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Non-Tidal Ocean Loading Correction for the Argentinean-German Geodetic Observatory Using an Empirical Model of Storm Surge for the Río de la Plata

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Abstract—The Argentinean-German Geodetic Observatory is located 13 km from the Río de la Plata, in an area that is frequently affected by storm surges that can vary the level of the river over ±3 m. Water-level information from seven tide gauge stations located in the Río de la Plata are used to calculate every hour an empirical model of water heights (tidal + non-tidal component) and an empirical model of storm surge (non-tidal component) for the period 01/2016–12/2016. Using the SPOTL software, the gravimetric response of the models and the tidal response are calculated, obtaining that for the observatory location, the range of the tidal component (3.6 nm/s^2) is only 12% of the range of the non-tidal component (29.4 nm/s^2). The gravimetric response of the storm surge model is subtracted from the superconducting gravimeter observations, after applying the traditional corrections, and a reduction of 7% of the RMS is obtained. The wavelet transform is applied to the same series, before and after the non-tidal correction, and a clear decrease in the spectral energy in the periods between 2 and 12 days is identify between the series. Using the same software East, North and Up displacements are calculated, and a range of 3, 2, and 11 mm is obtained, respectively. The residuals obtained after applying the non-tidal correction allow to clearly identify the influence of rain events in the superconducting gravimeter observations, indicating the need of the analysis of this, and others, hydrological and geophysical effects.

Key words: Non-tidal ocean loading, superconducting gravimeter, storm surge model, Argentinean-German Geodetic Observatory, Río de la Plata.

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1. Introduction

The Argentinean-German Geodetic Observatory (AGGO) is a joint initiative between the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) from Argentina and the Bundesamt für Kartographie und Geodäsie (BKG) from Germany. The observatory is strategically situated in the Southern Hemisphere, which makes it a key piece in the Global Geodetic Observing System (GGOS), and has several geodetic techniques: GNSS, VLBI, SLR, absolute gravity, and Superconducting Gravity (SG). Since AGGO is located near the Rio de la Plata, the water height variations that occur in the river affect the observatory. This variation can be considered through the ocean loading, which is a geophysical effect that affects the observations of all the mentioned geodetic techniques, and can be decomposed in a tidal and non-tidal component (Petrov 2015). The high sensitivity of the SG is a very useful tool for testing and validating correction models related to this effect (Virtanen 2004), and the gravity observations of the SG can be used to test corrections for other co-located geodetic observations such as GNSS, VLBI, and SLR (Virtanen and Mäkinen 2003). The superconducting gravimeter SG038 was installed in AGGO on December 16th, 2015 and has made uninterrupted gravity observations since then (Wziontek et al. 2016; Tocho 2016). The traditional processing of SG data usually considers the atmospheric mass changes, the Earth's tides, the pole tide, and the ocean tide loading. Then, the residuals are analyzed to obtain information about other geophysical signals, such as water storage changes or non-tidal ocean loading. In recent years, there has been increased interest on the effects of the non-tidal variation in ocean loading, including ocean circulation and special

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occasions such as storm surges (Nordman et al. 2015). In this paper, we analyze the incidence of the non-tidal ocean loading at AGGO, which is caused by seafloor pressure variations that relate directly to the water response to atmospheric pressure and wind stress (Geng et al. 2012) and by direct mass effects. This loading can affect the gravity observations in the microgal range, and several mm in the vertical and horizontal displacements. Fratepietro et al. (2006) showed that a storm surge of 2 m in the southern North Sea produces vertical displacements up to −30 mm and increases of gravity up to 80 nm/s^2 in the coastal areas. Geng et al. (2012) studied the loading effects caused by a strong storm surge in the southern North Sea on 2007, and estimated the loading displacements at coastal stations on the order of 40 mm in the vertical direction and over 5 mm in the horizontal direction. Nordman et al. (2015) analyzed the influence of non-tidal loading of the Baltic Sea using GNSS coordinates, and showed that the loading effects should be considered in geodetic measurements, especially near the coast. Virtanen and Mäkinen (2003) calculated that a uniform layer of water covering the whole Baltic Sea increases the gravity in Metsähovi geodetic observatory by 31 nm/s^2 per 1 m of water and the vertical deformation by −11 mm. AGGO is located 13 km from the Río de la Plata, in an area that is frequently affected by storm surges that can vary the level of the river over ±3 m.

The Río de la Plata is one of the biggest estuaries of the world (Fig. 1) with approximately 35,000 km^2, a water depth between 5 and 15 m (Guerrero et al. 1997), and a width variation from 2 to 220 km. According to Comisión Administradora del Río de la Plata (1989), D'Onofrio et al. (1999) and Dragani and Romero (2004), three regions can be identify in the river: the inner region, the middle region, and the exterior region (Fig. 1).

The hydrological regime of the Río de la Plata is highly influenced by the tidal wave progressing from the Atlantic Ocean, and the circulation is sensitive to the complicated geometry and bathymetry of the estuary (Simionato et al. 2004a). The astronomical tide in the Río de la Plata is mixed mainly semidiurnal type (SHN 2017), and the range is about 1.44 m at the mouth, but in the interior areas, it can reach 0.40 m (D'Onofrio et al. 2009). The main semidiurnal constituent (M2) takes about 12 h to reach the interior limit, so a full cycle of the M2 component is present at every moment inside the Río de la Plata (D'Onofrio et al. 2009, 2010; Simionato et al. 2004b). The astronomical tide is affected by meteorological forcing and by seasonal variations of the river. Meteorological forcing produces extreme high tides (positive storm surge) or extreme low tides (negative storm surge) according to the direction and intensity of the wind. Positive and negative storm surges are defined by the difference between the observed levels and the corresponding predicted tide, and in the region, they have been studied intensively by several authors (e.g., Balay 1961; D'Onofrio and Fiore 2003; D'Onofrio et al. 2008; Escobar et al. 2004; Campetella et al. 2007; Fiore et al. 2009, Pousa et al. 2013) whom indicate that positive and negative storm surges are more harmful if they coincide with a high-water period or a low one, respectively. The inner and middle regions of the Río de la Plata usually register higher storm surges values than the exterior region due to the funnel like shape of the river. The highest positive surge measured at Buenos Aires city occurred on April 15, 1940 when the water level up to 4.44 m over tidal datum, and the surge was 3.24 m (D'Onofrio et al. 2008). The water height value is the maximum level recorded since the beginning of systematic tidal measurements in 1905. On the contrary, the lowest observed level occurred on 29 May 1984 (−3.66 m), and on that occasion, the surge was −4.61 m. In opposition to the astronomical tide, that allow identifying regions of high tide and low tide simultaneously in the river, the storm surge can generate an increase in water level over the whole river at the same time.

