# Estimation of the geopotential value $W_0$ for the Local Vertical Datum of Argentina using EGM2008 and GPS/Levelling data

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**Abstract**

The main purpose of this paper is to estimate the zero-height geopotential value for the Argentinean Local Vertical Datum (LVD). The methodology is based on the computation of the mean geopotential offset between the value $W_0$ = 62 636 856.0 m$^2$ s$^{-2}$, selected as reference in this study, and the unknown geopotential value of the LVD ($W_0^{LVD}$). This estimation is based on the combination of ellipsoidal heights, levelled heights (referring to the LVD), and some physical parameters derived from the EGM2008 model (namely, geopotential values, gravity values, and geoid undulations). This combination is performed following two approaches: The first one compares levelled heights and geopotential values derived from the EGM2008 model using the Least Squares method to increase the robustness of the adjustment, while the second one analyses the differences between GPS/Levelling and EGM2008 geoid undulations. Both approaches are evaluated at more than 540 benchmarks (BMs) belonging to the vertical network of Argentina. The numerical computations include in addition the assessment of possible correlations of the estimated zero-height geopotential value with the height of the included BMs. The results show that the best possible estimation at present is 62 636 853.9 m$^2$s$^{-2}$; however, it is necessary to improve these computations by including proper physical heights (instead of the levelled ones) and global gravity models containing GOCE data.

**Keywords** Zero-height geopotential value, Argentinean Local Vertical Datum

# 1. Introduction

The Argentinean Vertical Datum is defined by the mean sea level at the tide gauge station in Mar del Plata, making it a local system that is not tied to a global vertical datum (Bolkas, 2012). From that initial point and through spirit and trigonometric levelling, the rest of the benchmarks are tied to the Local Vertical Datum (LVD) origin. Contrary, a global vertical datum is usually defined as a height reference (equipotential) surface for all continents and oceans. Indeed, the International Association of Geodesy (IAG) and its Global Geodetic Observing System (GGOS) aim, via the Working Group on Vertical Datum Standardization,, at the definition and realization of a global reference surface that allows the integration of the existing local vertical datums in a global one (Sánchez, 2013). This topic has gained increased focus since the dedicated-gravity satellite missions, like the Gravity Recovery and Climate Experiment (GRACE) and the Gravity field and steady-state Ocean Circulation Explorer (GOCE), support the determination of vertical shifts (either as height or geopotential differences) of regional/national vertical datums with respect to one and the same equipotential surface realized globally (Hayden et al., 2013; Gruber et al., 2012).

As outlined in Grigoriadis et al. (2014), the various methods for the estimation of the zero-height geopotential value can be categorized in two main classes, the first one based on adjusting collocated GPS/Levelling and Global Geopotential Model (GGM) data and the second one employing gravity anomaly data over various LVD areas within a geodetic boundary value problem. In this paper, within the frame of the first methodology, we present two possible approaches for the estimation of the Argentinean LVD zero-level geopotential value $W_0^{LVD}$ using EGM2008 (Pavlis et al., 2012) and GPS/Levelling data over a network of benchmarks (BMs). The first approach consists of an estimator based on a Least Squares (LS) adjustment of Helmert orthometric heights and EGM2008 over the entire GPS/Levelling network of Argentina. In this approach there is no need to use geoid heights in estimating the zero-level geopotential, so the inherent uncertainty for the topographic effects on geoid heights when evaluating them from a GGM is avoided. The second approach is based on the differences between geoid heights from GPS/Levelling measurements and those derived from EGM2008. The estimation of the mean offset can give us a direct link between the Argentinean local vertical datum and a certain $W_0$ value.

# 2. Methodology

Lets assume that physical orthometric heights $H_i$ are available over a network of Benchmarks (BMs) $i = \{1, 2, 3, ..., m\}$, derived by traditional spirit leveling, with their orthometric heights referring to the mean sea level realized by a tide-gauge station. The latter forms the origin of the LVD in the region under study, to which all orthometric heights refer to, with a, generally unknown, zero-level geopotential value $W_0^{LVD}$. An estimate of $W_0^{LVD}$ can be achieved, following two approaches, when for the same BMs ellipsoidal heights $h_i$ derived by GPS measurements, surface gravity $g_i$ and the geopotential $W_i$ computed from a GGM, are available.

## 2.1 Approach 1: Combination of Helmert orthometric heights, geopotential values and surface gravity derived from EGM2008 using a LS adjustment

The first approach refers to an estimation of $W_0^{LVD}$ using a LS adjustment scheme, based on the definition of Helmert orthometric heights. The orthometric height is defined by the geopotential number $C_i$ divided by the mean value of gravity $\overline{g}_i$ taken along the plumbline between the LVD and the BM. The orthometric height system is hard to realize perfectly in practice, since the Earth's gravity acceleration at all points along the plumbline need to be known (Heiskanen and Moritz, 1967, Eq. 4.4). This requires knowledge of gravity variations or mass-density distribution inside the topography. The orthometric heights are modeled as Helmert type of orthometric heights ($H_i^{Helmert}$), through the estimation of the mean gravity along the plumbline by the Poincaré-Prey reduction using the following equation (Heiskanen and Moritz, 1967, pp. 163–167, Eq. 4.26).

