Absolute Gravity Network in Spain

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ABSTRACT
Since the first absolute gravity measurements in Spain (in 1882 by Joaquín Barraquer y Rovira) no absolute measurements were performed till 1989 by J. Makinen, at the Institute of Astronomy and Geodesy of Madrid (IAG), with a Jilag-5 absolute gravimeter. BKG (Bundesamt für Kartographie und Geodäsie) of Germany and IMGC (Metrological Institute G. Colonetti) of Italy have measured six and three sites in Spain in the last decade of twentieth century. The National Geographic Institute of Spain (IGN) purchased the well known FG5 (num. 211) and A-10 (num. 006) absolute gravimeters. In order to have a reference of measurements to other absolute gravimeters three International Comparison of Absolute Gravimeters (ICAG) have been performed: ICAG2001 at the Bureau International des Poids et Mesures (BIPM) in Sèvres, ICSPAB03 at San Pablo de los Montes (Toledo, Spain) between European Center for Geodynamics and Seismology (ECGS) from Luxembourg and IGN from Spain and, finally, Walferdange 2003 International Intercomparison in Luxembourg. Not only absolute but also vertical gradient and relative measurements were also executed at every station for processing and datum reduction on the floor, because nominal height of absolute gravimeters is placed around 1.30 and 0.70 m above ground level. Results of Zero and a First order absolute gravity network will be presented, which hopefully will better the actual accuracies provided by the IGSN71 and RGFE73 and will serve for multidisciplinary purposes.

Keywords. Absolute Gravity, Absolute gravimeter, Gravity networks, ICAG, Gravity gradient.

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1. INTRODUCTION

The very first scientific task in Spain from the gravimetric point of view reported to the Int. Assoc. of Geodesy Commission was J. Barraquer´s work. His first measurements with Repsold's absolute pendulum were made in 1882 in the National Astronomic Observatory of Madrid, although he had performed some previous tests in 1877 in the old facilities of IGC (Fig. 1). Eight years later, observations of the absolute gravity network were carried out by several gravimetrists of IGN (Table 1). A new site was observed by P. Cebrián and F. de la Rica in Valladolid in 1901, which was never published before, possibly due to its higher standard error. Corrections were found by Helmert and measured by Kühnen and Furtwängler (1906) which refined Barraquer´s measurements, though the deviations from actual values amount to 10 miligal and more (Torge 1989; Rodríguez 2005).

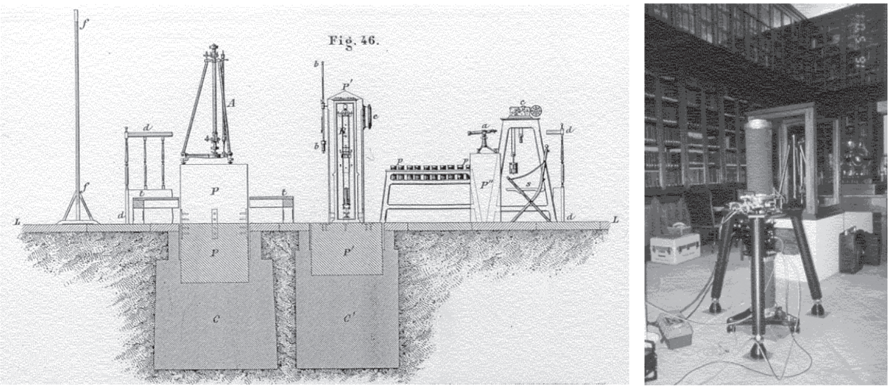

Figure 1. Old absolute gravity observations in Madrid. Old and new sites in Astronomical Observatory of Madrid.

Table 1. Old absolute gravity observations in Spain.

Place	Observer	Season	Year	Gravity (ms^{-2})	Error (ms^{-2})
OAN (Madrid)	J. Barraquer	June-May	1882-83	9.800156	0.000016
IGC (Madrid)	J. Barraquer	March-May	1877-79	9.800180	0.000027
La Coruña	A. los Arcos & P. Cebrian	August-September	1893	9.805497	0.000059
Pamplona	A. los Arcos & P. Cebrian	October	1892	9.803365	0.000041
Barcelona	A. los Arcos & P. Cebrian	October-December	1893	9.803262	0.000050
Valencia	Aparici & Mifsut	November-Jannuary	1895-96	9.801050	0.000072
San Fernando	A. los Arcos	October-December	1894	9.799473	0.000038
Granada	E. Escribano	October-December	1897	9.796933	0.000052
Valladolid	P. Cebrián	August-September	1901	9.800578	0.000233

A total of nine stations including Madrid was the very first absolute gravity set of points in Spain (Table 1). The first relative measurements with Von Sterneck Pendula were performed by Dr. Oscar Hecker (Potsdam Geodetic Institute) in his travel through the Atlantic Ocean (Potsdam, Rio de Janeiro, Lisbon, Madrid) in 1901. The relative network observed by many other spanish gravimetrists (Sans Huelin 1946) of around 210 stations was linked to Potsdam by Hecker´s value, allowing the first Bouguer and free air anomaly maps ever in Spain (1924). Between 1897 and 1989 no absolute gravity measurement is reported in Spain.

