Regional Model to Estimate Vertical Deformations Due to Loading Seasonal Changes

Romina Galván, Mauricio Gende, and Claudio Brunini

Abstract

Surface mass transfer produces changes in the terrestrial geometric reference frame that are clearly detectable by GNSS techniques. These deformations are mainly observed in the vertical coordinate component and show periodic behavior with seasonal cycles. Therefore, the assumption that the kinematics of the reference frame has a linear behavior is no longer sufficient.

This study focuses on a model of crustal vertical deformations caused by surface loading variations in the South American region. Thirty-four locations were analyzed in order to adjust a parametric exponential function that relates height changes with mass pressure variations.

This parametric function depends on regional rheological properties. Crustal deformations were characterized using multi-annual GPS time series provided by SIRGAS and the surface loading information was derived from GRACE spherical harmonic coefficients provided by GRGS (Release 2). The proposed parametric model was able to properly reproduce inter-annual variations observed in vertical displacement in a 9-year time-span (2003–2012). This study will contribute to a better understanding the kinematics of the reference frame and the elastic parameters on a regional scale.

Keywords

Geodesy • GPS • GRACE • Gravity • Green function • Seasonal variations • Surface loading • Vertical deformation

1 Introduction

Accurate time series of coordinates achieved by GNSS have allowed us to observe seasonal variations mainly in the vertical component (van Dam et al. 2001; Blewitt et al. 2001; Dong et al. 2002). Data from GRACE satellite mission has also shown seasonal variations in the Earth's gravity field (Tapley et al. 2004; Wahr et al. 2004). Both effects are caused by the same geophysical phenomenon: mass redistribution on the Earth's surface or around it. Several authors have studied how mass exchange affects the Earth system using both sources of data: GPS and GRACE, and they have concluded that temporal loading variations produce geometric deformations on the Earth's surface (e.g. Tregoning et al. 2009; Tesmer et al. 2011; Fu et al. 2012).

Global and regional reference frames are materialized by a set of fiducial stations with known positions for a given epoch and constant velocities. They are transformed to other epochs by means of applying linear coordinate changes (Altamimi et al. 2011; Brunini et al. 2009).

The representation of the kinematics of fiducial stations using a linear model, i.e. neglecting surface loading effects, will have an impact on the reference frame realization (e.g.

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Poutanen et al. 2002; Freymueller 2009; Collilieux et al. 2010, 2012; Zou et al. 2014).

In continental regions, the most relevant temporal loading variations are due to atmospheric (van Dam and Wahr 1987; Tregoning and Watson 2009), non-tidal ocean (Williams and Penna 2011; van Dam et al. 2012), and hydrological loads like water, snow and ice loads (e.g. Bettinelli et al. 2008; Fu and Freymueller 2012).

Those variations produce vertical displacements in geodetic benchmarks that can reach several centimeters in amplitude (e.g. van Dam 1998; Biessy et al. 2011). Therefore, GPS is well designed for estimating the effect of loads in the Earth's crust and determining a new model of elastic response for fiducial stations.

The classical approach used to convert surface loading into geometric deformations (e.g. van Dam 1998; van Dam and Wahr 1987; Kusche and Schrama 2005; Fu and Freymueller 2012; Fu et al. 2012) is based on a function that characterizes the Earth's response to loading, which depends on load Love numbers (Longman 1962; Farrell 1972). Those models do not take into consideration changes in the Earth's crust behavior due to local variations of the rheological properties.

We have investigated the possibility of using a variant to this conventional methodology which defines the Earth's response by a parametric and exponential function that considers different elastic properties of the crustal material. This function was first introduced by Seitz and Krügel (2009). In order to obtain a regional model to estimate vertical deformations produced by loading seasonal changes, we applied this methodology on a regional scale using GRACE data and GPS time series and tested it in the South American region. Although the distribution of GPS data over the Earth is not uniform, today in South America there is a very dense network of continuously operating sites that provide a unique opportunity.

2 Applied Methodology

Temporal loading variations applied on the Earth's surface produce geometric deformation changes in nearby regions where loading is applied. Those deformations are modeled by a function that addresses how those deformations change as we move away from the point where the load is applied. Usually, the displacements observed at P affected by a load applied at Q are described by the following function (Longman 1962; Farrell 1972; Moritz and Mueller 1987)

$$d_r(P) = \frac{R_E^3}{M} \int \int q_Q \sum h'_n P_n(\cos \varphi_{PQ}) d\sigma_Q, \quad (1)$$

where φ_{PQ} stands for the spherical distance between P and Q, P_n and h'_n are the Normalized Legendre Polynomials and the loading Love numbers of degree n, respectively; R_E represents the mean radius of the Earth and M is the total mass of the Earth. The expression

$$G(\varphi_{PQ}) = \frac{R_E}{M} \sum h'_n P_n(\cos \varphi_{PQ}), \quad (2)$$

represents the Green's function for vertical displacements (Longman 1962). This function depends on the loading Love numbers which change according to P and S body velocities, and ρ densities for a spherically-symmetric non-rotating elastic isotropic Earth model, SNREI such as PREM, iasp91, ak135, etc.

Due to crustal material inhomogeneities, Green's function does not handle variations of the physical behavior of the Earth's crust for loads in surrounding regions correctly. Our aim was to replace this Green's function with an exponential function that depends on the site where the deformation is calculated (Seitz and Krügel 2009)

$$F(\varphi_{PQ}) = 10^{-17} a \exp^{-b\varphi_{PQ}}, \quad (3)$$

where a and b are unknown physical parameters that represent crustal inhomogeneities. The parameter a provides a measure of the vertical deformation of a cell when it is loaded by a certain mass, while b shows to what extent a given mass can affect the Earth's surface. The parameter a has units of [m/Kg] and it is related to the Young's modulus E for the area where the load is applied, while b is dimensionless and depends on the elastic parameters of the neighboring cells.

