



## Research paper

## pyGrav, a Python-based program for handling and processing relative gravity data

Basile Hector<sup>\*,1</sup>, Jacques Hinderer

Institut de Physique du Globe de Strasbourg UMR 7516 CNRS/Université de Strasbourg, 5 rue Descartes, 67084 Strasbourg, France

## ARTICLE INFO

## Article history:

Received 11 September 2015

Received in revised form

14 March 2016

Accepted 17 March 2016

Available online 18 March 2016

## Keywords:

Relative-gravity

Time-variable gravity

Object-oriented

Python

## ABSTRACT

pyGrav is a Python-based open-source software dedicated to the complete processing of relative-gravity data. It is particularly suited for time-lapse gravity surveys where high precision is sought. Its purpose is to bind together single-task processing codes in a user-friendly interface for handy and fast treatment of raw gravity data from many stations of a network. The intuitive object-based implementation allows to easily integrate additional functions (reading/writing routines, processing schemes, data plots) related to the appropriate object (a station, a loop, or a survey). This makes pyGrav an evolving tool. Raw data can be corrected for tides and air pressure effects. The data selection step features a double table-plot graphical window with either manual or automatic selection according to specific thresholds on data channels (tilts, gravity values, gravity standard deviation, duration of measurements, etc.). Instrumental drifts and gravity residuals are obtained by least square analysis of the dataset. This first step leads to the gravity simple differences between a reference point and any point of the network. When different repetitions of the network are done, the software computes then the gravity double differences and associated errors. The program has been tested on two specific case studies: a large dataset acquired for the study of water storage changes on a small catchment in West Africa, and a dataset operated and processed by several different users for geothermal studies in northern Alsace, France. In both cases, pyGrav proved to be an efficient and easy-to-use solution for the effective processing of relative-gravity data.

© 2016 Elsevier Ltd. All rights reserved.

## 1. Introduction

Relative-gravity surveys are used in a wide range of applications, such as geothermics (e.g. Allis and Hunt, 1986; Hinderer et al., 2015), oil and gas exploration (e.g. Ferguson et al., 2008), volcanology (e.g. Greco et al., 2012; Jousset et al., 2000), or hydrology (e.g. Hector et al., 2015; Piccolroaz et al., 2015; Pfeffer et al., 2013; Jacob et al., 2010). They are classically used as an exploration tool for static imagery of the subsurface. Time-lapse gravity surveys are applied to the monitoring of mass redistributions.

Relative-gravity measurements are affected by several natural or instrumental processes such as earth tides and barometric pressure, long-term instrumental drift, transportation-induced drift and noise, temperature, etc. which must be corrected when a specific signal (e.g. water storage changes) is sought (Crossley et al., 2013). Furthermore, field data must be selected based on stability indicators (instruments tilts, measurements errors,

presence of spikes in the data, etc.) for obtaining high-quality gravity residuals. Due to the intrinsic drifting behavior of relative spring gravity meters, field studies focus on gravity differences between stations, rather than readings at single stations. Processing (both corrections and selection steps) of a dataset acquired within the same period leads to what is known as “simple differences”, which are gravity differences between each station of the network and a base station. From this result, static imagery proceeds to subsequent so-called “static corrections” for analyzing these differences in terms of Bouguer anomalies. On the other hand, from temporal repetitions of surveys, time-lapse gravimetry studies leads to “double differences” (Pfeffer et al., 2013), which are temporal differences of simple differences results. Static corrections are not needed in such studies as static effects cancel out in survey-to-survey differences.

Many codes and routines exist for processing relative-gravity data (e.g. CgxTool (Gabalda et al., 2003), Gravnet (Hwang et al., 2002), MCGravi (Beilin, 2006)), but they are mostly dedicated to static surveys, and are focused on single-tasks, usually network adjustment. They also lack user-friendly data selection interfaces particularly needed for time-lapse investigations when high precisions are sought. Several research teams have developed their own processing chain which usually consists of sequential calls to

\* Corresponding author.

E-mail address: [basilehector@gmail.com](mailto:basilehector@gmail.com) (B. Hector).<sup>1</sup> Present address: CNES/IRD/UJF-Grenoble 1/CNRS/G-INP, LTHE, UMR 5564, 38041 Grenoble, France.

different programs having specific I/O and formalisms. This complexity makes the whole processing chain very slow and not much friendly to new users and further hinders reproducible research. The time required for data processing also prevents rapid on-field check of the data and subsequent data reacquisition in case of problems. There is therefore a strong need for a flexible tool that would allow binding all processing steps together and still authorizing easy incorporation of new functions or function updates for teams who wish to integrate some of their own codes.

The recent Gravprocess MATLAB<sup>TM</sup>-based software (Cattin et al., 2015) is dedicated to the whole processing of complex gravity surveys and does not include an explicit data selection procedure. It is particularly suitable for large static surveys with several different base stations and allows the calculation of static corrections. It does not allow the simultaneous inversion of stations gravity values and drifts for overlapping or repeated lines within a short period where gravity changes (other than tides- and barometric-related ones) are assumed negligible (typically one or two days depending on environmental conditions). The study of time-lapse gravity changes usually requires high precision in the data acquisition and it is also highly important that stations and loops are repeated several times (e.g. Christiansen et al., 2011a, 2011b, 2011c; Jacob et al., 2010; Pfeffer et al., 2013).

With the ongoing development of gravity measurements for time-lapse studies, such as the Critex program in France for the monitoring of water storage changes in Critical Zone observatories (<http://critex.des-mondes-singuliers.coop/>), there will be an increasing need for such complete processing codes. They will need to be adaptable, for integrating outcome from new research, to be easy to manipulate and to be efficient for rapidly checking the data on field. This becomes particularly relevant with the emerging concept of hybrid gravimetry (e.g. Hector et al., 2015; Hinderer et al., Submitted, 2015). Hybrid gravimetry is the combined use of relative spring gravimeters with instruments measuring gravity changes at the network base station (i.e. superconducting gravimeters, measuring continuously, and absolute gravimeters, measuring episodically), in order to determine the absolute changes at all points of the network, see e.g. Okubo et al. (2002) or Sugihara and Ishido (2008).

