Analysis of co-located measurements made with a LaCoste&Romberg Graviton-EG gravimeter and two superconducting gravimeters at Strasbourg (France) and Yebes (Spain)

J. Arnoso[1], U. Riccardi[2], J. Hinderer[3], B. Córdoba[4], F.G. Montesinos[5]

(1) Instituto de Geociencias (CSIC, UCM). Madrid, Spain.
(2) Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse (DiSTAR). Università Federico II di Napoli. Naples, Italy
(3) Institut de Physique du Globe de Strasbourg (UMR 7516 CNRS, Université de Strasbourg/EOST). Strasbourg, Cedex, France.
(4) Instituto Geográfico Nacional. Observatorio de Yebes, Spain.
(5) Facultad de Matemáticas. Universidad Complutense de Madrid. Spain.

Corresponding author
Jose Arnoso
Instituto de Geociencias (CSIC, UCM)
Facultad de Ciencias Matemáticas
Plaza de Ciencias, 3
28040. Madrid. Spain
email: arnoso@ucm.es
Tel. +34 91 3944589

Abstract

Two experiments of intercomparison between the LaCoste&Romberg Graviton-EG1194 spring gravimeter and the superconducting gravimeters SG-026 and OSG-064, operating respectively at J9-Strasbourg (France) and CDT-Yebes (Spain), were analyzed. The main objective was to check the instrumental response of the spring meter, both in amplitude and phase as well as its time stability. A general conclusion is that normalization factors have been obtained with a similar ratio for main diurnal constituent O1 at both observing sites. The accuracy of scale factors was determined at the level of 0.03% (at J9-Strasbourg) and 0.1% (at CDT-Yebes). For the semidiurnal constituent M2, slight differences were found at J9-Strasbourg, which would require further investigations. Site effects were also demonstrated by considering the different response of the spring gravimeter to tilts and atmospheric pressure variations at both sites.

Keywords: Gravimetry; Spring gravimeter; Superconducting gravimeter

1. Introduction

Continuous gravity measurements made with spring type gravimeter are commonly used for different geophysical aims. For instance, the 4D (spatio-temporal) monitoring of the gravity

changes in active volcanic areas can be efficiently done with spring gravimeters to investigate sub-surface magmatic displacements and/or density changes in volcanic regions. (see, for instance, Berrino et al., 2006; Amoruso et al., 2008; Carbone et al., 2007; Battaglia and Hill, 2009). Further, accurate tidal studies are needed to validate body and ocean tide models to obtain reliable surface gravity measurements for the investigation of crustal structure models (e.g., Arnoso et al., 2001; Baker and Bos, 2003; Montesinos et al., 2003; 2006; Gottsmann and Battaglia, 2008). In recent years, gravimetry was also applied to hydrology to investigate mass transport due to variations in soil moisture and groundwater levels. All those scientific targets require well calibrated instruments for obtaining reliable results from high precision gravity monitoring.

In this study, a comparative analysis is made with the LaCoste&Romberg Graviton-EG1194 (hereafter referred as EG1194) spring gravimeter and two superconducting gravimeters. The EG1194 is being used to validate body and ocean tide models as well as to investigate time gravity changes in the Canary Archipelago (Spain), which is an active volcanic area (Arnoso et al., 2011). Thanks to the support provided by the gravimetry observatory J9 of Strasbourg (IPGS-EOST, France) and the gravimetry laboratory of the Center for Technological Developments (CDT), Yebes-IGN (Spain), two experiments of intercomparison were conducted between the EG1194 with the respective superconducting gravimeter (SG) operating at those sites. The experiments were aimed at checking the instrumental response of the spring meter, both in amplitude and phase as well as its time stability. SG is the most precise instrument nowadays available to study the time variation of gravity, and attain the maximum level of temporal stability (Hinderer et al., 2007). Moreover low instrumental drift rates allow SGs to achieve the most accurate tidal parameters as well as reliable temporal gravity changes (Imanishi et al., 2002; Crossley et al., 2005; Kroner et al., 2005; Meurers, 2012). Therefore, co-located gravity observations of spring gravimeters with well calibrated SG offer the best possibilities to compare the tidal parameters and thus to establish the corresponding normalization factors.

In this paper, about 3 months of co-located gravity records made by the EG1194 at J9 site with the SG GWR Instruments C026 (hereafter SG-026), and at CDT site with the SG GWR Instruments 064 (hereafter OSG-064) are analyzed. The respective observation periods were from June 23, 2011 to October 10, 2011 (J9) and from July 11, 2012 to October 15, 2012 (CDT). Results are presented in terms of accuracy and precision of the tidal parameters obtained in both sites.

2. Observing sites and gravity data

The first co-located measurements were made at the French J9 gravimetric observatory located about 15 km far from Strasbourg city (Fig. 1), during 2011. The observing site is housed in a bunker built at the end of 19th century. Two SGs have been operating there since 1987 and the current SG, compact model by GWR Instruments number SG-026, is running since 1996 (Hinderer et al., 2007). A second co-located observation session was made during 2012 at the gravimetric observatory CDT owned by the National Geographic Institute (IGN) of Spain. This observing site is located in Yebes (Fig. 1), 70 km far from Madrid. The gravimetric laboratory in the CDT was specially designed to control the thermal behaviour of the building (double chamber with air conditioning system in the external one) and has several isolated concrete pillars where gravity measurements can be made independently. The SG, model GWR Instruments number 064 (hereafter OSG-064), is operating there since year 2011, and became part of the Global Geodynamics Project (Crossley and Hinderer, 1995) and also of a Spanish-Portuguese network of geodetic fundamental stations devoted to monitor crustal dynamics of Eurasia, Africa and North America tectonic plates (Calvo et al., 2012). Table 1 summarises the coordinates of the observing sites and the respective period of observations.

The two SGs considered for the intercomparison with the EG1194 attain a very high standard for the calibration, thanks to the regular checks of their scale factors by means of co-located absolute gravity measurements (Rosat et al, 2009; Cordoba et al., 2013).