$$H_i^{Helmert} = \frac{C_i^{LVD}}{\bar{g}_i^{Helmert}} = \frac{W_0^{LVD} - W_i}{\bar{g}_i^{Helmert}}, (1)$$

where, $C_i^{LVD}$ is the geopotential value, $W_{\mathrm{i}}$ is the actual gravity potential or geopotential and $\bar{g}_i^{Helmert}$ is the mean gravity value at each BM, respectively. Both $W_i$ and $\bar{g}_i^{Helmert}$ can be computed from a GGM. $W_i$ may be synthesized from the gravitational potential $V_i$, also obtained from the spherical harmonic series expansion plus the centrifugal potential $\Phi_i$. In this way, Equation 1 has only one unknown.

$$W_0^{LVD} = H_i^{Helmert} \bar{g}_i^{Helmert} + W_i . (2)$$

It is possible to estimate the zero-height geopotential value $\hat{W}_0^{LVD}$ by means of a LS adjustment introducing as observation equation:

$$\hat{W}_0^{LVD} = \frac{\sum_{i=1}^{m} p_i (\bar{g}_i^{Helmert} H_i^{Helmert} + W_i)}{\sum_{i=1}^{m} p_i}, (3)$$

and satisfying the condition:

$$\sum_{i=1}^{m} p_i \delta W_i^2 = \min . (4)$$

Here $p_i$ represents the weighting of the input data and $\delta W_i^2$ is the residual of the unknown $W_0^{LVD}$.

$\bar{g}_i^{Helmert}$ is related to the gravity measured at the Earth's surface ($g_i$) according to Heiskanen and Moritz (1967, pp. 163–167).

$$\bar{g}_i^{Helmert} = g_i + 0.0424 H_i \text{ . (5)}$$

The estimation of $g_i$ in Eq. (5) can be achieved either by available gravity observations at the BM location or can be reconstructed, like in this study, from gravity disturbances directly computed through the spherical harmonic expansion series as (Filmer et al., 2010):

$$g_i = \gamma_i + T_r^i \text{, (6)}$$

where $T_r^i$ is the radial derivative of the disturbing potential. The normal gravity $\gamma_i$ can be computed with the Eq. 2.120-2.124 of Heiskanen and Moritz (1967).

One advantage of this method is that it does not depend on the evaluation of geoid heights and therefore it is not affected by geoid modelling errors and it is robust with respect to the uncertainties of surface gravity.

Equation 3 is evaluated, in this study, including levelled heights instead of Helmert orthometric heights, since the vertical networks of Argentina were adjusted without including gravity reductions. This omission could generate discrepancies up to several decimeters in comparison with properly computed physical heights.

## 2.2 Approach 2: Combination of GPS/levelling with geoid undulations derived from EGM2008

The second approach refers to an estimation of $W_0^{LVD}$ using surface gravity and geoid heights computed from a GGM and GPS/Levelling data. The geopotential number is the potential difference between an equipotential surface ($W_i$) and a reference equipotential surface ($W_0$) along a plumb line. The geoid is the traditionally used reference geopotential surface; a local/regional geoid model realizes the origin of a local vertical datum ($W_0^{LVD}$), while a global geoid model realizes the origin of a global datum ($W_0^{CVD}$), for a local datum, we talk about a local geoid. In that way, the geopotential number for the same station $i$ can be written as:

$$C^{CVD} = W_0^{CVD} - W_i \text{, (7)}$$

$$C_i^{LVD} = W_0^{LVD} - W_i \text{, (8)}$$

Consequently, the geopotential number difference at the benchmark can be expressed as:

$$\Delta C_i^{CVD/LVD} = W_0^{CVD} - W_0^{LVD} \text{, (9)}$$

By averaging Eq. (9) over the benchmarks, we may determine the zero-height geopotential value for the LVD by:

$$\hat{W}_0^{LVD} = \frac{\sum_{i=1}^{m} W_0^{LVD}}{m} = W_0^{CVD} - \frac{\sum_{i=1}^{m} \Delta C_i^{CVD/LVD}}{m} \text{, (10)}$$

where $\Delta C_i^{CVD/LVD}$ is given by:

$$\Delta C_i^{CVD/LVD} = (h_i - H_i^{Helmert} - N_i - N_0)\bar{g}_i^{Helmert} \text{. (11)}$$

$N_o$ represents the contribution of the zero-degree harmonic term to the GGM geoid undulations with respect to a specific reference ellipsoid. In this work, this is computed using Eq. 2.182 of Heiskanen and Moritz (1967):

$$N_0 = \frac{GM - GM_0}{R\gamma} - \frac{W_0 - U_0}{\gamma} \text{. (12)}$$

In Eq. (12), the parameters $GM_o$ and $U_o$ correspond to the geocentric gravitational constant of the reference ellipsoid and the normal gravity potential, respectively. The GRS80 ellipsoid is used as the reference ellipsoid for all numerical computations (Moritz, 2000), while the Earth’s geocentric gravitational constant $GM$ and the gravity potential at the geoid $W_0$ is set to $GM$=398600.4415 $10^9$ $m^3s^{-2}$ and $W_o$=62636856.0 $m^2s^{-2}$, as given by Petit and Luzum (2010). The mean Earth radius $R$ is taken equal to 6378136.3 m and the normal gravity $\gamma$ at the surface of the ellipsoid is computed by the closed formula of Somigliana (Moritz, 2000). As in the evaluation of Eq. (3), since the Helmert orthometric heights ($H_i^{Helmert}$) are not available, they are replaced by levelled heights in Eq. (11).