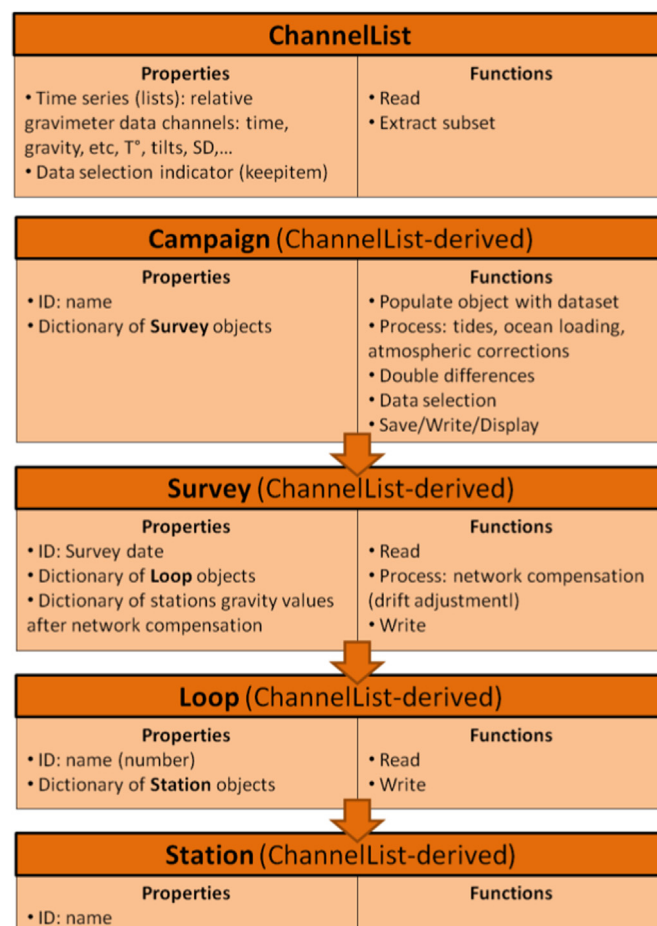
This paper presents pyGrav, a multi-platform, open-source, Python-based software for processing relative-gravity data. The code is fully object-oriented, which is highly appropriate for handling structured relative-gravity data as described in a first section. The complete processing chain of relative-gravity data, including a data selection frame that relies on an object-oriented scheme is then presented. Finally, two different case studies (hydrology and geothermics) are shown.

## 2. Relative gravity measurements and object oriented programming

Geophysical data sets make often object-oriented programming very intuitive, such as in seismology (e.g. the Waveloc seismic event detection and location code also written in Python Langet et al., 2014), or for magnetotelluric data (Krieger and Peacock, 2014). The climate community also widely use the Python object-based capabilities (for instance the UV-CDAT data analysis tool, <http://uvcdat.llnl.gov/>), and so do the geographic information system (GIS) community. For instance the widely-used QGIS open-source software makes extensive use of Python capabilities and provides Python bindings which allow users to interface their own scripts through the GIS. Such open-source initiatives contribute to the development of highly collaborative work, sometimes through git repositories which allow different contributors to help developing a specific code.

Object-oriented programming is particularly suited for handling and processing relative-gravity data as data can be arranged as structures (objects –or classes, in Python) following a hierarchical definition: A relative-gravity *campaign* refers to a specific study and designates the whole data acquisition scheme, including stations network geometry, timing of measurements, acquisition protocol (e.g. Seigel et al., 1995), etc. A relative-gravity campaign may be composed of one or several *surveys*, each survey being undertaken under similar environmental conditions (e.g. assuming no significant changes of the target variable like water storage changes, ground deformation, mass changes, etc. during the survey period). This allows to process data of single surveys simultaneously, under the assumption that station values (once corrected for tides, air pressure and drift) should not have changed. Differences between surveys are the goal of time-lapse relative-gravity studies, as each survey gives access to a snapshot of the gravity field. Surveys include several *loops*, where each loop refers to the measurements of different *station*, with at least one station repetition (the base station) for drift control.

This intrinsic hierarchical structure allows for an easy and intuitive object-oriented programming frame for the handling and processing of relative-gravity data. Specific functions may be defined at the corresponding object (class) level (Fig. 1). For instance, network adjustment should be applied to a whole single survey. Earth tides and atmospheric corrections can be applied to the whole campaign, but data selection should be undertaken at the



**Fig. 1.** Objects (classes) and objects imbrications which are the core of the pyGrav program. Each instance of each object has specific properties, and each object is associated to specific functions. All objects are derived from a Channel List-type object, and inherit its properties. Note that functions which imply graphical interactions (i.e. data selection) are defined in the main program script which includes PyQt functions.

station level. This intuitive structure makes it easy for anyone to implement new functions, I/O to other programs, or even plot windows, by identifying the object application level, and being inspired by already existing portions of the code. Test-cases are available in pyGrav, using both the pyGrav graphical user interface and Python scripts for calling single pyGrav functions.

### 3. pyGrav functions

pyGrav is written in Python 2.7 and needs the standard Numpy and Scipy modules to be installed, as well as the Matplotlib module for data plots. pyGrav classes and associated functions can be called from the command line or any Python script by loading the module which contains pyGrav main classes (an example is provided with the source files). pyGrav can also run within a Graphical User Interface (GUI), and further requires the PyQt4 module to be installed. pyGrav GUI is subdivided into several processing sections, which are also usually applied sequentially when using a user-defined script (see example provided) for calling pyGrav functions. First, a reading section fills the Python objects (classes) which handle gravity data. Then, tide and air pressure corrections can be applied at various levels of precision. Each station time series may be explored in detail for selecting relevant data (through the GUI only), or automatic selection procedure may be applied based on simple thresholds on gravity values or other channels (measurements errors, tilts, etc.). Drift and station values can be obtained by least-square data adjustment, to produce simple differences. These steps can be undertaken iteratively (i.e. by controlling a posteriori variances of simple differences, the user may choose to start again the selection process in a more restrictive way). Finally, double differences can be calculated from a dataset containing several surveys.

It is also possible to save the data at any time of the process (after tides and barometric corrections, after data selection, or after network adjustment) to use another code designed for a specific task, such as the weighted constraint model for station values retrieval (Hwang et al., 2002). No static corrections, such as *terrain* or *free-air* corrections, are implemented in pyGrav so far, although this is an achievable task by simply adding functions at the appropriate object level. In addition, it is also possible to provide the Gravprocess software (Cattin et al., 2015) with data previously selected using pyGrav.

#### 3.1. Organizing data

Currently only Scintrex CG5 output ASCII files are read, but any other file format, from other instruments, may be read by adding the appropriate function. A single file is read as raw data for a single campaign, and several options are available for organizing the data into different surveys. The user may choose between providing start and end times of a single survey, or loading a file containing a list of start/end times of each survey. Alternatively, the user may also choose an automatic procedure by providing a time threshold for the identification of single surveys. Once the data are arranged into different surveys, loops are automatically identified by base station reoccupations. The data are eventually stored within a hierarchical frame based on nested objects.

