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Measurement of absolute gravity acceleration in Firenze

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Abstract

This paper reports the results from the accurate measurement of the acceleration of gravity g taken at two separate premises in the Polo Scientifico of the University of Firenze (Italy). In these laboratories, two separate experiments aiming at measuring the Newtonian constant and testing the Newtonian law at short distances are in progress. Both experiments require an independent knowledge on the local value of g. The only available datum, pertaining to the italian zero-order gravity network, was taken more than 20 years ago at a distance of more than 60 km from the study site. Gravity measurements were conducted using an FG5 absolute gravimeter, and accompanied by seismic recordings for evaluating the noise condition at the site. The absolute accelerations of gravity at the two laboratories are $(980\,492\,160.6 \pm 4.0)$ µGal and $(980\,492\,048.3 \pm 3.0)$ µGal for the European Laboratory for Non-Linear Spectroscopy (LENS) and Dipartimento di Fisica e Astronomia, respectively. Other than for the two referenced experiments, the data here presented will serve as a benchmark for any future study requiring an accurate knowledge of the absolute value of the acceleration of gravity in the study region.

1 Introduction

Over the past few years two separate experiments, one for measuring the Newtonian constant and one for testing the Newtonian law at short distances, are under development at the Physics laboratories of the University of Firenze. The experiment for the Newtonian constant measurement in room 67 building 3 (Department of Physics and Astronomy) is based on an atomic gradiometer that detects the differential acceleration induced by very well known source masses Lamporesi et al. (2008); Sorrentino et al. (2010). The atomic gradiometer is a matter-wave interferometer where two clouds of laser cooled ^{87}Rb atoms, separated by a distance $D \simeq 30$ cm are used for a simultaneous measurement of local gravity with respect to the common reference frame identified

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by the wave-fronts of the laser beam used for the atom interference interrogation. The instrument directly detects the differential acceleration Δg between the two clouds and thus the common mode acceleration noise induced on the wave-fronts by acoustic and seismic vibrations is rejected. The instrument is an excellent gradiometer since the gravity gradient in the vertical direction is simply $\Delta g/D$ and can be determined with a statistical error essentially equal to $\Delta D/D$ (with ΔD the uncertainty on the measure of D) which is lower than 0.1%. From Δg and from the knowledge of the added mass distribution, it is possible to determine the value of the Newtonian constant if a reasonably accurate value of g is also known. Since each atom cloud can be operated also as a gravimeter, g can be obtained by the atom interferometer itself and indeed state-of-the-art instruments based on atomic interference have been built Peters et al. (1999). Due to the differential nature of the measurement, however, no special care has been taken in insulating the experiment from seismic noise and the statistical error is limited after 3 min of integration to a sensitivity $\Delta g/g = 5 \times 10^{-7}$. Moreover with an independent value for g of at least comparable accuracy we can check our instrument against various systematic effects.

The experiment in room 44 building 4 (LENS) is based on optically-trapped strontium atoms. The small size and high sensitivity of the atomic probe allow a model-independent acceleration measurement at distances of a few µm from the source mass, giving direct access to a poorly tested range of the Newtonian law Ferrari et al. (2006); Ivanov et al. (2008). In the experiment laser-cooled strontium atoms are trapped in a 1-dimensional vertical optical lattice and the combination of the periodic optical potential and the linear gravitational potential gives rise to Bloch oscillations. From the measured Bloch frequency ν_B the gravity acceleration along the optical lattice is estimated with a sensitivity of $\Delta g/g \simeq 10^{-7}$ after 30 min of integration. In this experiment, that in principle is not devoted to an absolute g-measurement, the performance in measuring g is an index of the stability of the atom probe for the investigation of forces at small spatial scales Poli et al. (2010).

