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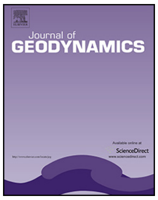

Hydro-gravimetry in West-Africa: First results from the Djougou (Benin) superconducting gravimeter

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ABSTRACT

The increasing number of hydro-gravimetry studies proves the rising interest of the hydrology community toward this monitoring method. The accuracy of superconducting gravimeters (SG) potentially allows the retrieval of small water storage changes (WSC) down to a few millimeters of equivalent water thickness. However, the importance of corrections applied to SG data to achieve such a precision in gravity residuals should be recalled. The Djougou permanent gravity station presented in this paper and located in northern Benin, West-Africa, provides a good opportunity to review these considerations. This station is equipped since July 2010 with the superconducting gravimeter SG-060 aimed at deriving WSC at different time-scales, daily to inter-annual. In this area, WSC are (1) part of the control system for evapotranspiration (ET) process, a key variable of the West-African monsoon cycle and (2) the state variable for resource management, a critical issue in storage-poor hard rock basement contexts such as in northern Benin. The potential for deriving WSC from time-lapse gravity data partly depends on environmental features such as topography and the instrument shelter. Therefore, this issue is addressed first, with the background idea that such sensitivity analysis should be undertaken before setting up any new instrument. In Djougou, local topography is quite flat leading to a theoretical straightforward relationship between gravity changes and WSC, close to the standard Bouguer value. However, the shelter plays a significant masking role, which is the principal limitation to the retrieval of fast hydrological processes such as ET following a rain event. Several issues concerning classical gravity corrections are also addressed in the paper. These include gap-filling procedures during rain-events and drift estimates for short time series. Special attention is provided to atmospheric corrections, and different approaches are tested: a simple scalar admittance, a filtered scalar admittance, a frequency-dependent admittance and direct atmospheric loading calculations. It is shown that the physically based approach of direct loading calculations performs better in both residual minimization and ET retrieval. Moreover, non-local hydrological effects are investigated and account for about 20% of the gravity residuals. Finally, gravity residuals are briefly analyzed at two distinct time scales: rapid (up to a few days) and seasonal. At the rapid time-scale, it is shown that ET retrieval is hardly achievable given shelter size and state-of-the-art atmospheric corrections. Still, mean values retrieved from this study are in accordance with known values of potential ET and lateral flow. Direct comparison of gravity changes with hydrological data (neutron probe monitoring and water table levels) show some discrepancies, particularly for the hydrological year of 2011, for which all hydrological data show a deficit, but SG and FG5 data do not. This preliminary analysis both provides a basis and call for further hydro-gravity modeling, to comprehensively investigate the water-cycle at the Djougou station.

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1. Introduction

Hydro-gravimetry is increasing year to year in importance, as evidenced by the interest of the community toward the new-generation superconducting gravimeter (SG), mostly dedicated to hydrological studies, the *i*Grav^{TM} (Warburton et al., 2010). The retrieval of local water storage changes (WSC) from time-lapse gravity data allows many hydrological applications, such as providing estimates of aquifer specific yield (Montgomery, 1971; Lambert and Beaumont, 1977; Peter et al., 1994; Pool and Eychaner, 1995; Pool and Schmidt, 1997; Metzger et al., 2002; Howle et al., 2003; Pool, 2008; Gehman et al., 2009; Pfeffer et al., 2011; Hector et al., 2013), bringing further constraints on hydrological modeling (Naujoks et al., 2010; Christiansen et al., 2011a,b; Jacob, 2009), identifying water redistribution processes (Kroner and Jahr, 2006; Naujoks et al., 2008; Chapman et al., 2008; Gettings et al., 2008; Davis et al., 2008; Jacob et al., 2008, 2009, 2010; McClymont et al., 2012; Pfeffer et al., 2013), establishing catchment storage–discharge relationships (Creutzfeldt et al., 2012a), studying WSC response to climate variability (Creutzfeldt et al., 2012b), and so on. More generally, WSC is usually considered as the residual term of the hydrological budget equation, and derived indirectly from the observation of other components (rainfall, runoff, evapotranspiration, etc.), by closing the budget. Hydro-gravimetry helps then to fill a significant gap in hydrological observations, which should further constrain the other components of the budget equation. Some objectives that hydro-gravimetry could achieve, such as the direct retrieval of evapotranspiration (ET), are still challenging, mainly due to the limited accuracy of both the instruments and the applied corrections (the removal of other time-variable effects on gravity).

