Hybrid Gravimetry as a Tool to Monitor Surface and Underground Mass Changes

J. Hinderer, B. Hector, A. Mémin, and M. Calvo

Abstract

This paper is devoted to an overview of the use of hybrid gravimetry in Earth and Environmental Sciences. We first recall the concept of hybrid gravimetry which relies on the simultaneous use of different types of gravimeters either superconducting, absolute or relative spring gravimeters. This combination of instruments provides a complete tool for time-lapse gravimetry: while superconducting gravimeters and/or absolute gravimeters are used to obtain temporal gravity changes at one or several base stations, relative gravity surveys provide spatial differences with respect to these base stations, and allow to cover a much wider area than base stations only. Hybrid gravimetry therefore provides time-lapse gravity changes at a survey scale. We present here an overview of different published applications in hydrology, glaciology, volcanology and geothermics in order to point out that hybrid gravimetry is a powerful tool to monitor spatially and temporarily surface and underground mass changes.

Keywords

Hybrid gravimetry • Mass changes • Time-lapse gravity

1 Introduction

The term Hybrid Gravimetry (HG) was first introduced by Okubo et al. (2002) in a study dedicated to the gravity monitoring of a Japanese volcano (Mt Fuji) where the design for a gravity network included a transportable absolute gravimeter (AG) acting as reference for relative measurements (RG) done with spring meters. Later on Sugihara and Ishido (2008) introduced the concept of Super Hybrid Gravimetry (SHG) for geothermal reservoir monitoring by adding a new generation of superconducting gravimeter (SG) to the hybrid system (AG + RG). A last example of Hybrid Gravimetry can be found on Micro-g LaCoste Web site (http://www.microglacoste.com) as an announcement for HybridGravity™ Survey by adding A10 AG measurements to Scintrex CG-5 RG measurements. Earlier work also used the concept of hybrid gravimetry, although without naming it (e.g. Pool et al. 2000; Crossley and Hinderer 2005).

In this paper, we will first review the concept of Hybrid Gravimetry and will try to show the interest or even the necessity to combine different types of gravimeters in many research fields. To illustrate this we later give some examples of published applications in close connection to Earth and Environmental Sciences. We begin with hydrology and consider the case of a small catchment in West Africa. We then move to glaciology in Svalbard where hybrid gravimetry

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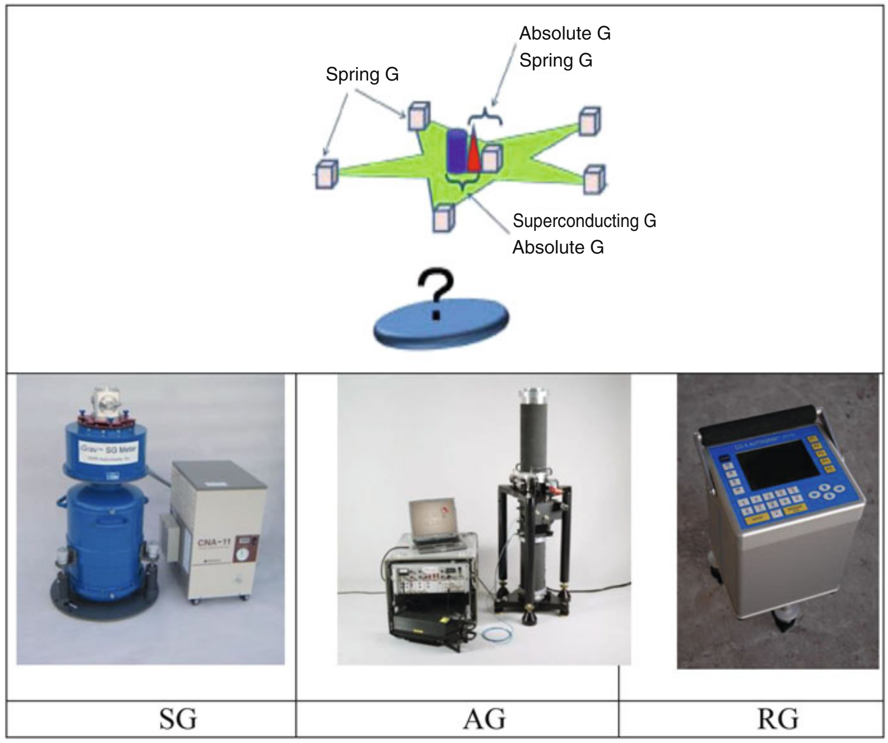


