Towards the Definition and Realization of a Global Absolute Gravity Reference System

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Abstract

For many years, there has been a recognized discrepancy between the accuracies of absolute gravity determination and the hitherto valid gravity reference system of the International Association of Geodesy (IAG), the International Gravity Standardization Net 1971 (IGSN71).

Scientists from metrology and geosciences agreed on a proposal to base a new absolute gravity reference upon repeated instrument comparisons under metrological rules for traceability to SI quantities. In a strategy paper, which originated from the lively discussion of a mixed working group in metrology and geodesy with the objective to define and harmonize the measurements at the highest accuracy level, it was proposed to continue the comparisons under the International Committee for Weights and Measures (CIPM) every four years at alternating locations with the aim to distribute comparison results over a global network of carefully observed gravity reference and comparison sites. Their gravity variations are recorded by a combination of repeated absolute gravity measurements and continuously operating superconducting gravimeters. The results of comparisons and the gravity variations of the reference stations will be documented in a registry, part of the AGrav database, maintained jointly by the International Gravimetric Bureau (BGI) and the Federal Agency for Cartography and Geodesy (BKG).

By means of this network of comparison and gravity reference stations it will be possible to establish a global gravity reference system covering the needs of the geodetic and metrological communities and with capabilities to integrate observations of any new kind of absolute gravimeters including that based on cold atoms. Recorded gravity variations in an absolute reference system complement the Global Geodetic Reference Frame and will be used for combination with other geoscientific data and the investigation of mass transports and global change processes in the context of the Global Geodetic Observing System, GGOS. The implementation of the new gravity reference system will be based upon the international standards and conventions of the IAG. During the IUGG General Assembly in Prague 2015, the IAG adopted Resolution No. 2 and initiated the *Establishment of a Global Absolute Gravity Reference System*.

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International Association of Geodesy Symposia,
DOI 10.1007/1345_2016_245,

Keywords
Absolute gravity • Global network • Gravimeter • Metrology • Reference system

1 Introduction

The international geoscientific community needs accurate and reliable measurements of absolute gravity acceleration *g*. This follows from the requirement of modern geodesy to provide long-term stable global reference frames for gravity and height necessary for monitoring global change processes and investigating their causes. It is a basic precondition for monitoring the three fundamental geodetic observables: Earth shape, Earth gravity field and Earth rotation. Hence, the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) recommends maintaining a global accurate reference frame which ensures a long-term monitoring of the geodetic observables, provides consistency of geometric and gravimetric products and guarantees clear and consistent standards and conventions for geometry and gravimetry (Drewes 2012). The activity is supported by the International Gravity Field Service (IGFS) and the International Gravimetric Bureau of the IAG (BGI). Absolute gravity has a high value for providing an accurate and unified global gravity reference as well as for the observation and investigation of post-glacial uplift (Timmen et al. 2012), tectonic height changes (Van Camp et al. 2011), mass transports of the geophysical fluids and other effects (Forsberg et al. 2005)

In metrology, similar importance is placed upon the watt balance experiment (Jiang et al. 2013), the consistent definition of fundamental physical constants and the integration of new measurement principles like the cold atom interferometry or the use of ultraprecise clocks for the determination of the gravity potential (Robinson 2012; Pereira dos Santos and Bonvalot 2016).

At present the desirable target uncertainty in absolute *g* measurements for geodetic and metrological questions is estimated to $\pm$ (1-2) $\times 10^{-8}$ m s^{-2} or $\pm$ (1-2) μGal.

2 Development of the Gravity Reference Systems

Until today, gravity reference systems have been based upon one or more reference sites which were assumed to be stable. The classical realization of such a system was the Potsdam Gravity Datum of 1909. The uncertainty of the gravity values derived with one absolute pendulum apparatus and distributed with relative pendulum observations was estimated with $\pm$1 mGal. Some decades later, stationary absolute pendulum observations in Europe and U.S.A. indicated discrepancies in the order of 14 mGal to the Potsdam Gravity Datum. With the appearance of new, ballistic absolute gravimeters in the 1960'ies the systematic offset of the Potsdam datum was confirmed. In the meantime, relative spring gravity measurements were also used for a global densification of the network.

Consequently the global gravity reference system had to be improved: In 1971 the IUGG general assembly in Moscow adopted the International Gravity Standardization Net (IGSN71) (Morelli et al. 1974). The IGSN71 station uncertainty is $\pm$0.1 mGal and basis for the determination of location-dependent gravity variations. But in the sixties and seventies of the last century time-variable absolute gravity variations of less than $\pm$0.1 mGal mostly were covered by instrumental uncertainties.

