ORIGINAL ARTICLE

Retrieving geophysical signals from GPS in the La Plata River region

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Abstract

Over the last few years, efforts to model short-term deformations of the Earth's crust have multiplied. Sudden water level rise can cause sporadic, but significant, motions in the solid Earth's surface. In this work, we address the problem of retrieving reliable estimates of the vertical displacement of a Global Positioning System (GPS) station located very close to the eastern shore of the La Plata River, during a strong storm surge event. Capturing sub-daily GPS displacements demands an elaborate processing strategy because several highly correlated parameters must be estimated simultaneously. We present a successful strategy that reduces the number of unknowns that have to be estimated simultaneously, by using an empirical model that describes the elastic response of the Earth's crust to the hydrological load variations. We incorporate this model into the observation equations so that, instead of estimating the station position, we estimate every epoch a single parameter of the empirical model, i.e., the empirical elastic parameter EEP, that is assumed to be a constant of the Earth's crust in the region of the GPS station. We verify that the estimated parameter agrees well with the value calculated from the CRUST 1.0-A model of the Earth's crust. The GPS receiver was tied to an external cesium clock, which allowed us to process the data according to two different strategies: (a) estimating the receiver clock error (Δt) as an epoch-wise free parameter, which is equivalent to ignoring the presence of the external clock, and (b) conditioning the variability of that estimate with a small a priori variance compatible with the external clock's variability. We find that, without having an external atomic clock, the estimation of all the parameters, i.e., the zenith tropospheric delay, Δt, and the EEP, worsens when the GPS station is affected by sub-daily vertical displacements.

Keywords Sub-daily effects · Clock modeling · GNSS vertical deformation · Storm surge · Crustal loading · La Plata River

Introduction

Transient and seasonal variations in the time series of Global Navigation Satellite Systems (GNSS) positions are generally attributed to the elastic response of the Earth's crust to non-tidal loading (NTL) (Blewitt 2001). The spatiotemporal mass variation of the ocean, the atmosphere, and the hydrological system is sources of these loading episodes, affecting mainly the vertical position (van Dam et al. 2001). Accurate position estimates are important, both for improving the materialization of the International Terrestrial Reference Frame (Collilieux et al. 2012) and for better understanding the geophysical processes underlying the phenomenon (Zou et al. 2014). A particular case of a non-tidal transient hydrological load, known as storm surge, occurs when wind drag causes an increase or decrease in the height of a water body with respect to the value predicted by the astronomical tide. Fratepietro et al. (2006) showed that large storm surges, with a typical duration of around 1 day, can change the vertical position of the affected area by up to a few centimeters.

Several studies have shown that NTL effects can be identified in the time series of coordinates derived from the Global Positioning System (GPS); for example, Virtanen and Mäkinen (2003) reported a vertical displacement

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of 0.11 m caused by 1 m of water loading; Nordman et al. (2015) showed a significant reduction in scattering in the time series of GPS-derived coordinates after accounting for NTL effects, hence suggesting an improvement in the accuracy of the obtained coordinates; and Geng et al. (2012) showed that displacements caused by a storm surge are of the same order of magnitude as the white noise present in GPS measurements, hence exposing the complexity of the problem.

Santerre (1991) and Santerre et al. (2017) provided the first in-depth studies on the propagation of errors in GPS measurements on the parameters to be estimated, such as zenith tropospheric delay (ZTD), receiver clock error (Δt), and the vertical coordinate of the station. He showed that, due to the dependence on the elevation angle, these estimates can partly compensate each other, obtaining a good adjustment of the observations but still have wrong estimates.

The estimation of positions with high temporal resolution, e.g., sub-daily, is intrinsically a problem with many degrees of freedom; the higher the desired temporal resolution, the greater the number of independent parameters to be estimated from the same data sample. The number of parameters depends on the actual situation, for example whether the receiver is moving. Since not exploiting the stability of certain unknowns reduces the reliability of the estimated parameters, strategies have been developed to reduce, or at least constrain, these without losing the temporal resolution of the estimated positions. An example of this is the approach used by Weinbach and Schön (2009), who a priori constrained the temporal variability in the estimation of Δt. More recently, Weinbach and Schön (2015) showed that sudden vertical displacements caused by an earthquake can only be captured by GPS observations if the receiver clock variability is properly modeled.