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These activities brought us to set reference absolute value of the acceleration of gravity with an independent instrument and with a precision of 1 part in 10^{-8} or better in the sites where we are going to perform our gravity measurements. The absolute acceleration of gravity g has been measured in the two laboratories at the Polo Scientifico of University of Firenze in Sesto Fiorentino using the Micro$g$-LaCoste FG5#238 absolute gravimeter: in Department of Physics where the atom interferometry experiment aims at an accurate determination of Newtonian constant Lamporesi et al. (2008); Sorrentino et al. (2010), and in LENS where the cold strontium experiment is employed to investigate possible deviations from the Newtonian law at short distances Ferrari et al. (2006); Ivanov et al. (2008). As far as we know the closest and most recent measurement of the acceleration of gravity is the measurement realized beneath the Italian Zero Order Gravity Net Marson et al. (1994). The measurement was done at Palazzo al Piano (about 60 km from our location) in 1989 where a g value at ground of 980 391 580(8) μGal was found, and it was performed using the absolute gravimeter of the IMGC (now INRIM) in Torino (see D'Agostino et al. (2008) and references therein). Of course the value of absolute g could be derived from the one taken in Marson et al. (1994) to our location using a relative spring gravimeter, but the main limit is that there are no informations on the stability of the measurements in Palazzo al Piano since measurements have not been repeated (Germak, personal communication, 2010) on this site. The poor reliability of the operation persuaded us to measure absolute g directly in our laboratories.

This paper discusses the measurements of the absolute acceleration of gravity taken in Firenze in the period 4–6 October, 2009. In Sect. 2 we present the general description of the site: Section 2.1 outlines the geological setting and Sect. 2.2 is dedicated to the study of the seismic noise at the measurement locations. In Sect. 3.1 data processing and the corrections to the measurements are described, and Sect. 4 is dedicated to the conclusions.

2 The site

The buildings of the Polo Scientifico of the University of Firenze in Sesto Fiorentino have been constructed recently, and became fully operational by late 2000. The specific sites where the FG5 instrument has been placed are in the room 67 in the building 3 and in the room 44 in building 4. Both laboratories are at the ground floor, at an elevation of about 40 m a.s.l. (elevation data taken from the Gauss-Boaga Fuso1 map of Regione Toscana, 1:2000 scale, at WGS84 coordinates 43.81916° N 11.19319° E)). The concrete floor where we installed the instrument is on the basements of the buildings and it is covered by solid tile. In room 67 air conditioning maintains the temperature at $(20.0 \pm 0.1)^{\circ}$C, while temperature stability in room 44 is not better than $\pm 3\,^{\circ}$C.

2.1 Geological setting

The site is located close to the NW border of the Middle Valdarno basin, hereinafter referred to as the Firenze-Prato-Pistoia basin. This is one of the tectonic basins which developed since the Neogene in the Tyrrhenian side of the Apennines thrust and fold belt, striking parallel to the main chain axis (Fig. 1). The genesis of these depressions is related to an extensional tectonic regime developed since Upper Tortonian age (11–7 Myr before present) and due to the opening of the Tyrrhenian Sea (see Boccaletti et al. (2001) and references therein). The Firenze-Prato-Pistoia basin extends in a NW-SE direction with a roughly rectangular shape and is delimited by Neogene-Quaternary faults, the most important of which is oriented NW-SE bounding the northeastern margin of the basin.

The substratum of the basin is mainly formed by rocks pertaining to the Ligurian Units s.l. (shales, calcareous-quarzitic sandstone, calcareous turbidites and marly limestones) that outcrop NE of the basin (Monte Morello-Calvana Ridge) and tectonically overlie the turbiditic formations of the Tuscan Unit (Macigno sandstone). Maximum thickness of the lacustrine deposits in the middle of the basin extends up to 500 m. However, the depth of the bedrock within the basin varies significantly, as a consequence of several NE-SW trending faults which subdivide the bottom of the basin in a block-like structure.

Below the study area, the thickness of the sedimentary cover has been estimated on the order of 450 m Capecchi et al. (1975). Four main sedimentary phases are recognised (depths are referred to sea level): from about −400 m to −20 m: fluvio-lacustrine succession, constituted by sands, pebbles and clays whose age is generally considered to be Upper Pliocene-Lower Pleistocene (≃2.5 My before present); from −20 m to −5 m: pebbles, gravels and silt of fluvial fans resulting from erosion of the Monte Morello-Calvana ridge; from −5 m to +10 m: lacustrine clays and gravels; from +10 m to surface: Fluvial clays and gravels.

The static level of the water table varies between 0.5 m and 2 m below the surface, as also visible at the numerous drainage channels present in the area Crespellani et al. (1991).