When replacing this function in Eq. (1), the vertical displacement can be estimated by the following function:

$$d_r(P) = 10^{-17} \sum_{k/\varphi_{PQ}<R} q_{Q_k} A_{Q_k} a \exp^{-b\varphi_{PQ}}, \quad (4)$$

where A_{Q_k} represents the area of the cell k, which depends on the spatial resolution of the loading data. The summation is set for all cells within a radius R where mass loads affect the deformation observed in P. The method has been tested in the Amazon region where we can observe the most relevant annual vertical deformations due to the temporal variations in the Amazon River and its affluents.

The geometric deformations have been characterized with SIRGAS GPS time series of the region, while loading variations have been estimated with the GRACE satellite mission.

In order to estimate numerical values for a and b parameters, we linearized the problem [Eq. (4)] and performed an iterative least square adjustment where we set initial values for the parameters.

With the estimated parameters, we calculated a weekly vertical deformation of the surface and we compared it with the displacements observed for the selected GPS sites.

3 Data Sources

In order to estimate both the geometrical deformation of the Earth's surface and the temporal loading variations in the South American region, we have used GPS time series of SIRGAS Continuously Operating Network (SIRGAS-CON) and spherical harmonic coefficients of the Earth's gravity field estimated from GRACE data.

3.1 GPS Data

SIRGAS is the Geocentric Reference System for Latin America and the Caribbean (Brunini et al. 2009) and it is a regional densification of ITRF. Its definition corresponds to the IERS International Terrestrial Reference System (ITRS) and it is realized by a network of 368 continuously operating GNSS stations (Fig. 1). It is processed on a weekly basis by the SIRGAS analysis centers, which generate weekly solutions for station positions. Each GNSS station is aligned to the current ITRF reference stations. The accuracy of the positions in the reference epoch is estimated to be better than 1.0 mm in the horizontal component and 2.9 mm in the vertical component. These GPS data are available at http://www.sirgas.org.

The analysis was carried out with Bernese 5.1 software (Dach et al. 2007) and a 30-s interval was used for every station. The elevation mask was set to 3° and an elevation angle dependent function weighing between 3° and 5° was applied. Also, ocean tide loading was modeled according to the FES2004 ocean tide model (Letellier 2005). The Niell (1996) dry mapping function was applied to map the a priori zenith delay (dry part), which is modeled using the Saastamoinen (1973) model. The wet part of the zenith delay was estimated at a 2-h interval within the network adjustment and it was mapped using the Niell wet mapping function (Niell 1996).

We have used weekly solutions of the GPS time series from every station within the network. These stations are aligned to the IGS05 reference frame using a six parameter similarity transformation: no-net-rotation (NNR), no-net-translation (NNT) (Brunini et al. 2012).

Figure 2 shows the displacements observed for a SIRGAS-CON station located in the Amazon Basin. The first and second plots correspond to horizontal displacements, while the red dots correspond to the vertical ones. As we can observe, the horizontal components have a mostly linear behavior. However, this is not true for the vertical component, where the movements reported the biggest amplitudes with a strong seasonal variation. This is why our work focuses only on the vertical component.

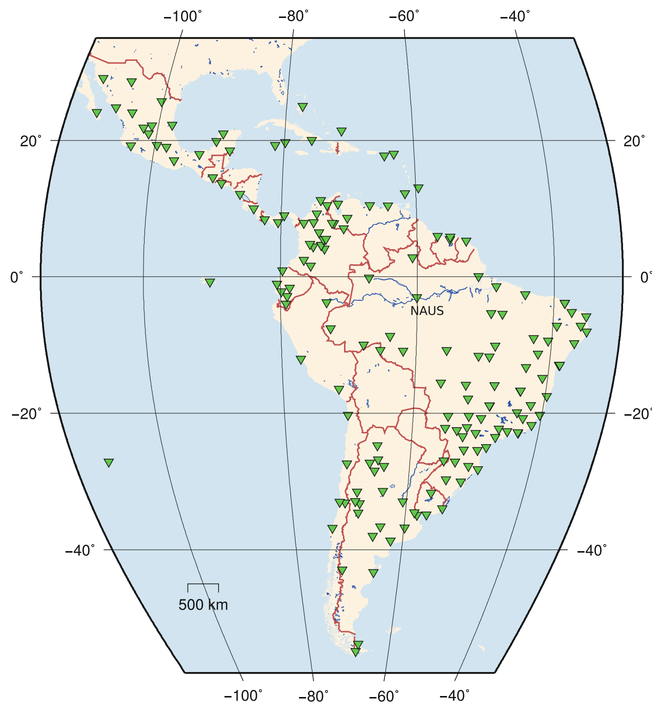

Fig. 1 SIRGAS-CON network

In order to test the model, we started with a sample of 368 stations and we selected only those whose time span was longer than 3 years, those whose vertical components had visible seasonal variations and we checked that a similar behavior was observed in nearby stations. Additionally, we did not take into account those stations which had sudden changes or trend variations caused by earthquakes, extensive data gaps, those cases where local effects dominated the signal, or those when the signal was very noisy. After ruling out those stations, a group of 34 South American GPS sites was considered. We used, when available, GPS weekly solutions between 2003 and 2012 so that they matched the time interval of GRACE data. We removed the linear trend of the time series and we applied a low-pass filter assuming that periods shorter than 4 months were not related with the loading effects we tried to model. We used samples of 343 observations on average.