Due to the advances in technical development and first mobility of the instruments, absolute gravimeter comparisons were started at the International Bureau for Weights and Measures (BIPM) in 1981 (Boulanger et al. 1983). During this period as well, an International Absolute Gravity Base station Network (IAGBN) was proposed (Boedecker and Fritzer 1986).

With a scientific manufacturing of a small series of freefall absolute gravimeters and later the industrial production of commercial instruments, the consistency and reliability of the absolute gravimeters improved at the end of the twentieth century to a few microgals. Today about 100 transportable instruments exist, the majority come from one manufacturer. As showed in Van Camp et al. (2016) and Pálinkáš et al. (2013), the offsets between instruments have to be known to detect subtle geodynamic signal at microgal level.

The comparisons between instruments thus became crucial for estimating the overall accuracy and sensitivity of absolute gravimeters and checking each individual instrument. An absolute gravimeter relies upon its instrumental measurement standards for time and frequency units. The necessity of a careful calibration of laser and frequency generator underlines the need for a successful cooperation between metrology and geoscience specialists. Improved transportable absolute gravimeters and the participation in the comparisons allow the establishment of independent national gravity networks and networks for scientific applications because the absolute gravimeter has the capability to realize its own gravity reference (Wilmes et al. 2003).

3 Cooperation of Metrology and Geosciences

Comparisons of absolute gravimeters have been carried out since 1981 and were hosted by the BIPM in Sèvres (France). The participating institutions represent geodetic stakeholders, scientific institutions and institutions representing the national metrology institutes.

In 2003, advanced comparison rules were introduced in metrology with the "Mutual Recognition Arrangement" (BIPM 2003). As a consequence, the international comparisons of absolute gravimeters were developed to key comparisons (KC). The new Working Group on Gravimetry of the Consultative Committee for Mass and Related Quantities (CCM-WGG) prepared the following comparisons and evaluations. The implementation of KCs improved the procedures and consistency of the comparisons and results (Jiang et al. 2012). Also these procedures specify the correction models, procedures and algorithms of the comparisons. Comparisons are guided under the partnership of a regional metrological organization like e.g. EURAMET (European Association of National Metrology Institutes). However, a consequence of this cooperation under metrological rules was that only the absolute gravimeters from the national metrology institutes and designated metrology institutes (NMI/DIs) contribute to the key comparison result. Therefore the discussion started about a satisfactory solution for the remaining institutions.

The members of the CCM-WGG together with the representatives of IAG Commission 2 (Gravity Field) and two IAG working groups: JWG 2.1 (Techniques and metrology in absolute gravimetry) and JWG 2.2 (Absolute gravimetry and absolute gravity reference system) managed to prepare a formal document about the "CCM - IAG Strategy for Metrology in Absolute Gravimetry" (CCM 2015). The objective of this document is to connect and balance the official rules in metrology with the needs of the non-metrological institutions, mainly from the geodetic community. It is understood as an important contribution for the geodetic community, because for the first time a formal agreement has been reached on the traceability of absolute gravity measurements to SI units at the uncertainty level of a few parts in 10^{-9} through comparison and calibration of the absolute gravimeters. Further, it connects terminologies and conventions used in metrology and geodesy for the observations, correction models and evaluations procedures. This mutual recognition of the gravity standards is an extremely important precondition for the realization and maintenance of a global consistent and homogeneous absolute gravity reference system. It prepares and explains the conditions and rules how the comparisons shall be continued under CIPM in the future.

The document was submitted to the IAG Executive Committee which agrees with the initiative between the geodetic and metrological community in the field of absolute gravimetry. The IAG Executive Committee accepts the document as most relevant, and important, as it will assist in the establishment of a global absolute gravity reference system. Furthermore it is a contribution to the Global Geodetic Observing System (GGOS).

4 Realization of a New Absolute Gravity Reference System

Based upon this agreement and the continuation of absolute gravimeter comparisons under the International Committee for Weights and Measures (CIPM), the series of CIPM comparisons will define the measurement standards in gravimetry (absolute gravimeters) (Vitushkin 2011) and gravity standards (gravimetry sites) for metrology and geodesy as from now. The participating absolute gravimeters represent, strictly speaking, the measurement standards of acceleration unit in gravimetry and it makes it possible to establish the metrological traceability of other gravity measurement instruments and the sites of a distributed reference network to measurement standards in gravimetry. Some groups of the international community already make use of such gravity standards for monitoring the gravity variations at a given site by combining a very sensitive continuous recording gravimeter and an absolute gravimeter previously checked at international comparisons (Crossley et al. 2013).