# 3. Data availability and numerical results for $W_0^{LVD}$

## 3.1 Input data

As already mentioned, the height values $H_i^{Helmert}$ in Eq. (3) and (11) are replaced by pure levelled heights since no gravity reductions have been considered in the processing of the vertical network of Argentina. This network was installed and is maintained by the Instituto Geográfico Nacional (IGN) using spirit and trigonometric levelling techniques. The zero-height origin is realized by the mean sea level determined at the reference tide gauge Mar del Plata, with an unknown $W_0^{LVD}$ value. Like in most of the countries, no luni-solar tide reduction has been applied to the levelling measurements and therefore, the Argentinean levelled heights are given in Mean Tide (MT) system. To improve the reliability of these computations, these levelled heights are transformed from MT to TF system following Ekman (1989).

$$H^{TF} = H^{MT} - 0.68(0.099 - 0.296\,sin^2\varphi). \quad (13)$$

More details about the vertical data available in Argentina are presented by Tocho et al. (2014).

For the estimation of $W_0^{LVD}$ with approach 1, the gravity potential values $W_i$ have been computed from EGM2008 (Pavlis et al., 2012) complete to degree and order 2159 and in the TF system. For the computation of the gravitational part of $W_i$, the harmonic_synth_v02 program has been used and for its centrifugal potential part, the GPS derived spatial coordinates of each station have been used (Grigoriadis et al., 2014). The surface gravity at each the BM station necessary to compute Eq. (5) is also calculated with EGM2008 according to Eq. (6).

To apply Approach 2, we used the traditional technique based on the differences found between geoid heights from 542 GPS/Levelling measurements across Argentina and those derived from EGM2008 with the computation of *No* based on Eq. (12). Figure 1 depicts the distribution of the available GPS/Levelling BMs over Argentina.

**Figure 1**

## 3.2 Numerical Results

The results after applying both approaches are summarized in Table 1.

According to Approach 1, the mean geopotential offset between the $W_0$ value selected as the reference and the estimated $\hat{W}_0^{LVD}$ is about -3.2 $m^2s^{-2}$; whereas, the estimation provided by the Approach 2 is -3.0 $m^2s^{-2}$. Both results are very similar (only 0.2 $m^2s^{-2}$ of discrepancy). This is explainable since both approaches are combining the same input data: the same levelled heights, the same GPS positioning data (in form of geocentric coordinates for the first approach and in form of ellipsoidal heights for the second approach), and the same global geopotential model (in form of potential values for the first approach and in form of geoid undulations for the second approach). Indeed, the only difference between both approaches is that the first one makes the combination in terms of geopotential values, while the second one performs the combination in terms of heights (ellipsoidal, levelled, and geoid heights).

Table 1: Estimation of the zero-height geopotential value for Argentina applying different approaches and different weighting functions. Unit: [$m^2\ s^{-2}$].

| Approach 1 | Weighting scheme | $\hat{W}_0^{LVD}$ | Differences between weighting functions and the un-weighted solution | Number of points | Difference $\hat{W}_0^{LVD}$ with $W_0$ = 62 636 856.0 $m^2\ s^{-2}$ |
|---|---|---|---|---|---|
| | $p_i=1$ | 62 636 852.8 ± 0.04 | | 542 | -3.2 |
| | $p_i=1/(H_i)$ | 62 636 854.0 ± 0.02 | $p_i=1/(H_i)$ - $p_i=1$ 1.2 | 542 | -2.0 |
| | $p_i=1/(H_i^2)$ | 62 636 854.4 ± 0.01 | $p_i=1/(H_i^2)$ - $p_i=1$ 1.6 | 542 | -1.6 |
| | $p_i=1/(H_i^{0.5})$ | 62 6368 53.5 ± 0.03 | $p_i=1/(H_i^{0.5})$ - $p_i=1$ 0.7 | 542 | -2.5 |
| Approach 2 | | 62 636 853.0 | | 542 | -3.0 |
| Approach 2 - Approach 1 *($p_i=1$)* | | | 0.2 | 542 | -0.2 |

Since the levelled heights are not reduced by gravity effects, it is probably that benchmarks located at large heights (more than 500 m) introduce some biases in the results. In order to confirm this, a weighted LS adjustment is performed applying three different a priori weights, i.e., $p_i=1/(H_i)$, $p_i=1/(H_i^2)$ and $p_i=1/(H_i^{0.5})$. This experiment is carried out using the formulation of Approach 1 (Eq. 4 and 6) only, but it is expected that Approach 2 produces similar values. The weighted $\hat{W}_0^{LVD}$ estimates present differences between 0.7 $m^2\ s^{-2}$ to 1.6 $m^2\ s^{-2}$ with respect to the un-weighted adjustment ($p_i=1$) (Table 1). Assuming that these differences are caused by height-dependent systematic errors, two further adjustments are performed categorizing the available data into height-classes. The first adjustment includes all BMs below a certain elevation threshold (500 m, 1500 m, and 3500 m), while the second adjustment includes only the BMs available at a certain height-class(i.e. 500 - 1500 m, 1500 - 3500 m). The obtained $\hat{W}_0^{LVD}$ estimates are shown in Table 2.