From both direct and indirect measurements, shear-wave velocities have been determined to vary between 200–300 m/s at the surface and 600–800 m/s at 40 m depth.

2.2 Seismic noise

The site is located within an industrial area, and close to the A11 Highway, the Airport and a major construction site. The intense ground vibrations of both anthropic and natural origin cause an acceleration noise which may induce a significant drop-to-drop scatter of the gravity observations.

In order to quantify the noise conditions at the measuring site, we thus conducted a microseismic survey during an 8-day-long period encompassing the gravity measurements. For these measurements, we used two Nanometrics Trillium 120P seismometers (http://www.nanometrics.ca), whose response function is flat over the 120 s–0.02 s period range. Acquisition was performed using two 24-bit Reftek 130 portable recorders, with a digitising rate of 125/samples/second/channel, independently synchronised to the UTC time base via GPS receivers.

Data presented hereinafter are from station A667, which was operated at room 67 throughout the duration of the microseismic survey. Figure 2 shows the time series of noise amplitude obtained from the standard deviation of consecutive, 600-s-long windows of signal band–pass filtered over the 0.1 Hz–50 Hz frequency band using a 2-pole, 0-phase-shift Butterworth filter.

Seismic noise exhibits a typical weekly and daily pattern, such as the 8-hr workday, due to the intense human activities conducted both inside and in proximity of the laboratories. Ground vibrations at day time are 2.5–3 times larger than those observed during the night.

Figure 3 illustrates the probability density function (PDF) McNamara et al. (2004) of acceleration power spectral densities during the 24-hour-long period of gravity measurements. The PDF is representative of 130 spectral estimates obtained via Welch's method Welch et al. (1967) applied to 10 not-overlapping, 120-s-long windows of noise. Individual spectral estimates have been stabilised using a 0.1-Hz-wide smoothing window. For reference, these data are compared to Peterson's (1993) Low- and High-Noise Model curves Peterson et al. (1993). At periods between 5 s and 10 s, the noise PDFs are very narrow, and their peaks are rather close to the Low-Noise-Model. This is not surprising, once considering that the main noise source over this particular period range is marine microseismic activity, and the test site is located about 80 km far from the coast.

At shorter periods (0.05–1 s, corresponding to the 1 Hz–20 Hz frequency band), the PDF becomes wider, and encompass the High-Noise-Model. The spreading of amplitude distributions over this period range is likely related to the day-night variation of vibrations, thus suggesting a dominance of anthropic sources. At periods shorter than 0.05 s (frequencies above 20 Hz), several narrow spectral peaks indicate the action of non-stationary, monochromatic vibrations from nearby sources, such as the air conditioning system.

3 The absolute gravity acceleration instrument and measurements

3.1 The absolute gravimeter

The Micro*g*-LaCoste FG5#238 ballistic absolute gravimeter Niebauer et al. (1995) is a high precision, high accuracy, instrument that measures the vertical acceleration of gravity g. The operation of the ballistic FG5 is to observe the free-falling of a repeatedly dropped corner cube reflector. This test mass is contained in a co-falling servo-controlled motor-driven drag-free chamber and falls over 20 cm in 0.2 s inside a vacuum chamber. A laser interferometer is used to determine the position of the test mass as a function of time during its free-fall. This interferometer is a modified Mach-Zender type, with a fixed (reference) arm and a variable (test) arm. During a drop, the motion of the test mass affects the path length of the test beam. The interference fringes that result from the recombination of the test beam and the reference beam provide an accurate measure of the motion of the test mass relative to the mass suspended on the superspring, which provides an inertial reference frame. As the object falls, interference fringes are formed at the optical output. The interference fringes are converted to a digital signal, which is transmitted to the time interval analyzer card in the system controller. These fringes are counted and timed with an atomic clock to obtain precise time and distance pairs. A least-squares fit to these data is used to determine the value of g. The distance scale is given by a frequency-stabilized helium-neon laser used in the interferometer. The absolute gravity measurements are therefore directly tied to the time and length SI units.

