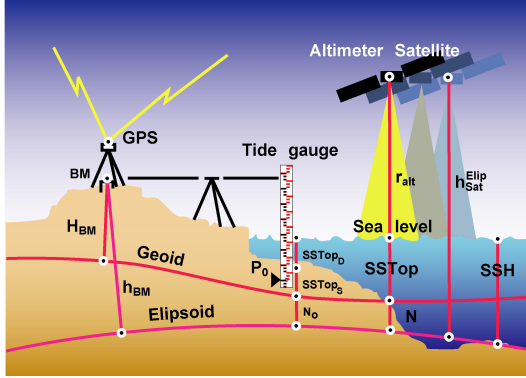


Fig. 3 Principle of the extrapolation of altimeter data towards tide gauge position. (Acuña et al., 2002a)

The absolute comparison of the altimetric sea level time series and the tide gauge registrations then consist of three stages:

(a) Processing of the tide gauge data: For the period covered by altimetry inconsistencies in the hourly tide gauge registrations were first repaired by harmonic analysis and *Least Squares Collocation* - LSC (Moritz, 1980). The repaired series was then reduced to daily values using a convolution filter. With the ellipsoidal height of P_0 , obtained by GPS and leveling, the tide gauge series is referred to the geocentric system, compatible with altimeter data. For details see section 3.3.

(b) Generation of the multi-mission altimetric sea level time series: TOPEX/Poseidon and ERS-1/2 altimeter data around the tide gauge are reduced by geoid heights and the stationary or permanent sea surface topography ($SSTop_S$). The geoid (N) is obtained from the new high-resolution local gravimetric model (see section 3.2), while the $SSTop_S$ is derived by weighted means of all differences $CORSSH-N$ that could be performed within the period 1992-2000. The residual signal, the dynamic or temporal sea surface topography ($SSTop_D$), is modeled by LSC and extrapolated towards the position and times of the daily tide gauge registrations. The final series is obtained restoring the contributions of the geoid and the stationary sea surface topography (Fig. 3). The

analysis of the altimetric sea level time series is described in detail in section 3.4.

(c) Absolute comparison: both sea level time series, referenced to a common geocentric system (ITRF/GRS80) are directly compared, considering correlation, RMS and trend of their differences. Absolute comparisons with other reference surfaces defined in the tide gauge (local geoid, EGM96, mean sea levels) are also performed. See section 3.5 for details.

3.2 Geoid Determination

The extrapolation of the altimeter data towards the tide gauge position requires a precise, high-resolution geoid model. Therefore, a gravimetric geoid model with $1' \times 1'$ resolution has been calculated for the La Guaira area, improving the quality of previous geoid determinations. The model, called LGGGM (*La Guaira Gravimetric Geoid Model*), was specifically calculated for this study and covers an area of $3^\circ \times 3^\circ$ as shown in Fig. 4. An additional zone of 0.5° width was considered to avoid boundary effects. 36322 free-air gravity anomalies on land and marine areas were used. They originate from PDVSA (Petróleos de Venezuela S.A.), BGI (Bureau Gravimetrique International) and the GEODAS data base of NGDC (National Geophysical Data Center). To increase the resolution in marine areas, $1' \times 1'$ gravity anomalies derived from altimetry (Sandwell and Smith, 1997) were also included.

All data was standardized and referred to the IGSN71/GRS80. Atmospheric effect on the gravity anomalies were removed according to (Moritz, 1992). The EGM96 global geopotential model (Lemoine et al., 1998) was used as reference and determined the long wavelength geoid signal. The short wavelength contributions were derived from a digital model that includes land elevations and bathymetry with resolutions of $30''$ [GTPO30 model (USGS, 1997)] and $2'$ [S&Sv8.2 model (Smith and Sandwell, 1997)], respectively.