In this study, we compare the gravimetric response of the non-tidal ocean loading model from the Río de la Plata with the residuals of the SG at AGGO, for the period 01/2016–12/2016, and show the improvement in terms of reduction of RMS of gravity residuals when subtracting the non-tidal gravimetric response from the river. We also compare tidal vs non-tidal components to identify which component is more influent in the Río de la Plata. With the purpose of obtaining the gravimetric response of the river, water-level information from seven tide gauge stations located in or nearby the Río de la Plata are used to calculate an empirical model of water heights (tidal + non-tidal component) and an

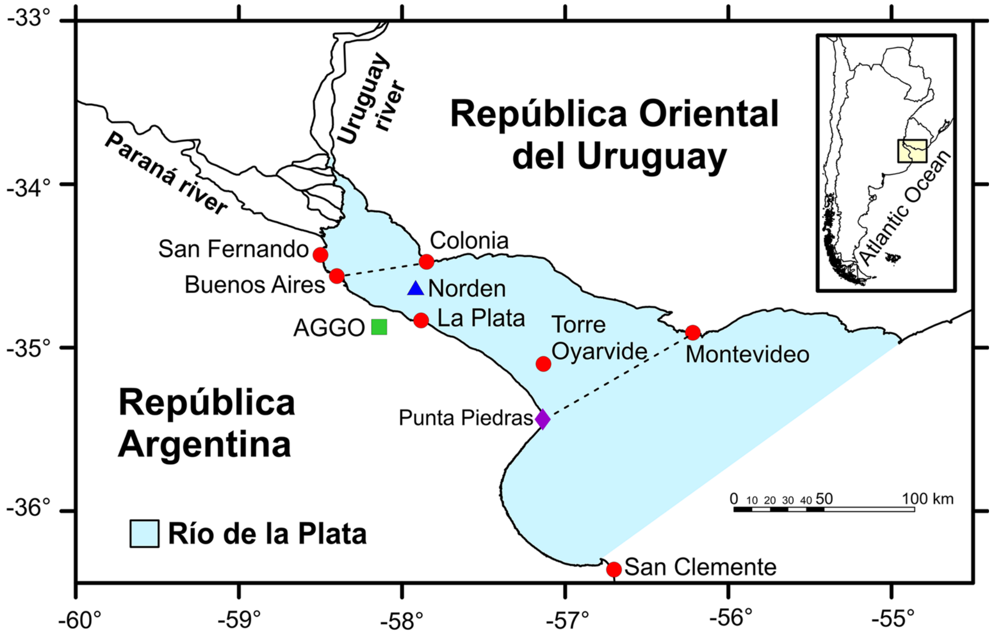

Figure 1
Geographical location of Rio de la Plata estuary, and delimitation of the inner, middle, and outer regions. Tide gauge stations used for the empirical models are represented by *dots*, AGGO location is shown with a *square*, and Norden station, used for the validation of the models, is marked with a *triangle*

empirical model of storm surge (non-tidal component). Then, using the SPOTL software (Agnew 2012), the gravimetric response of each model is calculated for the AGGO location, and compared with the gravimeter residuals after applying corrections for Earth tide, atmospheric effects, pole tide, and ocean tide loading. Using the same software, the vertical and horizontal displacements are also calculated for the indicated period. Although several authors have shown the relation between the storm surges and the SG data (Fratepietro et al. 2006; Boy et al. 2009; Virtanen and Mäkinen 2003), the aim of this work is to quantify the influence of this geophysical signal for the newly installed SG038 and for the co-located instruments at AGGO.

2. Data

2.1. Superconducting Gravimeter Data

The superconducting gravimeter (SG) is the most sensitive and stable spring-type relative gravimeter, where the mechanical spring is replaced by a magnetic levitation of a superconducting hollow sphere in the field of superconducting, persistent current coils (Goodkind 1999; Hinderer et al. 2007). The SG shows only a low and almost linear instrumental drift, providing unequaled long-term instrumental stability, and enables the highest sensitivity. The levitated sphere as the basic element of the sensor is moved from its initial position by gravity changes or inertial accelerations. The displacement is detected by a capacitance bridge and compensated by the feedback force generated by an additional superconducting coil. The required voltage represents the gravity signal and is recorded by a high precision digital voltmeter.

The time series acquired by SG038 at AGGO with 1-s temporal resolution was filtered and reduced to a sample rate of 10 s to eliminate microseismic background noise. The signal was calibrated using a scale factor of -736.5 nm/s^2/V as determined from comparisons with numerous absolute gravimeter measurements at the previous location of the instrument in Concepcion, Chile. A time lag of the whole system including the analogue low-pass filter of −8.3 s was applied as determined from step response experiments (Antokoletz et al. 2017). During preprocessing, disturbances and one step due to a planned power interruption on November 1, 2016 were corrected after removal of a first tidal model (Antokoletz et al. 2017) and atmospheric effects using the local air pressure record and a nominal admittance factor of 3.0 nm/s^2/hPa. Both effects were restored afterwards and the series was further down-sampled to 1 h resolution. Atmospheric effects were now corrected based on the numerical weather model ICON of the Germany Weather Service (DWD) as provided by the atmospheric attraction computation service Atmacs of BKG (Klügel and Wziontek 2009). The local air pressure record was used to improve the temporal resolution of this correction. By this, atmospheric effects are eliminated more efficiently and independently from the measured gravity time series, especially during extreme weather events. This is important as the gravity effects under consideration are related to such situations.

An extensive tidal analysis utilizing the updated and enhanced versions of ETERNA V60 (Schüller 2015), partitioning 49 wave groups and including a hypothesis-free modeling of degree three constituents of the tidal potential, was performed. In this way, the effects of solid Earth tides and ocean tide loading starting from diurnal tides were removed, leaving almost no energy in the tidal spectrum. The fortnightly and monthly tides are with amplitudes of less than 1.5 nm/s^2 extremely low at the latitude of the station and cannot be analyzed from a 1-year record. Instead, the tidal model was completed based on the non-hydrostatic model of Dehant et al. (1999), including annual and semiannual components. The gravity effects caused by the variable Earth rotation and changes of its rotational axis (pole tide and length-of-day variations) were corrected based on the EOP C04 series of IERS. Since the instrumental drift of SG038 is not determined so far by absolute gravity observations, an overall linear trend of 184 nm/s^2/a was removed from the residual time series, which includes possible long-term gravity changes. The remaining fluctuations cover a range of 80 nm/s^2.