The Graviton-EG improves previous LaCoste&Romberg models G and D spring gravimeters, being specifically designed for continuous recording as well as making most of operational functions automatically handled (LaCoste&Romberg LLC, 2002). This type of meters has a resolution of about 1 μGal ($1μGal = 10$ nms^{-2} = 10^{-8} ms^{-2}) and can achieve an accuracy of around 0.1 μGal, which allows to study tidal phenomena (Baker and Bos, 2003; Pálinkás, 2006). The EG1194 was acquired in 2005 and is periodically calibrated on the calibration line Madrid-Valle de los Caídos (Vieira et al., 1992), attaining a repeatability of about 0.1% in the scale factor.

3. Disturbing effects and instrumental drift on Graviton-EG1194

Spring gravimeters commonly exhibit a strong and irregular drift, often requiring nonlinear functions to be modelled. In the experience we reported here, we detected different behaviour of the EG-1194 in response to the disturbing effects peculiarly characterizing each observing site. These effects could deteriorate the quality of the collected data and hide real gravity changes produced by geodynamical phenomena (Riccardi et al., 2011), as for instance gravity

signals from volcanic and hydrological processes (Carbone et al., 2007; Creuzfeldt et al., 2010). In this study, we are going to consider only the effects produced by instrument tilts and atmospheric pressure variations. Those effects are investigated after subtracting other known signals from the gravity time series, namely solid Earth and ocean tides, the gravity-pressure admittance and a linear component of the instrumental drift. In case of J9-site, and for the total period of observations of about 3.5 months, the linear trend of the drift has a value of 4.0 ± 0.001 µGal/day. Same computation at CDT-site leads to a variation of about 3.9 ± 0.003 µGal/day, for a period of 3 months, which results in a good agreement at the two observing sites.

The observation noise produced by changes in the ocean weather (microseisms) can also influence the gravimetric measurements (Longuet-Higgins, 1950). Papp et al., (2012) performed a joint analysis of gravity data and ocean weather parameters of the North Atlantic and North Sea regions. Their results show that the impact of both the near coast waves hitting directly the coastline of the North Sea (< 1500 km) and also more distant events (> 3000 km) can disturb the gravity observations at the level of 1 µGal (10 nms^{-2}) even in the middle of European continent. Furthermore, the changes in the microseismic noise at gravimetric observatories can significantly be increased from time to time, and even distinguished between summer and winter periods, the latter may even cause the dispersion of the noise level increases up to ± 4−5 µGal on noisy days. In our case, during the period of observations at two observing sites, the daily average noise for EG1194 was stable, of around 2 µGal and no remarkable changing in time was observed. Besides, various studies of noise levels of SG gravimeters recording at J9-Strasbourg have been carried out in the framework of the Global Geodynamics Project (GGP) (see e.g., Rosat et al., 2004; Rosat et al., 2011). Córdoba and Serna (2013) in a similar study based on SG-026 gravimeter data reported that noise levels at CDT-Yebes observatory was found similar to other GGP stations. Recently, Rosat et al., (2014) have performed an interesting comparison of the noise levels for various gravimeters (spring and superconducting) recording at J9-Strasbourg observatory during past decades, including the recent observations made by Graviton-EG1194. The results for Graviton at subseismic band (it includes the tidal frequency band) coincide well with noise levels of other spring gravimeters recording at this site (Scintrex and gPhone), whilst is 10 times noisier than the SG-C026 at seismic frequency band.

Tilt effect

As the spring or cryogenic relative gravimeters sense the change of the gravity acceleration, tilting of the instrument leads to apparent gravity changes and even affects the instrumental drift. Unlike the SGs, the spring gravimeters are not equipped with an active tilt feedback system to automatically keep the meter properly levelled along time (Riccardi et al., 2009). Then, the operator has to reduce the tilt effect as an ordinary signal pre-processing. The Graviton EG1194 is equipped with electronic levels that allow levelling the meter at the time of the installation through its electro-mechanical legs. However, the respective scale factors for each level were not provided by the manufacturer. Thus, a critical point is to calibrate their output to properly monitor the time tilt changes. The level outputs from the EG1194 have been calibrated using a platform of known base-length and equipped with micrometer heads, which allow tilting of the gravimeter. Then, a linear least-square fit between induced tilts and level units (see Figure 2), based on the model

$$Y = a + bX \qquad (1)$$

has provided us the corresponding scale factors. Table 2 lists the result of the fit thus obtained for each electronic level.

A classical parabola test was also performed for testing the position of the levels to set the gravimeter into the minimum sensitivity position for tilting (Figure 2).

The equivalent gravity effect due to the deviations of the meter from the vertical can be computed according to the expression (Riccardi et al., 2009; 2011):

$$\Delta g = g_0 \left[1 - \cos\phi_X \cos\phi_Y \right] \qquad (2)$$

where g_0 is the local gravity, Φ_X and Φ_Y are the calibrated output of the levels, TL and LL, respectively, representing the tilts of the gravity sensor about two horizontal axes (X and Y). Assuming $g_0 = 9.8$ m/s^2 and expressing tilts in radians, one can obtain the dependency of gravity on tilt changes through:

$$\Delta g = -0.49 \times 10^{-3} \mu Gal / rad^2 \qquad (3)$$

During the two experiments we are reporting here we detected peculiar tilt changes in time in the two observing sites. Extremely low tilt changes in time were recorded in J9-Strasbourg,

where the installation pillar resulted to be very stable from the tilting point of view and properly decoupled from the surrounding floor. The observed tilt change was so small, in the order of few tens of microradians, to lead to an equivalent gravity effect amounting to $1 \div 2$ nm/s^2 peak to peak, so it was definitively negligible compared to the observed gravity residuals. The largest tilt signals have been observed in the second experiment at Yebes, where the tilt changes in time reached a level of some hundreds of microradians (Fig. 3) leading to an equivalent significant gravity effect amounting to $50 \div 60$ nm/s^2. The time evolution of such a tilt-induced gravity change showed a typical trend, where fast (few days) and large ($10 \div 20$ nm/s^2) gravity changes are overlapped by a long term drifting variation.