Using the GRAVSOF software (Tscherning et al., 1992), the geoid undulations were computed with the *remove-restore* technique. This technique splits both, the observed gravity anomalies Δg (*remove*) and the corresponding geoid undulations N (*restore*) in three components,

$$\Delta g = \Delta g_{EGM96} + \Delta g_{RTM} + \Delta g_{RES} \quad (1)$$

$$N = N_{EGM96} + N_{RTM} + N_{RES} \quad (2)$$

where the subscript EGM96 indicates contributions of the global geopotential model, the subscript RTM indicates contributions of the terrain residual effects and the subscript RES denotes local residual components, not accounted for by the previous contributions.

The RTM contributions have been calculated through *prism* numeric integration taking into account the topographic anomalies relative to a mean height surface of 15'x15' resolution. This surface was obtained applying a moving average filter on the entire digital model of the region.

The contribution N_{RES} was calculated by converting the residual gravity anomalies to residual geoid undulations through evaluation of the Stokes integral with spherical approximation. After gridding the residual gravity anomalies by LSC, the residual geoid undulations were obtained by a multi-band two-dimensional spherical Fast Fourier Transform (2D-FFT), with 100% zero padding to limit the periodicity errors of FFT (Forsberg and Sideris, 1993). Statistics of the LGGGM components are presented in the Table 1.

Table 1. Statistics of LGGGM (Δg in mgals, N in meters).

	MIN.	MAX.	MEAN	STD.
Δg_{OBS}	-140.12	238.74	0.08	26.28
Δg_{EGM96}	-207.93	107.52	2.89	59.32
Δg_{RTM}	-64.83	123.26	-1.65	19.52
Δg_{RES}	-138.84	151.24	-0.78	24.75
N_{EGM96}	-40.56	-13.37	-23.50	6.31
N_{RTM}	-0.62	1.05	0.12	0.24
N_{RES}	-1.38	1.54	-0.08	0.46
N	-40.92	-14.07	-23.99	6.21

In marine areas the undulations of equation (2) were completed by the mean sea level deviations of POCM (Stammer et al., 1996), an oceanographic model of the ocean dynamic topography. The ocean topography was neither considered in the generation of the altimeter gravity anomalies nor in the reductions of the gravity observations in marine areas. This final step leads to a mean *synthetic sea surface* best suited for the comparison with altimetry.

3.2.1 Validation of LGGGM

38 GPS/leveling points, measured during a project for the geoid determination in Venezuela (Hoyer et al., 2002a) and 33624 CORSSH altimeter observations (Fig. 2) were used to validate the LGGGM geoid model on land and at sea, respectively. Comparisons with other geoid

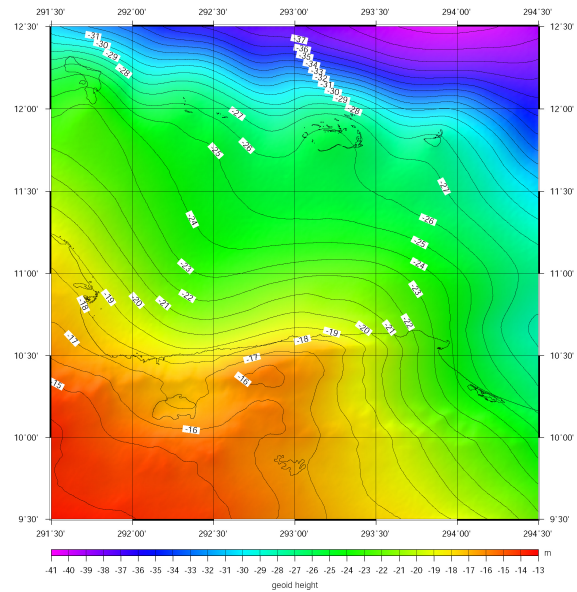


Fig. 4 LGGGM gravimetric geoid model.

models were also carried out.

For each GPS/leveling point, the differences $dN = h_{GPS} - H_{LEV} - N_{MOD}$ were formed with N_{MOD} representing the geoid undulations of LGGGM, EGM96, CARIB97 (Smith and Small, 1999) and GEOIDVEN (Hoyer et al., 2002b). Likewise, differences $dN = CORSSH - N_{MOD}$ were calculated for the altimeter data.