2.2. Sea-Level Data

Digital sea-level records from December 2015 to December 2016 at five tidal stations belonging to República Argentina and two to República Oriental del Uruguay were used in this work to obtain the empirical models of water level and storm surge (Fig. 1). Table 1 shows the location of the stations and the sampling interval of the measurements. The Argentinian stations are controlled and operated by the Argentinian Servicio de Hidrografía Naval and the tide gauges Colonia and Montevideo, located in Uruguay, are operated by Administración Nacional de Puertos de Uruguay and by Comisión Administradora del Río de la Plata (CARP), respectively. Besides the mentioned tide gauges, CARP's Norden station is used to validate the empirical models (Table 1; Fig. 1). All sea-level data were processed following D'Onofrio (1984), and since the needed sampling interval of the tide gauges data for the empirical models is 5 min, the series that have a bigger sampling interval are interpolated using a cubic spline interpolation. All observed heights are referred to the mean sea level (MSL) using the available information from the tidal datum of each tide gauge.

Storm surge models were developed using storm surge series for each location. These series were derived from the sea-level data by subtracting the astronomical tide prediction to the observations. The amplitudes and epochs used for each prediction were

Table 1

Location and sampling interval of the water-level gauges used for the empirical models (*) and for the validation of the models

Location	Latitude	Longitude	Sampling interval (min)
San Fernando*	−34°26′00″	−58°30′00″	60
Buenos Aires*	−34°33′45″	−58°24′00″	60
La Plata*	−34°50′00″	−57°53′00″	60
Torre Oyarvide*	−35°06′00″	−57°08′00″	60
San Clemente*	−36°21′30″	−56°42′03″	60
Colonia*	−34°28′30″	−57°51′00″	6
Montevideo*	−34°54′30″	−56°13′03″	5
Norden	−34°37′55″	−57°55′40″	1

The asterisks indicate locations used in the empirical models provided by the Argentinean Servicio de Hidrografía Naval.

2.3. Satellite Altimetry data

Corrected Sea Surface Heights (CorSSH) from Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) (http://www.aviso.oceanobs.com) are used for the period 12/2015–11/2016. For this period, 1319 CorSSH observations registered with Jason-2 (J2) altimeter were obtained for the Río de la Plata (Fig. 3). Due to the launch of Jason-3 altimeter, J2 modified its orbit in October 2016 to an intermediate orbit, obtaining CorSSH of the original orbit until October 2016, and CorSSH of the intermediate orbit from October 2016 to November 2016. This modification favors the validation of the models, since it allows to obtain a better spatial distribution of the data. Following Oreiro et al. (2016), and to make comparable the CorSSH data with the empirical models, the ocean tide (OT) and the dynamic atmospheric correction (DAC), provided in the CorSSH files, were restored to the CorSSH data without modifying the rest of the corrections. Since global ocean tide models do not have good performance in the Río de la Plata, for the comparison of the storm surge models, astronomical tide obtained from the SEAT model (D'Onofrio et al. 2012) was subtracted from the CorSSH with the restored OT and DAC corrections. In both cases, the CorSSH were referred to the mean sea level, which is the datum of the empirical models.

3. Methodology

3.1. Calculation of the Gravimetric Response at AGGO

For the ocean loading calculation of the Río de la Plata, the "nloadf" package of the SPOTL software (Agnew 2012) is used, since it has been developed for this kind of loading calculation. This package allows obtaining the gravity response of a regular grid for a given position, where the height of the water must be stored for each cell of the grid. As the variation of the water height analyzed in this paper is not only harmonic, this calculation must be performed for each time step for the entire period, resulting in a time series of gravimetric response of the Rio de la Plata at AGGO location. A regular grid of 0.005° × 0.005° (approximately 500 m × 500 m) that covers the entire Río de la Plata is generated between the coordinates 54.925°W–58.5°W and 33.8°S–36.38°S. The cells are classified in "wet" considering whether they are covered by water or "dry" otherwise. The grid has 370,172 cells (716 columns × 517 rows), where 125,304 cells correspond to "wet" and 244,868 cells correspond to "dry". Each "dry" cell is assigned to zero in the grid, while for each "wet" cell, the water height (or storm surge) is calculated every hour, for the entire period. The Gutenberg-Bullen Earth model A was used for the convolution through the selection of the Green's functions included in the "nloadf" package that were computed from Farrell (1972). The density of the water used is 1000 kg m^{-3}, and the origin of the coordinate system for the computation is assumed to coincide with the center of mass of the solid Earth.

3.2. Calculation of the Water and Storm Surge Heights

From the observed water level in the Río de la Plata, two empirical models of the water height of the river and two empirical models of storm surge are developed. One of each kind of the models uses information from seven tide gauge stations inside or nearby the river (Fig. 1), and the other two models use exclusively the observations of the station closest to the observatory (La Plata). These last models are developed to compare the gravimetric responses, and evaluate the differences between using all available water height information and the observations from the closest station to the observatory.

The propagation of the observed water level and the storm surge through the river is carried out considering the advance of the M2 tidal constituent provided by the cotidal chart calculated by D'Onofrio et al. (2012). Figure 2 shows the agreement of the high water and low water between the seven stations that provide information, by adding the time lag according to the information of the mentioned cotidal

