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Absolute gravity measurements in India and Antarctica

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A series of absolute gravity measurements have been made at National Geophysical Research Institute, Hyderabad and at Maitri, Indian Antarctic station to establish precise reference gravity stations and also to monitor long-term gravity changes for different geophysical studies. These precise measurements are made with an FG-5 absolute gravity meter, which measures the gravitational acceleration with an accuracy of 20 nm-s^{-2} (2 μGal). Non-tidal time series of measured absolute gravity values at these locations indicate systematic daily and seasonal variation of variable amplitudes. Daily changes are probably caused due to inaccurate global tidal model used in processing of data and suggest a need for better tidal model for the Indian subcontinent. Seasonal changes appear to be mainly caused due to hydrological effects, which can be modelled to derive the aquifer parameters.

Keywords: Absolute gravity, Maitri station, temporal gravity changes, water level.

THE FG-5 Absolute Gravity (AG) meter records[1] the earth's gravity field to a precision of 1 μGal (10 nn-s^{-2}) and thus allows us to observe very small signals arising due to redistribution of mass and vertical crustal motions caused by various geodynamic processes such as earthquakes, plate convergence, isostatic rebound, etc. Absolute gravity measurements are now widely used to study: the vertical crustal deformation in conjunction with GPS for complimentary verification[2,3], mass and elevation changes due to glacial rebound[4] and actual sea-level rise[5]. Sea-level changes along the Indian coast show a large spectrum[6] and an increasing trend from south to north, which might be caused due to some tectonic and local oceanographic reasons[7]. It appears that some of the tide gauges along the Indian coast are influenced due to vertical ground motions[8] that can be constrained by AG measurements. Furthermore, a reference absolute gravity value is the basic requirement for any gravity survey carried out using a relative gravimeter. In India, absolute reference gravity stations were established during middle of the twentieth century, either with pendulum observations or with relative gravimeters by tying them to known absolute gravity values. Uncertainties in earlier absolute gravity values are rather large and not well defined due to instrumental and environmental problems. Therefore, precise reference absolute gravity value is needed. The Antarctic land mass has few absolute reference gravity stations and none near the Indian station, Maitri. Therefore, the National Geophysical Research Institute (NGRI), Hyderabad in collaboration with the Department of Ocean Development (DOD), acquired an AG meter for addressing the problems of vertical deformation near tide gauges along the Indian coast and establishing the reference gravity stations in India and Antarctica. This communication provides details on precise absolute gravity measurements made in India and Maitri, Antarctica.

An FG-5 AG meter measures the acceleration of the earth's gravity field by precisely recording the time and distance of a free-falling object inside a vacuum chamber (Figure 1). The instrument mainly consists of (i) a dropping chamber, in which retro-reflector corner cube falls freely, (ii) an ion pump that maintains vacuum (10^{-4} Pa) in the

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dropping chamber, (iii) a laser source that generates stabilized laser illuminations, (iv) a Mach–Zender laser interferometer used to determine the position of a free-falling object as a function of time; (v) a super spring, an active long period seismometer (free period of ~ 60 s) on which another corner cube is mounted which acts as an inertial reference mass and (vi) a rubidium atomic clock, which measures the time of occurrence of fringes detected by an avalanche photo-diode. The general operation and observational procedure of an AG meter are well documented[9,10]. In short, a laser light beam falls on the lens of an interferometer and splits into two parts, namely test and reference beams. The test beam travels up and gets reflected by the free-falling corner cube in the dropping chamber, then travels down and gets reflected by the reference corner cube attached to the super spring. This reflected test beam interferes with the reference beam to form interference fringes at every half wavelength ($\lambda/2$) movement of the free-falling corner cube. The time of occurrence of interference fringes is determined with the help of the rubidium atomic clock. During each descent (~ 20 cm length) of the free falling object (corner cube), a total of 700 sets of accurate time and distance measurements are recorded, which are used to determine absolute gravity value. Since the gravity measurements are influenced by periodic tidal variations and local atmospheric effect, absolute gravity value is obtained after applying corrections for the earth tides, ocean loading, local atmospheric effect and polar motion effect from these sets of time and distance records. Corrections for the solid earth tide and ocean tide are applied to an accuracy of ~ 1 μGal using ETGTAB, a global tidal model[11]. A factor of 0.3 μGal/mbar is used to apply atmospheric pressure correction for each drop. The instrumental accuracy of the FG-5 AG meter is about 1 to 2 μGal after applying all these corrections[1].

