Using ground-based gravity measurements to monitor changes in terrestrial water storage

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ABSTRACT: Monitoring changes in the Earth's gravity field for terrestrial water storage change (soil moisture, ground water, snow etc.) is a relatively new and novel concept that has been inspired by the Gravity Recovery And Climate Experiment (GRACE) satellite mission. GRACE will soon be providing time varying maps of the Earth's gravity. However, there has been no field based study to demonstrate that such a signal can be extracted from either space or ground-based measurements of gravity. This paper seeks to show the potential to monitor changes in terrestrial water storage from measurements of changes in gravity, using a network of soil moisture, groundwater and gravity monitoring sites established in the Murrumbidgee catchment. Moreover, we assess the various factors that might contribute noise to the gravity measurement. As changes in the Earth's gravity field due to changes in terrestrial water storage are expected to be small, this type of measurement is pushing the accuracy envelope of ground-based gravity measurement to orders of magnitude higher than usual applications (i.e. 1 μGal for soil moisture compared to a typical mineral search application of 1000 μGal). We use a portable relative gravimeter (Scintrex CG-3M) with quoted accuracy of < 5 μGal and reading resolution of 1 μGal. A measurement protocol that enables correction for the high drift rate of the CG-3M ($\approx$400 μGal/day) involving repeat gravity readings at various sites, readings at a stable reference site, and at the superconducting gravimeter in Canberra is described. Sources of error and uncertainty in this approach are discussed in the context of the accuracy required to reliably estimate changes in the terrestrial water store.

INTRODUCTION

The twin Gravity Recovery And Climate Experiment (GRACE) satellites were launched on March 16 2002 and are currently locked into a near polar orbit with a period of 1.5 hrs. The tandem satellites are approximately 250 km apart and have their distance constantly measured by microwave radiometry together with acceleration via onboard accelerometers and absolute positioning by GPS. By monitoring the small increases and decreases in distance between the satellites it is possible to accurately map the Earth's gravity field once every month. Accuracy is increased as the area of interest and averaging time is increased; an area of at least 50,000 km^2 and time period of a month are required to obtain sufficient accuracy for hydrological applications.

It is anticipated that GRACE will provide time varying measurements of the Earth's gravity that can be used to determine total mass changes through time (Wahr et al. 1998, Rodell & Famiglietti 1999, 2001, Swenson & Wahr 2002). At monthly timescales for large areas these mass changes will be primarily a result of terrestrial water storage variations (soil moisture, groundwater, snow etc.). Preliminary modelling of the ability to monitor ground water changes in the High Plains aquifer, central U.S., has shown promise (Rodell & Famiglietti 2002). Data from GRACE will be available in late 2004.

Research is being conducted in Europe in the hope of validating GRACE from ground-based gravity measurements. This is being attempted with a network of permanently installed superconducting gravimeters (SG) that form the Global Geodynamics Project (Meurers 2001). As gravimeters primarily measure the gravity effects directly below the meter (and moisture changes under the building housing the meter are expected to be small relative to the adjacent landscape) these measurements are not expected to have significant hydrologic value. Moreover, spatial coverage is dense only over Europe, and some have claimed that a ground-based validation of GRACE measurements is theoretically impossible due to incompatible spatial scales (Velicogna & Wahr 2001).

We do not propose to validate GRACE from ground measurements, but rather, similar to Troch et al. (2003), determine whether in fact a terrestrial water storage signal is detectable in a ground measurement of gravity. We however use field-based (rather than lab) gravity readings at monthly or longer intervals to determine a change in gravity at specified locations within the Murrumbidgee catchment. At these locations, hydrological monitoring equipment is used to determine the corresponding water storage change. Firstly a simple temporal and spatial (over all field sites) correlation will be performed to assess whether the gravity data contains useful information about the change in water storage. This will be followed by an attempt to improve soil moisture predictions with local forcing data by assimilating the gravity data into a hydrological model. If the gravity data does contain a terrestrial water storage signal, then the assimilation should improve the predictions. This will provide insight into the potential usefulness of GRACE data and gravity data in general for hydrologic purposes.