Fig. 1 The concept of hybrid gravimetry to investigate an underground reservoir with the combination of superconducting gravimeter (SG), absolute gravimeter AG and relative spring meter RG (adapted from Sugihara et al. 2013)

helps in assessing geodetic consequences of Present-day Ice Melting (PDIM). We finally end this section by presenting studies in volcanology and geothermics.

2 Hybrid Gravimetry

Several studies have introduced the concept of hybrid gravimetry (Okubo et al. 2002; Sugihara and Ishido 2008; Hector et al. 2015) that is the ideal combination of different types of gravimeters (see Fig. 1):

– a permanent gravimeter which allows a precise continuous monitoring of the time-varying gravity at a reference station located on the investigated site; this is usually done with a superconducting gravimeter (SG) rather than a spring meter because of its very small instrumental drift and better precision;
– a ballistic absolute gravimeter (AG) that allows to control the long term gravity changes by repeated parallel recording over short periods of time with the SG, as well as to check the calibration stability of the SG;
– a spring relative gravimeter (RG) to repeat observations on a micro-gravimetric network around reference stations by successive loops in order to gain more insight into the space-time changes in the investigated region.

The concept of hybrid gravimetry (HG) is illustrated on Fig. 1 where a combination of SG, AG, and RG observations at the Earth's surface aims to characterize the time evolution of any redistribution of mass (density, geometry, location) whatever its origin (glaciology, hydrology, geothermal reservoir, CO_2 sequestration). The diversity of user requirements and of gravimetric observation techniques has become obvious in many fields (e.g. Boedecker 2002). Of course a number of geophysical effects have to be corrected first (Earth and ocean tides, air pressure, polar motion) before investigating the body of interest.

In general there are two main approaches in time-lapse gravity studies.

The first observational strategy is to use a continuous monitoring with a SG. The advantage of such a permanent station is a strong time resolution (typically 1 s) and high precision (better than 0.1 μGal) (Hinderer et al. 2007). The disadvantage is that no spatial coverage is achieved and the small remaining instrumental drift of the SG requires regular AG measurements.

The second observational strategy is to use gravity networks with a RG (Naujoks et al. 2010). The main advantage is a better spatial coverage and the control of the (large) instrumental drift of the RG by loop repetition but there is still a large disadvantage which is the need for a reference point where the gravity changes are known. Moreover network gravity studies are expensive in manpower and time for obtaining a large number of measurements and processing the data.

Hybrid gravimetry is in fact a way to combine both strategies to optimize gravity measurements and processing. We can separate the following approaches:

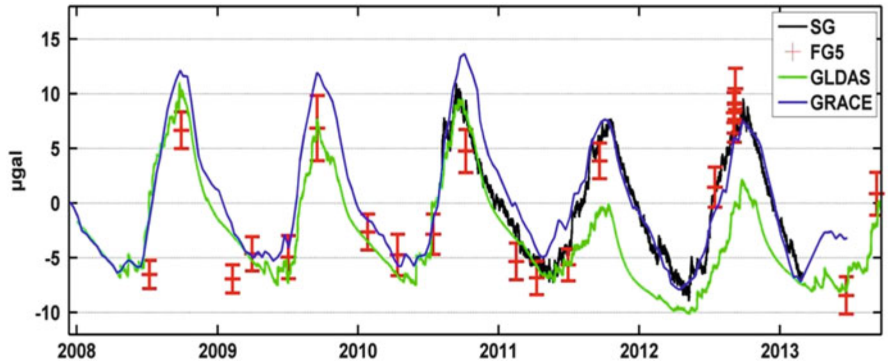


Fig. 2 Gravity changes in Djougou (West Africa) for the 2008–2013 period from the GRACE mascon solution (in *blue*), ground gravity from a SG (in *black*) and AG (in *red*) and predicted by GLDAS hydrology model (in *green*)

- To tie local measurements (RG) on a network (only relative with respect to? local base station) to a known reference (AG) leads to absolute changes in space
- To tie continuous local measurements (SG) to a reference (AG) leads to absolute changes in time
- The ideal solution is combining the two previous approaches which leads to the knowledge of absolute changes in both space and time.