To achieve higher accuracy and better performance of the instrument, there are two essential requirements for any absolute gravity site: (i) stable ground to avoid high frequency ground vibrations, which can be achieved by construction of a concrete platform or pillar, (ii) a temperature-controlled environment as the laser source used in the instrument performs best in a temperature range of 15–30°C. To meet the above-mentioned requirements, an observatory is constructed in the NGRI campus to house the FG-5 AG meter. Observations are recorded for a minimum of 24 h with 100 drops per hour to minimize the effect of errors in tidal corrections. Figure 2 shows one-day record of 24 sets (24 h) of hourly observations after incorporating all corrections. Uncertainty for each set represents the errors in corrections and instrumental factors that vary from set to set. The average gravity value on this day is 978326943 ± 3 μGal. It is interesting to note that the corrected gravity record in Figure 2 shows periodic variation, which appears to be largely in phase with the earth tidal correction and therefore might be caused due to inaccurate global tidal model. A long time series of gravity observations recorded at about a month interval provides an average absolute gravity value of 978326943 ± 6 μGal (Figure 3 *b*). This large uncertainty (± 6 μGal) of absolute gravity value is mainly due to seasonal variation in groundwater level and can be reduced after applying the required correction.

Since absolute gravity measurements are sensitive to seasonal hydrological changes around the observation site[12], annual gravity data recorded at one-month interval have

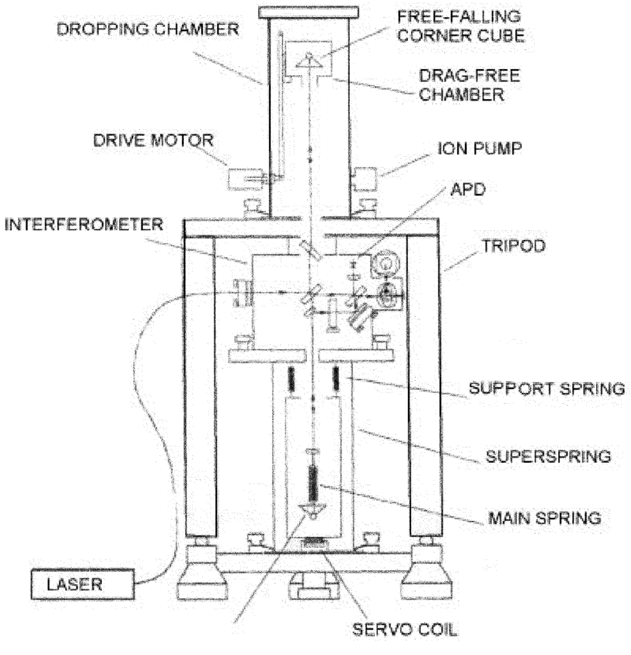

Figure 1. Schematic diagram of FG-5 AG meter.

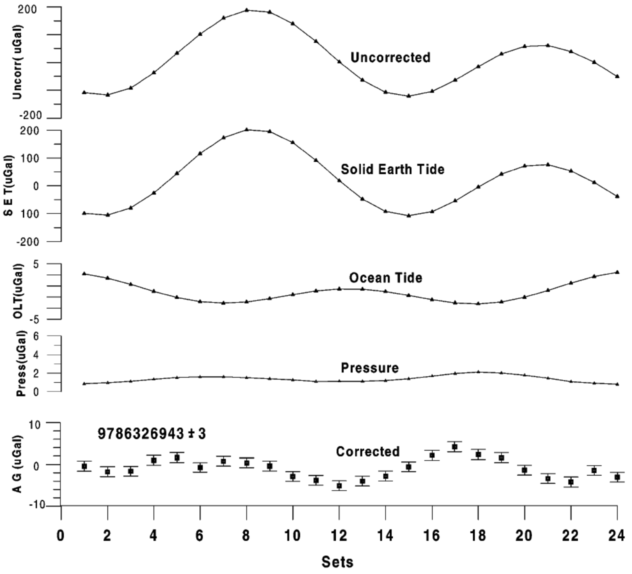

Figure 2. One-day record of absolute gravity observations at NGRI observatory. Plots of different corrections applied to absolute gravity data as well corrected gravity values with error bound and removal of mean gravity value. Reduced gravity field shows periodic variation in phase with tidal correction and thus suggests a need of better tidal model. Average gravity value with uncertainty for one day is also given.