It should be emphasised that data is still being collected and as such the assimilation and correlation analysis will not be conducted in this paper. Rather, a methodology for data acquisition and an analysis of potential error sources is presented.

GRAVITY THEORY

Using Newton's law of gravitation and second law of motion we obtain the gravitational attraction of the mass m,

$$\mathbf{g} = G\left(\frac{m}{r^2}\right)\mathbf{r} \tag{1}$$

where, G is the universal gravitational constant (equal to 6.672×10^{-11} m^3 /kg·s^2), r is the distance between m and the mass being acted on and $\mathbf{r}$ is a unit vector pointing to m from the mass being acted on (e.g. a gravimeter).

Taking m and r to be the average mass and radius of the Earth, and $\mathbf{r}$ as pointing towards the centre of the Earth we obtain,

$$g_{\text{Average}} \approx 9.8\,\text{m/s}^2 = 980\,\text{Gal}. \tag{2}$$

By differentiating (1) and inserting the average mass and radius of the Earth we obtain the 'free air correction',

$$\Delta g_{\text{Free Air}} = -2G\left(\frac{m_{\text{Earth}}}{m^3_{\text{Earth}}}\right) \approx 308.6\,\mu\,\text{Gal/m}. \tag{3}$$

This shows that a change in elevation of approximately 3 mm, between one measurement and the next, will result in a change in observed gravity of 1 μ Gal. Hence, high precision temporal gravity surveys require sub-millimetre vertical repositioning accuracy.

By calculating the gravitational attraction of a right vertical cylinder (from an elementary disc mass), and extending the radius of the cylinder to infinity, one obtains the Bouger slab approximation,

$$\Delta g_{\text{Bouger}} = 2\pi G\rho h\,\mu\,\text{Gal/m}, \tag{4}$$

where, ρ is density in kg /m^3, and h is the thickness (or height) of the slab in m.

It is clear from (4) that the Bouger slab approximation is not only independent of lateral extent, but also of depth to the anomaly.

Inserting the currently accepted value for G and a density of water of 1,000 kg /m^3 we obtain the Bouger slab approximation of the local gravity effect due to rainfall,

$$\Delta g_{\text{Rainfall}} = 41.92\,\mu\,\text{Gal/m}. \tag{5}$$

From (5) it is evident that to obtain a 5 μ Gal change in gravity (2 minute single reading accuracy of the Scintrex CG-3M gravimeter) we would need approximately 120 mm of rainfall (i.e. a 120 mm change in terrestrial water storage). Furthermore, (5) contains an implicit assumption of zero runoff, perfect infiltration, and zero ET (i.e. a bucket model).

It is possible to use the Bouger slab approximation to estimate the effect of a change in groundwater and also soil moisture below the gravity meter. For groundwater,

$$\Delta g_{\text{Groundwater}} = 41.92 S_y \Delta H \ \mu\,\text{Gal/m}, \quad (6)$$

where, S_y is specific yield and ΔH is the change in height of the water table, measured in metres.

For soil moisture,

$$\Delta g_{\text{Soil Moisture}} = 41.92 \Delta\theta\ H \ \mu\,\text{Gal/m}, \quad (7)$$

where, $\Delta\theta$ is change in volumetric water content and H is now the thickness of the soil profile that the water content is being measured over.

Thus, for a porosity of 10% (typical of the Murrumbidgee catchment), an increase in water table height of 1.19 m gives an increase in gravity of 5 μ Gal, and for a 3 m thick soil profile a 4% increase in volumetric water content will also give a 5 μ Gal increase in gravity. However, through repeat readings at each site, the uncertainty of the CG-3M measurement is reduced to 3 or 4 μ Gal. Furthermore, the groundwater and soil moisture contributions to gravity are complimentary, so that a rise in water table height of 1.19 m together with a 4% increase in volumetric water content results in a 10 μ Gal increase in gravity.

GRAVITY METERS

Gravity meters either take an absolute or relative measurement. Absolute meters typically measure the time taken for a proof mass to fall a fixed distance using laser interferometry, whereas (field) relative meters measure the extension of a spring using capacitance. Relative meters suffer from drift caused by elastic relaxation of the spring, with repeat measurements at a location of known gravity required to remove the effect. Once corrected for drift, relative meters give highly accurate measurements relative to another point in space or time. While absolute meters are not subject to drift, they have other problems such as systematic errors due to rotation of the proof mass as it falls (Hanada et al. 1996).