Between 1954 and 1958 around 144 Worden relative gravimeter stations built up the new fundamental network of Spain (Lozano 1958).

Observations provided by LaCoste & Romberg gravity meters during the sixties and the early seventies, resulted in a new set of fundamental stations in Spain inside the IGSN71 frame, which were called RGFE73. The IGSN71 network (Morelli 1974) allowed gravity values with mean errors around 0.025 miligal at the best sites. This network along with its less accurate densification, named RGFE73, is still in use.

Absolute gravity measurements with 10^{-6} accuracies were pioneered by Volet (1950), Preston-Thomas (1960), Faller (1963), Cook (1965), Hammond (1970), Sakuma (1970). The developement of free-fall absolute gravity meters in the last two decades of twentieth century, by Zumberge (1981) and Niebauer and Faller (1986), allowed to perform again absolute gravity measurements in Spain, this time close to 10^{-8} ms^{-2}. In the time period 1989-97, Mäkinen and Vieira observed in Valle de los Caídos and Madrid with the JILAG-5 (Vieira et al 2002). Owing to De Maria and Marson (1995a, 1995b), Cerutti and De María (1992) some stations were observed by IMGC in Barcelona (Fabra Astronomical Observatory, 1995), Spanish Center for Metrology in Tres Cantos (Madrid, 1992) and Las Mesas Geophysical Observatory (Tenerife, Canary Islands, 1995). Thanks to BKG, by means of the SELF I and II projects, some stations were observed and even repeated: Valle de los Caídos (IAG); Tarifa, Ceuta, Alicante, San Fernando, Granada (Wilmes and Falk, 2003, BKG). All of them are sumarized in appendix A.

The National Geographic Institute of Spain purchased a new free fall absolute gravity meter by Micro-G Solutions, named FG5#211, in order to observe a new absolute gravity network in the Iberian Peninsula and at least one point in every island of the Balearic and Canarian Archipelagos. This network will hopefully bring the fundamental gravimetric infrastructure in and will serve for geodetic (supporting the new High Precision Levelling Network, geoid, etc), geophysical, metrological, geodynamic and vulcanologic purposes, among others. The FG5 gravimeter reaches a nominal accuracy of 1.1 microGal (1 microGal = 10^{-8} ms^{-2}). The field A10 instrument achieves a nominal accuracy of 10 microGal. Absolute gravity observations are independent on the realization of a terrestrial reference frame or changes within this frame. Theoretically drift free, absolute gravity measurements can reach a precision comparable to GPS heights (e.g., Zerbini et al 1996).

2 OBSERVATION SITES

Most stations, placed in geophysical or astonomical observatories, have a strong well founded pier without any metallic reinforcement bar. Piers are usually connected to bedrock to reduce instrumental vibrations. Seismically quiet sites far from cultural and industrial noise bring up low scattered observations. In those cases where no such facilities were found, a special selection of old well founded buildings (abbeys, old churches, universities, etc) were chosen. Thus, examples such as Geophysical Observatory of Santiago de Compostela, Geophysical Observatory of Logroño, Geophysical Observatory of Málaga, Geophysical Observatory of Almería, Geophysical Observatory of San Pablo de los Montes (Toledo), El Miracle Cluster (Lleida), Astronomical Observatory of Fabra (Barcelona), Ebro Observatory (Tarragona), El Puig Monastery (Valencia), and Valle de los Caídos (IAGBN station) already observed, point up a quietness and very long permanence qualities.

The station Astronomical Observatory of Madrid is located inside the library of the main facility building of "Observatorio Astronómico Nacional", inside the "Parque del Retiro" in Madrid. The measurement was made in the pillar where Mr. Joaquin Barraquer placed the Strasser clock for his 1882 absolute gravity determination, which is about 1 meter to the west of the pier where he made the measurements with the Repsold Pendulum. The station is placed on a granite outcrop around 1.8 m deep in the ground. There is a IGSN71 point next to these piers (MADRID-B).

The geological stability and low noise (far from big roads) of the San Pablo de los Montes and Sonseca sites in "Montes de Toledo", in the Sistema Central Mountain Range, allows to join geodetic, magnetic, seimological and gravity instruments in the same site. Two piers are set up to measure gravity (Fig. 2).

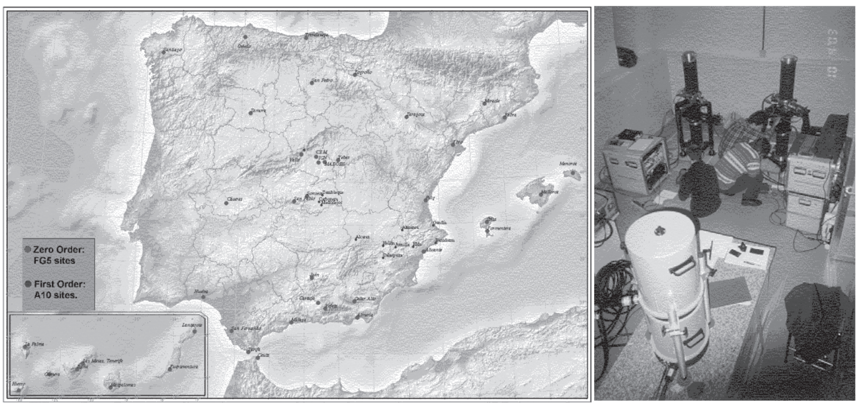

Figure 2. Spanish Absolute Gravity site project. San Pablo de los Montes during intercomparison.