Tables 2 and 3 show the statistics of the results. The LGGGM accuracy is indicated by standard deviation of ± 21 cm on land and ± 15 cm at sea, similar to CARIB97 and superior to EGM96 and GEOIDVEN.

Table 2. Validation of LGGGM on land using 38 GPS/leveling points.

Geoid Model	dNmax [m]	dNmin [m]	dNmean [m]	Std. [m]
EGM96	1.17	-0.74	0.13	0.39
CARIB97	0.58	-0.68	-0.07	0.23
GEOIDVE	0.71	-1.21	-0.26	0.41
N				
LGGGM	0.67	-0.41	0.03	0.21

Table3. Validation of LGGGM at sea using 33624 CORSSH altimeter observations.

Geoid Model	dNmax [m]	dNmin [m]	dNmean [m]	Std. [m]
EGM96	2.33	-1.24	0.21	0.62
CARIB97	0.72	-1.19	0.01	0.15
GEOIDVE	3.76	-6.01	-0.08	0.72
N				
LGGGM	0.67	-1.05	0.05	0.15

The Fig. 5 shows the comparison of altimeter observations with the LGGGM+POCM synthetic sea surface for the descending pass 076 of TOPEX/Poseidon (This pass, highlighted in Fig. 2, is closest to the tide gauge location). The excellent agreement between the synthetic sea surface and the altimeter data is evident.

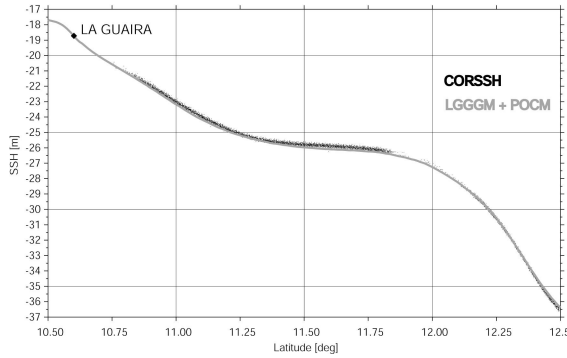


Fig. 5 TOPEX/Poseidon 076 pass and the synthetic sea surface (LGGGM+POCM).

3.3 Analysis of La Guaira Tide Gauge Data

For the 1992-2000 time period, 64545 hourly readings exist for the La Guaira tide gauge (Fig. 6a). In La Guaira, the sea level fluctuations are quasi-periodic. The Fourier power spectrum (Fig. 6b) shows most energetic fluctuations at diurnal, semi-diurnal, annual and semi-annual periods with amplitudes up to 9, 5, 7 and 6 cm, respectively. In August 1998, a change of the recording device (analog to digital) caused significant data losses and anomalous offsets (Fig. 6a). To reconstruct a consistent and continuous time series the registration offsets were identified and repaired by the following procedure:

The observed sea level heights $h_{SL}(t)$ can be explained b

$$h_{SL}(t) = h_{HARM}(t) + v \quad (3)$$

where $h_{HARM}(t)$ is a systematic part described by harmonic expansion of ocean tides and v are residuals that account for errors of observations and unmodelled local effects (e.g. meteorological tides). $h_{HARM}(t)$ can be estimated by

$$h_{HARM}(t) = h_0 + h_1(t) + \sum_{k=1}^{145} f_k(t) H_k \cos(\omega_k t + V_k + u_k(t) + G_k) \quad (4)$$

where h_0 represents the mean sea level at the tide gauge, $h_1(t)$ its time variation, H_k and ω_k the amplitude and frequency for each one of the 145 tide constituents k , V_k the argument or astronomical phase, $f_k(t)$ and $u_k(t)$ the nodal modulation factors depending on the longitude of the lunar node and G_k the phase lag relative to Greenwich (Le Provost, 2001).

An example of the harmonic analysis for April 1995 is shown in the Fig. 6c. During that period, semidiurnal tides are dominant. The differences between observations and the harmonic model have ± 4 cm RMS.