Another option is to load pre-arranged data, which can be obtained by saving previous pyGrav processing work or manually arranging the data into several surveys folders, each containing several loop files, and providing a file describing this data hierarchy (a list of survey directories and loop files).

#### 3.2. Tides and air pressure corrections

Earth tides can be corrected using different approaches. Either a preliminary correction provided by the dataset is available (e.g. CG5 instruments provide an earth tide correction channel if requested) and may be retained as the final correction, or a synthetic earth tide time series may be used for correction. In this case, either a synthetic time series is directly provided by the user, or it is calculated by two different possible means:

- the PREDICT function from the ETERNA package (Wenzel, 1996) using the HW95 tidal potential (Hartmann and Wenzel, 1995). In this case, the user provides mean latitude, longitude and altitude of the network. The user also chooses between a standard tidal parameter list provided within pyGrav, or may load any other tidal parameter list (obtained from a tidal analysis for instance). This last feature is particularly suited when a superconducting gravimeter is available on site, for instance, as tidal parameters from a local empirical tidal analysis may also include oceanic loading which occur at the same frequencies as solid earth tides. This empirical approach avoids further oceanic loading corrections.
- a direct non-harmonic computation of solid earth-tides effect is available in the fortran codes of (Agnew, 2007, 2012) later translated into MATLAB™ by Cattin et al. (2015) in their GravProcess software. This approach is based on a direct computation of the tidal potential from Munk and Cartwright (1966) and an internal ephemeris for the Moon and Sun locations. The code has been translated into Python to provide an alternative to the PREDICT software.

Ocean loading can be implicitly corrected using the interface to the PREDICT code (see above), or calculated similar to Cattin et al. (2015) in their GravProcess software, and following Agnew (2012). In this case, loading parameters for the semidiurnal (M2, S2, N2, K2), diurnal (O1, P1, Q1, K1) and long- period (MF, Mm, Ssa) tidal harmonics must be provided using e.g. the Scherneck's free ocean provider (<http://holt.oso.chalmers.se/loading/>).

Atmospheric corrections (see Hinderer et al., 2014) consist in using an atmospheric loading file containing both local and non-local effect, for instance such as available on the EOST/IPG Strasbourg site: <http://loading.u-strasbg.fr/>. As a first approximation, the user may provide a local barometric time series and use a nominal atmospheric admittance of  $-0.3 \mu\text{Gal/hPa}$ .

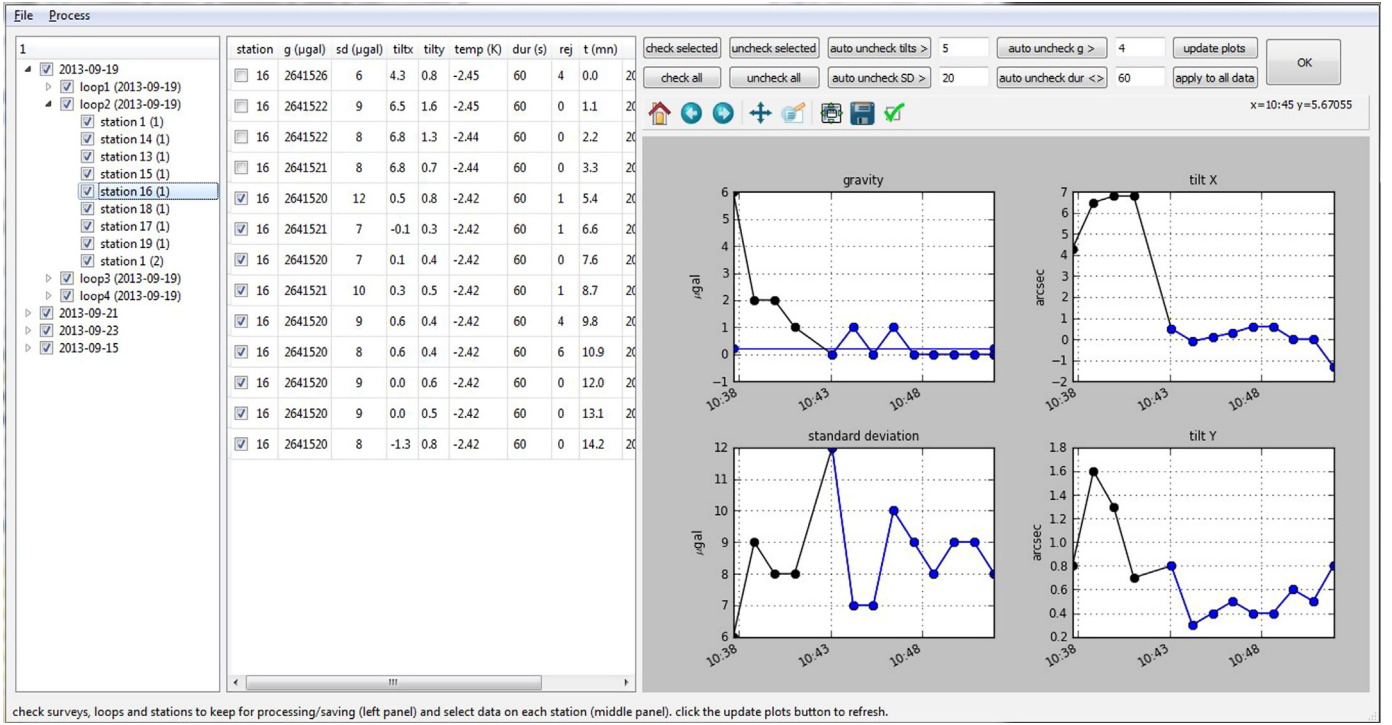
#### 3.3. Data selection

Data selection exploits the full advantage of the object-oriented frame for both the data-handling and the graphical sections. The whole hierarchical dataset is visible and any object (survey, loop, station, and measurement) may or may not be retained ("checked") for further processing of the data (Fig. 2). Tilts, gravity values, and measurement errors are plotted as time series for each station and selection can be done based on this information, or on the table view of the data. Also, thresholds on gravity values (with respect to the average of the three last gravity values of each station time series), measurements errors, tilts or measurement duration may be applied for automatic selection on each station separately or on the whole dataset. At any time, this selection can be saved and is then reusable in another session.

Good practice for selecting data is:

- Identify thresholds on standard deviations above which abnormal conditions are suspected (earthquake, anthropogenic noise, storm, etc.)
- Maintain absolute tilt values below 5 arcsec.





**Fig. 2.** Data selection window. The dataset hierarchy is visible on the left panel, and time series for each station are shown as a table (center panel) or graphical plot (right panel). Checked item are shown in blue on the plots and are retained for further processing. Thresholds can be defined on the upper box for automatic data selection.