Figure 1. The superconducting relative gravimeter located at Mt Stromlo, Canberra

Absolute gravimeters

The most accurate absolute gravimeter is the Micro-g Solutions FG5 (≈2 μ Gal). However it is bulky and requires long station occupancy times (≈5 days). The A10 can be transported in the back of a dedicated van but is much less accurate (≈10 μ Gal) and also requires long occupancy (≈1 day). Recently a small, field portable, accurate prototype has been built and tentatively named the FG6 (Faller & Vitouchkine 2004). While this instrument would seem to have great potential for hydrologic application, it is not yet available commercially.

Relative gravimeters

Relative gravimeters include the high precision, low drift, laboratory based superconducting meters and the less precise, high drift, field-capable spring meters.

Due to their high precision, bulky size, and setup requirements, GWR superconducting gravity meters (SG) are primarily used for Earth tide observations in the laboratory. However, a smaller field based version, the FSG, has become available recently. Both meters levitate a superconducting sphere within a magnetic field. A change in the electric current used to centre the sphere in a vacuum chamber indicates a change in gravity. An FG5 is typically used to periodically calibrate these meters and generate a gravity transfer function for the voltage reading. While the FSG is claimed to have the same desirable properties as the SG (accuracy < 0.05 μ Gal), with the advantage that it can be transported to multiple sites, its performance (in the field or otherwise) has not yet been documented in any scientific literature.

LaCoste & Romberg (LCR) and Scintrex manufacture field-capable spring gravimeters. The LCR meters operate on the principle of a mechanical zero length spring, whereas the Scintrex meters use a fused quartz sensor. Both companies provide a variety of meters, but the most accurate are the CG-3M (or CG5) from Scintrex, and the D meter from LCR with precisions of 1 μ Gal and repeatability of less than 5 μ Gal. In the field, both meters run off a 12 volt sealed lead acid battery that needs recharging after 12 hours.

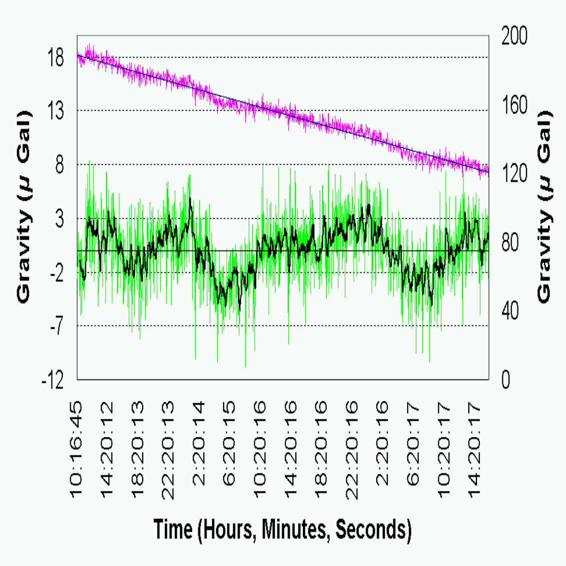

Figure 2. Gravity in soils lab at Melbourne University measured over two days with CG-3M. Top line is data with linear trend shown (a linear component of 392 μ Gal/day has already been removed). Bottom line is residual gravity after linear trend is removed. Bottom black line is a twenty minute moving average of the residual.

GRAVITY CHANGES

Significant temporal gravity changes are mostly caused by Newtonian attraction of bodies. However solid earth tides and crustal deformation due to surface loading can also have a significant effect by changing the elevation of the gravity measurement and the distribution of crustal mass.

Solar and Lunar Tides

Solar and lunar tides are caused by the Newtonian attraction of the sun and moon on the Earth. Together solar and lunar tidal accelerations generally cause changes in gravity in the order of 100 μ Gal, (Melchior 1978). All other temporal variations of gravity are at least an order of magnitude smaller. A spherical harmonic expansion of the tidal potential is usually performed so that each wave is a linear component, and the waves with smallest amplitude may be neglected. Many harmonic expansions of the tidal potential exist, Longman (1959) is one of the oldest and simplest with only 8 terms and is used by the Scintrex CG-3M gravimeter.