Table 2: Estimation of the zero-height geopotential value for Argentina using Approach 1 and different elevation threshold. Unit: [$m^2\ s^{-2}$].

| Threshold | Number of points | $\hat{W}_0^{LVD}$ | Difference $\hat{W}_0^{LVD}$ with $W_0$ = 62 636 856.0 $m^2$ |
|---|---|---|---|
| H < 500 m | 464 | 62 636 853.3 ± 0.04 | -2.7 |
| H < 1500 m | 527 | 62 636 853.0 ± 0.04 | -3.0 |
| H < 3500 m | 542 | 62 636 852.8 ± 0.04 | -3.2 |
| 500 m < H < 1500 m | 63 | 62 636 851.1 ± 0.15 | -4.9 |
| 1500 m< H < 3500 m | 15 | 62 636 845.1 ± 1.31 | -10.9 |

In Table 2, it can be seen that in both cases a strong correlation with height is evident for the estimated zero-height geopotential values. When using the BMs lower than 500 m, the estimate we get is reasonably close to the ones with the weighted scenarios (square root of height inverse and height inverse), since they differ by approximately -0.2 $m^2\ s^{-2}$ and -0.7 $m^2\ s^{-2}$, respectively. When BMs of higher elevation are used (<1500 m), then an additional offset of 0.3 $m^2\ s^{-2}$ is added, while when all BMs are included (<3500 m) then there is an additional offset of 0.2 $m^2\ s^{-2}$. This can be clearly seen, when investigating the determined $\hat{W}_0^{LVD}$ by the BMs available in each height-class solely. When using the BMs between 500 m and 1500 m, the determined $\hat{W}_0^{LVD}$ differs by -2.4 $m^2\ s^{-2}$ and -2.9 $m^2\ s^{-2}$ with the weighted ones. Finally, the BMs of high altitude (1500 m < $H_i$ < 3500 m) contribute the most to the biased estimates, since the determined $\hat{W}_0^{LVD}$ differs as much as -8.4 $m^2\ s^{-2}$ and -8.9 $m^2\ s^{-2}$ with the weighted ones. This can be also seen in Figure 2, where we plot the height residuals $e_i$ for the un-weighted solution against height. The height residuals are computed by the following equation:

$$e_i = H_i^{Helmert} - \frac{\hat{W}_0^{LVD} - W_i}{\bar{g}_i} . (14)$$

From Figure 2, it becomes clear that especially the BMs at high altitude refer to a “different” LVD since their scatter is minimal though around a mean value of ~ -0.8 m.

**Figure 2**

In order to investigate further this correlation with height and come to a more robust estimate for the zero-level geopotential value, a revised model considering the height-correlated data errors has been investigated by including a height-dependent parameter into the data adjustment as:

$$H_i^{Helmert} = \frac{W_0^{LVD} - W_i}{\bar{g}_i} + \lambda H_i^{Helmert} \,. \quad (15)$$

The height-dependent parameter $\lambda$ *i*n Eq. (15) describes the linear part of the height-dependent systematic errors. Including the determination of the parameter $\lambda$, the height residuals can be computed using:

$$e_i = H_i^{Helmert} - \frac{\hat{W}_0^{LVD} - W_i}{\bar{g}_i} - \hat{\lambda} H_i^{Helmert} \,. \quad (16)$$

Weighted adjustments have been performed with the results being summarized in Table 3, where both the estimated height-dependent parameter $\lambda$ and the final $\hat{W}_0^{LVD}$ are reported. From the estimated values it becomes apparent that the results are now more robust, since the differences between the un-weighted $(p_i=1)$ and the weighted solutions are smaller, the only exception is the solution with $p_i=1/(H_i^2)$ which will be discussed further. The rest of the weighted estimates differ with the un-weighted solution by 0.2 $m^2s^{-2}$ and 0.5 $m^2s^{-2}$ only, while the estimated parameters are in good agreement as well.

Table 3: Estimation of the zero-height geopotential value for Argentina including a height dependent parameter into the data adjustment.

| Weighting scheme | $\hat{W}_0^{LVD}$ [m$^2$ s$^{-2}$] | $\hat{\lambda}$ | Differences between weighting functions and the un-weighted solution | Number of points | Difference $\hat{W}_0^{LVD}$ with $W_0$ = 62 636 856.0 m$^2$ s$^{-2}$. |
|---|---|---|---|---|---|
| $p_i=1$ | 62 636 853.7 ± 0.05 | -3.343E-04 ± 9.600E-06 | | 542 | -2.3 |
| $p_i=1/(H_i)$ | 62 636 854.2 ± 0.31 | -5.300E-04 ± 2.897E-04 | $p_i=1/(H_i)$- $p_i=1$ 0.5 | 542 | -1.8 |
| $p_i=1/(H_i^2)$ | 62 636 854.5 ± 0.91 | 1.218E-03 ± 4.886E-03 | $p_i=1/(H_i^2)$ - $p_i=1$ 0.8 | 542 | -1.5 |
| $p_i=1/(H_i^{0.5})$ | 62 636 853.9 ± 0.14 | -3.654E-04 ± 5.491E-05 | $p_i=1/(H_i^{0.5})$ - $p_i=1$ 0.2 | 542 | -2.1 |

Table 4 summarizes the statistics of the height residuals from the LS adjustment without and with the height dependent parameter $\lambda$ Eq. 15 and 16, respectively). The standard deviation (std) of the height residual without $\lambda$ is found at the 0.26 m level.