Air pressure effect

Atmospheric pressure gives rise to perturbations on ground based gravity observations that must be modelled and removed for studying gravity signals from different sources (e.g., Crossley et al., 1995; El-Gelil et al., 2008). In this study, the barometric admittance was empirically calculated based on a single scalar coefficient, coming from a least squares fitting between local air pressure and gravity measurements. The tidal analysis software packages ETERNA 3.4 (Wenzel, 1996) and VAV (Venedikov et al., 2003) were used to obtain the respective regression coefficients for comparison.

Figure 4 displays the residual gravity obtained by EG1194 at CDT-Yebes site. It has been computed after subtracting known modelled signals from observed gravity records, that is,

$$g_{residual} = g_{observed} - g_{modeled} \qquad (4)$$

Thus, the contributions from atmospheric pressure (using an admittance factor of -3 nms^{-2}/hPa) and tides (solid Earth and ocean) have been subtracted from the recorded gravity series. Similarly, other possible disturbances as meteorological effects (air temperature, humidity), polar motion, tilt-induced effect and instrumental drift, could be considered (see, for instance, Hinderer et al., 2007). Besides, in Figure 4, a linear drift component (trend) has been calculated through a least-squares fit and then subtracted from residual gravity. Following the procedure described above, the gravity effect produced by level excursion has been modelled and, likewise, eliminated from the residual gravity curve (bottom plots at Figures 4a, 4b). Then, a clear correlation of the remaining residual gravity with atmospheric pressure is evidenced. Usually, at mid-latitudes the meteorological systems are dominated by front dynamics,

producing the long term trends in the air-pressure signals inversely correlated with gravity (Boy et al., 2002; Ray and Ponte 2003).

At CDT-Yebes, the single admittance coefficient calculated through the tidal analysis process is found 4.5 times larger than usual, as a consequence of a not complete reduction from residual gravity of all disturbing effects as, for instance, hydrology and/or instrumental drift. The response of spring gravimeters to air pressure variations differs from that of the superconducting gravimeters. Thus, the sealing of the sensor can induce abnormal response to air pressure changes (e.g. Arnoso et al. 2001, Meurers, 2002; Riccardi et al. 2011). In J9-Strasbourg site, however, the effect of air pressure on tidal gravity variations computed using ETERNA 3.4 and VAV, allows obtaining the respective coefficients -3.75 ± 0.18 nms^{-2}/hPa and -3.50 ± 0.15 nms^{-2}/hPa, both significant with respect the errors and within earlier determinations of the response of EG1194 to air pressure variations. A more exhaustive study of such effect on EG1194 made at J9-Strasbourg by Rosat et al, (2014-submitted) indicates that its response to atmospheric pressure changes has a non-linear phase behavior at periods larger than 1 hour, and although the coherence analysis made was slightly weak, the atmospheric pressure deconvolution is successful in reducing the spectral noise below 10^{-4} Hz.

4. Tidal analysis

It is well know that Earth tides contain information about internal structure of the Earth, can be used to remove tidal variations from other measurements and are a source of noise in other geophysical phenomena (Wang, 1997; Agnew, 2007). The goal of tidal measurements is to determine the response of the Earth to the tidal force through an observing instrument and using a modelling system. Basically, tidal analysis consist of finding the amplitude ratios (delta factors) and phase differences, for the different tidal waves and/or grouping of waves, between observed amplitudes and phases and their respective theoretical calculations based on a specific tidal potential development (e.g., Tamura, 1987, Hartman and Wenzel, 1995). In addition, comparisons of Earth response can be made with regard to theoretical solid Earth tide (or body tide) models, which nowadays are modelled using an average radial symmetric Earth with density and elastic profiles based on the Preliminary Reference Earth Model (PREM) of Dziewonski and Anderson (1981). The model DDW of Dehant et al. (1999), which takes also the effects of the nutation and ellipticity of the Earth into account, is widely used. In the present paper, we use results from harmonic analysis of Earth tides observations, that is, the modelled tides, as a calibration signal. Because SG gravimeters can reach high accuracy to attain the tidal gravimetric factors and phases of the harmonic constituents, co-located measurements made

with spring gravimeters do provide a check of the respective tidal parameters and, accordingly, allow to establish the corresponding normalization factors.

Although there exists different Earth tidal analysis methods, the most usual approach applies a harmonic analysis formulation and the tidal signal is modelled as a set of sinusoids at specific frequencies related to astronomical parameters. The fundamental signal in the tidal data is composed by waves with known periods, so a least-squares fitting is commonly used to solve the observation equations and determine the unknown parameters. Most differences between tidal analysis methods appear in the formulation of the observation equations, in the filtering procedure and in the error estimation of the parameters of the tidal waves, i.e., the unknowns (Wenzel, 1997; Ducarme et al., 2006, Agnew, 2007).

Before the tidal analysis process of the data series, the preparation of the data and a routine pre-processing of the gravity signal to remove spikes, jumps and other short term disturbances were performed using the software TSOFT (Van Camp and Vauterin, 2005). Although hourly values are quite enough for Earth tides analysis purposes, digital data acquisition systems can gather high sampling rates, being minute sampled data the most widespread option. In case of SG gravity data, a more specialized processing dealing with high sampling rates (usually at 1 s intervals) it is also required, as many of these instruments are operating in the framework of the Global Geodynamics Project (see e.g., Crossley et al.,1999). This fact, for instance, makes possible that the microseismic noise produced by ocean weather processes (typically ranging from 1s to 20s) can be present in the records. However, even if higher sampling rates from 1 to 10 seconds are available, a decimation to get one minute sampled data is applied using a zero-phase filter, so high frequency noise is considerably smoothed. Recent methods of pre-processing of tidal gravity data are based on *remove-restore* technique. A model of tides and air pressure effect is subtracted from the observations and the corrections are thus applied on the residues. The corrected gravity observations are finally recalculated adding the model of tides and the air pressure effect to the residues. A more detailed description of the complete data processing can be found in Hinderer et al., (2007).