A total of 700 time-position points are recorded over the 20 cm length of each drop. Even if a drops can be produced up to every two seconds, in routine operation, the repetition rate is 10 s. The average of 50÷100 drops is a set, which exhibits standard deviations of 40 to 150 nm/s^2 under normal conditions. Measurements usually consist of one or two sets per hour with the average of several sets (usually 12 to 48) providing a gravity value. The instrumental accuracy of the FG5 is about 2 µGal as reported by the manufacturer. A software supplied by the Micro*g*-LaCoste company is used for data

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acquisition. This software provides an immediate value for the local gravity, and it also includes a full-featured post-processor that allows to vary data analysis procedures and environmental corrections.

Before being used in Firenze, the FG5#238 absolute gravimeter took part in the 8th International Comparison of Absolute Gravimeters (ICAG-2009) organized by the Bureau International des Poids et Mesures (BIPM). The comparison was held from 14 September to 3 October, 2009 in Sèvres, France Arias et al. (2010). The primary objective of ICAG-2009 was to determine the level of uncertainty in the absolute measurement of free-fall acceleration on the ground and to evaluate the possibility of determining a comparison reference value for g at the sites of the BIPM gravity micro-network. Such a reference value allows determining correction factors for the instruments participating to the comparison. The FG5#238 measured the acceleration of gravity at three different sites. The expanded uncertainty obtained from these measurements ranges between 5.4 µGal and 6.5 µGal. The expanded uncertainty is obtained by multiplying the combined standard uncertainty by a coverage factor k correspondent to a confidence level of 95%, in our case $k = 2$. All absolute gravity values agree very well with the reference value of g at the three different sites.

3.2 Absolute gravity acceleration measurements

After the measurements taken in ICAG-2009 the instrument has been transported to Polo Scientifico of University of Firenze in Sesto Fiorentino and it has been installed first in the room 44 at building 4, then in the room 67 at building 3 (see Fig. 5 (top); the FG5 gravimeter was positioned in the available space as close as possible to the center of each room. The instrument was along the north-south direction within 10° in order to reduce the Coriolis effect as recommended by the manufacturer. The nominal measuring point elevation for the gravimeter is 129.4 cm above the floor, and it coincides with the top of the drop.

In room 44, acquisition started on 4 October 2009 at about 16:30 UTC, and lasted for about 15 h. In room 67 acquisition started on 5 October 2009 at 10:20 UTC, and lasted for about 24 h. During both experiments, we collected a measurement set every 30 min, each set being composed of 50 drops. We thus collected (29,45) sets and (1450,2250) launches for the two sites respectively. On every single set we calculated the standard deviation σ, rejecting all the measurements resulting out of the 3σ range. This led to 95% accepted drops for the room 44, and to 99% accepted drops for the room 67 data.

3.3 Data processing and correction

Data acquisition and processing is accomplished with the software supplied by the Micro$g$-LaCoste company, that we have also used for corrections due to systematic errors. The data are least-squares fit to a function that uses a known a priori vertical gravity gradient in a fourth-order equation of motion Niebauer et al. (1995). The finite value of the speed of light gives a correction for the calculated gravity signal since the optical interference accurs at a later time after the light is reflected by the dropped object, depending on interferometer arm length and speed of light. This contribution is a non negligible effect at the µGal sensitivity, and the corrected delayed time has to be taken by considering a retarded time in the function used for the least-squares fit.

The vertical gravity gradient has to be taken into account because the position of the free falling mirror changes considerably (20 cm) along the vertical during the measurement and so does the acceleration of the falling mirror. The gradient at the measurement location has been measured by the atom interferometer instrument Lamporesi et al. (2006) and it agrees with the commonly used standard free air value of the gradient 3.09 µGal/cm within 1%.

The gradient could be, in principle, a free parameter in the least-squares fit, but absolute gravimeter data are not generally used to determine vertical gravity gradient, because the accelerations are measured during the free fall of the object and hence at different times. As a consequence the seismic noise becomes important and reduces the sensitivity. Measuring the accelerations at the same time, like in the atom interferometer gradiometer, is a way to reject common mode noise. Nevertheless we have elaborated the data of the FG5 instruments to obtain information on the gravity gradient at the measuring site. We have grouped data from 50 drops (1 set, 500 s time) in which we suppose that both g and its gradient are constant. The average value for the gravity gradient is $(3.8 \pm 1.2) \times 10^{-6}\ \mathrm{s}^{-2}$. Results are shown in Fig. 4 where it is possible to notice that in the central part of the plot, corresponding to the night time, the data are less noisy and a determination of the gradient with a statistical error within 10% seems feasible.