Table 4: Statistics of the height residuals from the LS adjustment: Unit: [m].

| $e_i$ | Min | Max | Mean | std $\sigma$ |
|---|---|---|---|---|
| No parameter estimation | | | | |
| $p_i=1$ | -1.14 | 1.14 | 0.000 | ± 0.26 |
| With height dependent parameter estimation $\boldsymbol{\lambda}$ | | | | |
| $p_i=1$ | -0.85 | 1.15 | 0.00 | ± 0.21 |
| $p_i=1/(H_i)$ | -0.87 | 1.18 | 0.00 | ± 0.23 |
| $p_i=1/(H_i^2)$ | -0.82 | 1.46 | -0.11 | ± 0.34 |
| $p_i=1/(H_i^{0.5})$ | -0.86 | 1.15 | -0.00 | ± 0.21 |

Figure 3 and Figure 4 depict the variation of the estimated $\hat{W}_0^{LVD}$ with height for all weight scenarios, and the differences of the estimated $\hat{W}_0^{LVD}$ from the $p_i=1/(H_i)$, $p_i=1/(H_i^2)$ and $p_i=1/(H_i^{0.5})$ solutions with the un-weighted one. Finally, Figure 5 depicts the derived height residuals for the available BMs after the adjustment. In all figures, some problems with the weighted solution with $p_i=1/(H_i^2)$ can be seen. It is noticeable that while the other adjustment solutions manage to improve the residuals for the BMs at high-terrain, the solution with $p_i=1/(H_i^2)$ introduces a linear trend in the opposite direction compared to the mean residuals where no linear trend parameter has been estimated. This means that both a bias and a trend are introduced which can be further evidenced from the height residuals presented in Table 4.

After the introduction of the linear height dependent parameter in the observation equations, one would expect that the adjusted residuals would have a zero mean. Indeed, this is the case for all estimates apart from the one with $p_i=1/(H_i^2)$ where the mean of the residuals is at the -0.11 m level. This is not a surprising result since the particular weight factor is rather harsh and significantly down-weights most of the available BMs, thus blocking them from the adjustment procedure. In a sense, when the $p_i=1/(H_i^2)$ is employed, the high-elevation BMs do not participate in the adjustment at all, hence they have large residuals. But, the over-confidence put on the low-land points does not manage to provide reasonable adjusted residuals heights for the high-elevation BMs. From Figure 3 it can be seen that the BMs with elevations between 1000 and 1800 m provide *Wo* values very close to the estimated ones. Nevertheless, the use of $p_i=1/(H_i^2)$ cancels entirely their contribution in the final solution.

Therefore, this weight scheme makes the separation of the $\hat{\lambda}$ and $\hat{W}_0^{LVD}$ parameters practically impossible. In a practical sense, any of the three robust estimates un-weighted and weighted with $p_i=1/(H_i)$ and $p_i=1/(H_i^{0.5})$ can be used to provide the $\hat{W}_0^{LVD}$ for Argentina since their differences are within their precision level. To further validate that, if we compare the estimated zero-level geopotential value with Approach 2, we can see that it is closer to the un-weighted solution of Approach 1, without the linear height-dependent parameter (see Table 1, difference of 0.2 $m^2$ $s^{-2}$ only). Moreover it differs by 0.7 $m^2$ $s^{-2}$., 1.2 $m^2$ $s^{-2}$ and 0.9 $m^2$ $s^{-2}$ with the estimates presented in Table 4. In order to get a more realistic picture of the accuracy of the results we have to consider the bias introduced by EGM2008 itself, through the commission error over spatial wavelengths that exceed the extent of our test network. Given that our area spans 15$^o$×25$^o$, the maximum degree of EGM2008 not represented in this test region is selected equal to 10 (~1980 full-wavelength), which corresponds to a commission error of 2.8 cm. This error should be added to the formal prediction errors (through error propagation) of the zero-level geopotential values presented in Table 2 and Table 3 to get a more realistic picture of the achieved accuracy. Also, given the maximum degree of EGM2008, the omission error is of the order of 2.0 cm following e.g. the Tscherning and Rapp degree variance model (Vergos et al., 2014). So that error should be accounted for in the final estimates and can be probably reduced if proper the contribution of topography is taken into account, e.g., through an RTM model, in the $\hat{W}_0^{LVD}$ estimation.

**Figure 3**

**Figure 4**

**Figure 5**

A final interesting point comes from the comparison of the std of the height residuals with and without the linear height dependent parameter. The original std of the differences between the GPS/Levelling geoid heights and EGM2008 (to its $n_{max}$) is at the 0.24 m level. When the linear height-dependent parameter is not included in the adjustment, then the std of the mean residuals is at the 0.26 m, so that their difference of 2 cm m is very close to the EGM2008 commission error (2.8 cm) in the $\hat{W}_0^{LVD}$ estimation. On the other hand, when the $\hat{\lambda}$ and $\hat{W}_0^{LVD}$ parameters are estimated simultaneously, the std of the height residuals drops to the ~0.21 m level for the most reliable adjustment models $p_i=1$, , $p_i=1/(H_i)$ and $p_i=1/(H_i^{0.5})$. The latter is another indication that the so-determined $\hat{W}_0^{LVD}$ estimates are indeed robust, since the EGM2008 performance is improved by ~3 cm. In order to minimize the influence of the EGM2008 commission error to the $\hat{W}_0^{LVD}$ estimation, improved GOCE-based GGMs should and will be investigated in the future.

# 4. Conclusions

A preliminary determination of $W_0$ for Argentina is carried out considering a terrestrial network of BMs with collocated levelled heights $H$ and ellipsoidal heights $h$. A strong correlation with height is evident for BMs of higher elevations a height dependent parameter is introduced in the adjustment for $\hat{W}_0^{LVD}$ estimation. The best estimates achieved are those with $p_i=1/(H_i)$ and $p_i=1/(H_i^{0.5})$ with the height dependent parameter (Table 4), meanwhile the estimation with $p_i=1/(H_i^2)$ is problematic, given the biased residual heights. Any of these two solutions can be used in fact to provide the zero-level geopotential for Argentina, while if a choice would have to be made, then that would be the one with $p_i=1/(H_i^{0.5})$, i.e., 62 636 853.9 $m^2s^{-2}$.