Comparing the original readings with the harmonic model allows to detect and correct for anomalous offsets. In addition, LSC was applied to predict residuals such that missing data $h_{SLPRED}(t)$ was obtained by

$$h_{SLPRED}(t) = h_{HARM}(t) + C_P^T \underline{C}^{-1} v \quad (5)$$

where C_P and $\underline{C}$ are cross- and autocovariance matrices for the detrended residuals. These matrices were calculated with a time dependent exponential covariance function

$$C(t) = C_0 e^{-At^2} \quad (6)$$

that was fitted to the empirical autocovariance function (see Fig. 6d). A correlation distance of about 3 days was obtained and the predicted sea level readings showed errors of ± 6 cm RMS.

There was no evidence for a different precision of the two recording devices. Therefore, in the reconstruction both registrations were treated with the same weight (Acuña et al., 2002b). The restituted tide gauge series is displayed in the Fig. 6e. A total of 5607 new readings were predicted. Level changes up to 55 cm have been corrected.

Finally, the time series was filtered to daily mean values using a convolution filter of 119 points centered in the noon. This filter eliminates diurnal and semidiurnal frequencies. The time series with daily means is shown in Fig. 6f. The series has an RMS of ± 8 cm and a lineal trend of -9 ± 1 mm/year.

The negative trend of the La Guaira tide gauge series was already observed by Acuña et al. (2002a, 2002b). For monthly mean values they found a trend of -12 ± 5 mm/year for the period 1992-1999. Up to now there is no explanation for the significant negative trend.

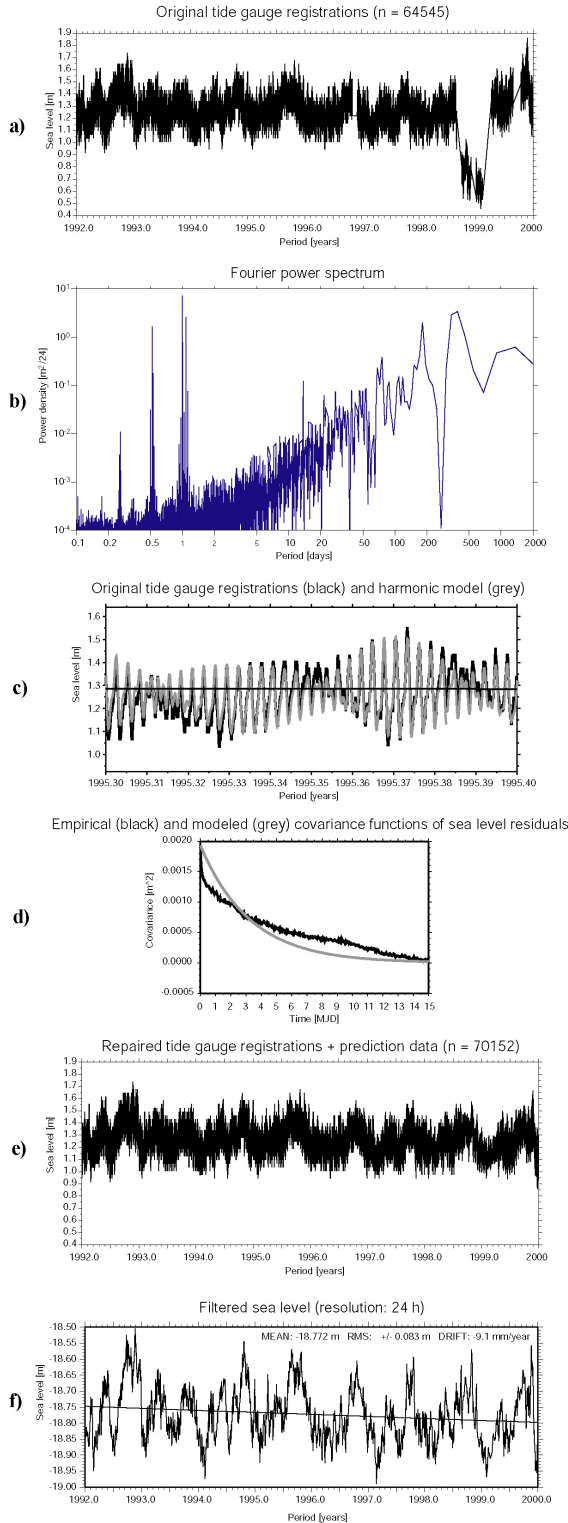


Fig. 6 Sea level time series by La Guaira tide gauge.