- No visible drift in the gravity time series (no more short-term transportation-induced drift): this requires the long term drift being previously removed from the data. This can be done by least squares regression on data acquired over more than a day in a single station (when the gravimeter rests between surveys for instance), or by correcting the drift using the CG5 capabilities.

#### 3.4. Drift corrections/network adjustments

Significant contribution concerning the least-square inversion of relative-gravity data and drift corrections is presented in the work of Hwang et al. (2002), which resulted in the Gravnet software. Extension of such work, for adjustment networks can be found in Beilin (2006) with the MCGravi software (provided along with pyGrav). In the present version of pyGrav, only the datum-free solution from Gravnet has been re-coded into Python. The weighted constraint model is still available, by writing MCGravi input files, launching MCGravi and reading MCGravi output files through the pyGrav interface. This option requires the MCGravi executable to be present in the pyGrav directory. The following paragraph details the datum-free least square inversion procedure available within pyGrav. One should note here that the whole pyGrav-MCGRAVI interface can also be viewed as an example for any user on how-to wrap an external code into pyGrav. For instance, some working groups use different, more sophisticated network adjustment schemes (e.g. Kennedy and Ferré, 2016) depending on studies objectives and specific targets, which could be implemented in pyGrav, as alternative options.

Gravity observations at a station can be a time series of several gravity measurements, each measurement  $m$  being the mean of several samples. For instance, a typical CG-5 measurement results from acquiring samples for more than a minute (85s is considered best, Merlet et al., 2008) at 6 Hz. Standard error (SE) on each measurement is therefore:

$$SE = \frac{\sigma}{\sqrt{n \text{ samples}}} \quad (1)$$

where  $\sigma$  is measurement standard deviation and  $n$  samples is the number of samples.

After data have been selected, a single observation  $l_i$  and a standard deviation  $\sigma_i$  are derived from the remaining time series of measurements  $m$ , for each station  $i$  using variance-weighted means:

$$l_i = \frac{\sum_{j=1}^n \frac{m_j}{SE_j^2}}{\sum_{j=1}^n \frac{1}{SE_j^2}} \quad (2)$$

$$\sigma_i = \frac{1}{\sum_{j=1}^n \frac{1}{SE_j^2}} \quad (3)$$

The standard deviation,  $\sigma_{ij}$  for a relative-gravity observation  $\Delta l_{ij}$  between station  $i$  and  $j$  is given by

$$\sigma_{ij} = \sqrt{\sigma_i^2 + \sigma_j^2} \quad (4)$$

while  $\Delta l_{ij}$  is given by

$$\Delta l_{ij} + v_{ij} = g_j - g_i + \sum_{T=1}^m a_T (t_j - t_i)^T + \sum_{k=1}^n b_k (t_j - t_i)^k \quad (5)$$

where  $v_{ij}$  are the residuals,  $g_i$  is the gravity value at station  $i$ ,  $m$  is the degree of the polynomial of coefficients  $a_T$  for the gravimeter drift and  $n$  is the degree of the polynomial of coefficients  $b_k$  for the temperature drift. The equation system is therefore

$$L^b + V = AX \quad (6)$$

where  $L^b$  is a vector containing  $n$  relative-gravity observations,  $V$  is a vector with  $n$  residuals,  $A$  is the design matrix and  $X$  is the vector of  $u$  unknowns (gravity values and drift parameters). To obtain a solution of  $X$ , one must hold fixed at least one gravity

value during the adjustment (the so-called gravity datum). This is done here by adding absolute gravity observations  $L_g^b$  at the base station:

$$L_g^b + V_g = A_g X = [I \ 0] \begin{bmatrix} X_g \\ X_f \end{bmatrix} \quad (7)$$

Where  $X_g$  contains gravity values and  $X_f$  contains drift parameters.

Introducing the vector  $S$  with  $k$  (number of gravity values) first values equal to one and  $u - k$  last values equal to zero, which satisfies:

$$S^T X = 0 \quad (8)$$

one may find the least-square solution of  $X$ :

$$X = (A^T P A + S S^T)^{-1} A^T P L^b \quad (9)$$

The weight matrix  $P$  is composed of the inverse of variance terms for observations.

The a posteriori variance of unit weight ( $\sigma_0^2$ ) is given by

$$\sigma_0^2 = \frac{V^T P V}{n + 1 - u} \quad (10)$$

and the a posteriori covariance matrix  $S_X$  is given by covariance propagation:

$$S_X = \sigma_0^2 (A^T P A + S S^T)^{-1} A^T P A (A^T P A + S S^T)^{-1} \quad (11)$$

### 3.5. Simple and double differences

Eq. (9) produces the simple differences to fixed gravity values which have been introduced, associated with the a posteriori covariance matrix of Eq. (11). The reference datum can be a base station, by selecting a particularly stable location, or a station where gravity changes are known (i.e. from measurements with a superconducting or absolute gravimeter) in the case of a hybrid gravity framework.

When several surveys are processed, it is possible to compute double differences by selecting a reference survey. According to Pfeffer et al. (2013), double differences for each station  $x$  and survey at date  $t$ ,  $Dg_{x-x_0}^{t-t_0}$ , with respect to a reference survey at  $t_0$  and a base station  $x_0$ , are given by

$$Dg_{x-x_0}^{t-t_0} = (g_x - g_{x_0})_t - (g_x - g_{x_0})_{t_0} \quad (12)$$

The associated variance is

$$\sigma_{x,t-t_0}^2 = S_{xx,t} + S_{xx,t_0} \quad (13)$$

Alternatively, it is possible to compute double differences with respect to the network mean gravity value,  $MDg_x^{t-t_0}$ , to avoid the reference to a single station:

$$\begin{aligned} MDg_x^{t-t_0} &= Dg_{x-x_0}^{t-t_0} - \overline{Dg_{x-x_0}^{t-t_0}} \\ &= Dg_{x-x_0}^{t-t_0} - \sum_{l=1}^k \frac{(g_l - g_{x_0})_t - (g_l - g_{x_0})_{t_0}}{k} \end{aligned} \quad (14)$$

It is also worth noting that Eq. (14) reduces to

$$MDg_x^{t-t_0} = \left( g_x - \sum_{l=1}^k \frac{g_l}{k} \right)_t - \left( g_x - \sum_{l=1}^k \frac{g_l}{k} \right)_{t_0} \quad (15)$$

## 4. Results: two case studies

### 4.1. Hydrogravimetry in West Africa

We monitored gravity changes due to water storage changes in a small catchment (16 ha) in northern Benin (9.74° N, 1.60° E) using a CG-5 relative gravimeter (Hector et al., 2015) and both superconducting gravimeter (SG, Hector et al., 2014) and FG5 absolute gravimeter (Hector et al., 2013) instruments for base station monitoring in a hybrid-gravimetry approach.