In this contribution, we tackle the problem of retrieving reliable estimates of the vertical displacement of a GPS station located very close to the La Plata River estuary during a strong storm surge event. For this purpose, we used an original approach based on: (1) describing the vertical displacement with an empirical model of the elastic response of the Earth's crust to storm surge variable loading, which allows a description of the vertical displacement with a temporal resolution of 1 h, which is the temporal resolution of the storm surge model, with the estimation of a single parameter that we call the empirical elastic parameter EEP, and (2) constraining a priori the variability of the estimated Δt, taking advantage of the stability of the atomic clock linked to the GPS receiver.

In the following section, we describe the GPS data processing software used in this work, including its modification to represent the vertical displacement of the observing station as an empirical model of the Earth's crust elasticity. Following this, we present the data used in this work and the strategies used for their processing. Then, we introduce the obtained results and discuss the differences between the parameters estimated using the different processing strategies that we applied. In closing, we summarize our conclusions.

Proposed approach

For processing the GPS data, we used the TOmographic Model for precise IOnospheric sounding and GNSS navigation (TOMION) v.2 software (Hernández-Pajares et al. 2003). TOMION is an in-house set of programs, originally written by Hernández-Pajares and further extended by Graffigna, which implements the Precise Point Positioning (PPP) method, introduced by Malys and Jensen (1990) and Zumberge et al. (1997). The program set computes a solution using either user points or control segment points. PPP has been widely used in the last decade, especially since Wübbena et al. (2005) demonstrated the possibility of solving carrier-phase ambiguities at the undifferentiated observation level. The core of TOMION is a Kalman filter that allows, in particular, the estimation, either in post-processing or real time, and in absolute or relative mode, of the station position coordinates simultaneously with Δt, the ZTD with its horizontal gradients, and carrier-phase bias. This last unknown, which includes the integer cycles ambiguity and phase instrumental delays depending on receiver and transmitter, is computed as a single one. Moreover, TOMION implements the option of carrier-phase ambiguity resolution by means of a synergistic combination of the geometric and ionospheric models (Hernández-Pajares et al. 2000 Juan et al. 2012), which has not been needed in this research. The GPS satellite orbits and high-rate clocks are fixed to the values provided by the Center for Orbit Determination in Europe (Dach et al. 2016). Corrections for the solid Earth tide, permanent tide, and solid Earth pole tide are applied, as described in Petit and Luzum (2010). The ocean tide loading is computed using the FES2004 model (Lyard et al. 2006). The atmospheric tide loading, caused by diurnal and semidiurnal constituents, is computed using the model of van Dam and Ray (2010). Dry and wet tropospheric delays are modeled according to Boehm et al. (2006), and ZTD horizontal gradients are mapped using the Chen and Herring (1997) gradient mapping function.

For this work, we modified the way in which TOMION estimates the receiver coordinates. We neglected the effect of the storm surge on the horizontal components of the position, since this is assumed to be three times smaller than the effect on the vertical (Geng et al. 2012). Therefore, the horizontal coordinates remained equal to their initial values, computed for the 2 days prior to the period studied in this work. To describe the variation

in the vertical coordinate of the station, we adopted an empirical elastic model based on the Boussinesq (1885) theory, as implemented by Bevis (2005), which assumes that the Earth's crust behaves as an elastic, homogeneous, and isotropic body, characterized by Young's modulus E and Poisson's ratio ν. We let e (east), n (north), and u (up) be the axes of the local coordinate system, the origin of which was set in the mean position of the station computed for the 2 days prior to the period studied. Then, the vertical coordinate of the station $u(t)$ at time t, due to the water height distribution $w(n, e, t)$ of the storm surge, is given as follows

$$u(t) = \frac{1 - \nu^2}{\pi E} P(t) \tag{1}$$

where $(1 - \nu^2)/(\pi E)$ is the EEP and $P(t)$ is the Newtonian potential created at the station location by the water height distribution of the storm surge:

$$P(t) = -\rho g \int_S \frac{w(n, e, t)}{\sqrt{e^2 + n^2}} \mathrm{d}e \mathrm{d}n \tag{2}$$

where S is the estuary region, ρ is the density of the water in the river (1003 kg m^{-3}), and g is the acceleration of gravity (9.8 ms^{-2}).