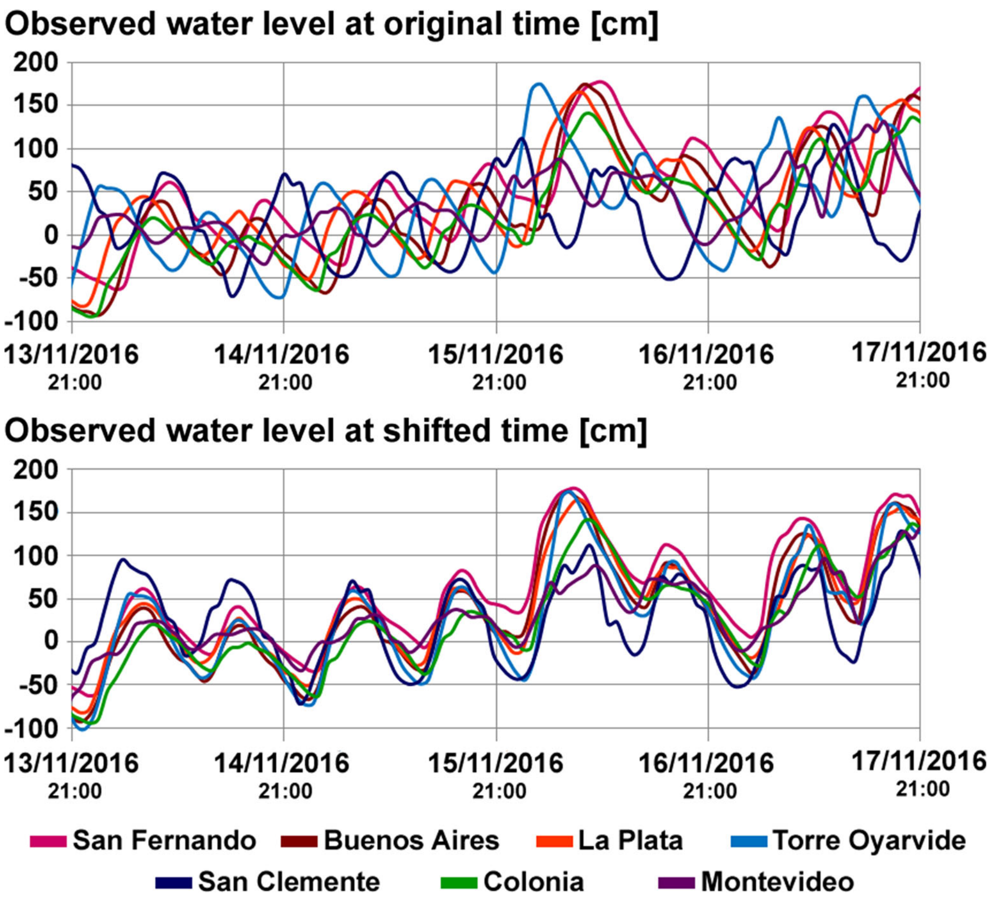

Figure 2

Agreement of high tides and low tides between the seven tide gauges used for the development of the empirical models. The *upper figure* shows the water levels at their original time, and the *lower figure* shows the water levels with the shifted time, according to the M2 cotidal chart and the speed of the constituent

chart, and the speed of the M2 constituent (28.9841042°/h).

To determine the height of the water (or the storm surge) considering the advance of the tide in the river, the M2 cotidal chart is use to classify the "wet" cells of the grid. The cotidal chart indicates the regions, where the epoch of the tide (high tide, low tide, etc.) occurs at the same time. A 5-min time classification is applied to the cells, determining regions, where the epoch of the tide occurs at the same time. Figure 3 shows this classification, allowing to easily identify the curvature of the M2 cotidal chart. The cells which are located in the same region as La Plata station are classified as 0 min, defining the origin or time reference. Then, the cells of the regions located towards the outer edge of the river are classified by increasing (+) the time offset in 5-min intervals, while the cells of the regions located towards the inner edge of the river are classified by reducing (−) the time offset by the same amount. With this procedure, all cells are classified according to the time lag to La Plata tide gauge station, and the value assign to a cell indicates the time needed to obtain the tide epoch of that cell in La Plata station.

3.3. *Empirical Models Using Observations from the Closest Tide Gauge Station to AGGO*

Using the classification of the time lag of the cells to La Plata station, an empirical water height model

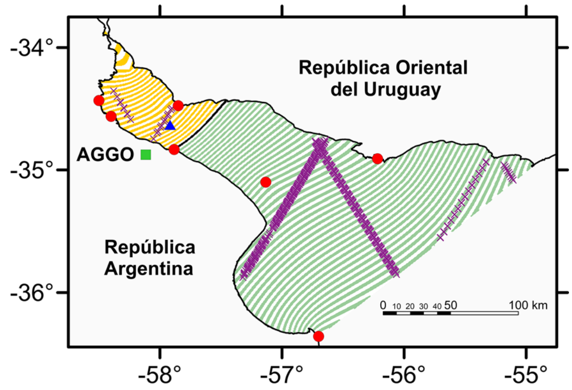

Figure 3
CorSSH data obtained in the Río de la Plata for the period 12/2015–11/2016 are shown with *crosses*. The AGGO location is marked with a *square*, Norden station with a triangle and the seven tide gauges used for the empirical models are marked with *circles*. The *black line* crossing the river is indicating the region of 0-min time frame, corresponding to the classification of the cells. From the *black line*, towards the outer edge of the river, the *lines* indicate the regions that increase in time steps of 5-min intervals, and towards the inner part of the river, the *lines* indicate the regions decreasing in time of 5-min intervals

(EWH_LaPlata) and an empirical storm surge model (ESS_LaPLata) are developed, using only observations from this station. For this, all cells classified as zero time lag at a particular time step are assigned to the corresponding water height (storm surge) at station La Plata. The remaining cells are assigned to the height (storm surge) observed at station La Plata at the time corresponding to the time step plus the time lag obtained from the classification described above. Although this model is an extremely simplified approximation of the water height (storm surge), since it does not consider the variation of the meteorological conditions in the whole river nor the difference of height between the shores, among other things, its calculation is straightforward as it uses information from a single tide gauge station only. In addition, since La Plata station is closest to AGGO, the observations of this station are of great importance to describe the water height of the cells closest to the observatory.

3.4. *Empirical Models Using Observations from 7 Tide Gauge Stations*

To obtain a more precise description of the water height and storm surge in the Río de la Plata, an empirical water height model (EWH_7TG) and an empirical storm surge model (ESS_7TG) are developed using information from six tide gauge stations around or within the Río de la Plata, and a station located near the outer edge of the river (Fig. 1). To obtain the height of the water (storm surge) of a cell at a particular time, different calculations are developed according to their relative location related to the tide gauges. In regions where the cells coincide with the location of a tide gauge station, the heights (storm surge) of these cells are taken over from the corresponding station. For the rest of the cells, the water height (storm surge) is calculated for respective time, taking the number of neighbor stations into account: if the cell is located between two stations or if the cell is located between a station and a border of the river. In the latter case, the height of the water (storm surge) is assigned in the same way described before, shifting the observed values at the nearest station in time. The water height of the cells between two stations is obtained using the information of the stations involved, following the procedure described below:

1. The values from the stations closest to the analyzed cell are repositioned considering the displacement of the M2 constituent, represented by its cotidal chart, to approximately match the time of occurrence of the high water and the low water.
2. A linear interpolation of the time-shifted series of the stations is performed, to obtain an interpolated series for each region between the stations. For example, if there are nine regions between the stations involved, then nine intermediate series must be obtained.
3. Finally, the intermediate series are time-shifted according to the time lag between each region and the stations, to use an interpolated series in each region.