Yebes Astronomical Observatory is a special facility for combining top quality techniques (VLBI, GPS and absolute gravity) also at the same site.

An easily accessible eccentric at every station will be set up to facilitate direct value of gravity. Some eccentrics were already measured.

3. ABSOLUTE GRAVIMETERS

The description of the FG5 instrument is well documented in Niebauer et al (1995), with an error budget of 1.1 microGal (Table 2). The field A10 gravimeter has an error budget of 10 microGal, mainly due to the use of a less stable laser, but has the same working principle and processing.

The FG5 is a new generation of absolute ballistic gravimeters based on a technology developed for forty years by Dr. J. Faller (National Institute of Standards and Technology of USA, NIST) and his followers. Starting with an white light interferometric system in 1962, the forerunners of the FG5 were six JILAG series gravimeters built in 1985, with several supporting institutions (NIST, DMA, NOAA, GSC, FGI, Hannover and Viena Universities). The principle of this gravity meter is to reproduce a free-acceleration of a test body in the gravity field while measuring time distance pairs (t_i, x_i) by means of a time interval counter and a laser interferometer. The He-Ne iodine stabilized laser plays a primary physical length standard role and requires no calibration. Inside the drag free chamber, where vacuum should be kept lower than 10^{-4} Pa, falls a corner cube (retroreflecting mirror), which generates laser interference fringes inside the Mach-Zender interferometer. A least square fit with a known a priori vertical gravity gradient g is performed at every drop (Niebauer et al., 1995):

$$x(t)_i = x_o + v_o(\tau_i + \frac{\gamma}{6}\tau_i^3) + \frac{g_o}{2}(\tau_i^2 + \frac{\gamma}{12}\tau_i^4) + (A\sin\omega_i\tau_i + B\cos\omega_i\tau_i)$$

$$\tau_i = t_i - \frac{(x_i - x_o)}{c}$$

where τ_i is the way to include the speed of light correction; x_o, v_o, g_o are the position, velocity and acceleration at t=0. c is the speed of light, and A, B parameters to fit for the laser modulation and w being the frequency of the dither modulation.

Table 2. FG5 budget estimate (Niebauer 1995).

Error Source	Uncertainty (microGal)	Comments
Residual air pressure	0,1	Pressure dependent
Differential temperature	0,1	Temperature and pressure dependent
Magnetic field gradient	0,1	Difficult to estimate
Electrostatics	0,1	Difficult to estimate
Atraction of apparatus	0,1	Fixed bias in instrument design
Verticality	0,1	Operator-dependent, always negati-ve
Air gap modulation	0,6	Set-up dependent
Laser wavelentgh	0,1	Iodine-stabilized laser
Corner-cube rotation	0,3	Can degrade with time
Coriolis effect	0,4	strong latitude and set-up dependence
Floor recoil and tilt	0,1	site dependent
electronic phase shift	0,6	
Frequency standard	0,2	
Glass wedges	0,3	
Difraction limit	0,2	Laser-system dependent
Total uncertainty	1,1	

Microseismic noise generated by human being affect the reference corner cube distance, because it alters the reference position. Noise periods range between 100 s to 0.01 s. A long period seismometer of 60 s (30 s in the A10) called "Super Spring" (46 cm high), whose inertial mass supports the fixed reference corner cube, reduces the noise several times. It is a considerable improvement from JILA series gravimeter. Macroseismic signals generate huge dispersion in gravity measurements, especially those quakes above magnitude 7, causing a set to be removed.

In some instruments the verticality of the laser beam, which is fundamental, is verified by means of a mercury bath. However, in the FG5 and A10, this is performed by an alcohol surface. The total angular resolution of the telescope and optical system is 12 microradian (equivalent to 0.07 microGal).

Mobile prism rotation must be less than 0,03 rad/s. The falling body is built up so that its gravity center and optical center coincide within 2.5 10^{-5} m plus a certain error (non-perfect balance). Measured rotation rates are of order 10 mrad/s. The gravity error is proportional to the imperfect balancing.

An atomic rubidium clock having stability of the order of 10^{-10} is used as a frequency standard. Calibrations of Laser frequency have been contrasted against BIPM pattern by the manufacturer in 2000 and by BIPM during ICAG 2001 intercomparison. The barometer and laser were also calibrated in CEM (Spanish Center for Metrology). The rubidium clock of FG5#211 was calibrated several times against Cesium and against Hydrogen Maser during the 2000-2004 observation period (Fig. 3). A certain offset of Maser from Cesium could lead to a difference of 0.4 microGal. For this reason the Cesium frequency calibration value was employed while processing observations.

