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ORIGINAL ARTICLE

Status of the International Gravity Reference System and Frame

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Abstract

The increasing importance of terrestrial gravimetry in monitoring global change processes, in providing a reference for satellite measurements and in applications in metrology necessitates a stable reference system reflecting the measurement accuracy achievable by modern gravimeters. Therefore, over the last decade, the International Association of Geodesy (IAG) has developed a system to achieve accurate, homogeneous, long-term global recording of Earth's gravity, while taking advantage of the potential of today's absolute gravity measurements. The current status of the International Gravity Reference System and Frame is presented as worked out by the IAG Joint Working Group 2.1.1 "Establishment of a global absolute gravity reference system" during the period 2015–2019. Here, the system is defined by the instantaneous acceleration of free-fall, expressed in the International System of Units (SI) and a set of conventional corrections for the time-independent components of gravity effects. The frame as the systems realization includes a set of conventional temporal gravity corrections which represent a uniform set of minimum requirements. Measurements with absolute gravimeters, the traceability of which is ensured by comparisons and monitoring at reference stations, provide the basis of the frame. A global set of such stations providing absolute gravity values at the microgal level is the backbone of the frame. Core stations with at least one available space geodetic technique will provide a link to the terrestrial reference frame. Expanded facilities enabling instrumental verification as well as repeated regional and additional comparisons will complement key comparisons at the level of the International Committee for Weights and Measures (CIPM) and ensure a common reference and the traceability to the SI. To make the gravity reference system accessible to any user and to replace the previous IGSN71 network, an infrastructure based on absolute gravity observations needs to be built up. This requires the support of national agencies, which are encouraged to establish compatible first order gravity networks and to provide information about existing absolute gravity observations.

Keywords Gravity reference system and frame · Absolute gravimeter

1 Introduction

As delineated by Wilmes et al. (2016), a new gravity reference system needs to be established to overcome the discrepancy between the high accuracy achieved with current absolute gravimeters and the hitherto valid gravity reference system of the International Association of Geodesy (IAG), the International Gravity Standardization Net 1971 (IGSN71) (Morelli et al. 1974). Although it is widely used, at an uncertainty level of 10^{-6} m s^{-2} it fulfills neither the requirements nor the accuracy for the understanding of the Earth's System and applications in metrology.

Besides several successful prototypes, absolute gravimeters with an uncertainty in the few microgal level (1 μGal = 10^{-8} m s^{-2}) like FG5 (Niebauer et al. 1995) and FG5–X (Niebauer et al. 2011) are commercially available and widely

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Table 1 Scheme of the gravity reference system and frame

Reference system	Reference frame
The fundamental principles: The definition of gravity must be stable over time.	*The realization of the system*: The numbers actually obtained.
Instantaneous acceleration of free-fall expressed in the International System of Units (SI)	Observations with absolute gravimeters: (epoch, position, gravity, vertical gravity gradient, reference height)
Set of conventional corrections – Zero-tide system – Standard atmosphere ISO 2533:1975 – Earth rotation axis IERS reference pole define the conventional quantity "acceleration of gravity"	Comparisons of absolute gravimeters: traceability and compatibility of the observations and the processing, assessment of systematic effects Set of conventional models for correction of temporal changes (tides, ocean tide loading, atmosphere, polar motion) Compatible infrastructure (markers, points) and documentation (database)

used today. Field versions (e.g., A10 by Micro-g LaCoste) allow surveys with an accuracy of 5–10 µGal (Falk et al. 2012), and the rapid development of quantum gravimeters (Gillot et al. 2016; Freier et al. 2016) opens up new perspectives and has brought with the Absolute Quantum Gravimeter (AQG) a first model on the market (Ménoret et al. 2018). Such instrumentation guaranteeing a relative accuracy of 10^{-8} and better has been demonstrated to be relevant in metrology for the realization of the definition of the kilogram with the Kibble balance (Robinson 2011; Robinson and Schlamminger 2016) and in geosciences to study geodynamics, hydrology and global change in the Earth system (Van Camp et al. 2017).

Following IAG Resolution No. 2 "Establishment of a Global Absolute Gravity Reference System"[1] adopted at the XXVI, General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Prague 2015, the IAG Joint Working Group 2.1.1 was established to develop a concept for a modern and accurate gravity reference system. A long-term stable gravity reference based on the observations with absolute gravimeters provides the basis to monitor the time variable gravity field as one of the keys to understand the changing Earth and is a foundation to observe crustal deformations and mass transports. Absolute gravity observations at sites co-located to the International Terrestrial Reference Frame (ITRF) (Altamimi et al. 2016) and the International Height Reference Frame (IHRF) (Ihde et al. 2017) in conjunction with consistent standards and conventions will further strengthen gravimetry in the framework of the Global Geodetic Observing System (GGOS) (Plag and Pearlman 2009) as well as the Subcommittee on Geodesy of the United Nations initiative on Global Geospatial Information Management (UN-GGIM) and the Global Geodetic Reference Frame (GGRF). The efforts are further in alignment with the key objective of the GGOS Bureau of Products and Standards (BPS) to keep track of and foster homogenization of adopted geodetic standards and conventions across all components of IAG as a fundamental basis for the generation of consistent geometric and gravimetric products (Angermann et al. 2016)