As mentioned by several authors, WSC have slowly moved from “noise” to “signal” among the geodesy community, as the knowledge of the most common applications of time-lapse gravity (Earth tides, global geodynamics, etc.) increased, together with the instrumental sensitivity. However, now that WSC have become a signal to be retrieved from gravity data, precise corrections for non-hydrological signals are required, and all the knowledge about time variable gravity is therefore needed. This requires state-of-the-art corrections to recover for such small signals (in the range of a few μGals [1 μGal = 10 nm/s^2] for classical natural hydrological processes *vs* tens to hundreds of μGals for tides, atmospheric, and polar motion effects, see *e.g.* Crossley and Hinderer (2008)). It is now generally accepted that Earth tides are fairly well known. However, many processes still require very specific attention, such as the atmospheric contribution, which is about the same order of magnitude and acting at similar frequencies as hydrology. Once gravity residuals are obtained within some confidence intervals, a hydro-gravimetric analysis will become possible but requires further precautions.

First of all, there is a clear separation between the “local” and “non-local” surface loading effects of hydrology on gravity, in terms of distance to the station (Llubes et al., 2004). The correction of the non-local component can thus be undertaken, usually by using global hydrological model outputs or GRACE solutions, to allow the study of local hydrological effects (Longuevergne et al., 2009; Pfeffer et al., 2011).

Of particular importance in (local) hydro-gravity studies is the direct environment of the gravimeter location. Classical hydrological instruments (raingauges, moisture and suction probes, water table measurements, flow measurements, etc.) provide direct measurements of hydrological state variables in the vicinity of the sensor location. Although these variables can be integrating over a broader area (*e.g.* flow measurements), their values can be directly analyzed in terms of hydrological processes at their measurement location or further used as such for hydrological modeling (as forcing, calibration or validation variables) or spatially interpolated. On the contrary, time-variable gravity data are the measurements of the effect of the changes of a hydrological state variable – water storage – on the recorded variable, gravity, and are by nature influenced by the location of sources (distance, and sign of the relative height to the sensor). Therefore, time-variable gravity data somehow include topographical effects of the surroundings of the instrument. Consider for instance the case of a single rainfall event: the resulting gravity change will be depending on the rainfall amount but also on the topography. Later, water may redistribute in the underground or on the surface, and gravity changes will occur because of the change of masses *locations* as a result of the prevailing hydrological processes. This has been studied for instance by Kroner and Jahr (2006). The retrieval of WSC from gravity data thus requires proper understanding of the location of the storage units and potential flow processes. Two major features critically affect the local water redistribution: (a) the local topography in the vicinity of the gravimeter and (b) the shelter in which is located the gravimeter. These features can be easily accessed through a precise topographic survey.

To acknowledge the importance of such features, consider the following experiment: a gravimeter is located on the bottom of a small and incised valley, within a surface shelter, and records an increase in gravity that is identified as coming from hydrology (assuming all other contributions are well corrected). Several hydrological processes could lead to the recorded increase:

- infiltration nearby (and therefore below) the gravimeter,
- water flow on the valley slopes, moving masses from above to below the gravimeter,
- evapotranspiration on the valley slopes, removing masses from above the gravimeter,
- delayed infiltration underneath the shelter.

Therefore, time-variable gravity data should be interpreted with caution in terms of hydrological processes, when such features are significant (large shelter and strong topographic variations).

Such sensitivity analyses have been skipped by several authors, as they rather studied hydro-gravity by the mean of correlations studies between gravity residuals and water storage compartments, acknowledging the lack of accuracy on absolute WSC measurements (Bower and Courtier, 1998). However, this has also led to possible misinterpretation of gravity data. Goodkind (1986, 1990) at the Geysers geothermal field observed a rainfall admittance (gravity to rainfall amount ratio) of about 0.54 nm/s^2/mm and attributed the discrepancy to the nominal “Bouguer” value of 0.42 nm/s^2/mm (the gravity effect of an infinite flat layer of water) to specific hydrological processes (fast downward water transfer from an upper aquifer), and neglected the impact of the topography on this local admittance. Abe et al. (2006) analyzed the Bandung SG in Indonesia located in a constructed area, neglecting the importance of the buildings. Imanishi et al. (2006) found a 0.4 ± 0.02 nm/s^2/mm rainfall admittance for the Japanese Matsushiro SG, yet with a non-negligible topography and building size, calling for a need to model their effect. Van Camp et al. (2006) are among the first to use a digital elevation model (DEM) for the direct calculation of WSC gravity effect, but they only modeled a 200 m × 200 m zone around the gravimeter. Kroner and Jahr (2006) and Hasan et al. (2006) are among the first to recognize that such topographic effects, yet challenging to account for, imply different processes that hydro-gravimetry may or may not help to assess and quantify. They proceeded to the thorough study of such processes through important experiments, and concluded on the most likely process to produce the observed gravity change after modeling different hypothetical processes. Meurers et al. (2007) showed that topographic effects are very different from station to station,