Nevertheless, the necessity of comparisons between instruments is out of any doubt, thus allowing traceability chains and standards in gravimetry. The way in which observations are made in the International Comparisons are described in Vitushkin et al (2002), Francis and Van Dam (2003, 2004). The FG5#211 took part in the ICAG2001 which took place in Sévres (Paris) on July 2001. In the last two intercomparisons, only absolute and simultaneous measurements have shown an improvement in the results. FG5#211 behaviour during intercomparisons ranges from -8.6 to -1.3 microGal (Table 3). It should be underlined that this offset is always lower than the mean values.

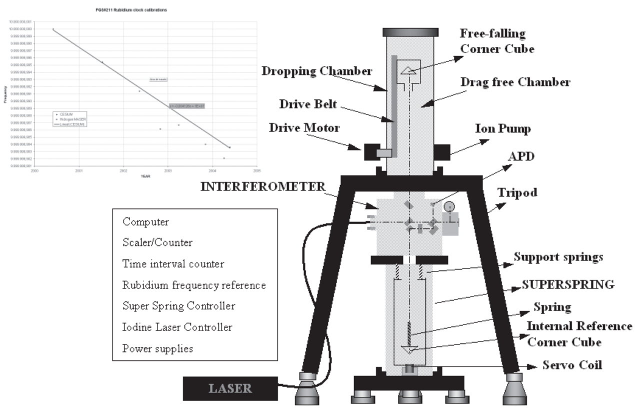

Figure 3. FG5#211 clock calibrations and FG5 diagram.

Table 3. Offsets from the mean value (microGal).

Instrument	ICAG94	ICAG97	ICAG2001	ICSPAB2003	ICAG2003
JILAG-5	-3,9	-0,5		-	-
FG5-101	-6,2	-2,7	2,3	-	-
IMGC	-1,2	9,7	-12,1	-	-47,6
FG5#211	-	-	-8,6	-3,02	-1,3
FG5#216	-	-	-	3,02	-1,1

Measurements from ICAG2001 revealed that the point A2 was 13.2 microGal down the mean value. This could be considered an outlier, bearing in mind that before the measurement the laser was tested and afterwards no APD (Avalanche Photo Diode) adjustment was made. A bad twidler lens and a scratched polarized lens were encountered during Microgsolutions revision at the end of 2001, which might have an influence in the previous instrument performances. In the ICSPAB2003 comparison held in San Pablo de los Montes between FG5#211 and FG5#216, the average mean offsets amounted to 3.2 microGal. The Regional Intercomparison carried out in Walferdange (Luxembourg) in 2003, showed the best performance of the instrument.

At the ICAG97, the instrumental anomaly of IMGC gravity meter, which was presented in an optical component, may have affected the measurements performed in 1997 (Becker et al 2002). However, we must consider the behaviour at Walferdange in 2003 although this fact would not affect other measurement made in Spain.

4. RESULTS OF ABSOLUTE GRAVITY OBSERVATIONS AND CORRECTIONS

More than 35 sites have been occupied from May 2001 until September 2004, including those of the intercomparisons for the zero order network, i.e. FG5 observations. Some sites have already been re-occupied, allowing thus the beginning of the time series (appendix C). All results (appendix B) must be considered in the frame of the international absolute intercomparisons and carefully observed in the future to detect outliers. All observation and processing protocoles are similar to those performed in the above mentioned intercomparisons and the World Gravity Standards (Boedecker 1988).

Before absolute measurements, true gravity gradient observations were made to introduce the best possible gradient in the absolute gravity formula and to translate the absolute value from effective height to the floor, see for instance Niebauer et al. (1989, 1995) and also Francis and Van Dam (2003). A LaCoste & Romberg, Model G, gravimeter with analog feedback system was used to develop this task. At least 24 hours of measurements were made in every station to obtain the final absolute value, 24 set of a hundred drops per set, namely about 2400 drops. The starting fringe was 30 for all cases, and the number of fringes were 600, namely a million and a half time-distance pairs. To obtain the final results, the g software processing tool from Microgsolutions Inc. (Niebauer et al 2002) has been employed.

In order to derive the final values, the raw gravity measurements are corrected with the mentioned tool for speed of light, solid Earth tides, ocean tide loading, gravity changes due to atmospheric pressure variations and polar motion (Niebauer et al 1995; Francis and van Dam 2003).

The employed interferometry produces an apparent relativistic time delay that is caused by the finite speed of light between the beamsplitter and the dropped object. Each time corresponding to a distance x is retarded by -x/c before the data is least-squares fitted to gravity, which is automatically included by using retarded times (about –11 microGal correction).