3.2 GRACE Data

GRACE is designed to monitor temporal variations in the fluid mass on the Earth's surface (Tapley et al. 2004). The GRACE geopotential solution can be used to recover time changes in water storage. There are four main GRACE data centers that provide temporal variations of the harmonic

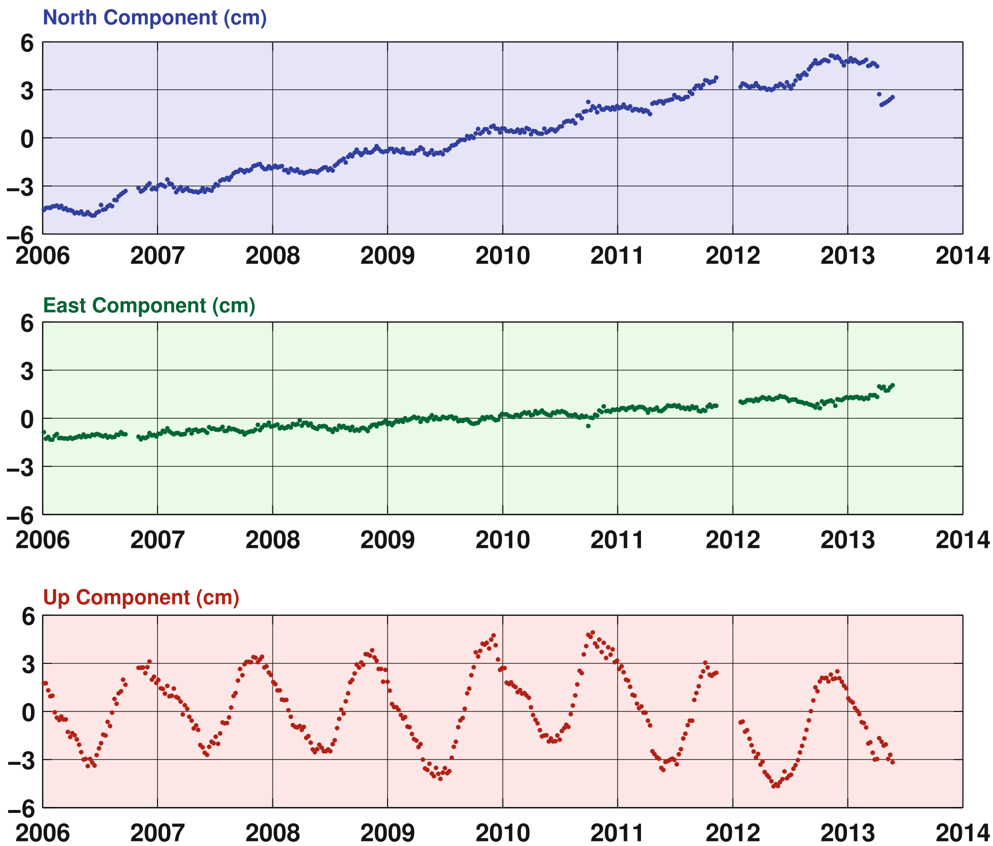

Fig. 2 GPS time series for a SIRGAS-CON station (NAUS)

coefficients: CSR (University of Texas, Center for Space Research), GFZ (GeoForschung Zentrum, Potsdam), JPL (Jet Propulsion Laboratory, NASA) and GRGS (Space Geodesy Research Group). They have different temporal resolution: CSR, JPL and GFZ provide monthly harmonic coefficients while GRGS offers data with a 10-day resolution. The main difference of the GRGS center is the solution strategy adopted. The constraint applied in the inversion method produces a better reduction of the North-South stripes. Consequently, a post-processing filtering or smoothing was not needed. Additionally, this center added harmonics of very low degree, in particular degrees 2 and 3, from Lageos data observations because they cannot be estimated accurately with GRACE data only. Although higher temporal resolution usually means noisier data, the noise associated with GRGS solution is comparable with the GRACE project solutions. For details, see Bruinsma et al. (2010).

We used this center latest improved releases, that is, the GRGS series of the gravity field model expressed in normalized spherical harmonic coefficients from degree 2 to 50. Given that the effects of atmospheric and non-tidal ocean loads have been removed from GRACE signal, but they are still present in GPS data, we have restored those effects to GRACE spherical harmonic solutions in order to maintain consistency. We have added GRACE's Atmosphere and Ocean De-aliasing Level-1B (AOD1B) solution that is based on 6-hourly ECMWF analysis data and output from the baroclinic ocean model for circulation and tides (OMCT). This product contains spherical harmonic coefficients up to degree and order 100 for four 6-hourly time stamps (0, 6, 12 and 18 h). We applied a time interpolation and we calculated spherical harmonic coefficients for a 10-day resolution so that they would be consistent with the time resolution of GRGS's data. It is also important to note that equivalent water height values, deduced from GRACE measurements, were corrected for the gravitational effect induced by crust geometric displacement as a response to water loading using an elastic Earth hypothesis as explained in Wahr et al. (1998).

We used the results to construct the equivalent water height at every point in a 1°-×-1° global grid. We filtered the signal in time as we did with GPS signals using the same assumption and we interpolated it and calculated weekly values so that they could be compared with GPS epochs.

Figure 3 shows an example of equivalent water height on a global scale for a given epoch. The amplitude of the Amazon Basin is large, as might be expected from the gravity and surface mass signals (Tapley et al. 2004).