Although this methodology allows to model the progress of the high and low tides along the river, the calculation of the time offset and its subsequent interpolation is done separately among the Argentinian stations (San Clemente, Torre Oyarvide, La Plata, Buenos Aires, and San Fernando), and the stations at the Uruguayan shore line (Montevideo, Colonia) as the height of the water (storm surge) is not the same at both margins. In this way, a model is obtained for each of the shorelines of the river. Then, the water height of the cells in the same region is calculated through a linear interpolation, using the calculated values from both shorelines, taking into account the distance to each side.

3.5. Validation of the Empirical Models

The empirical models developed in this work aim to obtain the gravimetric response generated by tidal and non-tidal ocean loadings and by non-tidal ocean loading only, through the modeling of water height and storm surge throughout the Rio de la Plata. Although the models generated are not intended to describe the water levels of the river in detail, the heights that they provide are expected to be accurate enough to obtain an adequate gravimetric response. To validate the models and to obtain a statistical error of the calculated heights of the water, CorSSH from J2 altimeter and observations of the tide gauge Norden, which was not used for the development of empirical models, are used (Fig. 3). The water heights (storm surge) of the empirical models are compared with the water heights (storm surge) observed in Norden and the CorSSH, and the standard deviation of the differences is calculated to obtain a statistical estimate of the error of each model.

By the above-described empirical models, the gravimetric response generated by tidal and non-tidal ocean loadings, or by non-tidal ocean loading only, should be obtained from the water height and storm surge distribution throughout the Rio de la Plata. Although the created models are not intended to describe the water level of the river in detail, the heights that they provide are expected to be accurate enough to infer the gravimetric response precisely enough. To validate the models and to obtain a statistical uncertainty estimate for the calculated grids, CorSSH values from J2 altimeter and observations from the tide gauge Norden, which were not used for the development of empirical models, are used (Fig. 3). The water heights (storm surge) of the empirical models are compared with the observations at Norden and with the CorSSH values, and the RMS of the differences is calculated to obtain a statistical estimate of the errors of each model.

4. Results

4.1. Empirical Models

Figure 4 shows for February 24th, 2016 00:00, the water heights and the storm surge of the empirical models using observations from seven tide gauge stations and from La Plata station, allowing to identify some differences between the models. For example, in the models obtained using La Plata data only, regions of cells with the same time interval have the same height of the water, or storm surge, throughout the entire region. On the other hand, in the models that use information of the seven tide gauges, the height of the water or the storm surge changes within the same region of cells with the same time interval. In addition, the empirical storm surge model obtained from La Plata observations shows negative values that do not agree with the storm surge from the tide gauges of the exterior region of the river.

4.2. Validation of the Empirical Models

Figure 5 shows the differences between CorSSH data and the empirical water height models EWH_7TG and EWH_LaPlata and the differences between the CorSSH storm surge and the empirical storm surge models ESS_7TG and ESS_LaPlata. The biggest differences visible in Fig. 5 correspond to the models based on the observations at the La Plata station only. These discrepancies can also be characterized in the standard deviation of the differences of each model, where for the water height models, the standard deviation is 13.3 and 21.9 cm for EWH_7TG and EWH_LaPlata, respectively, and for the storm surge models, the standard deviation of the differences is 13.1 and 24.4 cm for ESS_7TG and ESS_LaPlata, respectively.

The standard deviation of the differences of the models using Norden station data is 4.4 and 7.4 cm for the water height models EWH_7TG and EWH_LaPlata, respectively, and 5.9 and 12.2 cm for the storm surge models ESS_7TG and ESS_LaPlata,

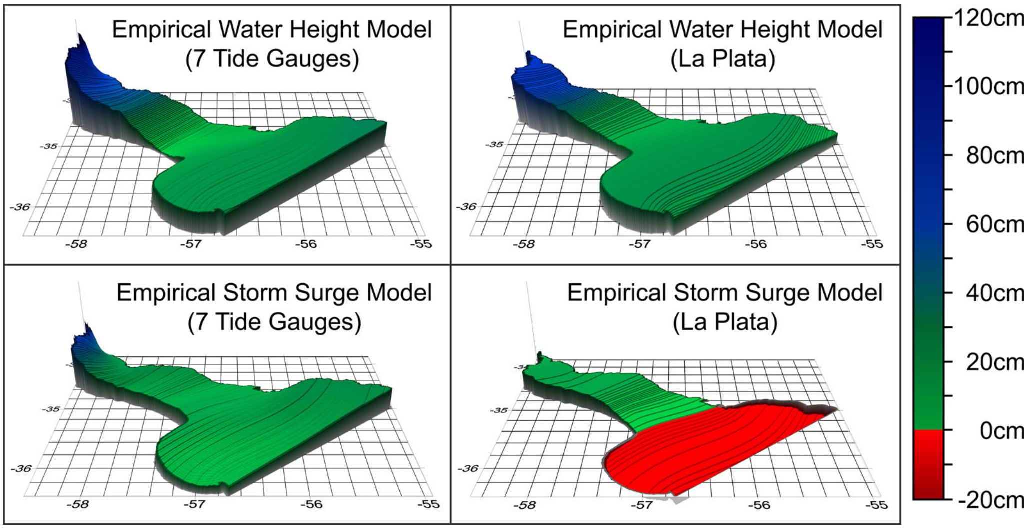

Figure 4
Empirical water height and storm surge models for the Río de la Plata for February 24th, 2016 00:00

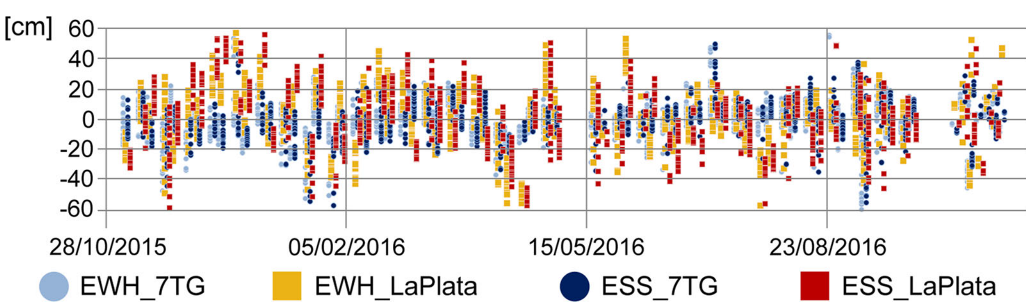

Figure 5
Differences between CorSSH data and CorSSH storm surge, and empirical water height and storm surge models

respectively. The standard deviation found in this comparison is considerably smaller than the ones obtained in the comparison with CorSSH data, probably because Norden station is close to the stations used to generate the empirical models in that region.