The series was then referred to the ITRF97/GRS80 using the GPS and leveling measurements which link the tide gauge P_0 with the

BM GUA2 about 10 m apart. The 3 days of GPS observations were analysed with the Bernese v4.2 software (Hugentobler et al., 2001) and precise ephemerides taken from IGS (International GPS Service). Observations at the IGS permanent stations MARA and CRO1 were processed jointly and their coordinates kept fixed. The position coordinates and the ellipsoidal height of the BM were obtained with errors of ± 2 and ± 3 cm, respectively. The results refer to the ITRF2000 frame, epoch 2002.3. For comparison they were transformed to the ITRF97 frame, epoch 1997.0 with parameters, provided by IERS at URL <ftp://lareg.ensg.ign.fr/pub/itrf/ITRF.TP>.

The leveled height difference between BM and P_0 , a well documented constant, was then used to relate the official $MSL_{1953-1971}$ and the tide gauge data to a geocentric ellipsoid.

3.4 Analysis of Altimetric Sea Level Time Series

The corrected sea surface heights (CORSSH) refer to the ellipsoid of the TOPEX/Poseidon mission and the CSR95L01/95D02 reference frame (Nerem et al., 1998) and were transformed to the GRS80 ellipsoid and the ITRF97 frame, epoch 1997.0, using the parameters published in (Ries et al., 1999). ITRF97 is consistent with the reference frame for EGM96 used as reference model for the LGGGM determination. The ocean tide corrections for CORSSH are based on the CSR3.0 model (Eanes, 1994) and were replaced by the GOT00.2 model (Ray, 1999).

After this preprocessing the CORSSH observations were split into following components

$$CORSSH = N_{LGGGM} + SSTop_S + SSTop_D + v \quad (7)$$

where N_{LGGGM} are the undulations of the local geoid. The stationary part of the sea surface topography, $SSTop_S$, was calculated as weighted mean value of the differences $CORSSH - N_{LGGGM}$ by

$$SSTop_S = \frac{\sum_{i=1}^n (CORSSH - N_{LGGGM}) \cdot w_i}{\sum_{i=1}^n w_i} \quad (8)$$

with weights

$$w_i = 1 + \frac{9d_i^2}{r_{\max}^2}; r_{\max} = 1^\circ \quad (9)$$

depending on the distance d_i to the tide gauge position. The dynamic sea surface topography ($SSTop_D$), was modeled and extrapolated at the position and times of the daily tide gauge registrations using again LSC

$$SSTop_{D_{TG}} = C_P^T C_{\underline{\underline{C}}}^{-1} SSTop_D \quad (10)$$

where

$$SSTop_D = CORSSH - N_{LGGM} - SSTop_S \quad (11)$$

The C_P and $\underline{\underline{C}}$ matrices were set up by a 2-dimensional covariance function

$$C(d, t) = C_0 e^{-(Ad + Bt)} \quad (12)$$

depending on time t and distance d . The empiric and modelled covariance functions are shown in Fig. 7b. The correlation lengths in time and distance are 30 days and 117 km, respectively. All components of equation (7) were then used to evaluate the altimeter sea level time series at the tide gauge position.

$$CORSSH_{TG} = N_{LGGM_{TG}} + SSTop_{S_{TG}} + SSTop_{D_{TG}} \quad (13)$$

Fig. 7a shows the altimeter time series with 11267 altimeter observations processed within 1° spherical distance from the tide gauge location. The model of equation (7) approximates the data with an RMS of ± 4 cm.