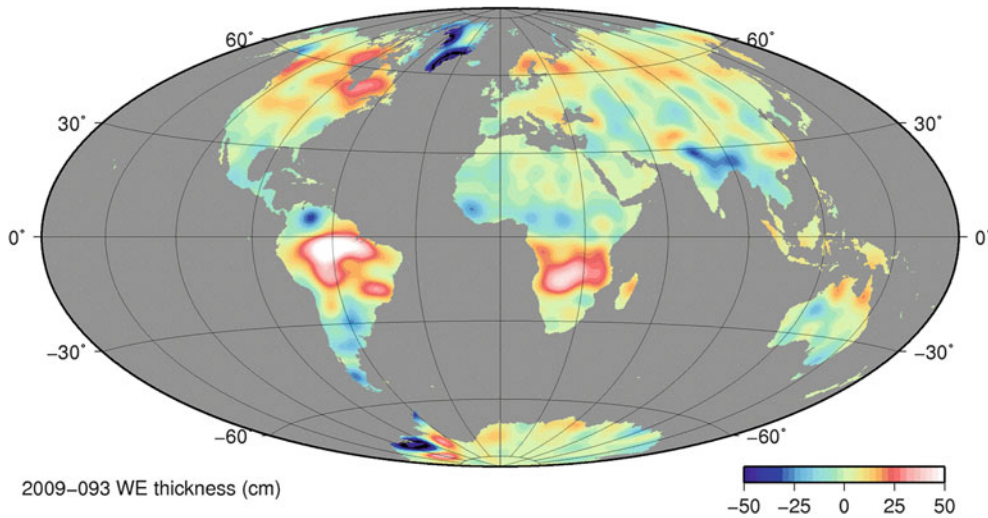

Fig. 3 EWH from GRGS center

4 Correlation Coefficient and Parameter Adjustment

If we superimpose EWH and vertical displacements for a station located in the Amazon basin, when EWH grows, the vertical displacement is expected to decrease and vice-versa.

Figure 4 shows both signals for NAUS station. This figure demonstrates that GRACE is very sensitive to hydrological loading. It is worth noting that we are observing two different effects with different vertical scales, where EWH is represented in green and the vertical displacements in blue. The former effect has amplitudes of about 100 cm while the latter reaches 5 cm.

Nevertheless, we would expect the correlation coefficients between both effects to be close to −1. We calculated the correlation coefficients for every selected station as we explained in Sect. 3.1 (34 GPS sites) and we decided on modeling only those stations whose correlation was lower than −0.75. Figure 5 shows the correlation coefficient for the 20 stations that fulfill the above requirement. At middle latitudes, the correlation coefficients are systematically large given their proximity to the Amazon River.

We estimated the numerical values of a and b parameters by applying the inversion method based on an iterative least square adjustment using Eq. (4). Each of the GPS-derived vertical displacements and the corresponding EWH for grid cells within a radius R, both with respect to weekly time values were taken as observations.

5 Results

The least squares adjustment of the parameters was performed for data between 2003 and 2012, taking into account that crustal deformations measured in a point P are caused by loads within a radius R of 200 km from P, according to Bevis et al. (2005) and Seitz and Krügel (2009). We defined as initial values for unknown parameters those proposed by Seitz and Krügel (2009), $a = -12.5$ and $b = -35$ that were obtained by fitting a function to the mentioned Green's function.

We found mean values of −16 and −27 for a and b, respectively. These values are consistent with those adjusted by Seitz and Krügel (2009).

A weighting function for each station using the best fit parameters was calculated. Also, we compared it with both the function obtained by Seitz and Krügel (2009) for the region and Green's function based on global values of load Love numbers for continental crust up to degree $n = 2{,}000$. In Fig. 6, all fitted weighting functions are plotted as a blue continuous line, the red line represents the initial function that best fits Green's functions, and Green's function for a normal continental crust was plotted in black.

The adjusted functions F differ slightly from those proposed initially and they seem to agree with Green's function. We estimated displacements due to loading variations for each station and we compared them with the observed displacements in GPS sites. Figures 7 and 8 show estimated displacements in blue and observed displacements in red dots for two stations. We have selected an example of a station with a strong harmonic behavior and another example in which interannual variations are visible.

In order to assess whether varying these parameters is a significant improvement or not, standard deviation (STD) between computed displacements and observed displacements was calculated and we compared it with that STD obtained using the Farrell's method. Figure 9 shows those results.

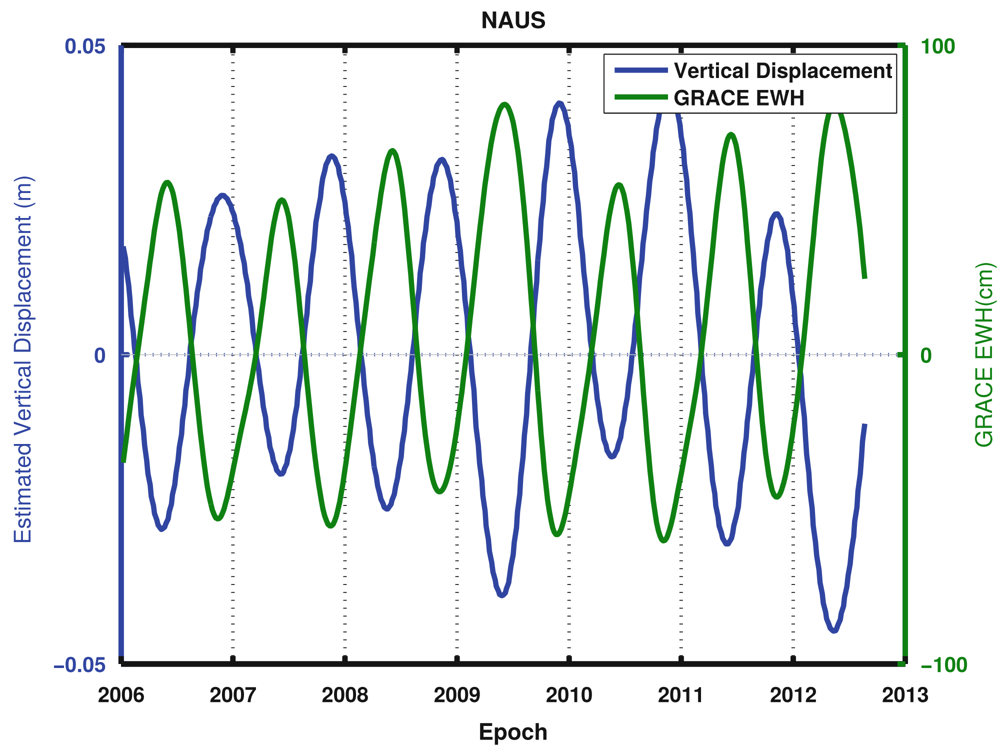

Fig. 4 EWH vs vertical displacements for a station located in the Amazon basin (NAUS)