Nowadays, the more extended tidal analysis methods based on the least squares approach are ETERNA (Wenzel, 1996) and VAV (Venedikov et al., 2003) packages. BAYTAP-G method (Tamura et al., 1991) is a different development and uses a Bayesian model in the analysis to get nonlinear estimates of the tidal parameters. In our case, the tidal analysis was carried out by the least squares harmonic analysis method using the software packages VAV and ETERNA (release 3.4), and considering Tamura (1987) and Hartmann-Wenzel (1995) tidal potentials, respectively. Although the methodology of VAV and ETERNA packages is similar, the main

differences deal with the filtering process, the calculation of the precision of the tidal parameters, the model of the drift as well as the residual gravity (Dierks and Neumeyer, 2002; Ducarme et al., 2006).

ETERNA uses a data format that was officially adopted by International Centre for Earth Tides (ICET), can process data with various sampling rates, for instance 1 minute or 1 hour. ETERNA has available different tidal potential developments, can process observations from all tidal components (gravity, tilt, strain,..) and can handle data containing gaps. Also, it uses additional channels containing meteorological parameters as inputs to evaluate their influence on the tidal data, through respective linear regression coefficients.

VAV program can deal with data of any time step and unevenly spaced data, can calculate estimations (and eliminate) of the effect of other disturbing signals (air pressure, temperature, e…) through the own filtering process, and the drift can be obtained according to different possibilities (low power polynomials) within the filtered data. VAV program has also the possibility of increasing the precision of the estimation of the tidal parameters by selecting a threshold level of significance, for a selected probability confidence interval, to be compared to the corresponding residuals of the least squares adjustment within the tidal analysis process. This test of the residuals can be iterated recursively, even choosing different thresholds, allowing localization of anomalous data that can be omitted from the tidal analysis.

We have obtained comparable results with the associated RMS errors for the two softwares ETERNA and VAV. Table 3 shows the observed gravimetric amplitude factors (delta) and phases for the main harmonic components. Comparison of EG1194 to SGs gives a similar ratio of gravimetric delta factors as well as phase differences for O1 tidal wave at both observing sites. Also for the same wave, in case of J9-Strasbourg a scale accuracy of 0.03% is obtained, whereas in case of CDT-Yebes the scale accuracy is of 0.1%. The last result could be due to some instabilities of the internal clock of the EG1194 at the end of the observation span, as mentioned in the previous section. Phase differences for O1 are coherent at both observing sites, amounting to about 30 seconds. The large discrepancy ($\approx 0.2\%$) in the M2 tidal band, obtained at J9-Strasbourg, should require further investigations. Time stability of the delta factors has been tested with the software VAV, by performing tidal analyses of 30 day segments shifted by 15 days each. Figure 5 shows the time variations of gravimetric factors for EG1194 and OSG064, for O1 and M2 tidal harmonics. It has not been possible to investigate the time stability of the delta factors at J9 because of the data gaps, all produced by episodic malfunction of an internal power card of EG1194 during the experiment.

It is worth to mention the difference of about 3% found in the observed gravimetric factors (both for EG1194 and SG gravimeters) for M2 tidal wave, at both observing sites (see Table 3). This is due to the fact that a gravimeter observes the gravitational attraction of the Moon and Sun as well as the ocean tide loading (OTL). To a greater extent, the OTL effect is produced by the direct gravitational attraction of the varying mass of the ocean tide and by the change of gravity produced by the vertical displacement over the observing site due to the weight of ocean tides. Also, the deformation of the ocean floor induces a change in the Earth's gravity field caused by the mass redistribution inside the solid Earth. Following the procedure of Farrell (1973), OTL effect can be computed in practice by convolving global ocean tide models with appropriate Green's functions, which depend on the crustal and upper mantle structure of the Earth (see, e.g., Baker and Bos, 2003). Thus, a simple evaluation of the influence of the ocean tide on the tidal gravity observations made at both observing sites, without including a detailed study considering different global ocean tide models and/or even different Green's functions, yields an amplitude and phase for harmonic M2 of 3.9 μGal and 99º.2, respectively, at CDT-Yebes. In the case of J9-Strasbourg, the values are, respectively, 1.6 μGal and 61º.6. That is, OTL effect is about 2.5 times larger in amplitude at Yebes than Strasbourg, for harmonic M2. If we correct from OTL effect the observed gravimetric factors for this tidal constituent, the result obtained for EG1194 gravimeter is 1.1620 at CDT-Yebes and 1.1595 at J9-Strasbourg. That is, the difference between corrected gravimetric factors is about 0.2%, which is considerable lower than the value obtained for the observed gravimetric factors. Similar results can be reached in case of SG gravimeters for harmonic M2 at both observing sites.

5. Conclusions

As other spring gravimeters, EG1194 clearly exhibits non-linear behaviour of the residual gravity, which is basically influenced by several disturbing effects (meteorological, ground tilts,..). The experiment reported here demonstrates that co-located gravity records at sites instrumented with well calibrated SGs is a powerful tool to check the instrumental response both in phase and amplitude of spring gravimeters, routinely used for field record and measurements. Moreover, this experience claims for a careful reduction of some site dependent effects as the tilt changes in time could affect the time evolution of gravity residuals, preventing the detection of some long-term gravity changes of geophysical interest. Concerning the behaviour of EG1194 at tidal frequencies, results for major harmonic constituents O1 and M2 were determined with suitable accuracy, and present similar values of the mean square deviations at both observing sites, except for semidiurnal band, which shows errors slightly

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higher at J9-Strasbourg. Besides, the ratio of delta factors and phase differences are good enough to establish accurate normalization factors for EG1194. It must be pointed out that a deviation of about 3% in gravimetric factor observed at CDT-Yebes and J9-Strasbourg was found for harmonic M2, for both EG1194 and SG gravimeters. Such deviation becomes negligible after suitable OTL correction. Finally, comparisons made using two different software packages, ETERNA 3.4 and VAV, did not exhibit significant differences in the tidal parameters and the respective errors.

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Figure captions

Figure 1. Location map showing the observing sites J9 (Strasbourg, France) and CDT (Yebes, Spain) as well as their respective superconducting gravimeters GWR-C026 and GWR-064, with the Graviton EG1194 meter in the foreground.