Since the absolute determination of gravity with the FG5 instrument and with the atom interferometer experiments are neither carried out simultaneously nor at the same spot, we need to take into account gravity variations in time within each laboratory. Corrections that have been considered are Earth tides and ocean loading contributions, polar motion effects, and barometric corrections. These corrections require local instrumental measurements or geographical parameters. Moreover to be a truly useful measurement, we have considered the sites elevations, the measured setups heights, and we have calculated contributions due to the nearby mass distribution.

Due to the solar and lunar attraction the local value of g will change of hundreds of µGal. The common approach to correct observed gravity data for tidal effects is to use a tidal prediction program (such as Wenzel, 2002) that makes use of observed or predicted amplitude tidal gravity effect. The surface loading of the Earth due to the weight of the ocean tides causes a time varying deformation of the solid Earth, which is called ocean tide loading. The vertical component of the ocean tide loading varies spatially and it is in addition to the Earth's body tide deformation, which is typically 40 cm peak to peak in mid-latitudes.

As the Earth wobbles on its axis, the local centripetal acceleration will change the local value of g. This is known as Polar motion effect. The correction for polar motion has an amplitude of ± 10 µGal and two principal periods of 365 days and 435 days. It is modeled with an uncertainty much better than 1 µGal Wahr (1985). By entering

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parameters related to the Earth's current orientation into the software, this effect can be corrected.

Barometric pressure correction has to be considered because as the local air pressure changes, so will the measured gravity value due to direct attraction. By comparing the current pressure with the standard local value, the gravity value can be corrected to estimate the value on a "normal" day. A typical barometric factor of −0.3 µGal/mBar is considered.

Manufacturer also recommends to take into account uncertainties due to laser frequency (± 0.01 µGal) and to Rubidium oscillator clock (± 0.50 µGal), together with a "set-up" uncertainty (± 2 µGal) depending on the instrument and on the operator.

The floor of room 67 is 61(1) cm higher than the floor of room 44. This elevation difference has been measured using a laser level Bosch mod.BL30 (nominal accuracy 0.3 mm/m). Considering a theoretical vertical gradient of 3.09 µGal/cm we expect to see a difference of about 188 µGal in the measured value of g in the two locations. During the measurements the rooms were occupied by optical tables and room 67 by the source masses for the Newtonian constant experiment. The FG5 gravimeter is positioned close to the optical tables and, because their positions may change in the future, the effect of the nearby mass distribution has been evaluated for the two laboratories as shown in Fig. 5. This correction is less than 1 µGal at both laboratories. By the time of our measurements no rainfalls occurred and so we do not expect any significant gravity variations associated with changes in local hydrological accumulation.

After corrections due to systematics effects, the values of the acceleration of gravity in the laboratories are (980 492 160.6 ± 4.0) µGal in room 44 and (980 492 048.3 ± 3.0) µGal in room 67. In Table 2 absolute gravity acceleration values are resumed with the relevant systematic effects and the respective estimated uncertainties. The difference between the two values can be explained with difference in building structures and geological structures, causes that we can assume as time invariant.

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4 Conclusions

The measurement of the absolute acceleration of gravity g has been carried out in two laboratories at Polo Scientifico of University of Firenze in Sesto Fiorentino: room 67 building 3 (Department of Physics) where atom interferometry is used for accurate measurement of the Newtonian constant, and room 44 building 4 (LENS) where a cold strontium atom sample is used for precision gravity measurements and for a test at short distances of the Newtonian law.

A geological description of the site is reported and in order to quantify the noise conditions at the measuring site, we have conducted a microseismic survey during an 8-day-time covering the time interval of the gravimetric measurements. The seismic noise spectra show that ground vibration at day time are 2.5–3 times larger than those observed during the night, due to the intense human activities conducted both inside and in proximity of the laboratories.

We have also taken into account gravity variations in time and in space within each laboratory. Gravity corrections considered are Earth tides and ocean loading contributions, polar motion and barometric effects, site elevation, measured setup and height corrections. We have also introduced other corrections due to the nearest mass distribution near the FG5 location. During the measurements procedures the FG5#238 absolute gravimeter worked reliably and the uncertainties of the absolute gravity acceleration in laboratories 44 and 67 are 4.0 µGal and 3.0 µGal respectively. However, since there is no guarantee that the gravity acceleration value is constant at these two sites, repeated measurements in time might be especially important to verify the stability of the sites.