Further investigations and the possibility of repeating this study using better input data, like proper physical heights, the original leveling traverses and GOCE/GRACE based GGMs, are still needed to improve the LVD analysis over Argentina.

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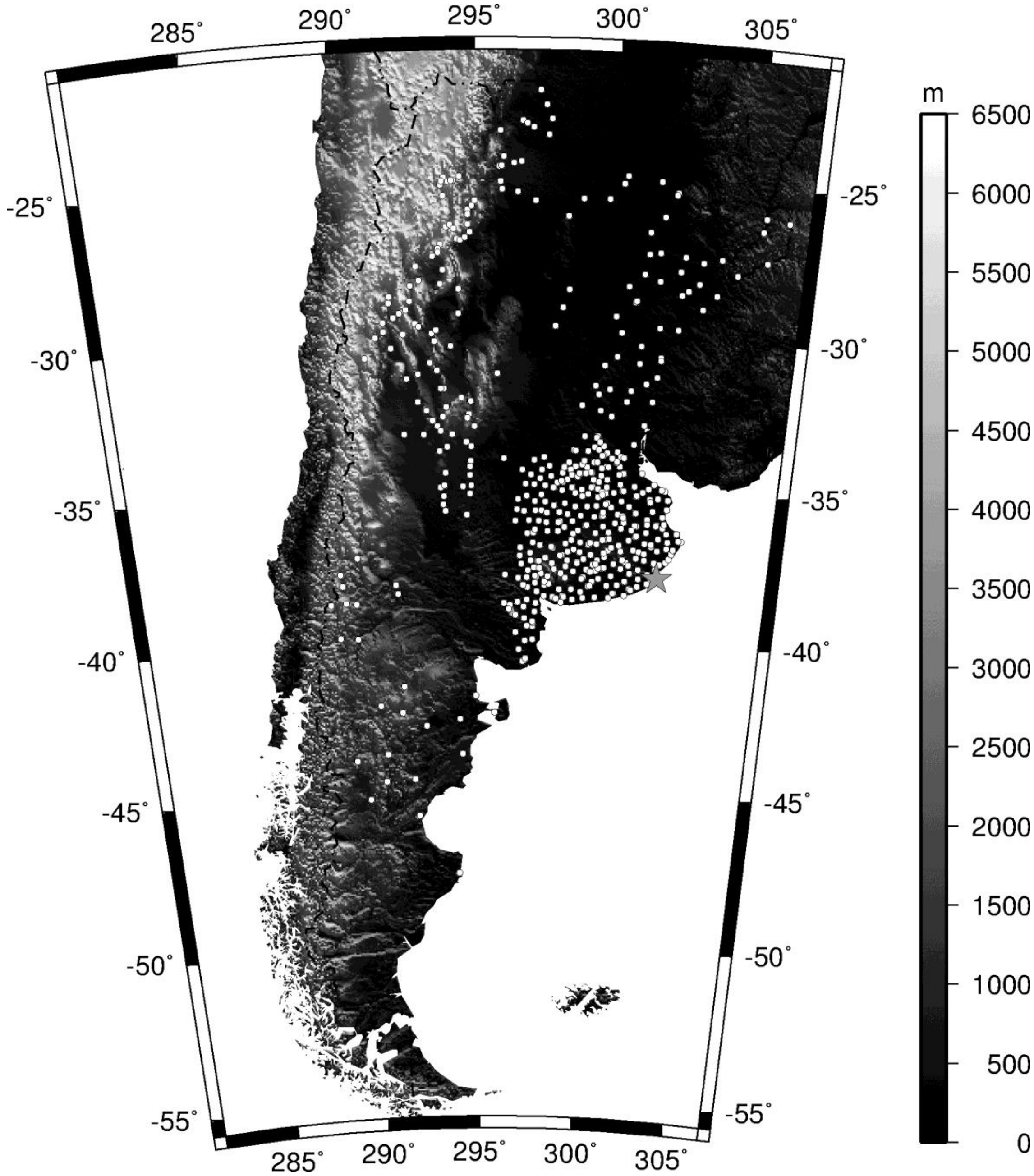
**Fig. 1:** Geographical distribution of GPS/Levelling BMs in Argentina.

**Fig. 2:** Heights residuals of the un-weighted solution with no height dependent parameter.

**Fig. 3:** $W_0^{LVD}$ variations from the un-weighted and the weighted LS adjustment (with height dependent parameter estimation).

**Fig. 4:** Differences between the $W_0^{LVD}$ variations between the un-weighted and the weighted LS adjustment (height dependent parameter estimation).

**Fig. 5:** Residual heights computed from the un-weighted and the weighted LS adjustment (height dependent parameter estimation).