In order to compare with the tide gauge data the altimetric time series was finally resampled to the same daily events generated for the tide gauge data. 2662 values could be generated (see Fig. 7c).

This final altimeter time series shows an RMS variation of ± 7 cm and a linear trend of $+4 \pm 1$ mm/year. The positive trend of the altimeter time series appears to be significant - although the annual rate of change depends to a certain extent on the different altimeter mission data used to generate the time series (see Table 4). Bosch et al. (2002) found a mean annual sea level change of $+2$ mm/year, based on a rough estimate with TOPEX/-Poseidon altimeter data during the period 1993-2000.

3.5 Absolute Comparison

Both final geocentric time series, the tide gauge and the altimetric sea level data are shown together in Fig. 8a. For the period 1992-2000, the

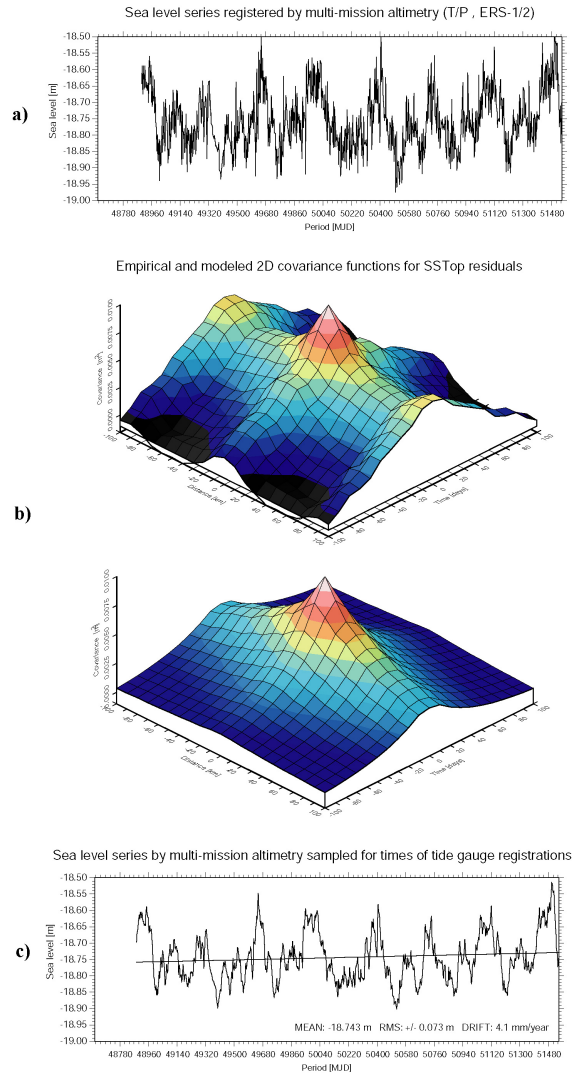


Fig. 7 La Guaira sea level time series by multi-mission altimetry.

Table 4. Impact of different altimeter data groups on the sea level trend estimate for the period 1992-2000.

MISSION	MSL [m]	TREND [mm/year]
T/P + ERS1 + ERS2	-18.74 ± 0.07	$+4.1 \pm 0.7$
T/P + ERS2	-18.74 ± 0.07	$+3.4 \pm 0.6$
T/P	-18.75 ± 0.07	$+2.7 \pm 0.6$

two time series differ by an RMS of ± 5 cm. There is a mean offset of only $+3$ cm with the altimeter time series being higher. The scatter plot in Fig. 8b illustrates the rather high correlation factor of 0.85. The large drift of $+13$ mm/year for the differences, shown in Fig. 8c, is mainly caused by the observed drift of the tide gauge data (Fig. 6f), but even

enlarged by the opposite sign of the secular change found for the altimetric data (Fig. 7c).

The negative drift is remarkable and inconsistent with a secular rate of change of -0.6 ± 0.3 mm/year found by Acuña et al. (2002a) for six other tide gauges in the Caribbean Sea. Further investigations are required to identify the cause of the large negative drift in La Guaira.