2 Definition of Gravity Reference System and Frame

The definition of the system reflects the fundamental principles and must be stable over time, while the frame as the realization of the system is based on observations with absolute gravimeters and a set of conventional models for their processing (Table 1). Due to its principle, absolute gravity observations at individual stations are not linked to each other eliminating the need to build up classical observation networks. The reliability of all absolute gravimeters used for the realization of the system has to be ensured by comparisons and regular monitoring at reference stations. In contrast to historical gravity reference systems where scale and level had to be controlled and adjusted, only the absolute level needs to be realized today.

In accordance with other geodetic definitions, the acronyms IGRS/IGRF were fixed for the International Gravity Reference System and Frame, respectively.

2.1 International Gravity Reference System

The International Gravity Reference System (IGRS) is defined by the instantaneous acceleration of free-fall as the measurand, expressed in the International System of Units (SI). It is completed by a set of references for the time-dependent corrections of this quantity comprising constant components: the zero-tide system for the tidal correction, the standard atmosphere ISO 2533:1975 (DIN 5450) for the correction for atmospheric gravity effects and the reference pole of the International Earth Rotation and Reference Systems Service (IERS) for the correction for polar motion. These references define the conventional quantity "acceleration of

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[1] https://iag.dgfi.tum.de/fileadmin/IAG-docs/IAG_Resolutions_2015.pdf.

gravity”. Changing these references should be avoided in the future, to guarantee the long-term stability of the system.

2.2 International Gravity Reference Frame

The International Gravity Reference Frame (IGRF) as the realization of the IGRS is represented by absolute gravity measurements traceable to the SI that contain conventional temporal gravity corrections. The IGRF contains a global set of stations where reliable absolute gravity values with a relative accuracy of 10^{-8} and better are provided to the users.

Due to the lack of a natural reference for the acceleration of free-fall, absolute gravimeters have to be checked at comparisons, where the gravity reference is realized based on a set of measurements by a group of absolute gravimeters and the functional model for their processing.

The series of key comparisons[2] carried out by the Consultative Committee for Mass and Related Quantities (CCM) of the International Committee for Weights and Measures (CIPM) in context of the CIPM Mutual Recognition Arrangement (MRA) provide the backbone of the IGRF (Wilmes et al. 2016), following the “CCM - IAG Strategy for Metrology in Absolute Gravimetry”[3], which also describes the traceability chain in gravimetry. Additional comparisons as a component of this strategy are used to distribute the common level further. Besides the key comparison results, the acceptance of all absolute gravimeters participated in comparisons including those not operated by national metrology institutes or their designated laboratories needs to be documented, using the International Absolute Gravity Database AGrav (Wziontek et al. 2012) as registry.

Observations with absolute gravimeters should contain at least the following information tuple:

- Observation epoch,
- Position of the marker (geodetic latitude, longitude, referred to the ITRF),
- Physical height of the marker, including the height system,
- Mean absolute gravity value after applying the corrections documented in Sect. 3
- The height above the marker where the absolute gravity value is referred to,
- Vertical gravity gradient used for transfer of the gravity value along the vertical,

Systematic effects common to a particular type of instrument, e.g., for self-attraction (Niebauer et al. 2012; Pálinkáš et al. 2012; Biolcati et al. 2012; Li et al. 2015b, a), diffraction of the laser beam (van Westrum and Niebauer 2003; Robertsson 2007), verticality (Křen et al. 2018) or signal distortion (Křen et al. 2019) need to be documented and applied.

A set of conventional models as described in Sect. 3 define minimum requirements for the correction of temporal gravity changes covering the Earth tides, ocean tide loading, atmospheric variations and polar motion and the transfer to a reference height.

3 IGRS Conventions 2020

The presented conventions are based on the International Absolute Gravity Basestation Network (IAGBN): Absolute Gravity Observations Data Processing Standards by Boedecker (1988) which are already applied for decades. They are mostly implemented by processing software like the “g” Absolute Gravity Processing Software by Micro-g LaCoste[4]. Minor updates were necessary to reflect the current state of the art and the compatibility with existing processing results. A further unification of processing standards is subject of the IAG Joint Working Group 2.1.2 “Unified file formats and processing software for high-precision gravimetry”. Where applicable, the basis for the following recommendations is in accordance with the IAG/IUGG resolutions and the IERS Conventions (2010) (Petit and Luzum 2010). Definitions of the IGRS which are not subject to future changes are *emphasized*. All corrections and reductions should be added to measured quantities.