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Table 1. Summary of relevant parameter for environmental corrections on the g measurements in room 44 and in room 67.

	Room 44	Room 67
Time	4–5 October 2009	5–6 October 2009
Longitude E	11.19319°	11.19319°
Latitude N	43.81916°	43.81916°
Height a.s.l.	40.5 m	39.9 m
Nominal Atm. Press.	1008.39 mBar	1008.46 mBar
Bar. coefficient	−0.3 µGal/mBar	−0.3 µGal/mBar
Reference height	129.4 cm	129.4 cm
Vertical gradient	3.09 µGal/cm	3.09 µGal/cm

Table 2. Summary of corrections and uncertainties on the g measurements in room 44 and in room 67. Reference height of the measurements is 129.4 cm from the floor and heights a.s.l. are 39.9 m and 40.5 m respectively.

	Room 44 Value (µGal)	Uncertainty (µGal)	Room 67 Value (µGal)	Uncertainty (µGal)
Average Solid Earth Tide	0.04	± 0.09	−88.05	± 0.09
Average Ocean Loading Tide	−0.05	± 0.10	0.00	± 0.10
Measured g value (tide corrected)	980 492 161.7	± 3.25	980 492 051.9	± 1.85
Polar motion	−3.74	± 0.05	−3.74	± 0.05
Barometric Pressure	2.89	± 1.00	1.03	± 1.00
Set-up	0.00	± 2.00	0.00	± 2.00
Laser	0.00	± 0.01	0.00	± 0.01
Clock	0.00	± 0.50	0.00	± 0.50
Nearby mass distribution	−0.27	± 0.05	−0.93	± 0.05
Corrected g value	980 492 160.6	± 4.0	980 492 048.3	± 3.0

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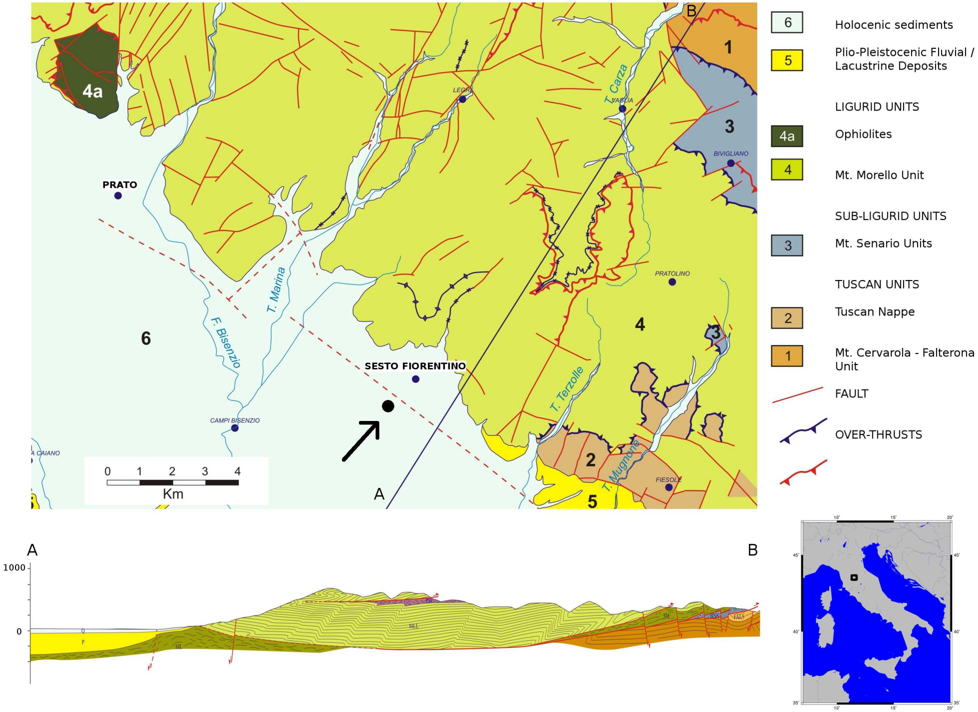

Fig. 1. Sketch map of the study area, outlining its main geological and structural features. The arrow marks the location of the measuremnt site. At the bottom, the geological section through points A–B in the map. The inset at the bottom right shows location of the study area with respect to Italy. The map is modified from Sheet 263 of the Geological Cartography series of the Regione Toscana, available at http://www.regione.toscana.it, last accessed December 2010.