3 Examples of Hybrid Gravimetry Studies

3.1 Hydrology

Underground water storage changes (WSC) are fundamental unknowns of the water cycle which are still challenging to derive from classical point measurements (i.e. moisture probes, water table depths . . .). Hydrogravimetry has become very important in linking spatially-integrated WSC to surface gravity changes using SG, AG and RG measurements or specific combinations of the three (Davis et al. 2008; Hare et al. 2008; Jacob et al. 2008, 2010; Longuevergne et al. 2009; Creutzfeldt et al. 2010; Naujoks et al. 2010; Pfeffer et al. 2011; Hector et al. 2015).

We focus here on the study of a small (16 ha) subcatchment of the Ara river in West Africa near Djougou (Benin). This catchment belongs to the Upper-Ouémé catchment in northern Benin with a humid Sudanian-type climate. This catchment is studied since several years by hydrologists in the frame of the AMMA-CATCH observatory (Lebel et al. 2009; Séguis et al. 2011). A dense monitoring network dedicated to water redistribution process studies has been set up since 2003, including neutron probe (NP) measurements. A NP allows to derive moisture contents (hence WSC) from neutron counts in a 0.15 m radius around a borehole at each measurement depth. Gravity observations were added to the previously existing hydro-meteorological sensors for air pressure, soil humidity, and aquifer levels in the GHYRAF (Gravity and Hydrology in Africa) project since 2008 (Hinderer et al. 2012). In the beginning we mainly relied on episodic AG measurements 4 times a year (Hector et al. 2013). Later on, in 2010 we installed a permanent SG on this catchment a few meters besides the AG pillar (Hinderer et al. 2013; Hector et al. 2014).

We also established in 2011 a gravity network with RG measurements (Hector et al. 2015). The repetition of this network of 13 stations was typically once a month in the dry season and once a week in the rainy period i.e. in summer. The uncertainty we achieve on this network where the RG is hand-carried on small distance loops is excellent (<2.5 μGal). In this hybrid gravity experiment, we hence have available a continuous series of the SG complemented with regular AG measurements, and a dense RG repetition network. Figure 2 shows the gravity temporal changes as seen by the continuous SG data with episodic AG measurements (Hector et al. 2013, 2014), as well as GRACE satellites data and GLDAS (Rodell et al. 2004) global hydrology model prediction. The GRACE data shown here are obtained from the mascon (mass concentration) solution (Luthcke et al. 2013). AG measurements helped in validating the removal of the instrumental drift (modeled as an initial exponential followed by a linear part). It is interesting to note the close agreement between the surface measurements (SG/AG) and GRACE. On the contrary, more discrepancies exist with the hydrology model, especially in summer 2011.

The large set of available data (70 surveys between July 2011 and September 2013) allowed us to perform an EOF (Empirical Orthogonal Function, a well suited method for the extraction of coherent time and space patterns in the data) decomposition of the gravity field and water content from the neutron probe data.

A recent gravimetry study performed using the EOF method is illustrated in Crossley et al. (2012). Figure 3 shows the results of this EOF decomposition on a time span covering 2 contrasted years (Hector et al. 2015) with, respectively, the EOFs of the first mode for gravity changes and NP-derived WSCs. For both datasets, the first mode explains much of the variance in the data (79% for gravity changes, and 90% for WSCs) meaning that the signal can be