The standard deviation of the differences found in the water height and the storm surge models is similar to the water height differences between model vs observations found by other authors, whom made similar comparisons with SG data (Boy et al. 2009; Geng et al. 2012). There is no doubt that the performance of the empirical models can be improved, especially in the middle and exterior regions; however, for the purpose of this work, the standard deviation of the differences found is considered acceptable for the latter calculation.

4.3. *Gravimetric Response of the Empirical Models*

Figure 6 shows the gravimetric response of the water height and storm surge empirical models calculated using SPOTL, and Fig. 7 shows the four response series overlapped in a shorter period, where the differences between the models can be better distinguished. All four models have similar gravimetric response in a range from -10 to 20 nm/s^2. The minimum and maximum differences in the gravimetric response between water height models are -3.7 and 6.4 nm/s^2 and between the storm surge

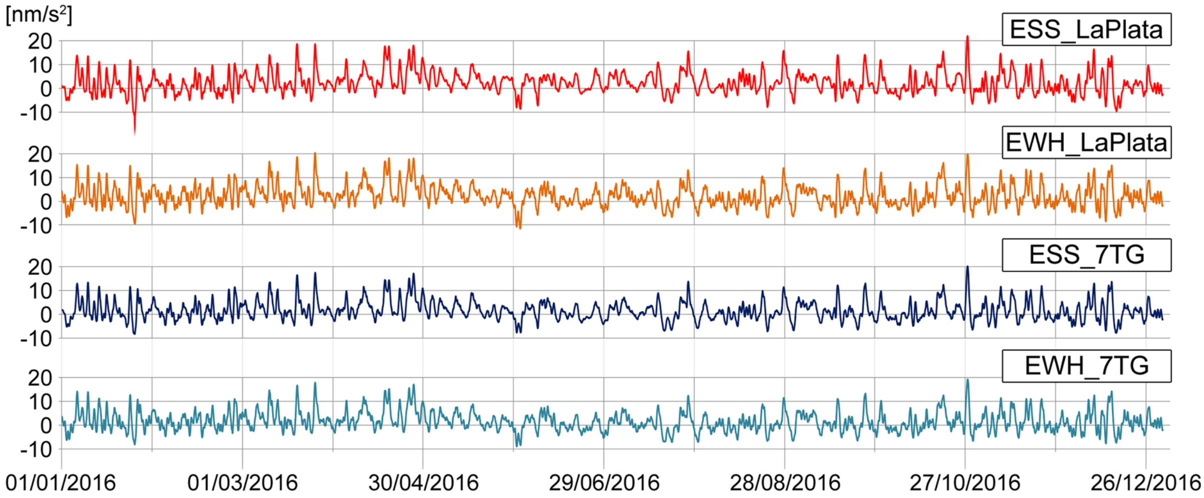

Figure 6
Gravimetric responses of the water height and storm surge empirical models calculated using SPOTL

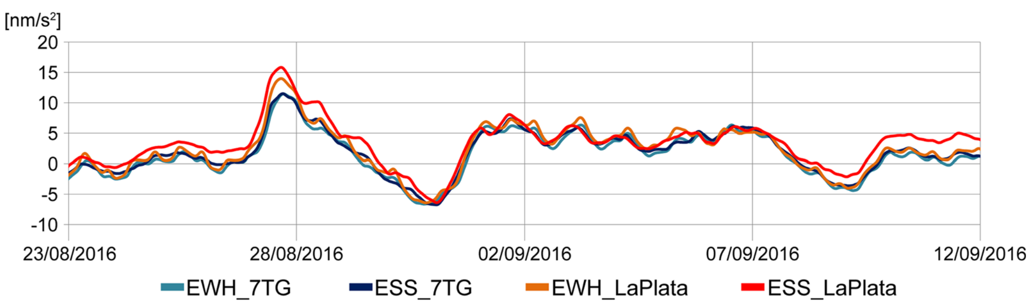

Figure 7
Detail of gravimetric responses of the water height and storm surge empirical models calculated using SPOTL

models are −4.7 and 4.6 nm/s^2. The RMS of the difference of the water height models is 1.0 nm/s^2 and between the storm surge models is 1.4 nm/s^2.

The RMS of the differences between the water height model and the storm surge model is 0.7 and 1.7 nm/s^2 for the seven tide gauges and La Plata models, respectively. The results show that all four gravimetric response series are very similar to each other, with an RMS of the differences smaller than 5% of the range.

Considering the source origin of the data (La Plata station, seven tide gauge stations), the RMS of the differences between the water height model and the storm surge model is 0.7 and 1.7 nm/s^2 for the seven tide gauges and La Plata models, respectively. The results found and show that the four gravimetric responses are very similar to each other, with RMS of the differences smaller than 5% of the range.

A tidal model can be obtained from the subtraction of a storm surge (non-tidal) model from a water height model. For the Río de la Plata, this calculation can also be applied for the gravimetric response of the calculated empirical models, where the result is the gravimetric response of the tidal component of the loading. Figure 8 shows the gravimetric response of the tidal component of the loading subtracting ESS_7TG model from the EWH_7TG model. This subtraction was verified by subtracting the empirical models cell by cell, and then calculating the gravimetric response using SPOTL. The gravimetric response of the tidal component of the loading has a range of approximately 12% of the range of the

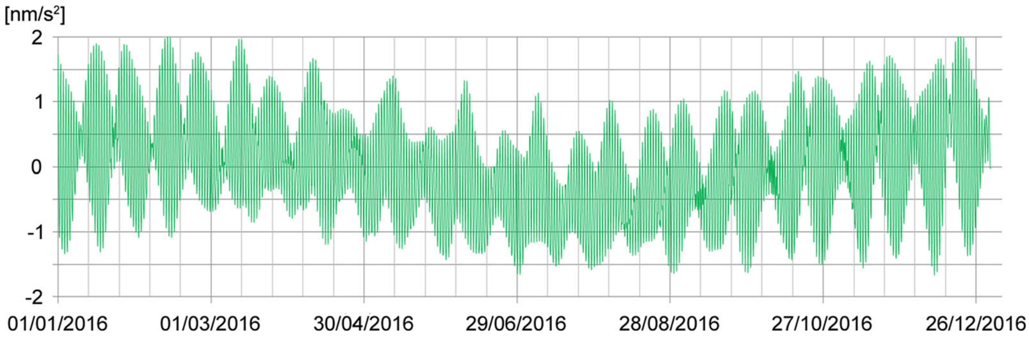

Figure 8
Gravimetric response of the tidal component of the loading, obtained by subtracting ESS_7TG model from EWH_7TG model

non-tidal component for the analyzed period. This difference in range can be explained considering the characteristics of the astronomical tide in the Río de la Plata. The amplitude of the astronomical tide in the river is smaller than 1.5 m, and a full cycle of the M2 constituent is always present in the river, meaning that a low tide and a high tide are present in different regions at the same time. These results show that the non-tidal component defines most of the behavior of the loading in the Río de la Plata.