The observed gravity is normalized to a nominal pressure at each site by applying a correction based on the observed atmospheric pressure during the observations. The local barometric pressure correction C_p (microGal) is applied at each drop through the formula (Int. Assoc. of Geodesy, Resolution num. 9, 1983):

$$C_p = A\,(P_o - P_n)$$

where A is the barometric admittance factor. This value is usually between -0.30 and -0.42 microGal/hPa. Typical value is -0.30, as recommended in the above mentioned resolution; P_o (hPa) is the observed atmospheric pressure, and P_n (hPa) is the nominal pressure at the site. The nominal pressure is computed, in accordance with DIN standard #5450, as follows:

$$P_n = 1013.25\,(1 - 0.0065\,h_m/288.15)^{5.2559}$$

where h_m is the topographic (mean sea level) elevation in m.

The polar motion correction takes into account the daily changes in centrifugal acceleration due to variation of the distance of the Earth's rotational axis from the absolute gravity station. This correction is normally re-computed using pole positions that are determined nearest to the observation time for each station (Boedecker 1988).

$$\delta g = -1.164 \times 10^8\,\omega^2\,a\,2\sin\varphi\cos\varphi\,(x\cos\lambda - y\sin\lambda)$$

where δg is the polar motion correction (μGal); ω is the Earth's angular rotational velocity (rad/s), a is the equatorial radius (semi-major axis) of the reference ellipsoid (m); φ and λ are the geodetic latitude and longitude, respectively, of the station (rad) and x,y are the pole coordinates in IERS system (rad). Bulletin A gives daily pole coordinate prediction and Bulletin B gives final daily pole coordinates, which are issued monthly by IERS (International Earth Rotation Service, US Naval Observatory Earth Orientation Department).

The "g" software provided by MicrogSolutions allows Earth tide corrections with two methods, which can include ocean tide loading models. The first one uses the non-harmonic correction originally written by J. Berger in 1969, and modified by other authors (Niebauer 2002). The second one, that employes an harmonic correction, is based on ETGTAB software (Wenzel 1994), which implicitly uses Tamura´s potencial (1987). To compute the ocean tide loading the Farrell's (1972) formalism is used, with the convolution between gravity Green's functions for PREM (Dziewonski and Anderson 1981) model and three different ocean tide models that can be selected, Schwiderski (1980), CSR3.0 (Eanes and Bettadpur 1995) and FES95.2 (Le Provost et al 1998).

Other geophysical effects such as soil water content, water table level are not considered. In this work we show results processing by means of the Berger method without ocean tide loading correction, named solution 1, and the final results, named solution 2 (appendix B), through processing with the ETGTAB software (using Tamura´s potential) with two sets of parameters computed by the OceanLoad software (supplied with "g"): the body tide parameter set is obtained with DDW model (Dehant et al 1999); the ocean load gravimetric factor set was obtained using the Schwiderski ocean tide model. The final values are expressed mainly at 1.25 m height, in order to minimize the uncertainties due to gravity gradient (see Appendix B).

Finally, eight sites have been occupied with the A10 gravimeter for the beginning of the first order network (Table 4). Most of these sites have also a concrete pier to obtain a good stability, sharing accelerometer sites. Measurements of gradient were carried out to translate the 0.7 m nominal height value to the floor datum. All stations were processed identically as the zero order stations.

Table 4. A10 absolute sites observed.

SITE	gradient	Absolute gravity (microGal)	Set std dev.
Alcaraz	-362.4	979 809 328.73	10.7
Benidorm	-249.4	980 051 640.73	11.8
Gandía	-345	980 085 409.35	7.0
Calasparra	-315	979 866 861.48	10.4
Elda	-333.09	979 905 733.16	13.7
Jumilla	-236.08	979 869 054.15	11.4
Almansa	-333.97	979 879 443.10	7.2
Hellín	-426.2	979 876 705.89	8.6

5. DISCUSSION

More than 35 sites have been occupied from May 2001 until September 2004 in Spain for the zero order network. In the Iberian Peninsula the induced gravity effects expected and observed are mainly of diurnal and semidiurnal frequency and reach up to 11 microGal. However, a stronger effect is found at Santiago site (Fig. 4), even more than 20 microGal peak to peak. In the case of ocean tide loading correction, observation models are good enough to the ± 2-5 microGal level. In the west stations or in some east stations close to the coast, the mismodelling reach the upper value. On the contrary, the continental sites placed in the center of the Iberian Peninsula showed a lower mismodelling of ocean tide loading for semidiurnal tides. A significant low value is showed at the Veleta site, placed at the Sierra Nevada Mountain Range, next to the highest mountain peak in the Iberian Peninsula, where the ocean tide loading effect is the lowest of all sites (Fig. 5).