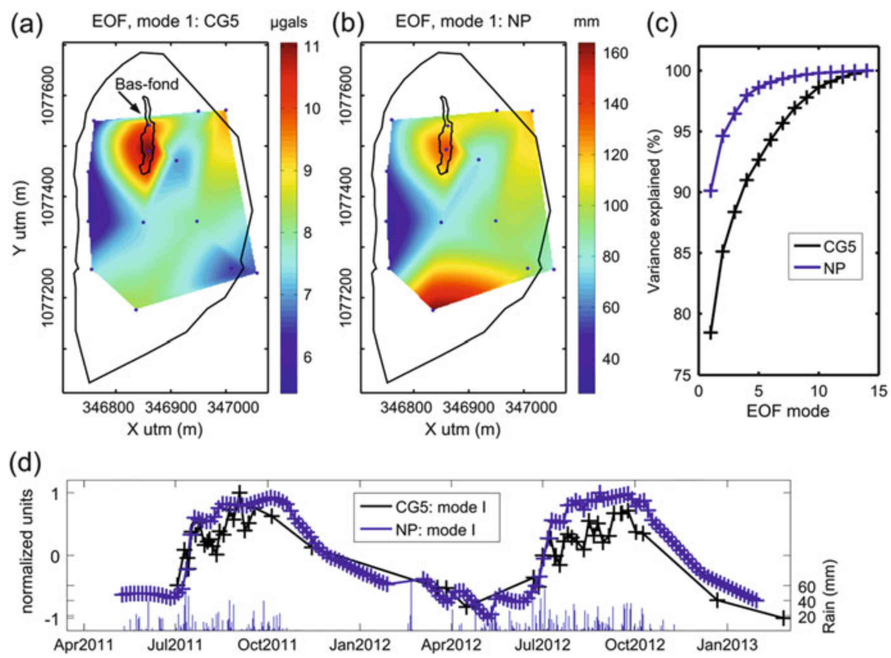


Fig. 3 EOF results for gravity and NP data in Djougou (West Africa): (**a**) Mode I EOF for hybrid gravity data. (**b**) Mode I EOF for NP data. (**c**) Cumulated variance explained for each EOF mode for each dataset. (**d**) Expansion coefficients of mode I for hybrid gravity data and NP data and daily precipitation (from Hector et al. 2015)

reconstructed up to 79% for gravity and up to 90% for WSCs. The temporal aspect of mode 1 for all datasets shows that it is the seasonal signal that dominates the variance. EOFs therefore represent the spatial distribution of variations in this seasonal behavior.

WSCs from NP data show similar space-time patterns than gravity changes despite different footprints (about 100 m radius for gravity observation and about 0.15 m radius for NP data). In the study of Hector et al. (2015), these patterns could be related to the catchment lithology, explaining the similar results from both datasets with different footprints, and streamflow generation processes were derived from these observations. It is important to note that, without the inclusion of the seasonal changes, brought by the SG monitoring of the reference station and which contribute highly to the signal variance, the EOF decomposition of the RG data alone fails because of signal to noise problems. In this case, the variance is governed by higher frequency components (i.e. days to weeks) which often fall within the data error bars. There is much less space and time coherence of the variance when using RG data only. It is clearly the hybrid gravimetry approach that enables us to extract the coherent spatio-temporal variation of the gravity field.

3.2 Ice Melting

Our second example of interest for hybrid gravimetry deals with glaciology such as in Svalbard (Norway) in the Arctic. Svalbard is known to be one location where PDIM occurs in addition to past ice melting. Besides, there is a geodetic reference station, in Ny-Alesund, coupling gravity and positioning measurements. The goal there is to relate surface gravity variations and crustal vertical motion to ice melting from glaciers (Mémin et al. 2009) either originating from today deglaciation (PDIM), caused by global warming, or from past (Pleistocene) deglaciation (Mémin et al. 2011, 2012, 2014). This goal was achieved by combining the hybrid gravimetry approach with positioning measurements.

The station of Ny-Alesund benefits both from precise positioning with the help of various independent techniques (VLBI, GPS, DORIS), tide gauge observations and gravity measurements thanks to a permanent SG since 2000 and regular (once a year or once every 2 years) AG measurements (Fig. 4). When considered alone the AG values (in blue) lead to a trend of -1.23 ± 0.51 μGal/year which is quite uncertain (error of about 42%). But if one takes into account the seasonal variability as observed by the SG and corrects the AG values (the hybrid approach), the gravity trend becomes -1.39 ± 0.11 μGal/year (Mémin et al. 2014). This value is larger than before but, more important, the scattering of the corrected values around the linear trend is greatly reduced which leads to a trend uncertainty reduced by a factor close to 5 (corresponding to an error of about 7%).