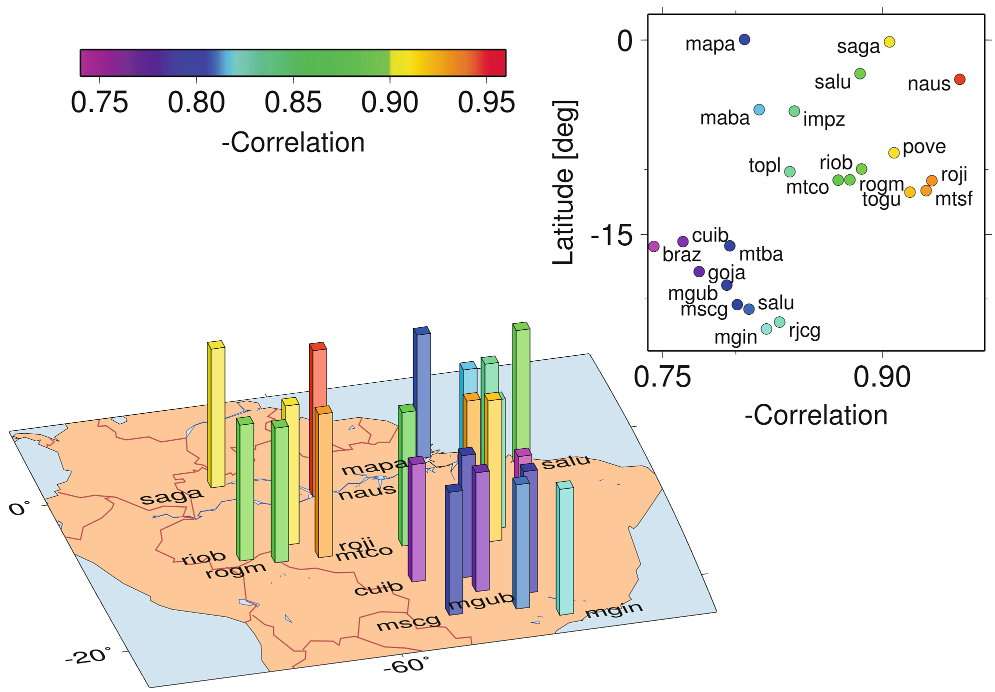

Fig. 5 Correlations between loading variations (EWH) and vertical displacements for South America