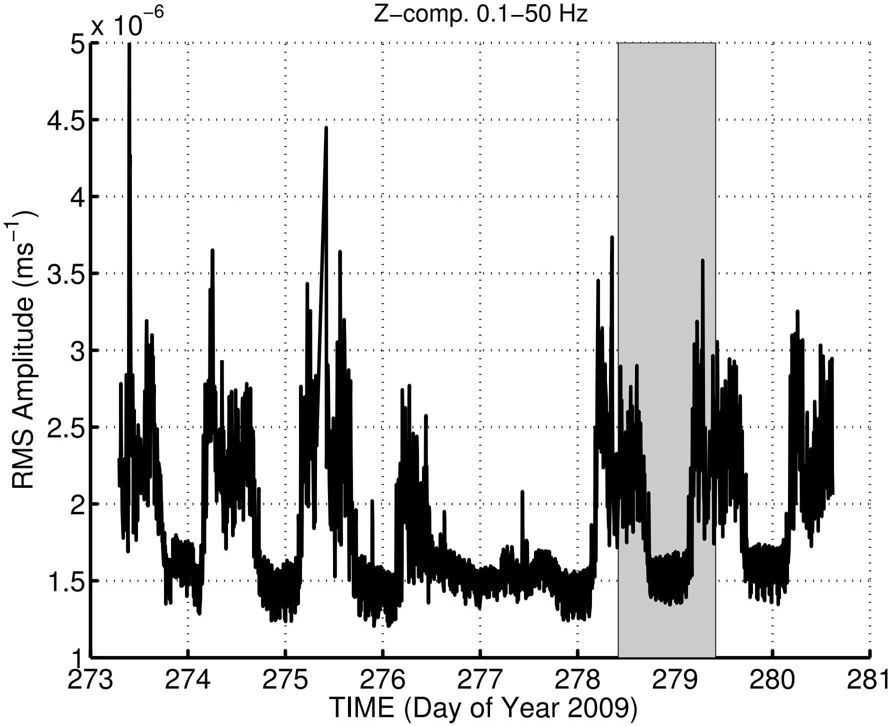

Fig. 2. RMS amplitude of seismic noise at the measuring site from 30 September, 2009 through 7 October 2009. Data represent the standard deviation of the 0.1–50 Hz vertical component of ground velocity computed over 10-minute-long time windows.

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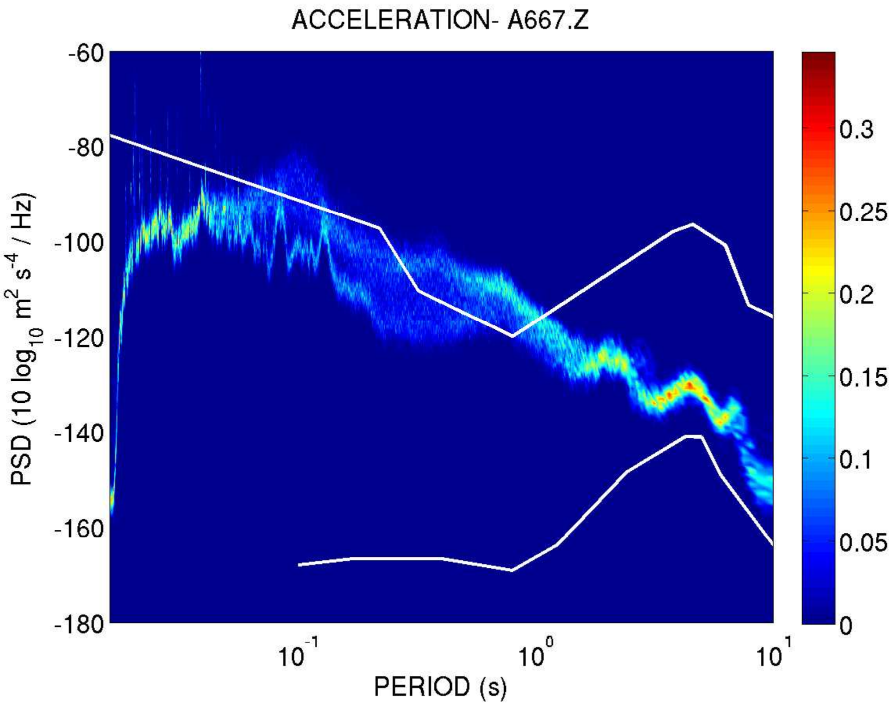