The focus was on spatial distribution of seasonal water storage changes, which were expected to be in the range of a few micro-gals requiring a thorough protocol definition to maximize the data accuracy. Detailed acquisition protocol, data processing and sensitivity analysis can be found in Hector et al. (2015). Also, data selection within station time series is a very important step, as one must be sure that no transportation drift, spikes (in raw data but also other channels such as tilts, temperature or standard deviation), or out-of-bounds tilts or standard deviations remains in the data.

Thirteen stations and 1 base station were retained within a very small network (less than 450 m away from the base station). Fifty surveys were conducted between July 2011 and February 2013, covering two wet seasons, with frequent measurements (approximately every 4–5 days) and a dry season with less frequent measurements (approximately every month).

Fig. 3 shows the mean standard deviation resulting from the processing for each station as a distance to the base station. Distant stations suffer from a lower precision, probably due to the transportation effect. Overall, very low standard deviations are obtained thanks to the short distances and thorough acquisition protocol.

For each of the 50 surveys, base station gravity value was set to zero in the network adjustment in pyGrav. The SG gravity value at the time of each survey is then added to the double differences results to produce the processed hybrid gravity dataset.

Empirical Orthogonal Functions (EOF) decompositions are applied on the processed hybrid gravity dataset to capture the dominant spatial and temporal patterns of water storage changes. Results are shown in Fig. 4.

Fig. 4a shows that the first mode of the EOF captures 78% of the total signal variance. The spatial distribution of this first mode is shown on Fig. 4b together with station locations, the catchment borders, and the seasonal stream originating from the lowland Bas-fond. The temporal distribution of the first mode is shown on Fig. 4c together with daily precipitation. Here, topographic effects are negligible and gravity changes can be directly interpreted in terms of water storage changes on the first order (Hector et al., 2015). The variance captured by the first mode corresponds to the seasonal signal, for which the spatial distribution shows marked heterogeneities. This large dataset was efficiently processed using pyGrav, which is now a routine tool for processing subsequent data being acquired in this study.

### 4.2. Geothermics in Northern Alsace

The production of geothermal energy is often associated with fluid injection and/or withdrawal, resulting in an associated mass balance of the system. Management strategies for sustainable geothermal utilization focus on this mass balance, for which the monitoring of geothermal reservoirs by relative-gravity measurements has proven to bring significant inputs (Sofyan, 2012). Examples can be found in experiences from New Zealand geothermal fields (Allis and Hunt, 1986; Hunt and Bowyer, 2007; Hunt and

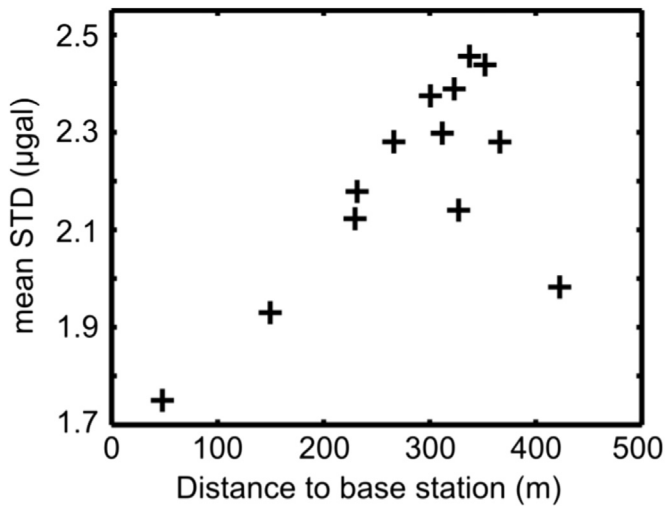


Fig. 3. Mean standard deviation (STD) for each station. From Hector et al. (2015).

Graham, 2009), or in Japan (Sugihara and Ishido, 2008; Takemura et al., 2000) for instance.

We show hereafter the application of pyGrav to the gravity monitoring of two close geothermal fields in Northern Alsace during successive surveys in summer 2014. The Soultz-sous-Forêt geothermal site is the first EGS (Enhanced Geothermal System) demonstration site producing electricity in France. Several wells have been drilled down to 5000 m depth for hydraulic stimulation

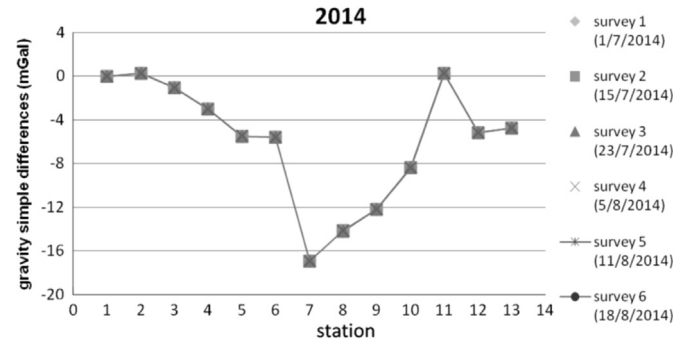


Fig. 5. Gravity simple differences of the stations of the Soultz-sous-Forêts and Rittershoffen relative-gravimetric network. All symbols overlap in the figure. From Hinderer et al. (2015).

and circulation experiments. The system has evolved from a two-well approach to a multi-well system for monitoring, measuring and managing the geothermal system during exploitation (Genter et al., 2010, 2013). The Rittershoffen geothermal site is the location where the ECOGI (Exploitation of Geothermal Heat for Industry) experiment takes place. With a geological context similar to the Soultz-sous-Forêts project, this geothermal project is dedicated to an industrial use for heat application (24 MWth at 160 °C). The first well was drilled in 2012 and a second one in spring 2014, both to a depth close to 2500 m.