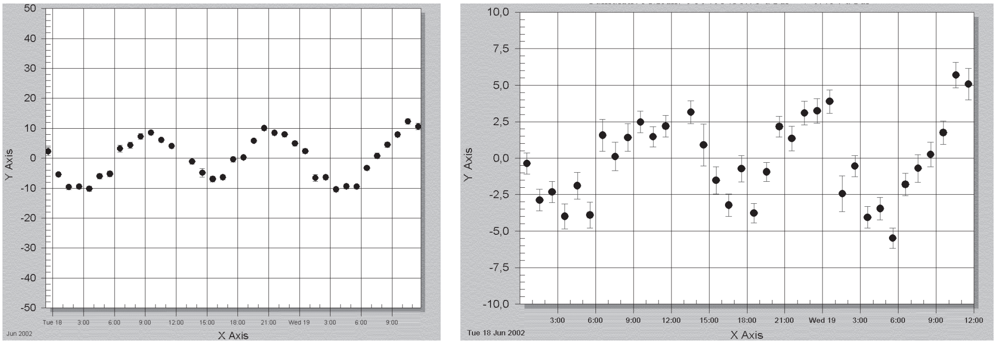

Figure 4. Santiago de Compostela site observations processed by means of solution 1 and solution 2.

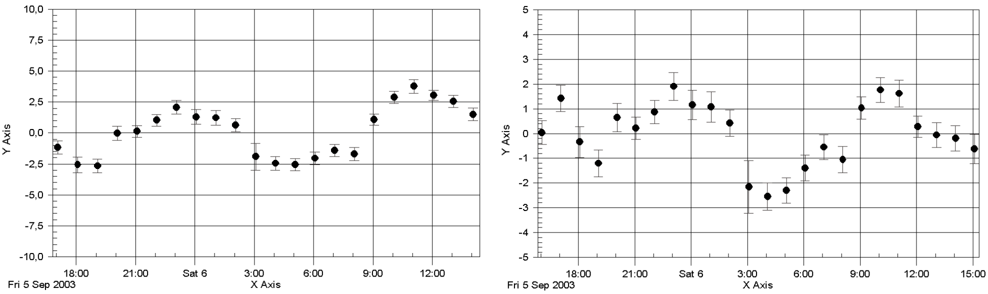

Figure 5. Veleta IRAM site (2850 m above sea level): processed by means of solution 1 and solution 2.

Reobservations of sites will result in an absolute gravity time series in Spain, as well as a permanent infrastructure available for several geodetic, geophysical, metrological, geodynamic and vulcanologic purposes.

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APPENDIX A

Table 5. Absolute stations between 1989 and 2000.

STATION	DATE	g (μms^{-2})	σ (μms^{-2})	h (m)	gradient (μGal/m)	Instrument	Agency
San Fernando	1994.20	9798263.393	±0.036	1.25	-2.500	FG5#101	BKG
Tarifa	1994.20	9797372.485	±0.037	1.25	-2.800	FG5#101	BKG
Ceuta	1994.20	9797550.222	±0.030	1.25	-3.420	FG5#101	BKG
San Fernando	1998.19	9798263.410	±0.036	1.25	-2.502	FG5#101	BKG
Tarifa	1998.21	9797372.486	±0.013	1.25	-2.796	FG5#101	BKG
Ceuta	1998.20	9797550.211	±0.011	1.25	-3.417	FG5#101	BKG
Alicante	1998.23	9800259.207	±0.014	1.25	-3.090	FG5#101	BKG
Granada	1998.22	9796365.091	±0.008	1.25	-2.930	FG5#101	BKG
Valle de los Caídos	1998.19	9798845.168	±0.012	1.25	-3.123	FG5#101	BKG
CEM	1992.68	9799499.824	±0.013	0.93	not reported	IMGCrise&fall	IMGC
Las Mesas	1995.46	9793296.187	±0.020	0.94	not reported	IMGCrise&fall	IMGC
Fabra	1995.49	9802255.867	±0.011	0.92	not reported	IMGCrise&fall	IMGC
Madrid CC.FF. & old Maths Building	1989.35	9799641.268	±0.010	0	2.920	JILAG-5	FGI
Valle de los Caídos	1989.36	9798849.000	±0.010	0	3.070	JILAG-5	FGI
Madrid New Maths Faculty building	1992.59	9799653.286	±0.058	0	-2.710	JILAG-5	FGI
Valle de los Caídos	1992.58	9798849.035	±0.043	0	-3.100	JILAG-5	FGI
Valle de los Caídos	1994.87	9798849.021	±0.039	0	-3.100	JILAG-5	FGI
Valle de los Caídos	1997.46	9798849.057	±0.052	0	-3.100	JILAG-5	FGI
Madrid New Maths Faculty building	1994.87	9799653.310	±0.039	0	-2.710	JILAG-5	FGI
Madrid New Maths Faculty building	1997.45	9799653.253	±0.046	0	-2.710	JILAG-5	FGI

APPENDIX B

Table 6. Absolute stations between 2001 and 2004.