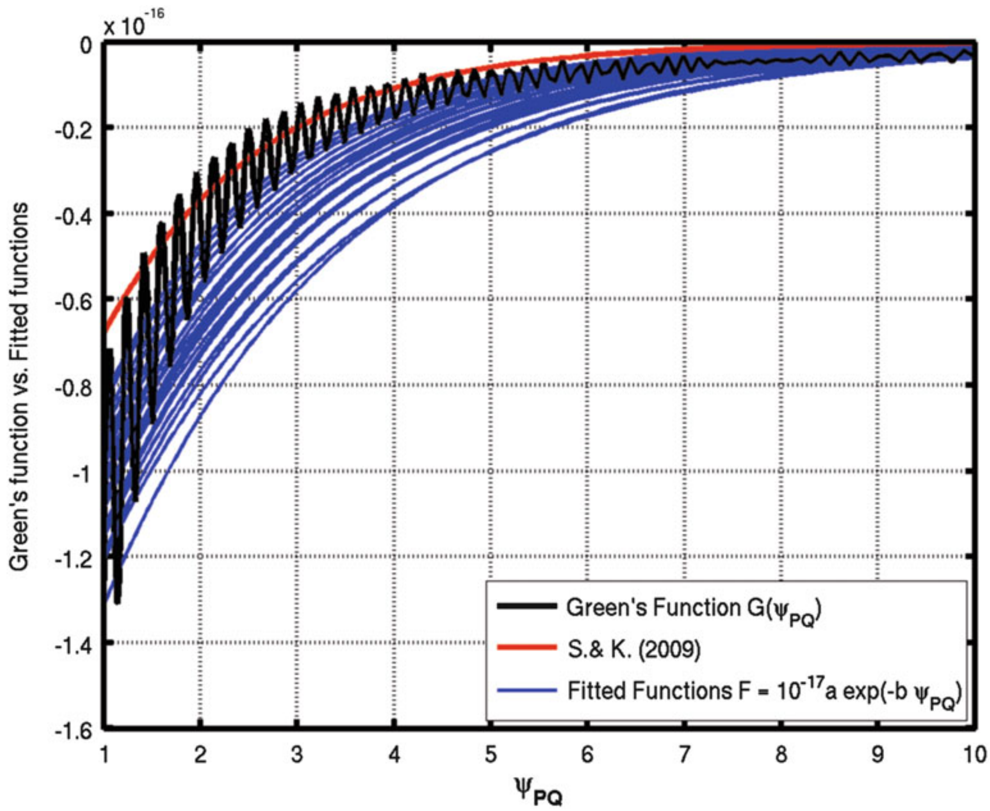

Fig. 6 Comparison between weighting functions

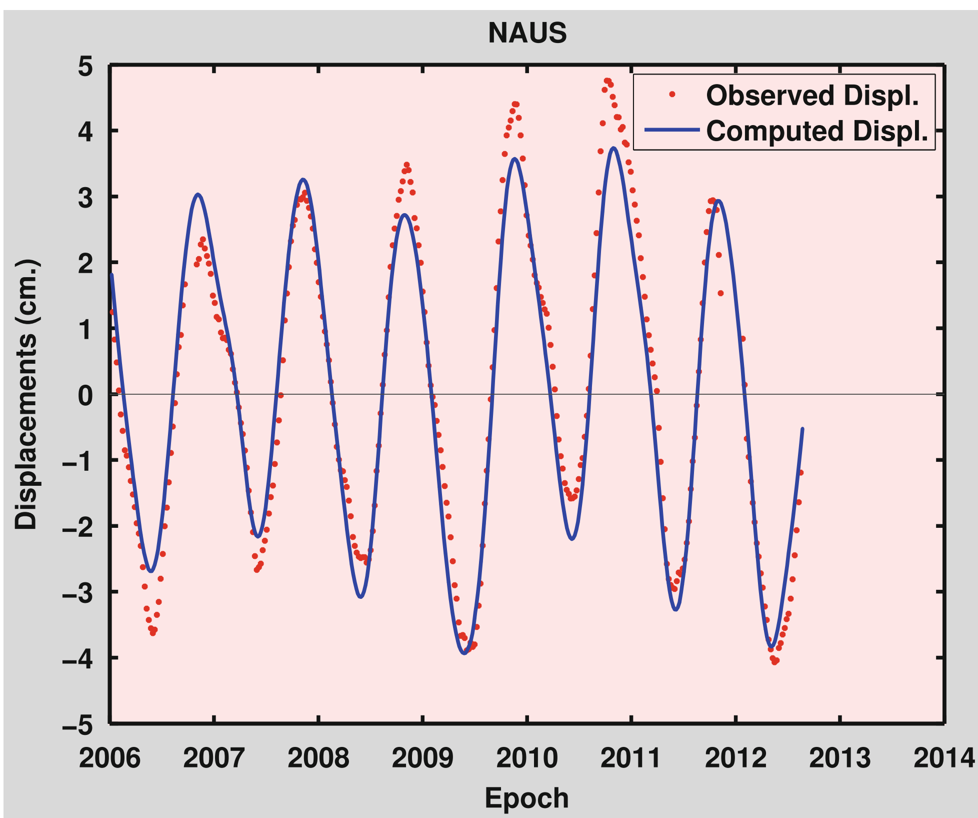

Fig. 7 Comparison between observed (red dots) and calculated (blue line) displacement for a station with strong harmonic behavior (NAUS)

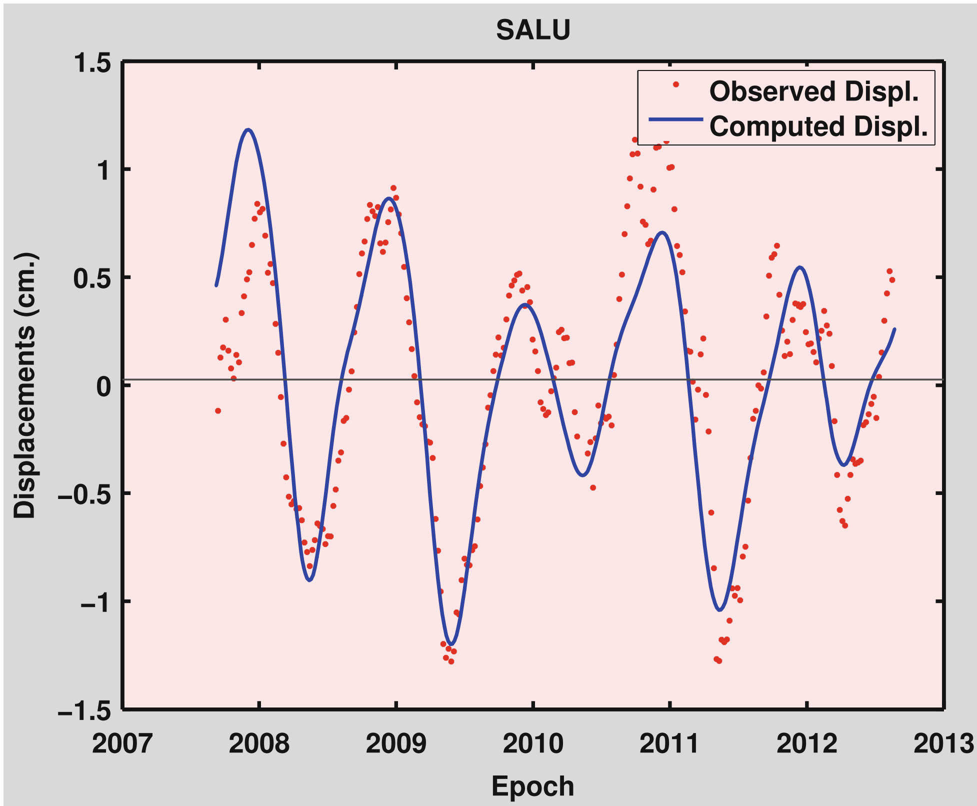

Fig. 8 Comparison between observed (red dots) and calculated (blue line) displacement for a station with visible interannual variations (SALU)