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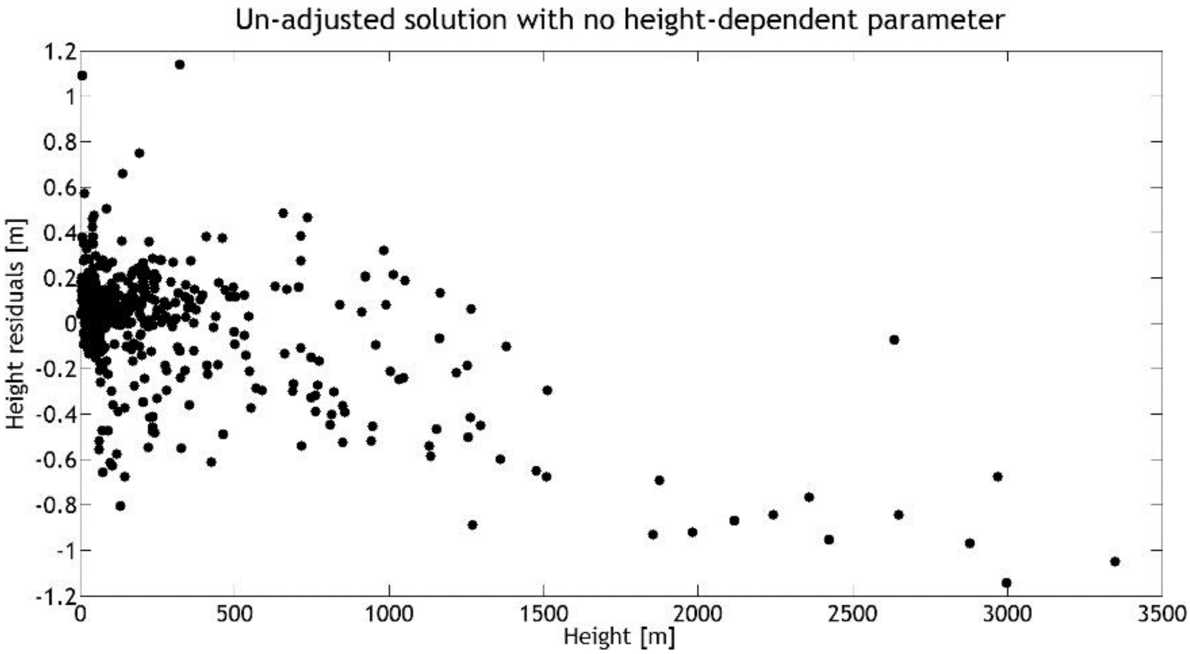



**Fig. 2:** Heights residuals of the un-weighted solution with no height dependent parameter.

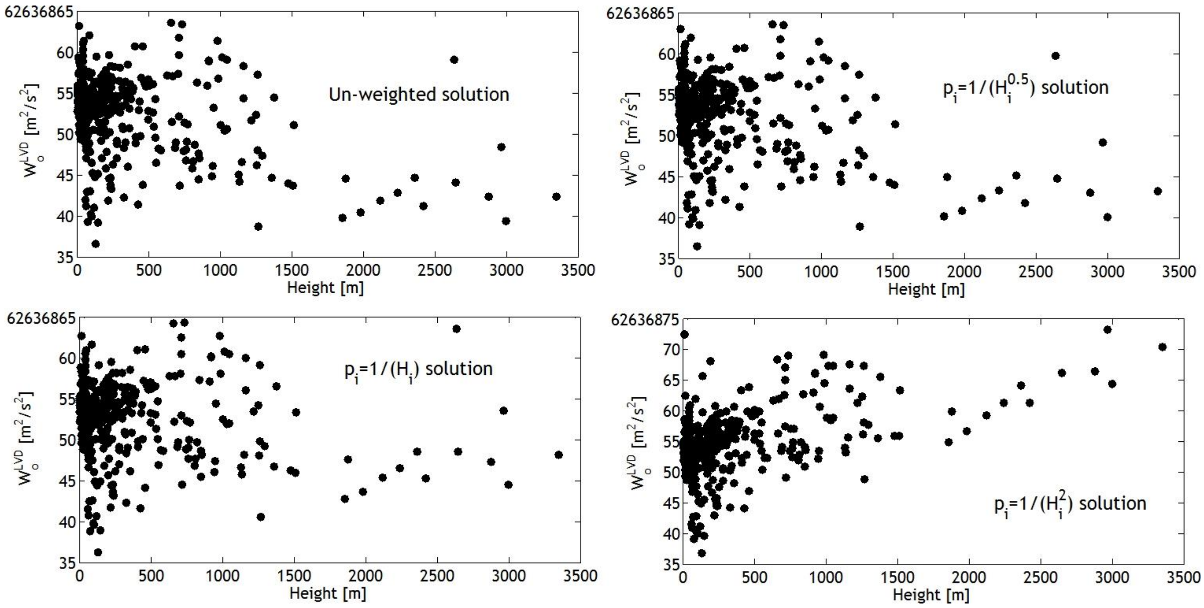



**Fig. 3:** $W_0^{LVD}$ variations from the un-weighted and the weighted LS adjustment (with height dependent parameter estimation).