Figure 2. Calibration test performed on the levels of the EG1194 gravimeter. (Up) Linear fit obtained to compute the respective scale factors for the longitudinal (left) and transversal (right) levels. The inlets show typical step displacements induced on the level for calibration. (Down) Parabola test used to verify the position of both electronic levels of EG1194, showing the corresponding polynomial fit.

Figure 3. Tilt changes in time observed at Yebes with the two electronic levels (top curves) of the EG1194 and the induced gravity changes (bottom curve).

Figure 4a. (Top) Residual gravity registered by EG1194 at CDT-Yebes and linear fit adjustment of the drift. (Middle) Induced gravity due to variations of the gravimeter's levels. (Down) Air pressure variation and residual gravity (after removing the linear drift and the tilt-induced effect).

Figure 4b. Same as Figure 4a for J9-Strasbourg site.

Figure 5. Time variations of gravimetric factors, from Graviton-EG1194 and Superconducting gravimeters at Yebes site, for harmonic tides O1 and M2.
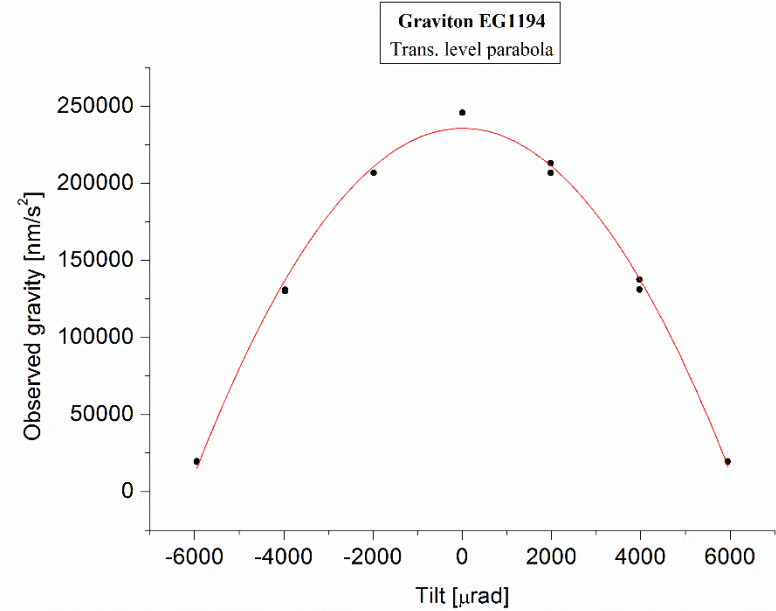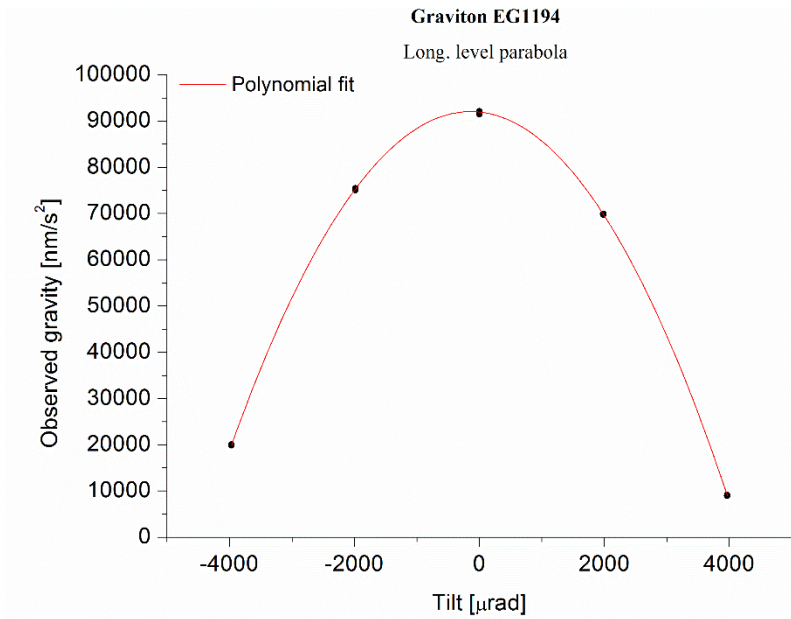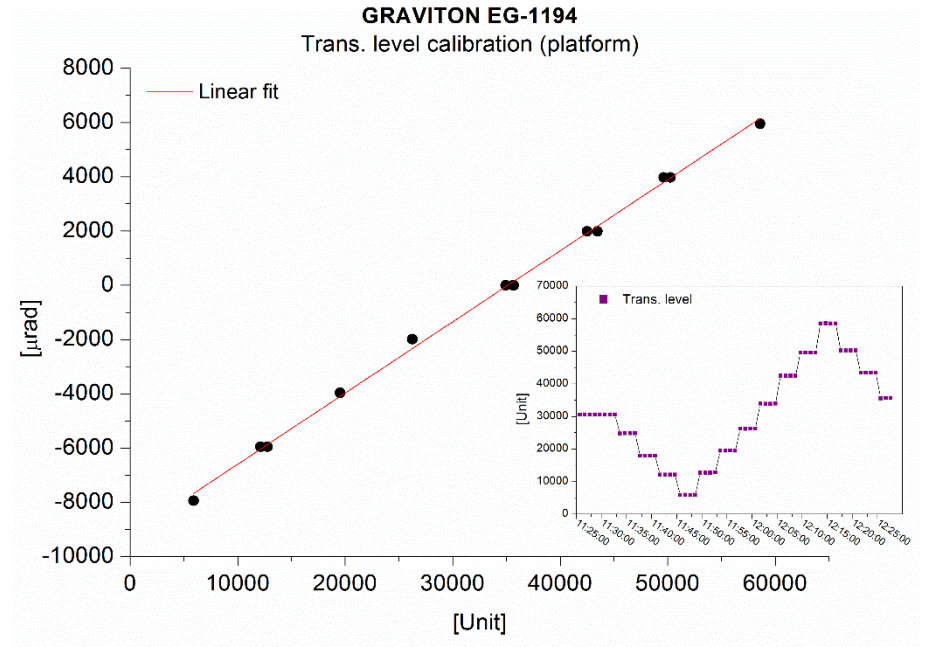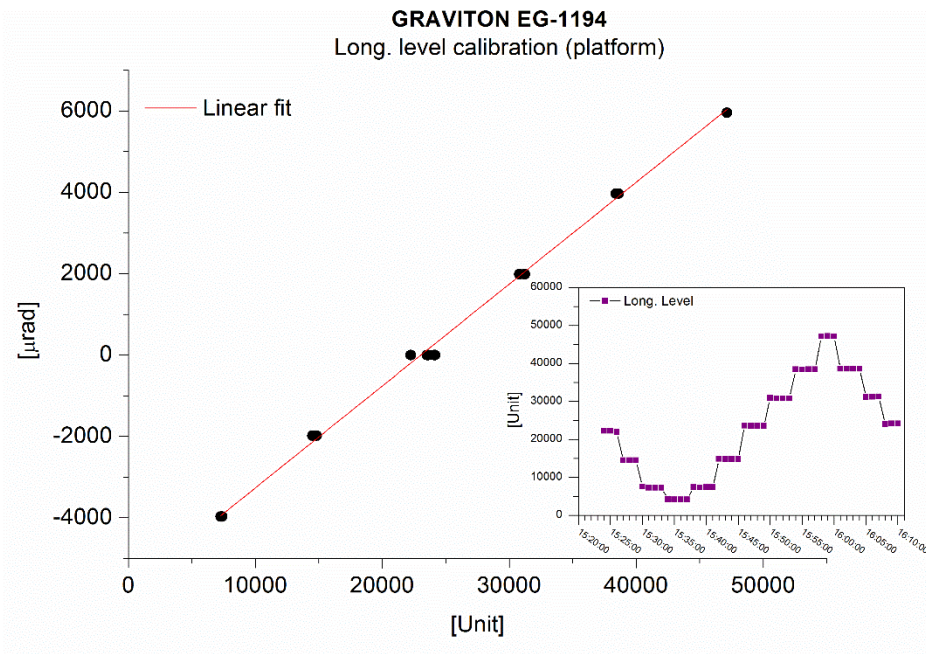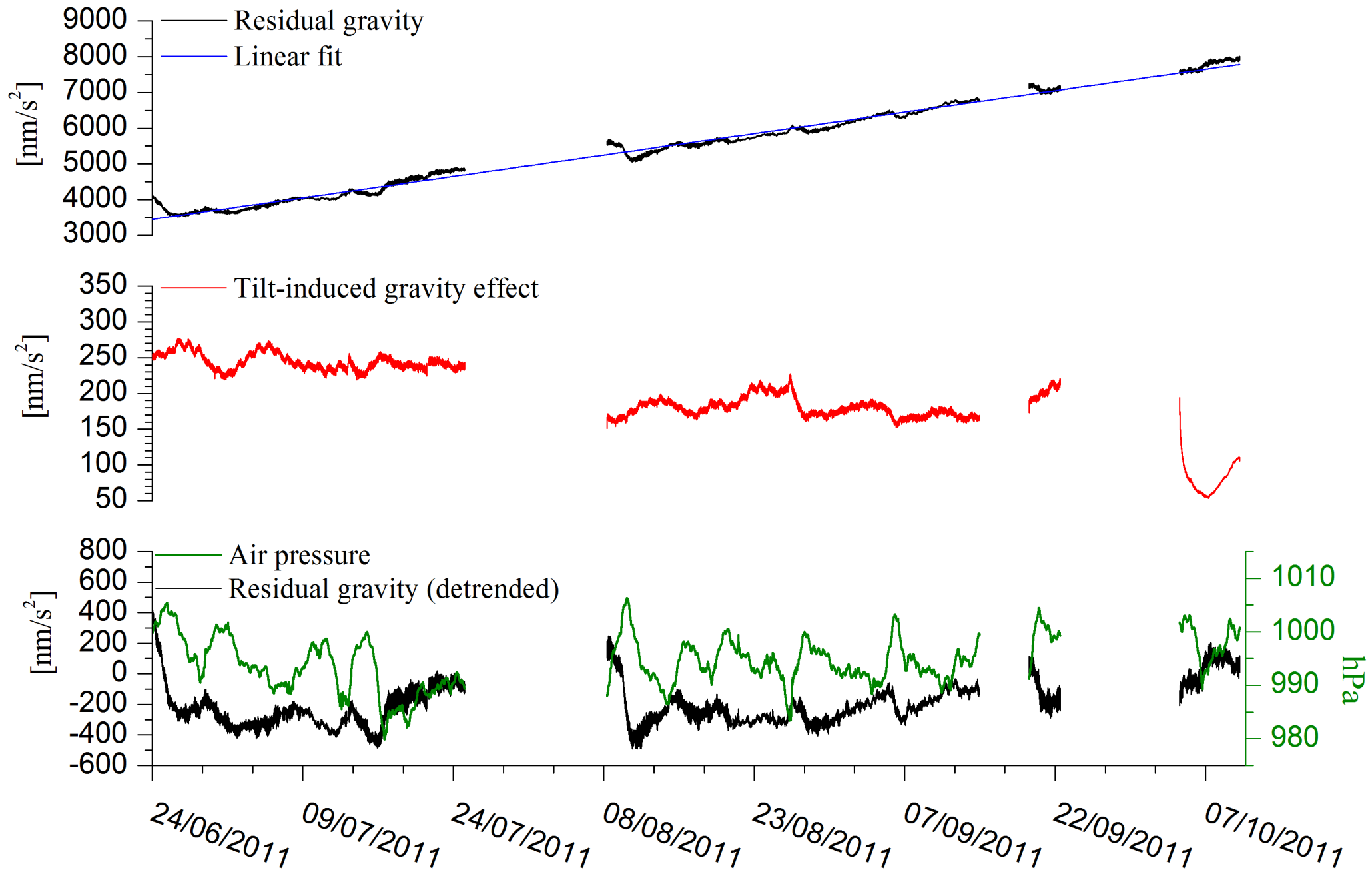
Figure 1