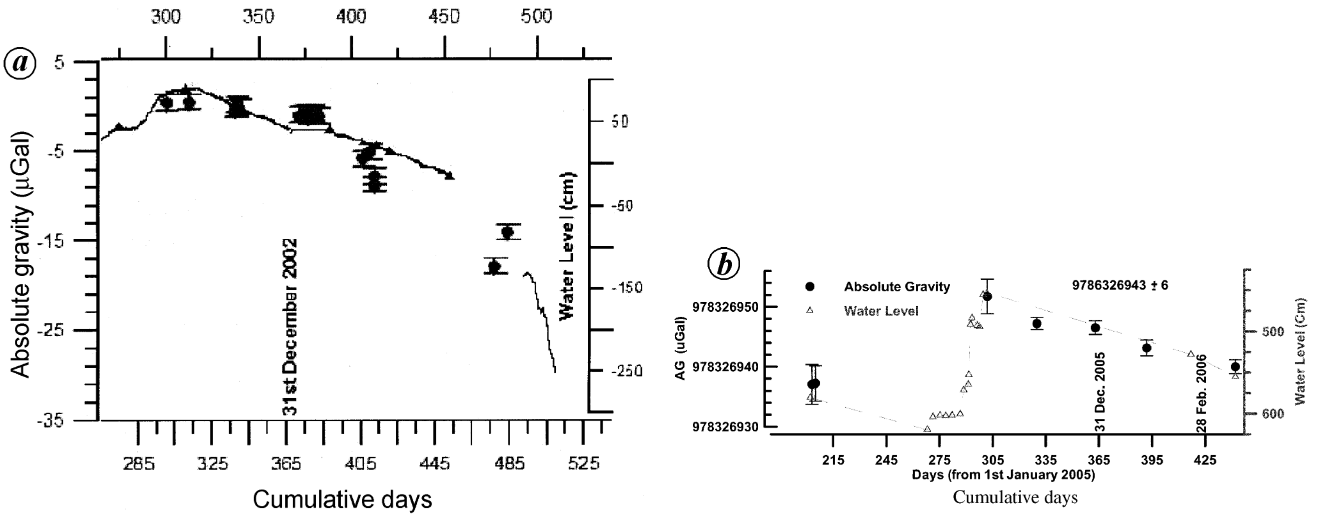

Figure 3. Annual record of absolute gravity measurements at NGRI observatory. ***a***, Gravity data show seasonal variation (dots with vertical bars) and have strong correlation with water-level changes (continuous line), suggesting the need for a hydrological database in the study of long-term gravity changes. ***b***, Gravity data show seasonal variation (dots with vertical bars) and have strong correlation with water-level changes (dashed line with triangle), suggesting the need for a hydrological database in the study of long-term gravity changes. Average gravity value with uncertainty for this period is also given.

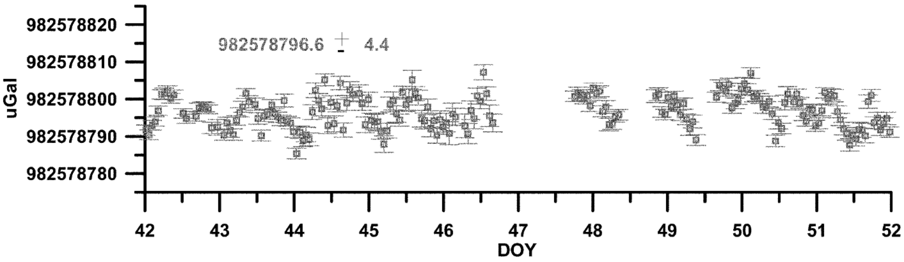

Figure 4. Ten-day records of absolute gravity measurements at Maitri, Antarctica. DOY, Day of the year 2004 (e.g. 43 is 12 February 2004). Average gravity value with uncertainty for this period is also given.