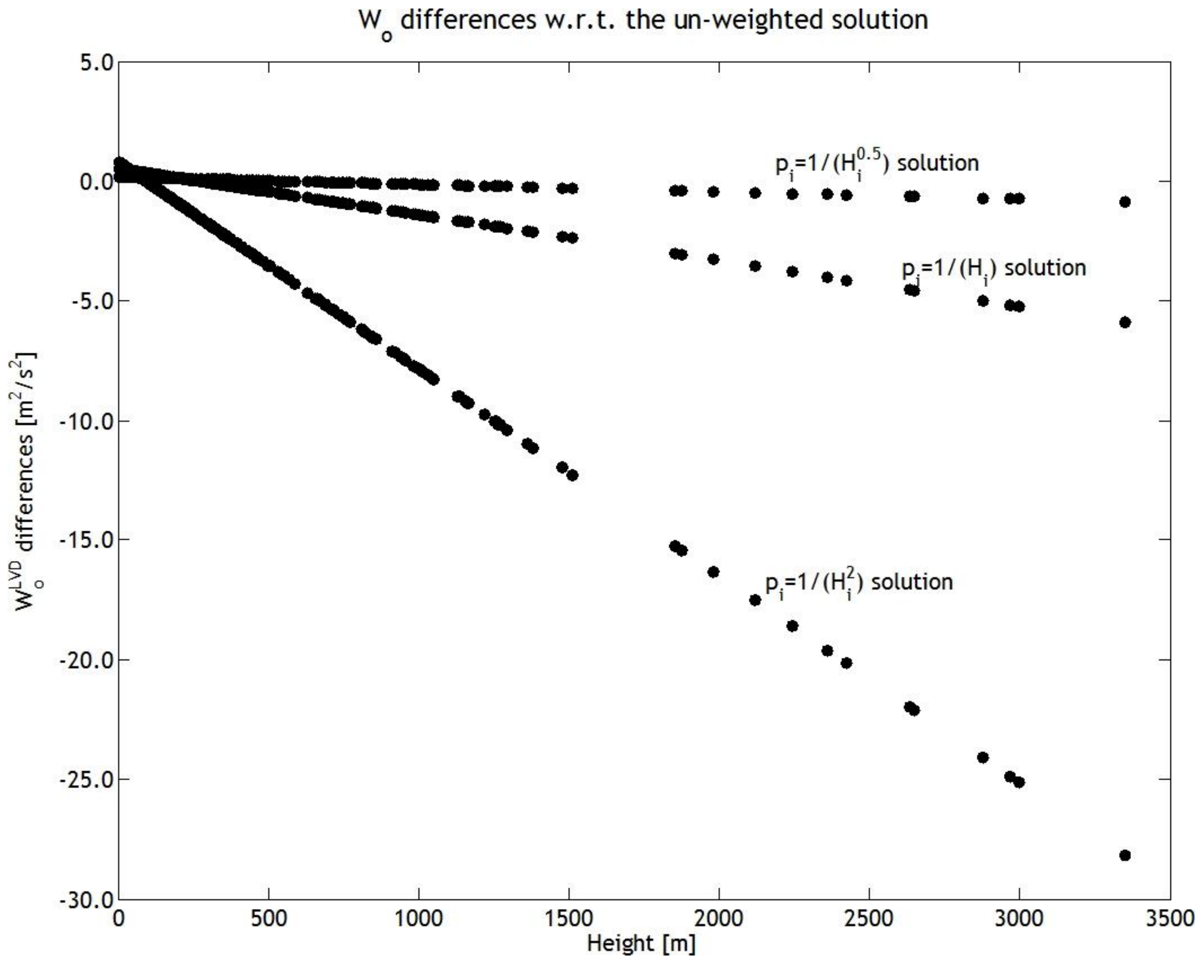
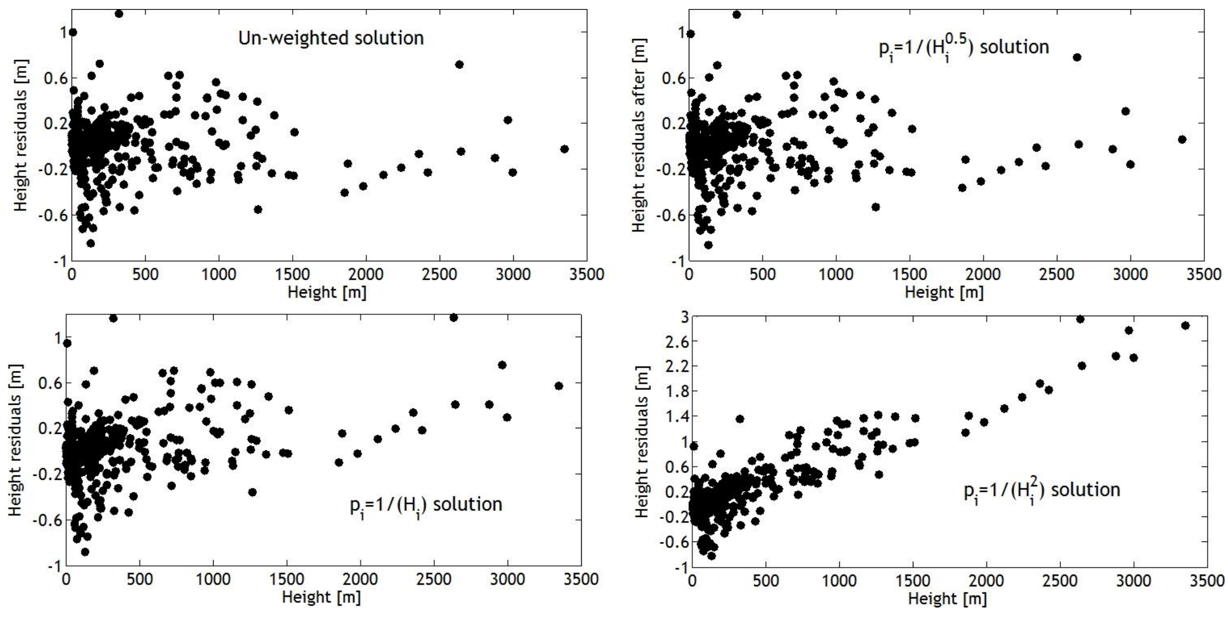



**Fig. 4:** Differences between the $W_0^{LVD}$ variations between the un-weighted and the weighted LS adjustment (height dependent parameter estimation).

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