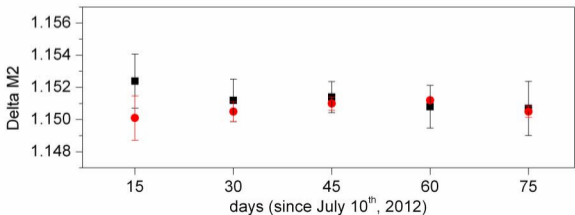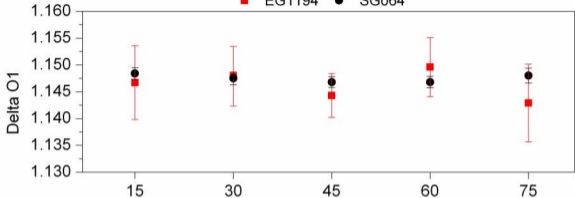**Figure 2**
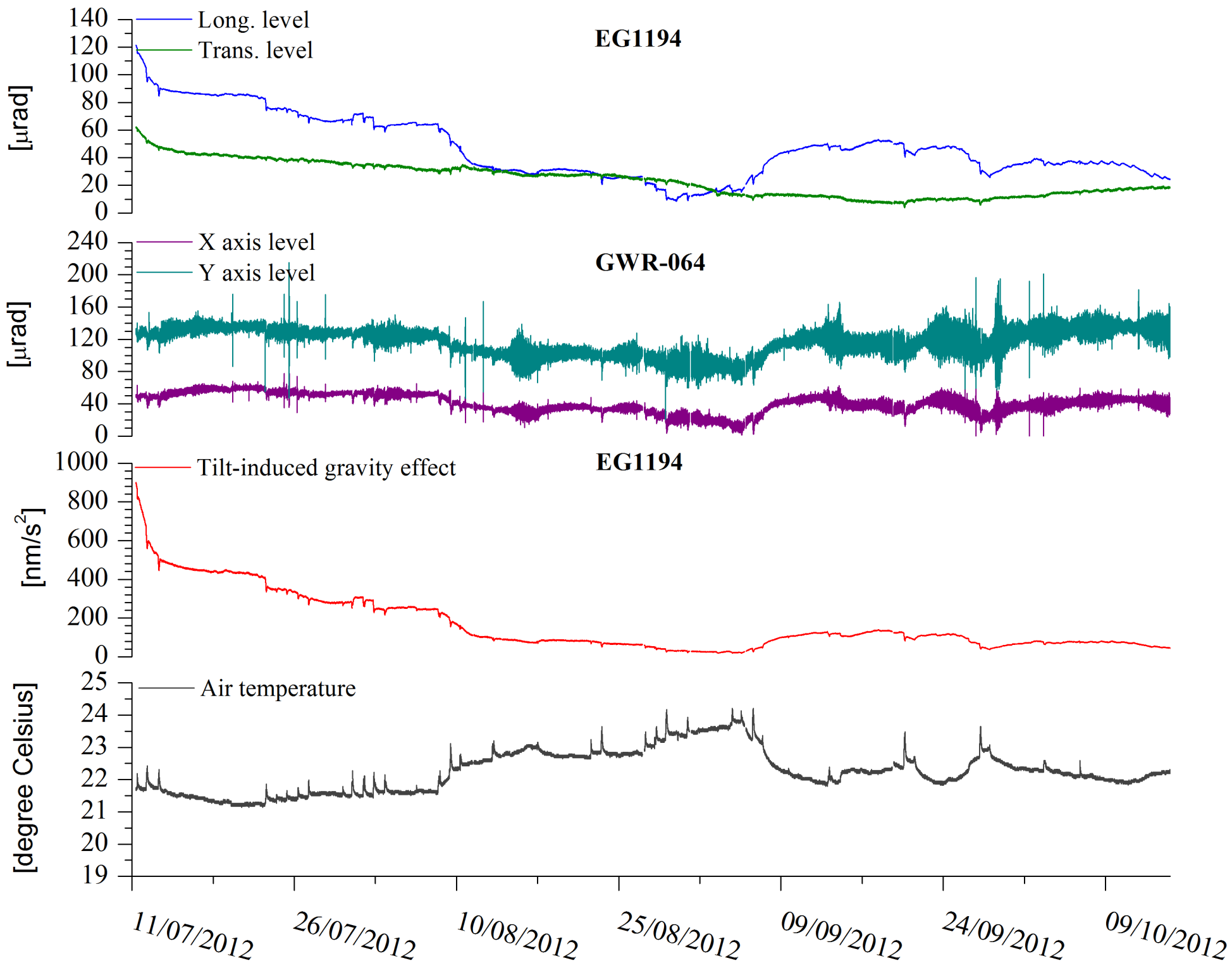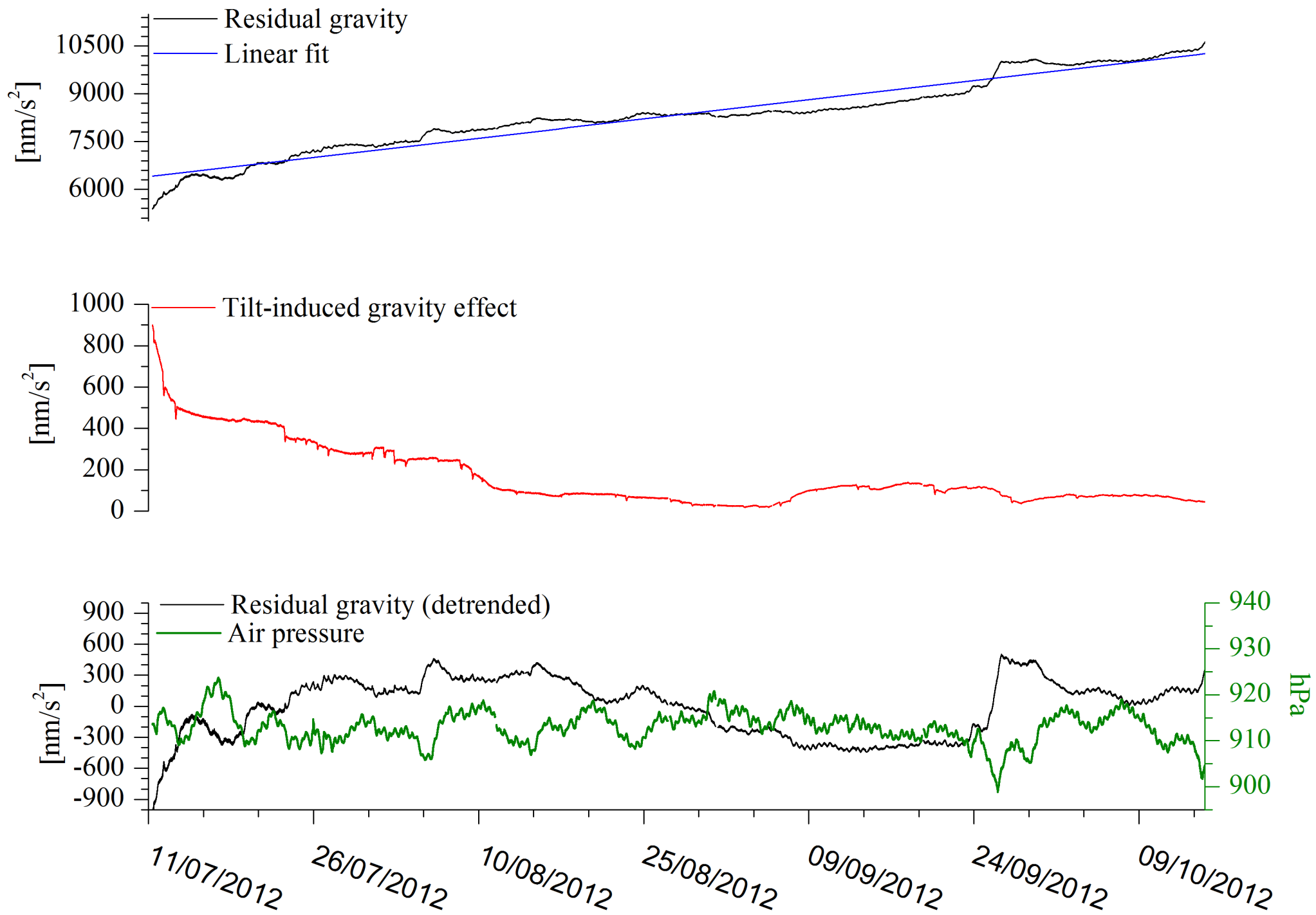
CDT-YEBES