A gravity reference function is generated by the combination of absolute gravity data with the continuous record of the superconducting gravimeter. Visiting instruments can connect to this gravity standard or verify their own results. The gravity reference function is an important dataset for the combination with other geosciences time series under the context of GGOS. The reference stations form the basis for the realization of the new absolute gravity reference system. Absolute gravity measurements are supposed to support the new time series with reference and scale. Reversely, the superconducting data provide a comparison reference function and offer the interpolation between the epochs of CIPM comparisons.

While the current repetition rate of the international CIPM comparisons of 4 years and the regional comparisons on continental scale between the CIPM comparisons are presently a matter of discussion, it seems adequate for the present instruments and teams and for the realization of an absolute gravity reference system. With such a four-yearly repetition rate it should be possible to detect changes related to the specific sensors and to provide enough opportunity for new teams and instruments to participate in the comparisons. With changing locations of the CIPM comparisons the gravity reference system is distributed to a global coverage.

The international absolute gravity database AGrav (http://agrav.bkg.bund.de/; http://bgi.obs-mip.fr/) (Wilmes et al. 2009; Wziontek et al. 2012) will be used as registry for the comparison results. Similar to the key comparison database of the BIPM it will store all observations from the metrological community. However, for its function as registry of the absolute gravity reference system it will also store the comparison results of the geoscientific instruments of the four-yearly CIPM comparisons. In addition it will take the results of all additional comparisons intermediate to the CIPM comparisons.

At the IUGG General Assembly in Prague 2015 an IAG resolution was passed on the subject of the establishment of a global absolute gravity reference system (IAG Resolutions 2015). The adoption of this resolution encourages continuing the work necessary for a state-of-the-art terrestrial gravity system and the replacement of the IGSN71. This objective will be also greatly facilitated by the increasing number of absolute gravimeters who are contributing in many countries since the last decade to the establishment of national absolute gravity networks.

5 Outlook

The IAG resolution 2015, No. 2 now provides the opportunity to realize the intended global gravity reference system. What are the next steps?

1. The next CIPM Key Comparison, for the first time in Asia at Changping Campus, Beijing, China in 2017 (CCM.G-K3), will be prepared under guidance of the CIPM, which defines the absolute gravity standard for metrology and geodesy over the following years.
2. A network of distributed gravity reference stations with superconducting gravimeters and repeated absolute gravimeter measurements is defined which have the ability to preserve the absolute gravity standard and realize an absolute gravity reference function. This will enable and support additional comparisons.
3. The comparison result of the participating absolute gravimeters will be transferred to additional instruments and reference stations; see document "CCM - IAG Strategy for Metrology in Absolute Gravimetry (CCM 2015)".
4. Records of all comparison results will be kept in the AGrav database operated by BKG and BGI. The documentation in the BIPM Key Comparison Database is limited to the CIPM comparison results.
5. Standard models and corrections (like tidal system, geometrical reference frame) will be defined in cooperation with the GGOS Bureau of Standards and Conventions.
6. Finally the participation in the CIPM comparisons will be agreed with the National Metrology Institutes.

In detail subsequent steps are the following:

A new working group with the subject "Establishment of a global absolute gravity reference system" in IAG Commission 2 will be installed to replace the working group JWG 2.2 which was closed at the IUGG/IAG General Assembly due to the IAG rules. The new working group will contact the CCM-WGG and work cooperatively.

The AGrav database will be extended to work as registry for the global absolute gravity reference system. This is an addition to the present function to document the absolute gravity measurements of the international community. The database is well prepared for observations with new measurement principles like cold atom gravimeters or ultra precise clocks which develop quickly and soon will have an influence upon the absolute gravimeter comparisons and the gravity field observations.

Close cooperation is foreseen with the new IAG service "IGETS: International Geodynamics and Earth Tide Service" (former Global Geodynamics Project, GGP, operating a global network of superconducting gravimeters) for the realization of the gravity reference and comparison stations.

To reach all these goals, continued support will be necessary from the international community working in gravimetry and metrology. Advanced absolute gravimeters, which are well compared and using consistent models, parameters and corrections models will make it possible to determine reliable time-variable gravity changes for the investigation of global change processes. The initiated new Global Absolute Gravity Reference System will provide the framework for it.

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