Several studies focused on explaining simultaneously the gravity changes and the vertical land motion due to the deformation induced by the past and present-day ice-mass changes and observed in Ny-Alesund (e.g. Omang and Kierulf 2011; Mémin et al. 2011). In that regard, they usually consider several melting histories. Thanks to the gravity rate estimated using the hybrid gravimetry strategy, Mémin et al. (2014) were able to refine the modeling and explain both gravity and vertical displacement changes in Ny-Alesund. They

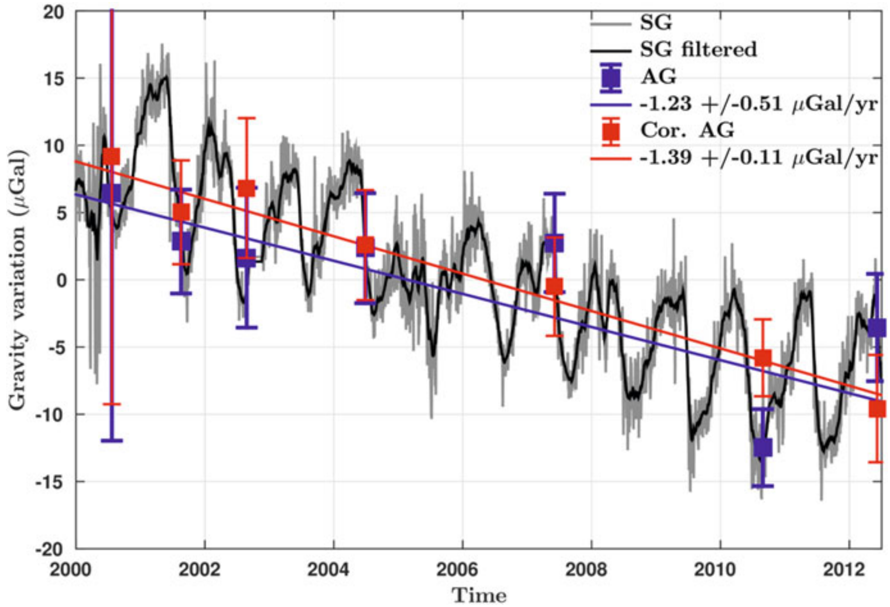


Fig. 4 Gravity variations measured at the Ny-Alesund geodetic observatory by a superconducting gravimeter (*grey line*) and an absolute gravimeter (*blue squares*). The *black line* shows the SG measurements after filtering out the high frequencies using a moving average over 1 month. The *red squares* show the absolute gravity measurements corrected for a seasonal signal estimated from the SG measurements. The *blue* and *red lines* are the linear trends estimated using the AG and the corrected AG measurements, respectively

added contributions to the deformation that were previously neglected. These contributions involve a new component to the melting history, known as the little Ice Age, and the sea level change due to present-day ice-mass change.