4.4. Comparison Between the Gravity Residuals and the Gravimetric Response of the Empirical Models

The gravimetric response of the ESS_7TG model was selected to be compared with the gravity residuals of the SG, as during processing of the SG data, the harmonic analysis eliminated the tidal component of the loading, and during the validation process, model ESS_7TG has shown a better performance than the ESS_LaPLata model. Figure 9 shows the comparison of the gravimetric response of the ESS_7TG model with the SG data after applying the Earth tide model (which already includes tidal loading), atmospheric corrections and removing pole tide effect for the whole period, and the final residuals after subtracting the storm surge gravimetric response from the measured gravity residuals.

Although the reduction of the RMS of the series after subtracting the gravimetric response of the storm surge model is minor (15.0 vs 13.9 nm/s^2), the coincident peaks between both series indicate the influence of the storm surge in the SG observations. To make this influence more evident, a wavelet analysis is performed, since it is one of the most appropriate spectral analysis techniques to describe the variability of non-stationary data series. The analysis is applied to the residual series of the SG before and after subtracting the storm surge gravimetric response (Fig. 10) using as mother wavelet the Morlet wavelet. The series without the storm surge influence shows a clear decrease in the spectral energy in the periods between 2 and 12 days, in comparison with the gravity residuals. These periods coincide with the periods of the storm surges in the Río de la Plata.

4.5. Vertical and Horizontal Displacements Using the Empirical Models of the Río de la Plata

Using the SPOTL software, the horizontal and vertical displacements, due to the tidal and non-tidal loading of the Río de la Plata, can be estimated with the empirical models described in this paper. Figure 11 shows North, East, and Up displacements found for the four models in the period 01/2016–12/2016, and Table 2 shows the minimum and maximum values for each direction, for all models.

The biggest displacements correspond to Up direction, where the differences can be easily identify in the minimum displacement values. For the analyzed period, the RMS of the differences between EWH_7TG and EWH_LP models is smaller than 0.4 mm for all the directions, and between ESS_7TG and ESS_LP is smaller than 0.6 mm for all directions.

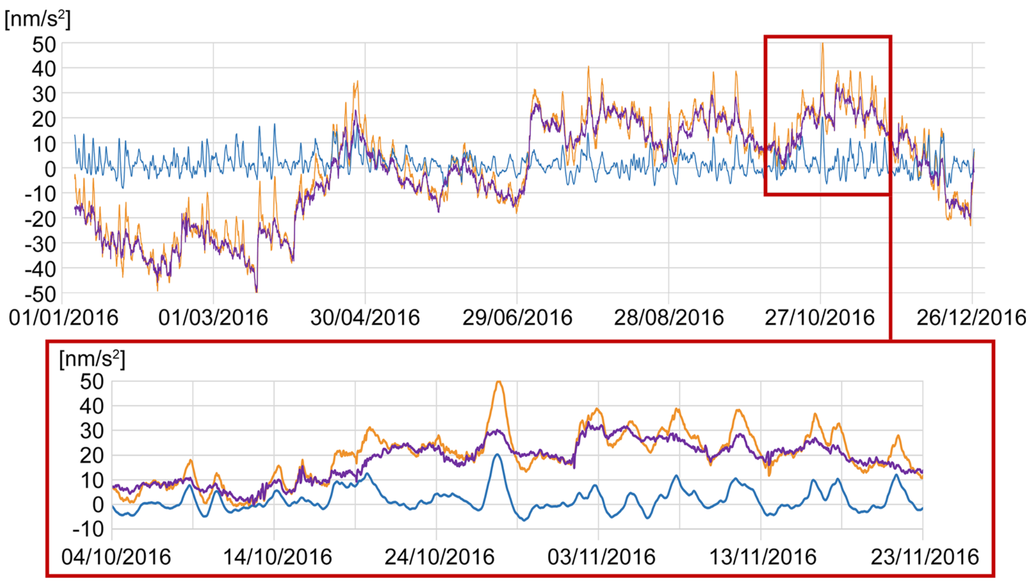

Figure 9
Gravimetric response of the ESS_7TG model (*blue line*), SG data after correcting for Earth tides, pole tide, tidal loading, and atmospheric pressure (*orange line*), and the difference between both series (*purple line*). The *upper figure* shows the comparison for the whole period and the *bottom figure* for a 50 days period

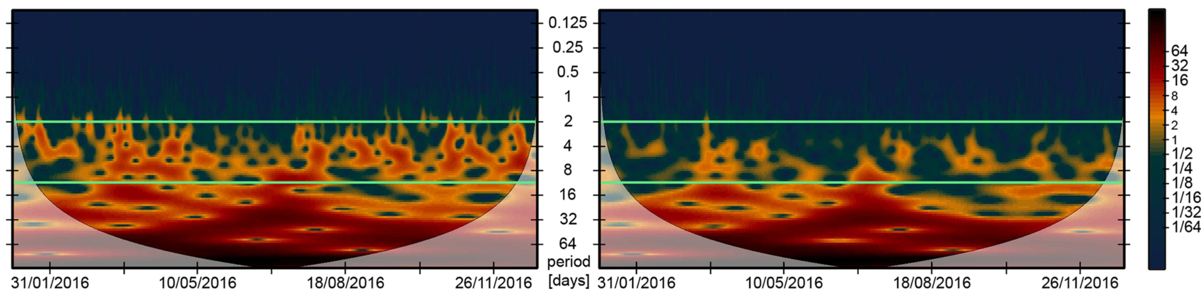

Figure 10
Wavelet power spectrum of the residual series of the SG, before (*left*) and after (*right*) subtracting the storm surge gravimetric response of the Río de la Plata

In addition, for the whole period, the maximum difference between the water height models is 2.4 mm corresponding to up direction, and between the storm surge models is 1.8 mm corresponding to up direction too.