STATION	DATE	g (μms^{-2})	σ (μms^{-2})	h (m)	gradient (μGal/m)	Instrument	Agency
CEM-A	2001.41	9799498.549	±0.030	1.31	-2.702	FG5#211	IGN
CEM-Hg	2001.42	9799498.283	±0.030	1.30	-2.789	FG5#211	IGN
Madrid Astronomical Observatory	2001.44	9799661.224	±0.017	1.25	-	FG5#211	IGN
Paris BIPM Sèvres Point B	2001.52	9809280.126	±0.010	0.90	-2.815	FG5#211	IGN
Paris BIPM Sèvres Point A	2001.53	9809256.946	±0.010	0.90	-2.992	FG5#211	IGN
Paris BIPM Sèvres Point A2	2001.53	9809256.935	±0.010	0.90	-2.937	FG5#211	IGN
Madrid IGN-A	2001.78	9799553.547	±0.010	1.25	-2.857	FG5#211	IGN
Santiago	2002.47	9804014.588	±0.010	1.25	-2.442	FG5#211	IGN
Logroño	2002.41	9805353.201	±0.010	1.25	-2.848	FG5#211	IGN
Sonseca	2002.39	9799354.945	±0.010	1.25	-3.172	FG5#211	IGN
San Pablo	2002.48	9798963.793	±0.100	1.25	-2.494	FG5#211	IGN
Málaga	2002.45	9798997.920	±0.010	1.25	-3.515	FG5#211	IGN
Madrid IGN-B	2002.05	9799553.524	±0.030	1.30	-2.857	FG5#211	IGN
Madrid IGN-A	2002.79	9799557.037	±0.010	0	-2.857	FG5#211	IGN
San Pablo	2002.85	9798963.979	±0.008	1.25	-2.494	FG5#211	IGN
Miracle	2002.87	9801079.421	±0.009	1.25	-2.865	FG5#211	IGN
Fabra	2002.88	9802254.540	±0.012	1.25	-4.158	FG5#211	IGN
Ebro	2002.89	9802020.322	±0.034	1.25	-2.726	FG5#211	IGN
Puig	2002.90	9801399.781	±0.012	1.25	-2.733	FG5#211	IGN
Valle de los Caídos	2002.93	9798845.150	±0.012	1.25	-3.115	FG5#211	IGN
CEM-Hg	2002.95	9799498.420	±0.030	1.30	-2.810	FG5#211	IGN
CEM-A	2003.05	9799498.720	±0.030	1.31	-2.702	FG5#211	IGN
San Pablo SPAB-A	2003.27	9798963.793	±0.013	1.25	-2.494	FG5#216	ECGS
San Pablo SPAB-A	2003.27	9798963.746	±0.011	1.25	-2.494	FG5#211	IGN
Jaén	2003.47	9797430.390	±0.011	1.25	-3.368	FG5#211	IGN
Almería	2003.45	9798912.478	±0.011	1.25	-2.546	FG5#211	IGN
Veleta	2003.68	9792346.192	±0.014	1.25	-3.869	FG5#211	IGN
Madrid IGN-A	2003.89	9799557.155	±0.013	0	-2.857	FG5#211	IGN
Walferdange, Luxembourg B4	2003.84	9809640.605	±0.008	1.30	-2.645	FG5#211	IGN
Walferdange, Luxembourg C4	2003.84	9809639.516	±0.006	1.30	-2.616	FG5#211	IGN
Walferdange, Luxembourg A5	2003.85	9809641.792	±0.007	1.30	-2.629	FG5#211	IGN
Madrid IGN-A	2003.89	9799557.051	±0.019	0	-2.857	FG5#211	IGN
Alicante	2003.95	9800259.235	±0.020	1.25	-3.090	FG5#211	IGN
Yebes	2004.34	9799474.865	±0.014	1.25	-3.286	FG5#211	IGN
San Fernando	2004.38	9798263.321	±0.036	1.25	2.502	FG5#211	IGN

APPENDIX C

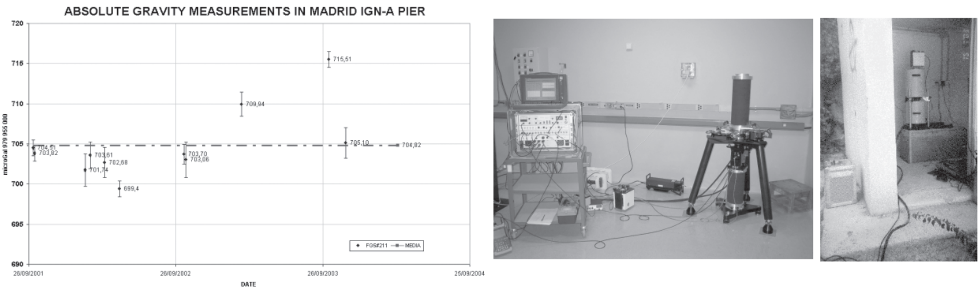

Figure 6. IGN (Madrid) time series. FG5#211and A10#006 instruments belonging to IGN (Spain).