Solid Earth Tides

Due to the elastic properties of the earth's crust, the observed solar and lunar tides are always more than the theoretical tides. In addition to an amplitude increase there is a phase shift. A global phase shift of zero, and amplitude factor of 1.16 is commonly used (Torge 1989), it is developed from a second order expansion of the tidal potential multiplied by a linear combination of Love numbers derived from a spherical, irrotational, elastic Earth model. This factor is used by the CG-3M in conjunction with the Longman expansion to correct for Earth tides. This correction is accurate to ±3 μ Gal (Scintrex Operator Manual 1995), the residuals can be seen in the bottom half of Figure 2.

Ocean Loading

Oceanic tides cause a temporal change of gravity in three ways. There is the Newtonian gravitational attraction of the additional oceanic tidal mass, the change in elevation of the gravity site due to flexure of the crust, and finally there is the change of gravity (a vertical acceleration) due to horizontal and vertical accelerations of the crust known as rippling The magnitude of ocean tide loading is usually 0.3–3 μ Gal (Baker & Bos 2003).

Ocean loading effects are therefore a significant source of error in the observed gravity differences. It is believed that the phase and amplitude parameters of the ocean loading tides are not significantly different in the Kyeamba creek catchment and Yanco areas from Canberra (100 and 200 km to the west, respectively). This will result in no modelling being required, as the difference in gravity between Canberra and a field site at any given epoch will cancel out the ocean loading and also solid earth tide effects. This is being tested both with ocean loading models and data based methods.

Atmospheric Pressure Changes

The effect of local atmospheric pressure changes on measured gravity has been studied extensively, with the admittance between local pressure and gravity having been found by both theoretical models and correlations between observations, to be between approximately -0.3 and -0.4 μ Gal /millibar. An accurate and currently accepted theoretical determination is that of Merriam (1992),

$$\Delta g_{\substack{\text{Local Atmospheric} \\ \text{Pressure}}} = -0.356\ \mu\text{Gal/mb} \quad (8)$$

The change in gravity is due to the direct Newtonian attraction of the air mass (causing a reduction in gravity), and also the crustal loading of the pressure cell (causing a reduction of the distance between the gravimeter and the Earth's centre and a corresponding increase in gravity). Clearly Newtonian attraction of the air mass is the dominant process.

Hydrological Changes

A number of studies into the effects of hydrological changes on gravity have been conducted, however these are almost all exclusively in the form of groundwater levels or rainfall correlated with continuous SG measurements. As an example, Bower & Courtier (1998) correlated rainfall, snowmelt and ET to gravity with great success. Crossley & Xu (1998) developed a rainfall-groundwater level model with quick and slow flow components. These components (recharge and discharge) are governed by exponential decay constants that are calibrated to the continuous SG gravity data via a Bouger slab approximation.

Of the few studies that have been conducted in the field Lambert & Beaumont (1977)

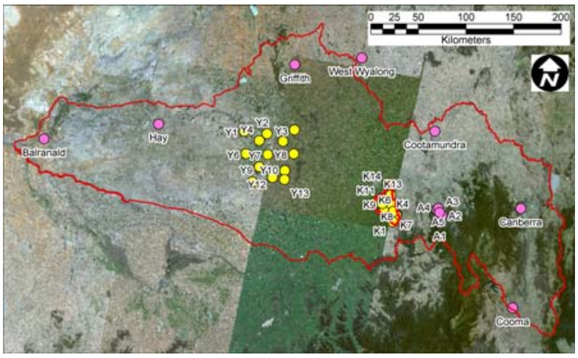

Figure 3. LANDSAT satellite image of Murrumbidgee River Basin. Yellow dots in grid formation on left are the soil moisture monitoring sites in the Yanco study area. Yellow dots in centre are the sites in Kyeamba Creek catchment. Pink dots are existing UoM sites.