Provided that $w(n, e, t)$ can be computed from a given model, see next section, we modified the TOMION software to estimate only the EEP for the entire studied period according to the expressions in (1) and (2), instead of a 3-D position per epoch. In this way, we computed a single EEP value, together with one ZTD and one Δt value per epoch, thus drastically reducing the degrees of freedom of the model and, therefore, improving the reliability of the estimated parameters.

Data and processing strategies

Located at about 35°S, on the eastern coast of South America, the La Plata River estuary provides an excellent natural laboratory for the investigation of hydrological loading phenomena. With a total area of 35,000 km^2, it is one of the largest estuaries in the world. Its width varies from 220 km at its mouth to 2 km in its interior, but the water depth is only 515 m (Guerrero et al. 1997). Its hydrological regime is rather complex due to the horizontal and vertical geometry of the estuary, the influence of tidal waves coming from the Atlantic Ocean, its interaction with the atmosphere, and the seasonal variations of the rivers that converge into the estuary (D'Onofrio et al. 2012). The range of the astronomical tide is 1.4 m at its mouth and 0.4 m in its interior. Storm surges can cause the water

level to rise above, or fall below, the astronomical tide (positive/negative storm) by about 1 m, with a historical maximum of 3.89 m, which happened in 1989 (D'Onofrio et al. 2008).

The time period analyzed in this study spans from March 16, 2016, at 0 UT (day of year [DOY] 76) to March 21, 2016, at 24 UT (DOY 81). During this period, a strong positive storm surge developed, raising the water level of the river from about 0.4 m below the astronomical tide (at DOY 77.92) to about 2 m above the same reference (at DOY 78.88), after which the level dropped for 3 days, until it resumed the regular astronomical tide regime (at DOY 81.75).

The water height distribution, $w(n, e, t)$, created by the storm surge, was computed using the empirical model developed by Oreiro et al. (2018), which is based on the records of seven tide gauge stations, the locations of which are shown in Fig. 1 (top panel). Also, in Fig. 1 (bottom panel), two lines are shown, one (purple) representing the time evolution of the Newtonian potential at GNSS station Montevideo, which resulted from the integration of the storm surge water height distribution according to the expression in (2), and the other
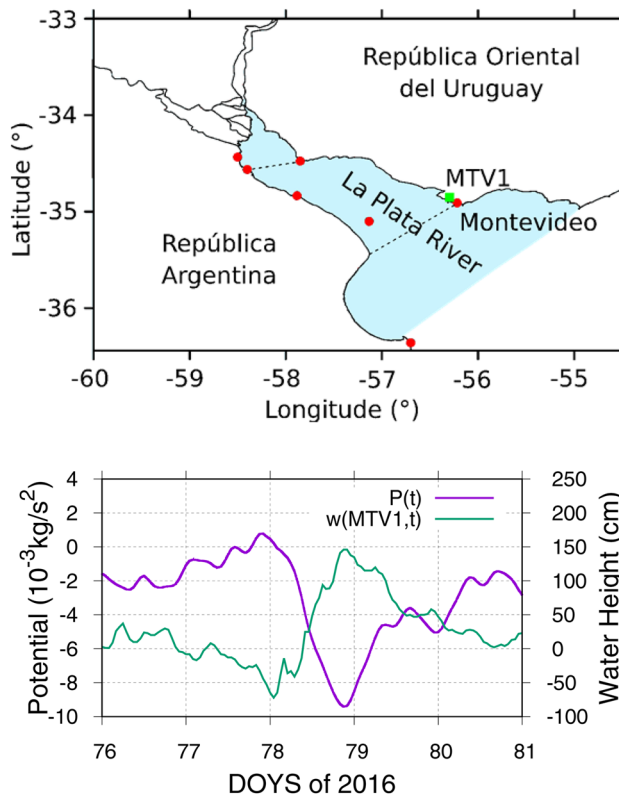
Fig. 1 Location (top) of the tide gauges indicated by red dots, used to compute the storm surge water height distribution, and the MTV1 GNSS station indicted by green square, and the time evolution (bottom) of the potential at the MTV1 GNSS station and water height caused by the storm surge