Fig. 9 shows differences between the local LGGGM geoid height, the EGM96 geoid height and various estimates of mean sea level at La Guaira. The differences to the mean sea level can be considered as estimates of the sea surface topography.

Using the altimetric sea level trend estimate of $+2.7$ mm/year derived from TOPEX/Poseidon (Table 4, considered as most reliable), the mean sea level at La Guaira was developed back from 1996 (mean of the period 1992-2000) to 1962 (the mean of the period 1953-1971). The 1962 altimetric mean sea level is then 10 cm below the LGGGM geoid, considered to be invariant with time.

Without any epoch correction, the mean tide gauge registration for the period 1953-1971, referred to the geocentric system through GPS and leveling, is 8 cm below LGGGM. For the period 1992-2000 the mean geocentric tide gauge registration is 4 cm below LGGGM. Vertical tectonic movements have not been taken into account.

4 Conclusions

During the period 1992-2000, the sea level time series estimated in La Guaira by multi-mission altimetry and tide gauge registrations show a good absolute agreement. The mean offset is only 3 cm and the differences have an RMS of ± 5 cm. The small numbers indicate the quality of the involved observations and verify the reliability of the applied procedure. The significant negative trend of -9 mm/year for the La Guaira tide gauge registration, however, can not be explained. It could be due to both, a mechanical drift of the tide gauge sensor or a tectonic vertical. With the single GPS campaign it is, of course, not possible to identify and estimate any vertical tectonic movement at the tide gauge location. More GPS campaigns or, even better, a continuous GPS monitoring at the tide gauge would be required.

The described method allowed to estimate the vertical displacement of the origin of the height system in Venezuela relative to a geoid with an error of several centimeters.

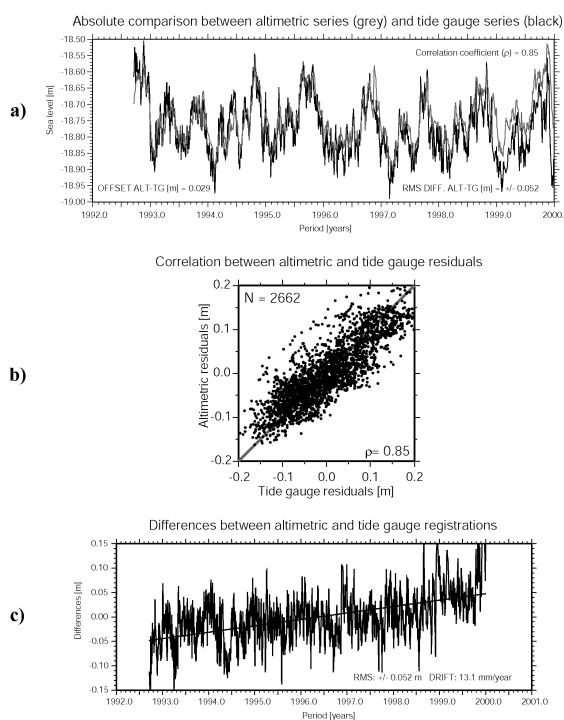


Fig. 8 Absolute comparison of sea level time series by altimetry and tide gauge registrations.

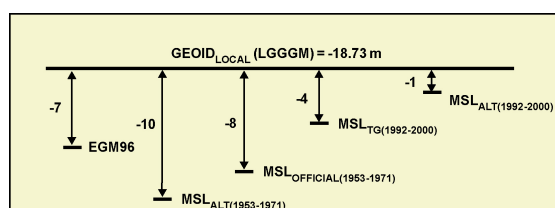


Fig. 9 Vertical displacements in La Guaira between geoids and various mean sea level estimates.

The vertical displacements between a new precise local geoid, the LGGGM, and several estimates of mean sea level are only a few centimeters – the same order of magnitude as the errors of extrapolating the altimeter data towards the tide gauge position. Errors of the geoid model are even larger. This suggests that the sea surface topography in La Guaira reaches a magnitude of up to 10 cm and is not considered significant for the definition of the Venezuelan vertical datum.

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