investigated the effect of groundwater changes on gravity by attaching mounts to the top of piezometers and conducting two surveys separated by 6 months, designed to capture the maximum and minimum water levels. They used two small study areas in their investigation (0.6 km and 3 km profile), with each area only containing a handful of sites (4 and 5). Because of this they were able to construct complete homogeneous gravity networks so that every pair of sites in each study area was connected by at least one measurement. This design has the advantage of being constructed by a series of interlocked triangles, the triangles form micro closure constraints on the observed gravity by requiring that the three gravity differences sum to zero. This allows the detection of outliers (tares) and also an even distribution of errors within the network via least squares (network adjustment). Their design and methodology showed success at the smaller site, but was slightly more ambiguous at the other, where they assumed unmeasured soil moisture storage was causing an additional gravity effect. Unfortunately the mounting of the gravity pads to the top of the piezometers, while useful for groundwater monitoring and also for keeping the elevation of the pad as stable as possible, is not very useful for the detection of soil moisture as the gravity meter is most sensitive to changes directly below it.

FIELD DATA

Currently a field program is being undertaken with the primary aim of determining how well temporal gravity variations can be related to variations in the terrestrial water storage. Also

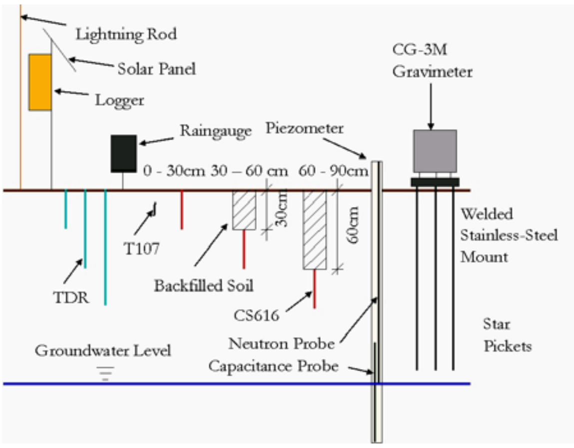

Figure 4. Schematic of a typical field site. Capacitance probe is removed when using NMM, TDR probes are 30, 60 and 90 cm long. Piezometer protrudes 15 cm. Groundwater was not reached at all sites.

techniques for using gravity measurements in hydrology are in development. Two areas have been chosen within the Murrumbidgee catchment for investigation; Kyeamba Creek catchment and the Yanco area (Figure 3).

Kyeamba Creek catchment is a medium to small catchment (approximately 600 km^2) with topography dominated by gentle slopes, some medium slopes and very few steep slopes. Land use is predominantly sheep and beef grazing with some dairy and cropping (hay). This catchment has been chosen to assess the impact of topography and streamflow on the observed gravity. The Yanco area is a large flat area (approximately 2,500 km^2) with minimal woody vegetation. Land use is irrigation in the west (Coleambally Irrigation Area) with rice and barley as the main rotations. Elsewhere in the Yanco area land use varies between dry land cropping (predominantly north) and native pasture (south-east). This study area was selected so that streamflow and elevation would not be important factors in the hydrology or gravity observations. See http://www.civenv.unimelb.edu.au/~jwalker/data/gsm/hydrograce.html for further site descriptions.

Despite the large depth to bedrock in the Coleambally Irrigation Area, there is a very high water table (4 m) due to irrigation induced recharge. The water table is much lower throughout the rest of the Yanco area (>12 m). The water table is also very high in the Kyeamba Creek catchment valley sites (4 m) but much lower on the slopes (>12 m). Both the

Figure 5. A typical site enclosed by 14 ft gates. Tipping bucket raingauge in left of enclosure, logger in centre, piezometer slightly to right and gravity meter in far right.

Yanco and Kyeamba Creek catchment areas have an unconfined aquifer overlying deeper confined aquifers.

Hydrologic Network

In addition to 18 existing soil moisture sites of which 7 are being used as part of this study, 20 new sites were installed and the existing sites augmented to give groundwater measurements and a location to take gravity readings. All sites have three Campbell Scientific CS616 water content reflectometers inserted vertically to give average 0–30, 30–60 and 60–90 cm soil moisture measurements, a tipping bucket raingauge, a soil temperature sensor, and an Odyssey capacitance probe to measure groundwater level. Measurements are also taken once every six weeks with a neutron moisture meter to give deeper soil moisture and with TDR to assist with calibration. A schematic and photograph for a typical site setup are shown in Figures 4 and 5.