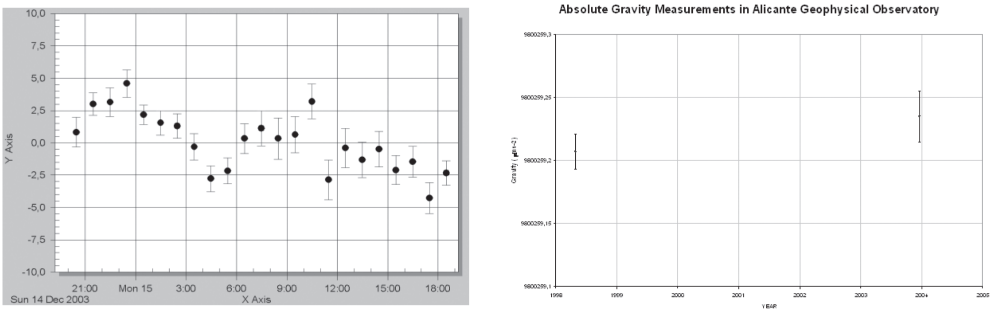

Figure 7. Alicante site observations after solution 2 correction and time series (BKG and IGN observations).

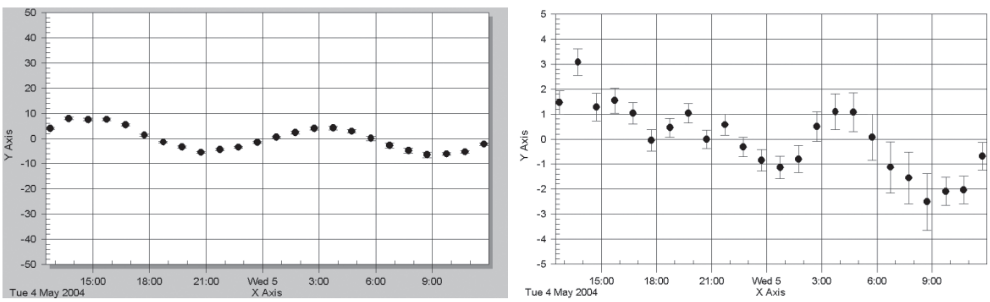

Figure 8. Yebes site processed by means of solution 1 and solution 2.

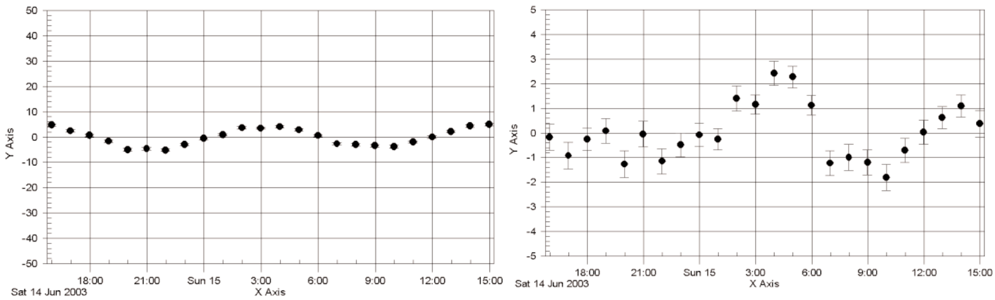

Figure 9. As Figure 8 but for Almería site.

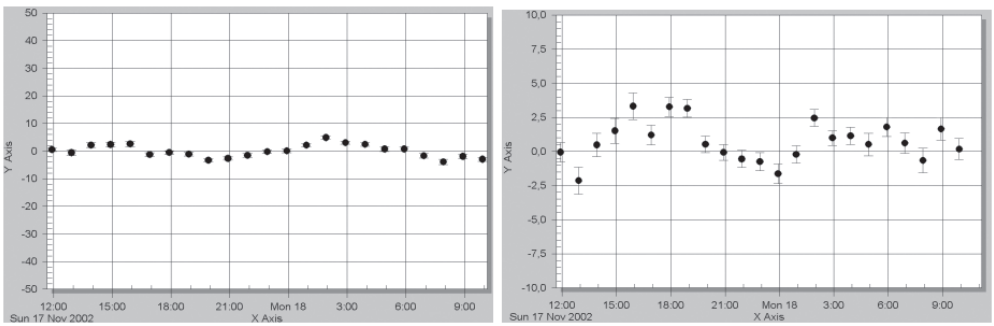

Figure 10. As Figure 8 but for Fabra site.

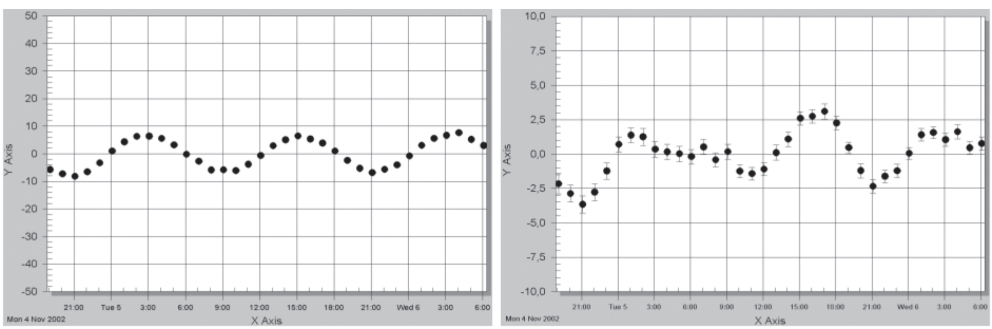

Figure 11. As Figure 8 but for San Pablo de los Montes site.