line (green) showing the time evolution of the storm surge water height, calculated by subtracting the astronomical tide from the height of the water recorded by a tide gauge located very close to the GNSS station.

GPS observations were obtained from MTV1 (56.1763°W, 34.9136°S), a core station of the International GNSS Service's global network. MTV1 operates a dual-frequency P-code GNSS receiver with a choke ring antenna. Also, the receiver is tied to an external cesium clock. Data records are given with a sampling rate of 30 s.

In order to investigate the effect that reducing the degrees of freedom of the problem exerted on the estimation of the different parameters, and taking advantage of the fact that the Montevideo GNSS receiver is tied to an external cesium clock, we estimated the EEP and ZTD by applying two different strategies to handle the Δt unknown:

(a) constraining a priori the Δt variability within a standard deviation of 2 10–12 s/epoch (equivalent to 0.0625 cm/epoch), which is compatible with the relative frequency stability of about 7×10^{-14} typical for a cesium clock (Krawinkel and Schön 2016); and.

(b) estimating an independent Δt value per epoch, which is equivalent to ignoring the existence of the external cesium clock and assuming that the receiver has a conventional quartz clock. This is also known as memory-free estimation, which corresponds to assigning an infinite process noise to Δt.

Results

In this section, we first discuss the effect that the aforementioned processing strategies had on the EEP estimate, and then the influence of considering or not considering the storm surge model had on the estimated parameters EEP, Δt, and ZTD. In the following, strategy (a) is referred to as 'constrained' and strategy (b) as 'white noise.'

Strategies (a) and (b) led to the estimation of quite different EEP values: 2.88×10^{-3} GPa^{-1} for constrained and 1.82×10^{-3} GPa^{-1} for white noise. To determine which of these two resultant values was more plausible, we relied on the CRUST 1.0-A model (Laske et al. 2013). Mostly based on seismic data, this model describes the Earth's crust and upper mantle by means of global grids of $1° \times 1°$ (latitude × longitude) and nine layers in depth. For each grid point, the model provides the velocities of the primary and secondary seismic waves, the layer density, and the layer thickness. These parameters allow the computation of Young's modulus E and Poisson's ratio ν (Mavko et al. 2009), which are shown in Fig. 2. We have obtained the following mean values for the studied region: $E = 97.8$ GPa and $\nu = 0.28$, from which emerges an EEP
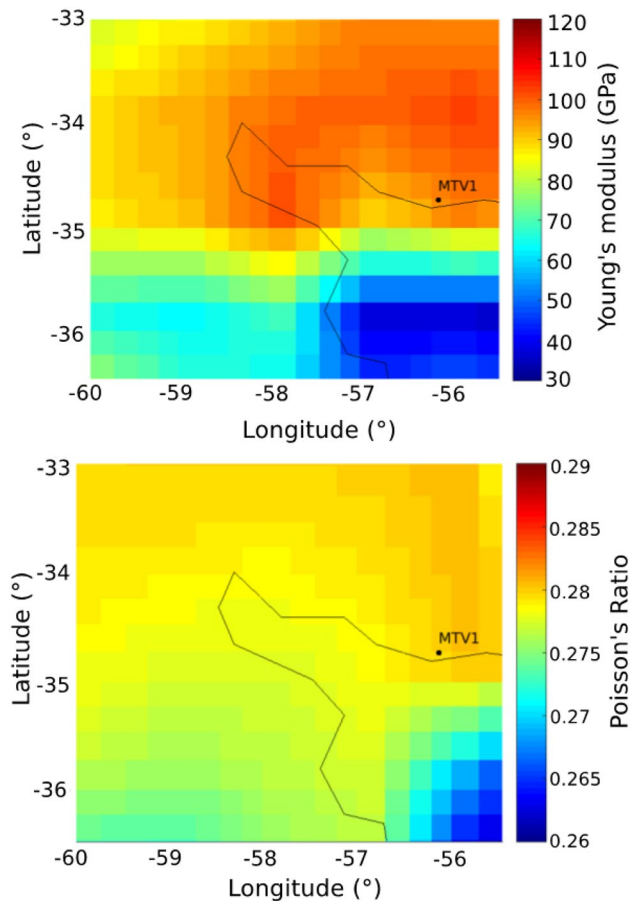
Fig. 2 Young's modulus (GPa; top panel) and Poisson's ratio (bottom panel), derived from the CRUST 1.0-A model
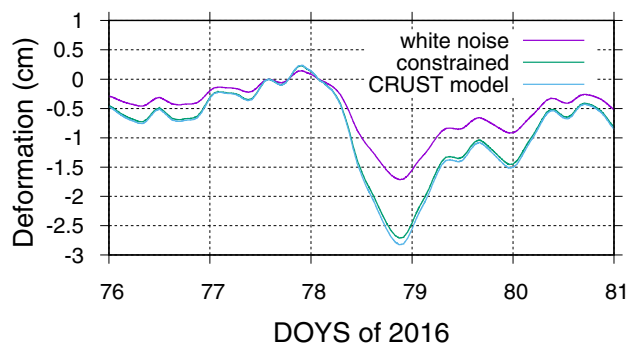
Fig. 3 Variation in the vertical coordinate of the station