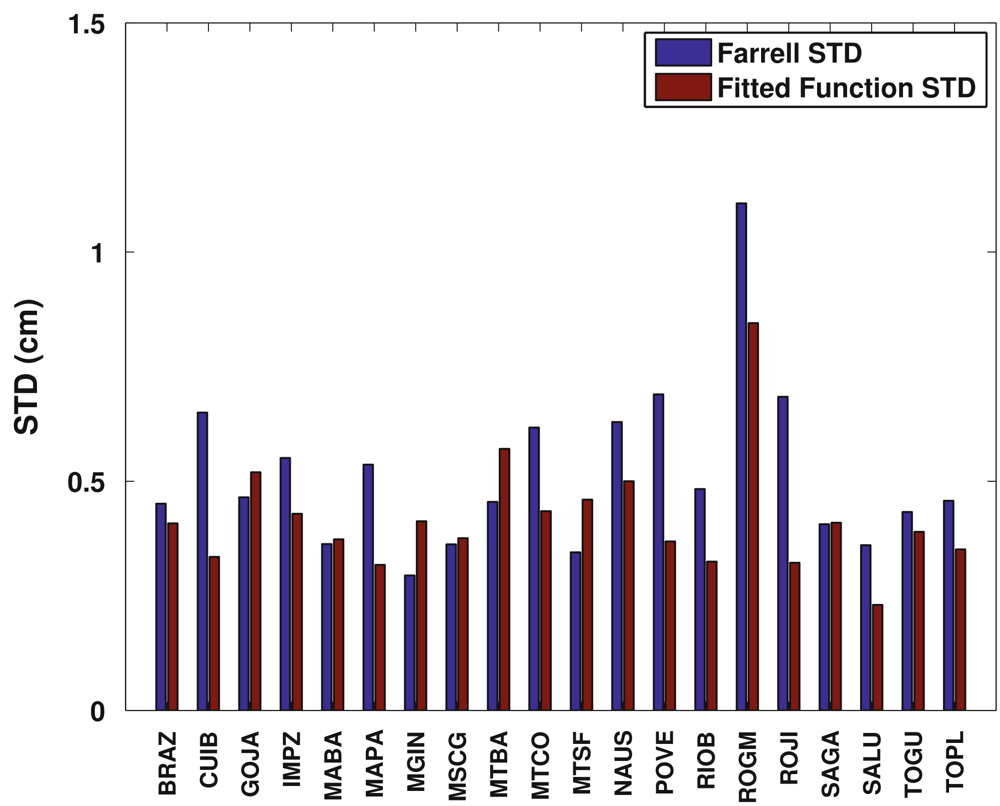

Fig. 9 STD for GPS stations

6 Summary and Outlook

This paper focused on a regional model of crustal vertical deformations caused by surface loading variations. We have used GPS data and GRACE data in order to quantify vertical surface displacements and temporal loading variations.

For those sites where the surface exhibits harmonic motion, the estimated displacements were very similar to those estimated with Farrell's method. For the remaining stations, the modeled displacements were capable of representing anomalous changes in time with good agreement. The observed displacements are dominated by a large annual continental mass signal and the differences in amplitudes between different years depend on local climate changes like *El niño* and *La niña*, etc.

These comparisons demonstrate that a physical mechanism is responsible for the correlation between both geodetic signals. We were capable of modeling changes in the surface due to load changes that differ from an annual or semiannual behavior, like flooding and dry seasons.

The main differences between the modeled and observed displacements are related to differences in maximum and minimum displacements. These may happen because GRACE can recover temporal variations of the Earth's gravity field due to mass redistribution that are spatially smoothed with a given resolution, while GPS data represents discrete point observations.

We have compared EHW values from the GRGS with those from CSR for the region of interest and we have not found significant differences in the solutions. Therefore, the use of any other GRACE data center is not expected to alter the main results presented in this work.

In this paper, we present a way to estimate vertical variations in GPS sites produced by persisting effects in current models. This method can be applied to other similar regions in order to achieve a better knowledge of the surface behavior.

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References

Altamimi Z, Collilieux X, Métivier L (2011) ITRF2008: an improved solution of the international terrestrial reference frame. J Geodesy 85:457–473. doi:10.1007/s00190-011-0444-4

Bettinelli P, Avouac JP, Flouzat M, Bollinger L, Ramillien G, Rajaure S, Sapkota S (2008) Seasonal variations of seismicity and geodetic strain in the Himalaya induced by surface hydrology. Earth Planet Sci Lett 266:332–344. doi:10.1016/j.epsl.2007.11.021

Bevis M, Alsdorf D, Kendrick E, Fortes LP, Forsberg B, Smalley R, Becker J (2005) Seasonal fluctuations in the mass of the Amazon river system and Earth's elastic response. Geophys Res Lett 32:L16308. doi:10.1029/2005GL023491

Biessy G, Moreau F, Dauteuil O, Bour O (2011) Surface deformation of an intraplate area from {GPS} time series. J Geodyn 52(1):24–33. doi:http://dx.doi.org/10.1016/j.jog.2010.11.005. http://www.sciencedirect.com/science/article/pii/S0264370710001572

Blewitt G, Lavallée D, Clarke P, Nurutdinov K (2001) A new global mode of earth deformation: seasonal cycle detected. Science 294:2342–2345. doi:10.1126/science.1065328

Bruinsma S, Lemoine JM, Biancale R, Valès N (2010) CNES/GRGS 10-day gravity field models (release 2) and their evaluation. Adv Space Res 45:587–601. doi:10.1016/j.asr.2009.10.012

Brunini C, Costa S, Mackern V, Martínez W, Sánchez L, Seemüller W, da Silva A (2009) SIRGAS: ITRF densification in Latin America and the Caribbean. In: Arabelos DN, Tscherning CC (eds) EGU general assembly conference abstracts, vol 11, p 2105

Brunini C, Sanchez L, Drewes H, Costa S, Mackern V, Martínez W, Seemuller W, Silva A (2012) Improved analysis strategy and accessibility of the sirgas reference frame. In: Kenyon S, Pacino MC, Marti U (eds) Geodesy for planet earth, international association of geodesy symposia, vol 136. Springer, Berlin/Heidelberg, pp 3–10. doi:10.1007/978-3-642-20338-1_1. http://dx.doi.org/10.1007/978-3-642-20338-1_1

Collilieux X, Altamimi Z, Coulot D, van Dam T, Ray J (2010) Impact of loading effects on determination of the international terrestrial reference frame. Adv Space Res 45:144–154. doi:10.1016/j.asr.2009.08.024

Collilieux X, van Dam T, Ray J, Coulot D, Métivier L, Altamimi Z (2012) Strategies to mitigate aliasing of loading signals while estimating GPS frame parameters. J Geodesy 86:1–14. doi:10.1007/s00190-011-0487-6