Fig. 3. Probability density function of vertical-component noise amplitude for a 24-hour-long time interval encompassing the gravity measurements. The distribution is obtained by binning at 1-dB interval the spectral power measured at consecutive discrete Fourier frequencies which, in our case, are spaced by 0.0083 Hz. White lines are the Earth's High- and Low-Noise Models (see Peterson et al. (1993)).

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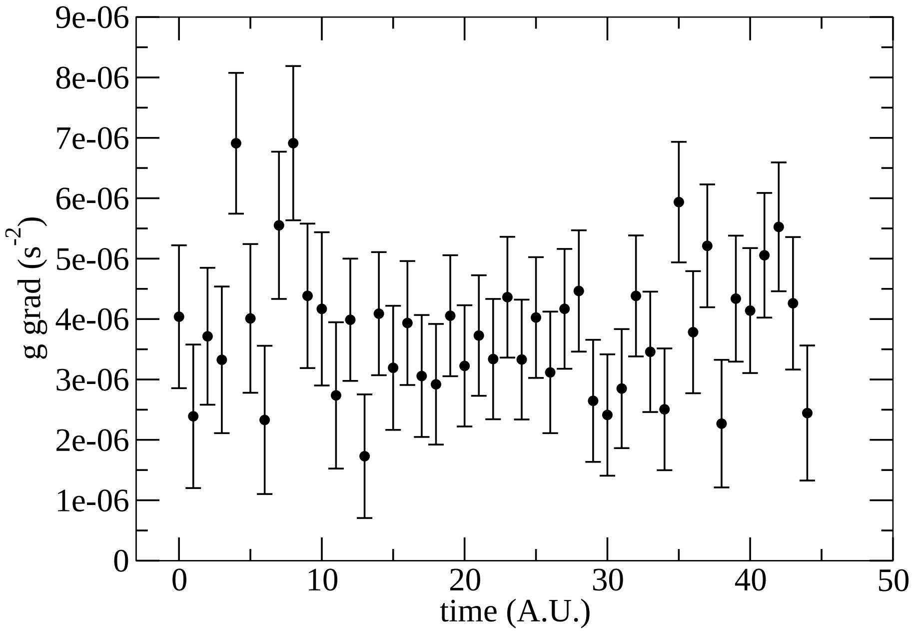

Fig. 4. Results of the best fit elaboration of the data provided by the FG5 gravimeter when installed in room 67. The best fit is used to obtain information on the gravity gradient at the FG5 site. We have grouped data from 50 drops (500 s time) in which we suppose both g and its gradient are constant. On x-axis there is the time after 10:20 UTC, 5 October, 2009 and the central part of the plot is during the night.

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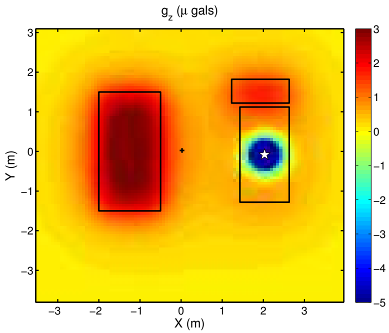

Fig. 5. (top) View of the FG5 gravimeter installed in the atom interferometry laboratory room 67 at the Department of Physics in Sesto Fiorentino. (bottom) Sketch map of the laboratory with location of the masses for which we calculated the gravity field. Black rectangles are optical tables, and the star is the source mass (≃350 kg at the measuring time) used for the determination of the Newtonian constant. The coloured map is the gravity field due to the distribution of these nearby masses at the reference height of the FG5 gravimeter 129.4 cm from the floor.