value of 3.00×10^{-3} GPa^{-1} [see (1)], hereafter referred to as the 'model' EEP. The good agreement between the constrained and model EEPs or, equivalently, the disagreement between the white noise and the model EEP, reinforces the idea that the white noise strategy produces a poor estimate of the EEP.

Figure 3 shows the variation in the vertical coordinate of the station, given by (1), in connection with the known potential $P(t)$. The three curves in this figure include those of the CRUST model, and the ones computed using the estimated EEP, for both the constrained and white noise variations. It can be seen that, for the entire period analyzed in this work, the constrained curve closely follows that of the model, with a maximum deviation of about 0.1 cm at DOY 78.8. On the other hand, the white noise curve deviates by up to 1 cm from the model's, especially following the triggering of the storm surge.

Let us now discuss the influence that inclusion of a model for the vertical deformation, as detailed above, may exert on the estimated parameters and on the correlation between the vertical deformation, Δt, and ZTD. To address this, we reprocessed the GPS data under identical conditions to the previous processing, but ignored the storm surge event. In practice, this was done by keeping the vertical coordinate of the station fixed to the value computed for the 2 days prior to the studied period. In this way, we obtained four different estimates of Δt and four of the ZTD, including the ones obtained from the previous processing, where the EEP was implemented and estimated, referred to as Δt and ZTD EE-modeled, which stands for 'empirical elastic', and

either constrained or white noise, which have been labeled as EEPCT and EEPWN, respectively, and the ones from the reprocessing, referred to as Δt and ZTD fixed, and either constrained or white noise, which have been labeled as FIXCT and FIXWN. All four processing strategies are summarized in Table 1.

The next step consisted of taking the estimates that emerged from the original processing (i.e., the reference values) and comparing them against the estimates from the reprocessing, under the premise that the differences between them must reflect the deficiencies (1) of the vertical displacement model or, explicitly stated, (2) of ignoring the action of the storm surge on the vertical coordinate of the station. The obtained results are summarized in Fig. 4. The four panels in this figure show differences in the fixed estimate minus EE-modeled estimate (FIX-EEP), plotted as $\delta\Delta t$ and δZTD. The top row corresponds to differences in Δt, which are multiplied by the speed of light in vacuum and therefore expressed in units of length, and the bottom row illustrates differences in ZTD. The left column corresponds to the constrained strategy, and the right column illustrates the white noise strategy. Figure 4 clearly shows that ignoring the vertical displacement of the station generated errors in the estimated parameters that, in this case, manifest as an underestimation of Δt and an overestimation of ZTD. The figure also shows that the error signature looks sharper when the constrained strategy is used but is less clear when the white noise strategy is used. Complementary reasoning leads to the idea that the vertical displacement caused by the storm surge would be better recovered when an external cesium clock is available at the GNSS station, and its performance is properly accounted for in the data processing.