Gravity Network

Three 8 ft long star pickets were inserted at each of the 27 sites to depth of refusal, and the tops cut off and levelled. The average cut off was 30 cm, resulting in approximately 2 m of star picket being inserted at each site. A stainless steel mounting plate was attached by a threaded bolt onto each star picket. This plate has a central pivot, v-slot groove and flat plate for the feet of the gravimeter stand to rest on. One leg of the stand always rests on the central pivot and has a permanent grub screw inserted in its mid-range; this provides ±10 mm adjustment to level the meter with the other two legs. This configuration ensures that the gravity meter is always exactly the same height above the mounting plate (provided it is clean).

Vertical repositioning is a significant factor when measuring gravity (a 3 mm change in elevation results in a 1 μ Gal change of gravity). The central pivot the gravimeter stand rests in is optically levelled off the top of the piezometer periodically to assess whether the star pickets or plate are moving relative to the surrounding soil.

Gravity is measured at each site with a Scintrex CG-3M gravimeter. Atmospheric pressure and air temperature (together with relative humidity and wind speed), are recorded at the same time with a portable weather tracker, as gravity meters are sensitive to changes in pressure and temperature.

The CG-3M has a large, mostly linear, daily drift of ~400 μ Gal. In order to remove the nonlinear component, regular measurements are made at a stable bedrock reference site within each field survey day. Following the recommendations of Dragert et al. (1981) for high precision gravimetry a complete homogeneous network has been constructed. Due to the large number of soil moisture monitoring sites (27) and large distance spanned it was necessary to concentrate on 4 focus sites in the Kyeamba Creek catchment. Two sites are hillslope sites with groundwater greater than 12 m and two sites are valley sites with groundwater less than 4 m. The valley sites and one of the hillslope sites (alternating) form a complete homogeneous network with the stable bedrock site that is sampled approximately every 6 weeks. Each sample takes 2 weeks and consists of 8 ties between each pair of sites. The first set of 8 ties is performed in one day (to minimise the effects of ocean loading) before moving to the next pair of sites (Dragert et al. 1981). Additionally the stable bedrock site is visited at the beginning and end of each day for drift control. The repeat measurements allow further drift analysis and tare detection. Tares (jumps in the value of the reading) are caused by bumps, jolts and vibrations during transport.

The SG in Canberra is used immediately before and after a field campaign to calibrate the CG-3M and tie to the bedrock reference sites. It is also used as a baseline measurement to be differenced from the field measurements. This ensures that solid earth tides, ocean loading and any other geophysical phenomena can be neglected (Scintrex Operator Manual 1995). Furthermore it is necessary for drift analysis and tare detection.

The stable bedrock reference sites (one for each area) were chosen to be close to the soil moisture monitoring locations and hydrologically stable (Canberra is 3 hours drive from Kyeamba creek catchment). Since there is no bedrock in the Yanco area, a sheltered concrete slab is used for the stable reference in that region.

GRAVITY EXPERIMENTS

Laboratory experiments are being conducted to evaluate the robustness of the CG-3M performance. Tests involve gravity response to the meter being: off-level, on DC power, repositioned, relevelled, and transported in a vehicle. Drift of the CG-3M is also very significant. It is assumed linear, however it has been claimed that it is in fact closer to quadratic over time periods longer than 3 days (Gabalda et al. 2003). Lab tests have shown that the drift is clearly linear over two days (Figure 2).

CONCLUSIONS

The gravimeter accuracy required for hydrological applications (<5 μ Gal) is provided by the Scintrex CG-3M in laboratory conditions. Whether this is the case in the field is still being determined. By regularly tying our field gravity measurements to the accurate superconducting gravimeter in Canberra, earth tides and ocean loading effects are removed, furthermore tares are detectable. Barometric pressure fluctuations can be removed with a barometer. After removing these contributing noise terms, the corrected data will be further analysed for a correlation with soil moisture changes.

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Mention of product names and manufacturers is solely used as a descriptive tool and does not constitute an endorsement by any of the authors.

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