We have hence set up a gravity network on these two geothermal fields composed of eleven stations (no. 1–11) including the reference station which are located around the injection and

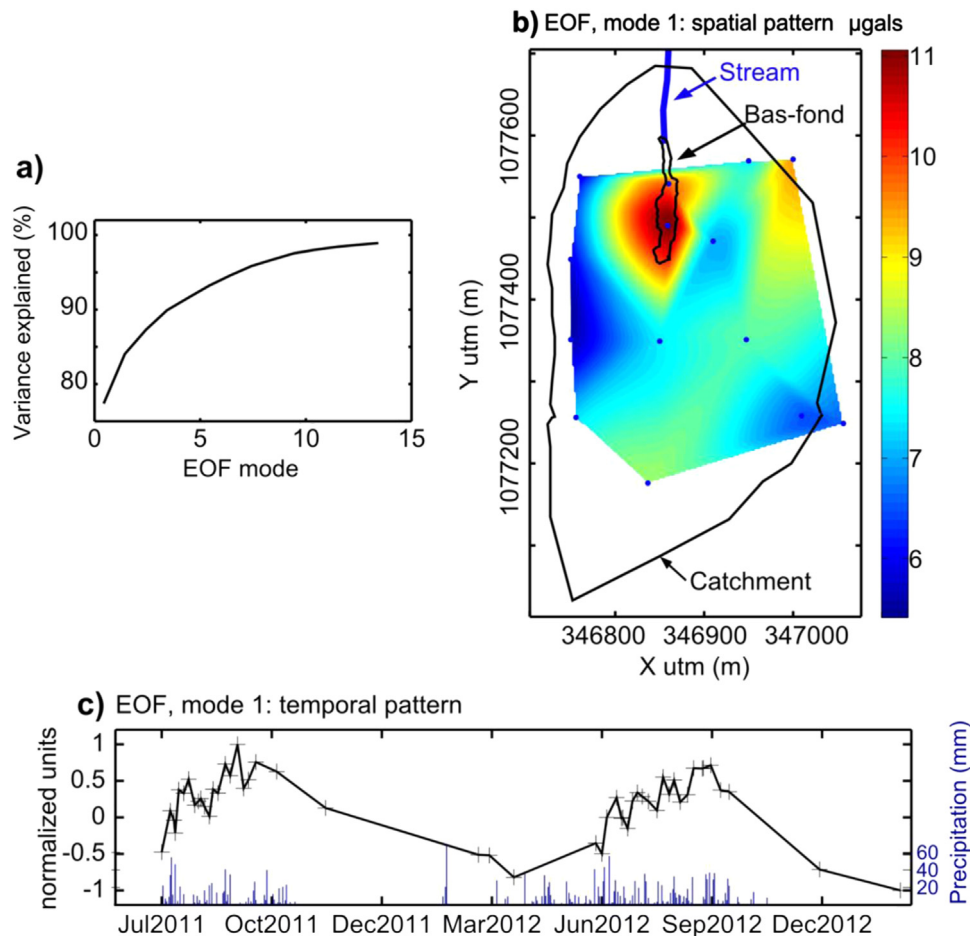
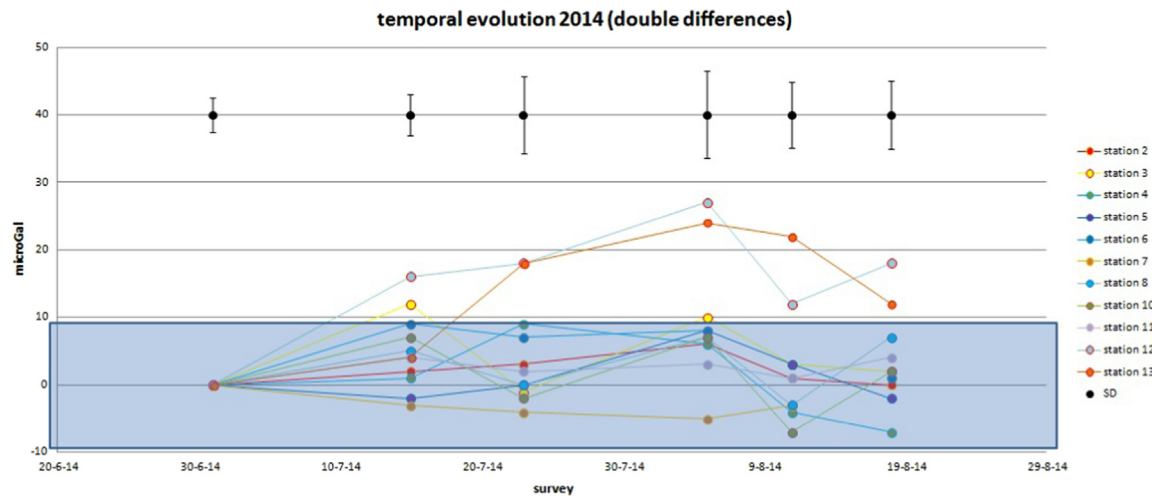


Fig. 4. Empirical orthogonal functions decompositions of the hybrid gravity data set. (a) Variance explained by each mode. (b) Spatial pattern of the first mode. (c) Temporal pattern of the first mode with daily rainfall in blue bars. Modified from Hector et al. (2015).



**Fig. 6.** Gravity double differences in 2014. The blue area is the  $\pm 2\sigma$  uncertainty band computed from the uncertainties in the measurements and processing of all surveys. From Hinderer et al. (2015).

extraction boreholes (GPK1 and GPK2) of the Soultz geothermal site, and two stations (no. 12 and 13) around ECOGI. All these stations are measured in 5 different interconnected loops (3 stations in addition to the base station are repeated in different loops).

The results of the pyGrav processing of all the data collected in 2014 from 6 different surveys are shown below. Fig. 5 shows the simple differences in gravity spanning a 17 mGal interval mostly due to differences in elevation.

Fig. 6 shows the double differences in gravity which are now in a much smaller range. The black error bars in the upper part of Fig. 6 indicate the standard deviation on a gravity change between two surveys which amount to a few  $\mu\text{Gal}$ .

One can easily see that most of the gravity changes (for all stations except stations 12 and 13) are not significant since they are within the  $\pm 2\sigma$  uncertainty range, where  $\sigma$  is the RMS error computed from the individual survey errors in the gravity double differences. This is in agreement with the fact that no geothermal activity occurred on the Soultz-sous-Forêts site during the measurement period. The changes seen for stations 12 and 13 are on the contrary correlated with injection test performed on the ECOGI site. For more details, we refer the reader to Hinderer et al. (2015).

## 5. Conclusions

pyGrav has been designed to bring together all processing steps for relative-gravity data, from raw data selection to network adjustment, within a graphical interface. The Python-based code is open-source and exploits the intrinsic hierarchical structure of relative-gravity data (campaigns, surveys, loops, stations, channels) in an intuitive object-oriented structure. This feature allows one to easily write additional functions and associated user-interface features, for instance to bind other existing processing codes, data plots, or I/O file formats. The data selection window also allows to rapidly check data at the end of a loop or survey in the field.