3.3 Volcanology

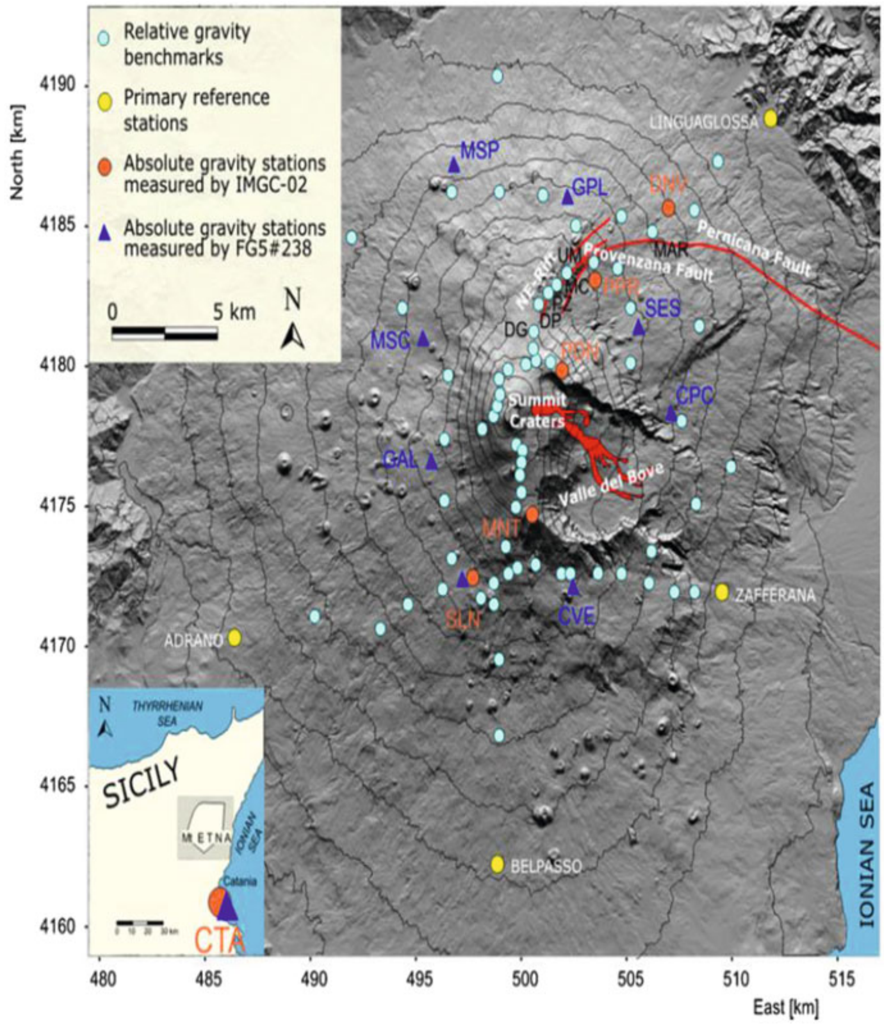
In volcanology the goal using geodetic and gravity observations is the modeling of volcano dynamics and associated eruptions. A nice example was given by Furuya et al. (2003) on Miyakejima volcano in Japan where the combination of AG and RG measurements together with GPS and tilt observations helped the authors to correct the gravity data for the effect of collapsed topography during an eruption and to propose a speculative scenario for the temporal evolution of the volcanic activity. For more references in volcano-gravimetry we refer the reader to Crossley et al. (2013).

New results were obtained from hybrid gravimetry on other volcanoes using mostly AG and RG measurements (Carbone and Greco 2007; Hautmann et al. 2010; Battaglia et al. 2008) that allow to determine absolute changes in the local network which were unknown in previous studies based only on RG observations (e.g. Jousset et al. 2000). An example of hybrid gravimetry approach can be found on Etna volcano in Italy. Figure 5 shows the network established on this volcanoe combining RG and AG measurements (Greco et al. 2012). More recently SG continuous monitoring was added to RG and AG and promising results are expected (Carbone and Greco 2015).

3.4 Geothermics

The final field where hybrid gravimetry is promising is related to geothermal activity (Nishijima et al. 2000; Oka et al. 2012; Sofyan et al. 2011; Sugihara and Ishido 2008; Takemura et al. 2000; Schultz et al. 2012) which has clearly become important as a possible alternative energy resource for the future. Many experiments have started and more references can be found in Hinderer et al. (2015). The goal of these studies is the modeling of the geothermal fluid circulation and mass transport which is often occurring at large depths (several hundreds or even thousands of meters); it is hence much more difficult to detect than surface or sub-surface mass changes like in glaciology or hydrology. A nice example of hybrid gravimetry applied to geothermics can be found in Oka et al. (2012) on the Takigami geothermal field in Japan producing 25 MW power. A study involving AG and RG (together with GPS) could identify the spatial distribution of gravity on this geothermal site just after the start of the power generation and the modeling leads to an estimate of 12 Mt of water extraction per year. Another example of using hybrid gravimetry to optimize time-lapse monitoring data can be found in Sofyan et al. (2015). Figure 6 (left) shows the network of the Kamojang geothermal field in Indonesia where both AG and RG measurements are regularly repeated. Figure 6 (right) shows the time evolution of the AG benchmarks indicating that at several locations gravity decreased between 2010 and 2011 while it was more constant in the period 2009–2010. This is important because gravity monitoring with RG alone assume