5. Conclusions and Discussion

The empirical models used in this paper allow reducing the variability of the gravity residuals observed by the SG038 located at AGGO by removing the gravity response of the storm surge in the Río de la Plata. The reduction of the residuals is effective at periods between 2 and 12 days, which is coincident with the storm surge periods. According to the validation, the empirical models developed with information from all available tide gauges represented the water height and the storm surge of the river more accurately and, therefore, the derived gravimetric response as well. Although the RMS of the differences from Norden station and CorSSH

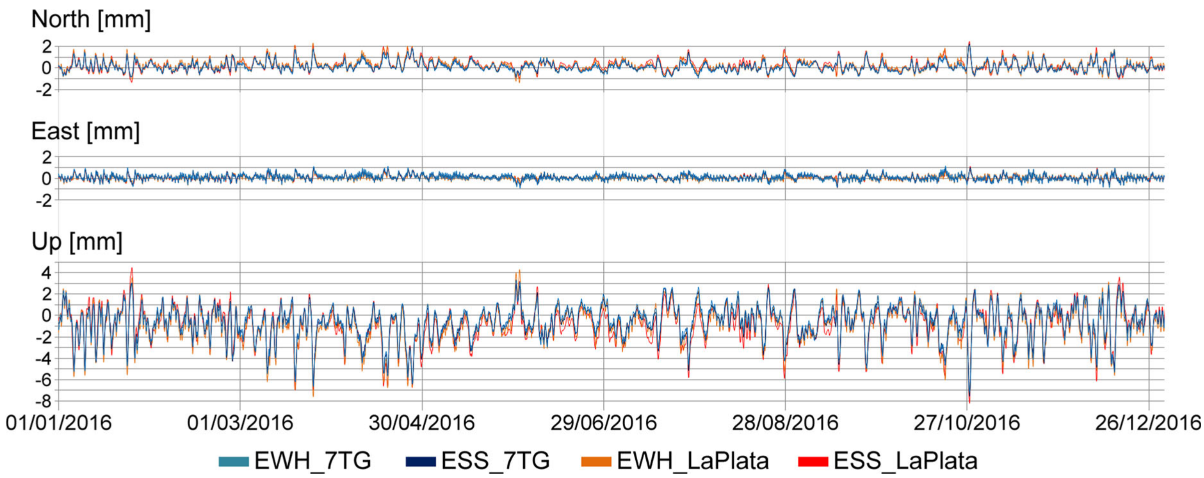

Figure 11
Horizontal and vertical displacements of the SG due to the tidal and non-tidal loadings of the Río de la Plata, obtained from the empirical models EWH_7G, ESS_7G, EWH_LaPlata, and ESS_LaPlata

Table 2

Minimum and maximum values of displacements for directions North, East, and Up obtained from the empirical models EWH_7G, ESS_7G, EWH_LaPlata, and ESS_LaPlata

Empirical model	Maximum negative displacement (mm)			Maximum positive displacement (mm)		
	North	East	Up	North	East	Up
EWH_7TG	−0.9	−0.9	−7.2	2.1	1.2	3.3
ESS_7TG	−0.9	−0.9	−7.6	2.3	1.0	3.1
EWH_LP	−1.4	−0.8	−7.6	2.3	1.0	4.3
ESS_LP	−1.4	−0.7	−8.2	2.5	1.1	4.5

comparisons confirms the better performance of these empirical models, the gravimetric response of the models using La Plata station only also allows reducing the RMS of the gravity residuals significantly. This can be explained by the close distance of the La Plata station to AGGO and to the minor variations of the water height in the vicinity of the inner part of the river.

The tidal and non-tidal loading effects of the river have different ranges; the tidal component is approximately 12% of the non-tidal component. In addition, the tidal component can be eliminated using harmonic analyses, since the frequencies of the oceanic tide are included in the frequencies of the Earth tide. If this technique is used, the storm surge model should be used to reduce the gravity time series after applying the conventional corrections. Otherwise, if the water height model is used, the gravimetric response of this model should be subtracted from the observed series before the harmonic analysis, to avoid a duplicate reduction of the tidal component.

The vertical and horizontal displacements found due to the storm surge are smaller than 1 cm, but will influence all geodetic space techniques installed at AGGO and should, therefore, be corrected to remove the non-tidal signal in the measurements. The observations from the closest tide gauge to AGGO, La Plata station, can provide essential information to model the gravimetric response of the storm surge and should be considered as significant auxiliary information for the observatory.

The results found in this paper will allow a better description of the vertical and horizontal displacements needed for other geodetic techniques, and also the modeling of geophysical signals not considered herein, such as rain and/or local ground water. Figure 12 shows the gravity residuals obtained after subtracting the storm surge gravimetric response, and the rainfall measured by the meteorological station SADL, located at the La Plata Aerodrome, close to AGGO. In Fig. 12, after each rain episode, a

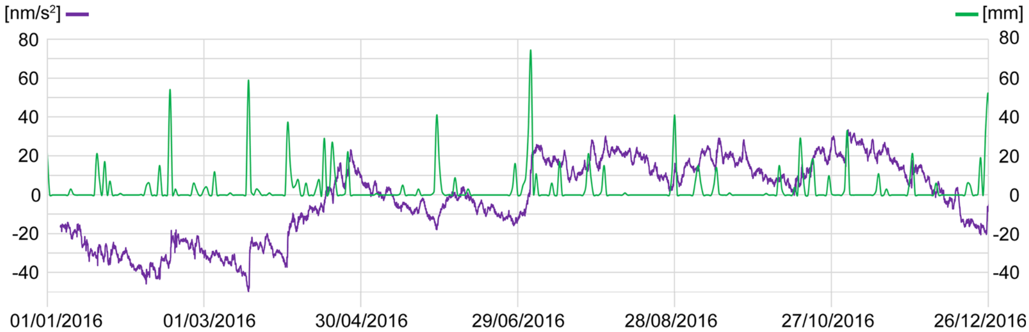

Figure 12
Gravimetric residues (in nm/s^2) obtained after subtracting the storm surge gravimetric response of ESS_7TG model (*purple*) and the rain fall (in mm) measure by the meteorological station SADL (*green*)

sudden increase in the gravity time series can be identified, followed by a gradual decrease until the next rain episode. A clear example of this behavior happened on July 4, when an important rain event occurred, and the gravity residuals increased by almost 35 nm/s^2 within a few days. The analysis of this, and others, hydrological and geophysical effects will be subject developed to in further future work, but is strongly supported by this study, as gravity effects are only separable by precise modeling.

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