Dach R, Hugentobler U, Fridez P, Meindl M (2007) Bernese GPS Software, Version 5.0. Astronomical Institute, University of Bern. http://www.bernese.unibe.ch/docs/DOCU50.pdf

Dong D, Fang P, Bock Y, Cheng MK, Miyazaki S (2002) Anatomy of apparent seasonal variations from gps derived site position time series. J Geophys Res Solid Earth 107(B4). doi:10.1029/2001jb000573. <Go to ISI>://WOS:000178917000010, n/a

Farrell WE (1972) Deformation of the earth by surface loads. Rev Geophy 10(3):761–797. doi:10.1029/RG010i003p00761. http://dx.doi.org/10.1029/RG010i003p00761

Freymueller J (2009) Seasonal position variations and regional reference frame realization. In: Drewes H (ed) Geodetic reference frames, international association of geodesy symposia, vol 134. Springer, Berlin/Heidelberg, pp 191–196. doi:10.1007/978-3-642-00860-3_30. http://dx.doi.org/10.1007/978-3-642-00860-3_30

Fu Y, Freymueller JT (2012) Seasonal and long-term vertical deformation in the Nepal Himalaya constrained by GPS and GRACE measurements. J Geophys Res Solid Earth 117(B16):B03407. doi:10.1029/2011JB008925

Fu Y, Freymueller JT, Jensen T (2012) Seasonal hydrological loading in southern Alaska observed by GPS and GRACE. Geophys Res Lett 39:L15310. doi:10.1029/2012GL052453

Kusche J, Schrama EJO (2005) Surface mass redistribution inversion from global GPS deformation and gravity recovery and climate experiment (GRACE) gravity data. J Geophys Res Solid Earth 110:B09409. doi:10.1029/2004JB003556

Letellier T (2005) Etude des ondes de marée sur les plateaux continentaux. http://books.google.de/books?id=_3UEOgAACAAJ

Longman IM (1962) A green's function for determining the deformation of the earth under surface mass loads, 1, theory. J Geophys Res 67:845–850. doi:10.1029/JZ067i002p00845

Moritz H, Mueller II (1987) Earth rotation: theory and observation, Earth: Rotation, Provided by the SAO/NASA Astrophysics Data System, New York, Unga. http://adsabs.harvard.edu/abs/1987erto.book.....M

Niell AE (1996) Global mapping functions for the atmosphere delay at radio wavelengths. J Geophys Res Solid Earth 101(B2):3227–3246. doi:10.1029/95JB03048. http://dx.doi.org/10.1029/95JB03048

Poutanen M, Koivula H, Ollikainen M (2002) On periodicity of gps time series. In: Adam J, Schwarz KP (eds) Vistas for geodesy in the new millennium. International association of geodesy symposia, vol 125. Springer, Berlin, pp 388–392

Saastamoinen J (1973) Contributions to the theory of atmospheric refraction. Bull Géod 107(1):13–34. doi:10.1007/BF02522083. http://dx.doi.org/10.1007/BF02522083

Seitz F, Krügel M (2009) Inverse model approach for vertical load deformations in consideration of crustal inhomogeneities. In: Drewes H (ed) Geodetic reference frames, IAG symposia, vol 134. Springer, pp 23–29. doi:10.1007/978-3-642-00860-3_4

Tapley BD, Bettadpur S, Watkins M, Reigber C (2004) The gravity recovery and climate experiment: mission overview and early results. Geophys Res Lett 31:9607–+. doi:10.1029/2004GL019920

Tesmer V, Steigenberger P, van Dam T, Mayer-Gürr T (2011) Vertical deformations from homogeneously processed GRACE and global GPS long-term series. J Geodesy 85:291–310 doi:10.1007/s00190-010-0437-8

Tregoning P, Watson C (2009) Atmospheric effects and spurious signals in GPS analyses. J Geophys Res Solid Earth 114:B09403. doi:10.1029/2009JB006344

Tregoning P, Watson C, Ramillien G, McQueen H, Zhang J (2009) Detecting hydrologic deformation using GRACE and GPS. Geophys Res Lett 36:15401. doi:10.1029/2009GL038718

van Dam T (1998) Modeling environment loading effects: a review. Phys Chem Earth 23:1077–1087. doi:10.1016/S0079-1946(98)00147-5

van Dam TM, Wahr JM (1987) Displacements of the earth's surface due to atmospheric loading - effects of gravity and baseline measurements. J Geophys Res 92:1281–1286. doi:10.1029/JB092iB02p01281

van Dam T, Wahr J, Milly PCD, Shmakin AB, Blewitt G, Lavallée D, Larson KM (2001) Crustal displacements due to continental water loading. Geophys Res Lett 28:651–654. doi:10.1029/2000GL012120

van Dam T, Collilieux X, Wuite J, Altamimi Z, Ray J (2012) Nontidal ocean loading: amplitudes and potential effects in GPS height time series. J Geodesy 86:1043–1057. doi:10.1007/s00190-012-0564-5

Wahr J, Molenaar M, Bryan F (1998) Time variability of the earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. J Geophy Res Solid Earth 103(B12):30205–30229. doi:10.1029/98JB02844. http://dx.doi.org/10.1029/98JB02844

Wahr JM, Swenson S, Zlotnicki V, Velicogna I (2004) Time-variable gravity from grace: first results. Geophys Res Lett 31:11501. doi:10.1029/2004GL019779. http://adsabs.harvard.edu/abs/2004GeoRL..3111501W

Williams SDP, Penna NT (2011) Non-tidal ocean loading effects on geodetic GPS heights. Geophys Res Lett 38:L09314. doi:10.1029/2011GL046940

Zou R, Freymueller JT, Ding K, Yang S, Wang Q (2014) Evaluating seasonal loading models and their impact on global and regional reference frame alignment. J Geophys Res Solid Earth 119:1337–1358. doi:10.1002/2013JB010186