Fig. 5 The hybrid gravity network of Etna volcano (Italy) showing the RG and AG benchmarks (from Greco et al. 2012)



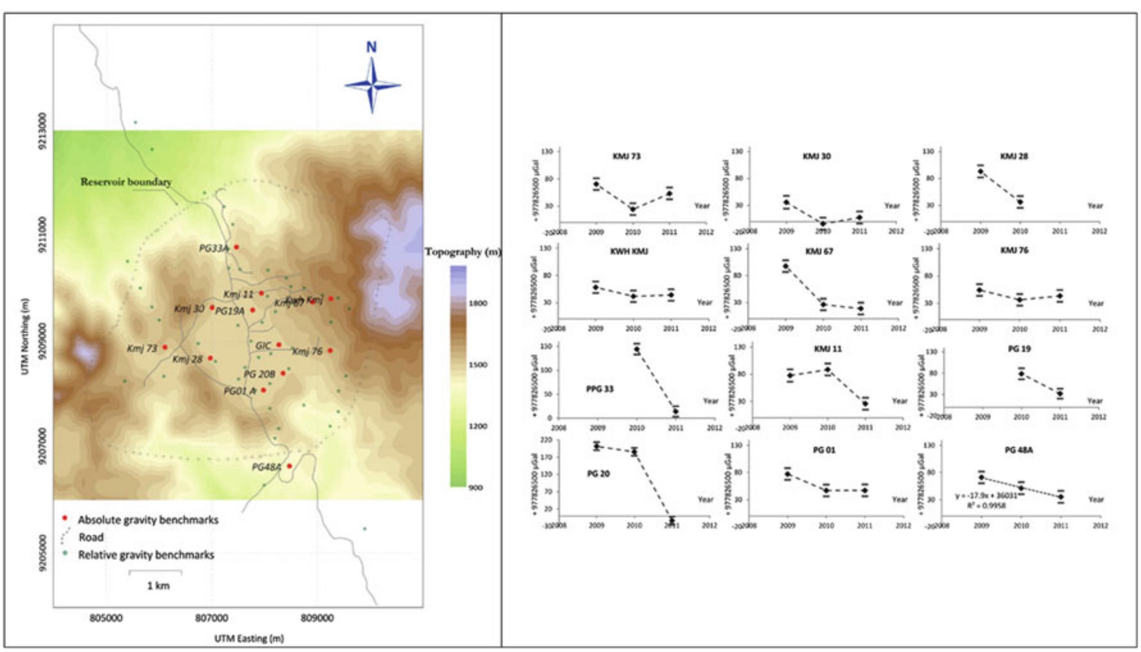


Fig. 6 The hybrid gravity network of the Kamojang geothermal field (Indonesia) showing the location of the RG and AG benchmarks (*left*) and the time changes of gravity at these absolute benchmarks (*right*) (from Sofyan et al. 2015)

that the reference station is constant. This assumption is not true if there is for instance a regional effect and AG measurements are then the best way to correct the gravity changes at the reference station.

4 Conclusion

The combination of several types of gravimeters (AG, SG, RG) involved in the hybrid gravimetry approach leads to valuable information on any surface or underground mass redistribution in time and space. Hybrid gravimetry associated with geodesy (GNSS, InSAR, VLBI) allows more insight into the physical processes since mass transport effects in gravity can be isolated from geometrical effects linked to the vertical motion of the ground. We have shown one example of application in hydrology in West Africa where hybrid gravimetry led to characterize the space-time behavior of water storage changes in a catchment of small size. Another example came from ice melting in Svalbard in the Arctic where combining continuous SG measurements to episodic AG observations led to infer a more precise gravity trend over a decade which helped in modeling the contribution of past and present-day ice melting. We also reviewed applications of hybrid gravimetry in volcanology and geothermic. More applications are expected in various fields in Earth and Environmental Sciences.

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