Table 1 Four processing strategies carried out in this research

Vertical coordinate	Δt	
	Constrained	White noise
EEP estimated—implemented	EEPCT	EEPWN
Fixed vertical coordinate	FIXCT	FIXWN

Fig. 4 Differences in fixed minus EE-modeled Δt (top row) and ZTD (bottom row), using the constrained (left) and white noise (right) strategies
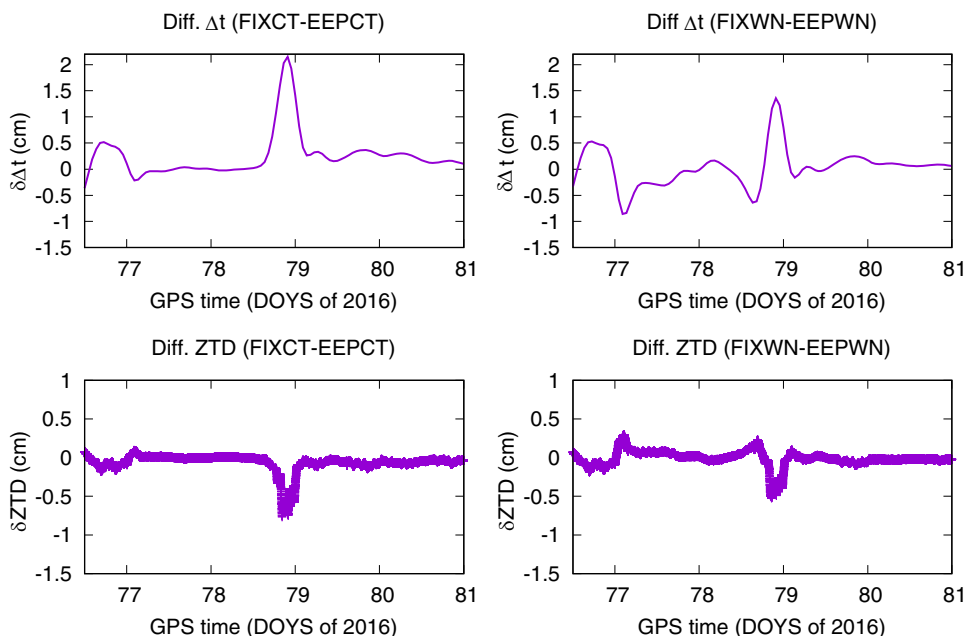
Conclusions

We have shown that the elastic response of the Earth's crust, resulting from a short-term loading event, can be successfully accounted for using an empirical storm surge model for the La Plata River. This model includes the time-dependent Newtonian potential to describe the variable mass load. By means of adjusting only one elastic parameter, instead of the vertical deformation for each time epoch, we were able to estimate a sub-daily displacement. This signal is difficult to capture in routine GPS processing because, for short-period signals, the correlation of the height with the ZTD and the Δt is such that the effect of the event is shared among them.

However, we determined that when the GPS receiver clock has high stability, constraining its stochastic process can reduce the correlation with the station height and, thus, allows better recovery of the loading caused by the storm. We captured an empirical elastic parameter, in good agreement with the CRUST 1.0-A model, when the atomic clock model was also considered, recovering a deformation that only differed from the model by 0.1 cm. Without constraining the receiver clock variability, however, the difference between the recovered signal and the model was of the order of 1 cm. Clock modeling provides the potential to achieve a more stable and reliable solution for the ZTD, and the Δt itself, over the days of the storm surge.

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