EG1194   SG064

Table 1. Coordinates of the observing sites and observation period. Latitude and longitude are positive in the North and East directions and altitude, in m, is above the sea level. N is the number of days used for tidal analysis.

Table 1

	Latitude	Longitude	Altitude	Period of observation	N
J9-Strasbourg France	48°.622	7°.684	180.0	2011/06/23–2011/10/10	78
CDT-Yebes Spain	40°.524	–3°.090	917.7	2012/07/11–2012/10/15	97

Table 2. Parameters (given in µrad), with their respective standard deviation, and adjusted R-squared of the linear least-square fit computed to attain the scale factors corresponding to each electronic level of the gravimeter EG1194.

Table 2

	a	b	R^2
Longitudinal Level (LL)	-5765.4 ± 46.73	0.2504 ± 0.0017	0.9983
Transversal Level (TL)	-9218.1 ± 0.26	0.2623 ± 0.0021	0.9983

Table 3a. Comparison of results of tidal analysis, in terms of gravimetric amplitude factors (delta), phases (given in degrees, with respect to local theoretical gravity tide; phase lags are negative) and their respective RMS errors from Graviton-EG1194 and SG-C026 gravimeters at J9-Strasbourg site. Ratio SG/EG of gravimetric factors and phase difference is included. Δ is the discrepancy between the respective gravimetric factors.

	EG1194		SG-C026		Comparison at J9-STRASBOURG		
	Delta	*Phase*	*Delta*	*Phase*	*Delta* [SG/EG]	*Δ%*	*Phase* [SG-EG]
O1	1.147 ±0.005	0.24 ±0.22	1.1473 ±0.0005	0.095 ±0.03	1.0003 ±0.004	-0.03	-0.15 ±0.22
P1S1K1	1.143 ±0.003	-0.05 ±0.16	1.1355 ±0.0004	0.31 ±0.02	0.9934 ±0.003	0.7	0.36 ±0.16
M2	1.184 ±0.003	2.6 ±0.13	1.1859 ±0.0002	2. 2 ±0.01	1.0016 ±0.002	-0.2	-0.40 ±0.13
S2K2	1.192 ±0.005	-0.9 ±0.26	1.1883 ±0.0005	0.72 ±0.02	0.9969 ±0.005	0.3	1.63 ±0.26

Table 3b. Same as Table 3a but for the site CDT-Yebes.

	EG1194		SG-064		Comparison at CDT-YEBES		
	Delta	*Phase*	*Delta*	*Phase*	*Delta* [SG/EG]	*Δ%*	*Phase* [SG-EG]
O1	1.146 ±0.004	-0.16 ±0.21	1.1473 ±0.0007	-0.27 ±0.04	1.0012 ±0.004	-0.1	-0.11 ±0.34
P1S1K1	1.137 ±0.003	-0.55 ±0.18	1.1367 ±0.0005	0.36 ±0.03	0.9997 ±0.003	0.03	0.91 ±0.18
M2	1.1509 ±0.001	4.37 ±0.05	1.1508 ±0.0002	4.42 ±0.01	0.9999 ±0.001	0.01	0.05 ±0.05
S2K2	1.190 ±0.002	1.21 ±0.09	1.1858 ±0.0002	3.17 ±0.02	0.9965 ±0.002	0.4	1.96 ±0.09