been analysed to study the effect of hydrological changes at the NGRI site. Figure 3*a* shows time series of AG measurements from November 2002 to October 2003, and Figure 3*b* shows measurements from July 2005 to January 2006 along with water level recorded near to the observational site. In spite of data in AG measurements, a correlation between gravity changes and water-level variation is appreciable. This suggests that the gravity changes might be attributed to hydrological effects as high resolution AG data are sensitive to mass changes due to water-level changes[12]. If gravity changes are solely attributed to changes in the water level, the former can be used to determine the porosity of the aquifer system using the formula based on Bouguer slab approximation[13],

$$\Delta g = 2\pi G\phi\rho\Delta h,$$

where Δg is gravity change, G is the universal gravitational constant; Δh is water-level variation, ϕ is porosity of rock matrix and ρ is density of groundwater.

From the above formula we derived the porosity of the rock matrix as ~ 10%, which is quite reasonable for the unconfined aquifer in weathered granite near the observation site. However, this quantification can be improved by more precise calculations incorporating precipitation, soil moisture data and extent of aquifer into consideration.

During the 23rd Indian Antarctic Expedition, an AG meter was carried to Antarctica by ship for establishing a reference gravity station at Maitri. A concrete pillar for absolute gravity measurements was constructed and covered under Aravalli hut with appropriate sealing to maintain the required temperature. Continuous measurements were made during 4–27th February 2004, except during bad weather days. We followed the same observational procedure mentioned earlier and recorded a set of observations of 100 drops. The number of effective data are 365 sets*100 drops*700 = 25,550,000, which provides absolute gravity at the reference pillar as 982578797 ± 4 μGal (Figure 4). Here uncertainty is mainly due to the inaccurate global tidal model, as the effect of hydrological changes would be minimal. This established reference gravity station at Maitri can be used for any future gravity surveys in this part of Antarctica for geodynamic studies and also for monitoring temporal gravity changes by measurements at the same location from time to time. Temporal gravity changes can provide a constrain to the elastic rebound due to deglaciation, because any change in the ice mass will deform the earth, which will result in crustal displacement and gravity changes[4].

We have established two high precision reference absolute gravity stations, one in India at NGRI, and the other at Maitri, Antarctica using FG-5 AG meter. The absolute gravity values at these locations have a measurement accuracy of about ~ 2 μGal with an overall uncertainty of ~ 5 μGal. These examples of gravity measurements describe the expected range of gravity variations and the measurement precision of the instrument. A correlation between water level and gravity changes demonstrates the utility of absolute gravity measurements for hydrological studies. It also suggests that water-level information is necessary for removal of seasonal effects from long-term gravity data recorded for the study of temporal variation of gravity field. This effect would be negligible in places like Antarctica, where subsurface mass changes are little and thus the reported absolute gravity value can be used for temporal changes.

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Muzaffarabad earthquake of 8 October 2005 (*Mw* 7.6): A preliminary report on source characteristics and recorded ground motions

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We present a preliminary source study of the Muzaffarabad earthquake of 8 October 2005 (*Mw* 7.6) and the far-field ground motions that it generated. Our analysis is based on regional broadband seismograms recorded at stations operated by the India Meteorological Department (IMD) which are situated to the south of the epicentre, and at non-IMD stations which are located to the north. We find that the source spectrum of the earthquake is reasonably consistent with ω^2-source model with a seismic moment, M_0, of 2.94×10^{20} N-m and a corner frequency, fc, of 0.051 Hz (Brune stress drop of 9.5 MPa). The radiated seismic energy, E_R, estimated from the empirical Green's function (EGF) technique is 2.70×10^{16} J. This yields a normalized radiated energy, E_R/M_0, of 9.1×10^{-5}, and an apparent stress, τ_a, of 2.7 MPa. The rupture area of

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