Solid-earth tides and ocean loading as well as air pressure corrections can be applied using various approaches. Then, each station time series is plotted in a user interface for selecting relevant data depending on channels available (gravity, tilts, standard deviation, etc.). Automatic selection is also possible for faster processing. Drift and station values are then obtained from least-square inversion of the dataset, to produce simple differences. Finally, double differences can be calculated from a dataset

containing several surveys, allowing for the efficient monitoring of gravity changes on a network. The complete processing chain developed in pyGrav facilitates reproducible research on relative gravity. It also permits the processing of relative-gravity on a near-real-time basis in the field.

This easy-to-use program allowed us to efficiently process both a large dataset for hydro-gravimetry in West-Africa and a dataset for geothermal studies in Alsace (N-E France) which was processed by several different users who benefitted from a single tool for processing all the data.

## Acknowledgment

This work has been entirely funded by the Labex G-EAU-THERMIE, which the authors would like to thank. The Labex also founded the acquisition of gravity data of the network dedicated to the monitoring of the geothermal field. African data has been acquired in the frame of the GHYRAF (Gravity and Hydrology in Africa) ANR project and the AMMA-CATCH observatory for the study of monsoon and continental hydrology couplings in West Africa. The authors also thank INSU-CNRS GMOB facility for the use of Scintrex CG5 gravimeter in West Africa. The authors are grateful to P. Jousset and an anonymous reviewer who provided significant inputs in the manuscript and the program and suggested some directions for the future development of pyGrav.

## References

- Agnew, D.C., 2007. 3.06 – Earth Tides. In: Schubert, G. (Ed.), *Treatise on Geophysics*. Elsevier, Amsterdam, pp. 163–195.
- Agnew, D. C., 2012: SPOTL: Some Programs for Ocean-Tide Loading, SIO technical report ([http://dx.doi.org/http://escholarship.org/uc/sio\\_techreport](http://dx.doi.org/http://escholarship.org/uc/sio_techreport)).
- Allis, R.G., Hunt, T.M., 1986. Analysis of exploitation-induced gravity changes at Wairakei Geothermal Field. *Geophysics* 51 (8), 1647–1660. <http://dx.doi.org/10.1190/1.1442214>.
- Beilin, J., 2006. *Apport de la gravimétrie absolue à la réalisation de la composante gravimétrique du Réseau Géodésique Français*. Inst. Géogr. Natl., Paris, France.
- Cattin, R., Mazzotti, S., Baratin, L.-M., 2015. GravProcess: an easy-to-use MATLAB software to process campaign gravity data and evaluate the associated uncertainties. *Comput. Geosci.* 81, 20–27. <http://dx.doi.org/10.1016/j.cageo.2015.04.005>.
- Christiansen, L., Haarder, E.B., Hansen, A.B., Looms, M.C., Binning, P., Rosbjerg, D., Andersen, O.B., Bauer-Gottwein, P., 2011b. Calibrating vadose zone models with time-lapse gravity data. *Vadose Zone J* 10 (3), 1034–1044. <http://dx.doi.org/10.2136/vzj2010.0127>.
- Christiansen, L., Lund, S., Andersen, O.B., Binning, P., Rosbjerg, D., Bauer-Gottwein, P., 2011c. Measuring gravity change caused by water storage variations:



- performance assessment under controlled conditions. *J. Hydrol.* 402, 60–70. <http://dx.doi.org/10.1016/j.jhydrol.2011.03.004>.
- Christiansen, L., Binning, P., Rosbjerg, D., Andersen, O.B., Bauer-Gottwein, P., 2011a. Using time-lapse gravity for groundwater model calibration: an application to alluvial aquifer storage. *Water Resour. Res.* 47. <http://dx.doi.org/10.1029/2010WR009859>.
- Crossley, D., Hinderer, J., Riccardi, U., 2013. The measurement of surface gravity. *Rep. Prog. Phys. Phys. Soc. G B 76* (4), 046101. <http://dx.doi.org/10.1088/0034-4885/76/4/046101>.
- Ferguson, J.F., Kloppe, F.J., Chen, T., Seibert, J.E., Hare, J.L., Brady, J.L., 2008. The 4D microgravity method for waterflood surveillance: part 3 — 4D absolute microgravity surveys at Prudhoe Bay, Alaska. *Geophysics* 73 (6), WA163–WA171. <http://dx.doi.org/10.1190/1.2992510>.
- Gabalda, G., Bonvalot, S., Hipkin, R., 2003. CG3TOOL: an interactive computer program to process Scintrex CG-3/3M gravity data for high-resolution applications. *Comput. Geosci.* 29 (2), 155–171. [http://dx.doi.org/10.1016/S0098-3004\(02\)00114-0](http://dx.doi.org/10.1016/S0098-3004(02)00114-0).
- Genter, A., Evans, K., Cuenot, N., Fritsch, D., Sanjuan, B., 2010. Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS). *Comptes Rendus Geosci.* 342 (7–8), 502–516. <http://dx.doi.org/10.1016/j.crte.2010.01.006>.
- Genter, A., Cuenot, N., Melchert, B., Moeckes, W., Ravier, G., Sanjuan, B., Sanjuan, R., Scheiber, J., Schill, E. and Schmittbuhl, J., 2013. Main achievements from the multi-well EGS Soultz project during geothermal exploitation from 2010 and 2012, in EGC 2013, p. 10 p., Pisa, Italy.
- Greco, F., Currenti, G., D'Agostino, G., Germak, A., Napoli, R., Pistorio, A., Del Negro, C., 2012. Combining relative and absolute gravity measurements to enhance volcano monitoring. *Bull. Volcanol.* 74 (7), 1745–1756. <http://dx.doi.org/10.1007/s00445-012-0630-0>.
- Hartmann, T., Wenzel, H.-G., 1995. The HW95 tidal potential catalogue. *Geophys. Res. Lett.* 22 (24), 3553–3556. <http://dx.doi.org/10.1029/95GL03324>.
- Hector, B., Seguis, L., Hinderer, J., Descloitres, M., Vouillamoz, J.-M., Wubda, M., Boy, J.-P., Luck, B., Le Moigne, N., 2013. Gravity effect of water storage changes in a weathered hard-rock aquifer in West Africa: results from joint absolute gravity, hydrological monitoring and geophysical prospection. *Geophys. J. Int.* 194 (2), 737–750. <http://dx.doi.org/10.1093/gji/ggt146>.
- Hector, B., Hinderer, J., Séguis, L., Boy, J.-P., Calvo, M., Descloitres, M., Rosat, S., Galle, S., Riccardi, U., 2014. Hydro-gravimetry in West-Africa: first results from the Djougou (Benin) superconducting gravimeter. *J. Geodyn.* 80, 34–39. <http://dx.doi.org/10.1016/j.jog.2014.04.003>.
- Hector, B., Séguis, L., Hinderer, J., Cohard, J.-M., Wubda, M., Descloitres, M., Benarrosh, N., Boy, J.-P., 2015. Water storage changes as a marker for base flow generation processes in a tropical humid basement catchment (Benin): insights from hybrid gravimetry. *Water Resour. Res.* <http://dx.doi.org/10.1002/2014WR015773>.
- Hinderer, J., Hector, B., Mémin, A., Calvo, M., Submitted. Hybrid gravimetry as a tool to monitor surface and underground mass changes. In: Proceedings of IUGG, IAG, Prag, Czech Republic.
- Hinderer, J., Hector, B., Boy, J.-P., Riccardi, U., Rosat, S., Calvo, M., Littel, F., 2014. A search for atmospheric effects on gravity at different time and space scales. *J. Geodyn.* 80, 50–57. <http://dx.doi.org/10.1016/j.jog.2014.02.001>.
- Hinderer, J., Calvo, M., Abdelfettah, Y., Hector, B., Riccardi, U., Ferhat, G., Bernard, J.-D., 2015. Monitoring of a geothermal reservoir by hybrid gravimetry: feasibility study applied to the Soultz-sous-Forêts and Rittershoffen sites in the Rhine graben. *Geotherm. Energy* 3 (1), 16. <http://dx.doi.org/10.1186/s40517-015-0035-3>.
- Hunt, T., Bowyer, D., 2007. Reinjection and gravity changes at Rotokawa geothermal field, New Zealand. *Geothermics* 36 (5), 421–435. <http://dx.doi.org/10.1016/j.geothermics.2007.07.004>.
- Hunt, T.M., Graham, D.J., 2009. Gravity changes in the Tauhara sector of the Wairakei–Tauhara geothermal field, New Zealand. *Geothermics* 38 (1), 108–116. <http://dx.doi.org/10.1016/j.geothermics.2008.12.003>.
- Hwang, C., Wang, C.-G., Lee, L.-H., 2002. Adjustment of relative gravity measurements using weighted and datum-free constraints. *Comput. Geosci.* 28 (9), 1005–1015. [http://dx.doi.org/10.1016/S0098-3004\(02\)00005-5](http://dx.doi.org/10.1016/S0098-3004(02)00005-5).
- Jacob, T., Bayer, R., Chery, J., Le Moigne, N., 2010. Time-lapse microgravity surveys reveal water storage heterogeneity of a karst aquifer. *J. Geophys. Res. Solid Earth* 115 (B6). <http://dx.doi.org/10.1029/2009JB006616>.
- Jousset, P., Dwipa, S., Beauducel, F., Duquesnoy, T., Diamant, M., 2000. Temporal gravity at Merapi during the 1993–1995 crisis: an insight into the dynamical behaviour of volcanoes. *J. Volcanol. Geotherm. Res.* 100 (1–4), 289–320. [http://dx.doi.org/10.1016/S0377-0273\(00\)00141-4](http://dx.doi.org/10.1016/S0377-0273(00)00141-4).
- Kennedy, J.R., Ferré, T.P.A., 2016. Accounting for time- and space-varying changes in the gravity field to improve the network adjustment of relative-gravity data. *Geophys. J. Int.* 204 (2), 892–906. <http://dx.doi.org/10.1093/gji/ggv493>.
- Krieger, L., Peacock, J.R., 2014. MTPy: A Python toolbox for magnetotellurics. *Comput. Geosci.* 72, 167–175. <http://dx.doi.org/10.1016/j.cageo.2014.07.013>.
- Langet, N., Maggi, A., Michelini, A., Brenguier, F., 2014. Continuous Kurtosis-Based Migration for Seismic Event Detection and Location, with Application to Piton de la Fournaise Volcano, La Réunion. *Bull. Seismol. Soc. Am.* 10. <http://dx.doi.org/10.1785/0120130107>.
- Merlet, S., Kopaev, A., Diamant, M., Geneves, G., Landragin, A., Santos, F.P.D., 2008. Micro-gravity investigations for the LNE watt balance project. *Metrologia* 45 (3), 265. <http://dx.doi.org/10.1088/0026-1394/45/3/002>.
- Munk, W.H., Cartwright, D.E., 1966. Tidal spectroscopy and prediction. *R. Soc. Lond. Philos. Trans. Ser. A* 259, 533–581. <http://dx.doi.org/10.1098/rsta.1966.0024>.
- Okubo, S., Satomura, M., Furuya, M., Sun, W., Matsumoto, S., Ueki, S. and Watanabe, H., 2002. Grand design for the hybrid gravity network around the Mt. Fuji volcano. In: Proceedings of International Symposium on Geodesy in Kanazawa Abstract, pp. 39–40.
- Pfeffer, J., Champollion, C., Favreau, G., Cappelaere, B., Hinderer, J., Boucher, M., Nazoumou, Y., Oï, M., Mouyen, M., Henri, C., Le Moigne, N., Deroussi, S., Demarty, J., Boulain, N., Benarrosh, N., Robert, O., 2013. Evaluating surface and subsurface water storage variations at small time and space scales from relative gravity measurements in semi-arid Niger. *Water Resour. Res.* 49, 3276–3291. <http://dx.doi.org/10.1002/wrcr.20235>.
- Piccolroaz, S., Majone, B., Palmieri, F., Cassiani, G., Bellin, A., 2015. On the use of spatially distributed, time-lapse microgravity surveys to inform hydrological modeling. *Water Resour. Res.* <http://dx.doi.org/10.1002/2015WR016994>.
- Seigel, H.O., Brcic, I., Mistry, P., 1995. A guide to high precision land gravimeter surveys. *Scintrex LTD, Concord, Ontario*.
- Sofyan, Y., 2012. Development of a new simple hydrostatic equilibrium model for sustainable evaluation in geothermal energy. *Energy Procedia* 14, 205–210. <http://dx.doi.org/10.1016/j.egypro.2011.12.918>.
- Sugihara, M., Ishido, T., 2008. Geothermal reservoir monitoring with a combination of absolute and relative gravimetry. *Geophysics* 73 (6), WA37–WA47. <http://dx.doi.org/10.1190/1.2991105>.
- Takemura, T., Shiga, N., Yokomoto, S., Saeki, K. and Yamanobe, H., 2000. Gravity monitoring in Yanaizu–Nishiyama geothermal field. In: Proceeding World Geothermal Congress, Japan, pp. 2937–2941.
- Wenzel, H., 1996. The nanogal software: earth tide data processing package: Eterna 3.3. *Bull. Inf. Marées Terr.* 124, 9425–9439.