3.1 Light propagation delay correction

For absolute gravimeters based on classical laser interferometry, each individual time sample should be corrected by

$$\delta t = k\, z(t)/c \qquad (1)$$

where $z(t)$ is the position of the test mass corresponding to the time t and $c = 299\ 792\ 458\,\mathrm{m\,s^{-1}}$ is the speed of light (IAG 1983 Resolution No. 1). The correction has a negative sign ($k = -1$) if the interferometer is positioned above the test mass, and a positive sign ($k = +1$) if below (Nagornyi et al. 2011a, b). The latter case is the standard for most of the users.

For absolute gravimeters based on an atom interferometer, the retardation effects caused by the finite speed of light have to be compensated accordingly, e.g., by the measurement scheme.

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[2] A key comparison is one of the set of comparisons to test the principal techniques and methods in the field.

[3] http://www.bipm.org/wg/CCM/CCM-WGG/Allowed/2015-meeting/CCM_IAG_Strategy.pdf.

[4] http://microglacoste.com/product/micro-g-lacostes-g-absolute-gravity-processing-software/.

3.2 Earth tides

The reduction of Earth tides should be based on the development of the tide-generating potential of Tamura (1987) with 1200 constituents, expanded up to the fourth-degree potential of the Moon and the third-degree of the Sun. Higher resolution and well recognized developments, like Hartmann and Wenzel (1995) or Kudryavtsev (2004), can also be applied. To account for the response of the Earth due to tidal deformation, parameters (amplitude factors and phase lags) deduced from observations or from a recognized Earth model, preferably Dehant et al. (1999), should be used. The details must be reported as part of the observation document.

The permanent part of the tide-generating potential can be written as

$$M_0 S_0 = A \left(\frac{r}{r_0} \right)^2 \left(\sin^2 \Phi - \frac{1}{3} \right) \tag{2}$$

where Φ is the geocentric latitude, r the radial distance of the observation point and r_0 a scaling factor for distances. With the normalization $r_0 = 6378136.3\,\mathrm{m}$ used in the tidal potential coefficients in Hartmann and Wenzel (1995) which is commonly applied in software for tidal analysis and prediction, the value $A = -2.9166\,\mathrm{m^2\,s^{-2}}$ in the epoch 2000.0 can be deduced from the IERS Conventions (2010). The tidal developments mentioned in the first paragraph all agree with this value of A within the last digit given. They also include the rate of change in A which is $-0.0009\,\mathrm{m^2\,s^{-2}}$/century. Any of them can be used to calculate the $\mathrm{M_0S_0}$ and derived quantities. The correction for the permanent tide is for gravity

$$dg\,(M_0 S_0) = -\delta \frac{\partial}{\partial n} M_0 S_0 \tag{3}$$

where the derivative is taken in the direction of the downward vertical. This is implemented in programs of tidal synthesis. According to IAG Resolution No. 16 of 1983, the indirect effect due to the permanent yielding of the Earth should not be removed, which effectively results in the zero-tide system. Therefore, the *correction for the permanent tide* $M_0 S_0$ *must be included with an amplitude factor* δ *of 1.0*.

The transformation from mean-tide gravity to zero-tide gravity can also be conveniently performed by writing $dg(M_0 S_0)$ as a function of geodetic latitude φ. We then have (Mäkinen 2020)

$$dg(M_0 S_0) = 30.49 \;-\; 90.95 \sin^2(\varphi) \;-\; 0.31 \sin^4(\varphi)\; 10^{-8}\,\mathrm{m\,s^{-2}} \tag{4}$$

3.3 Ocean tide loading

Where no local tidal model from observations is available, the effect of ocean tide loading needs to be corrected. The loading effect should in general be calculated based on the model FES2004 (Letellier 2004; Lyard et al. 2006). Other recognized ocean tide models may be used for specific regions, if providing a better correction. It is recommended to obtain the site specific loading parameters (amplitude and phase) from the Ocean Tide Loading Provider[5] (Bos and Scherneck 2013). In order to obtain most precise results, it is strongly suggested to include an interpolation into the complete tidal spectrum using an admittance obtained from the given set of coefficients for the main tidal constituents. This is implemented, e.g., in the program packages SPOTL[6] (Agnew 2012) or ttimm[7].

3.4 Polar motion

Variations in the geocentric position of the Earth's rotation axis (polar motion) cause deformation within the Earth due to centrifugal forces. *The actual position of the rotational axis is referenced to the IERS pole* and described by the pole coordinates (Bizouard et al. 2019). The gravity correction for the solid Earth pole tide is expressed by, e.g., Wahr (1985)

$$\delta g = -\delta\, \omega^2\, a\, 2 \sin(\varphi) \cos(\varphi)\, (x \cos(\lambda) - y \sin(\lambda))\;\; \mathrm{m\,s^{-2}} \tag{5}$$

where

x, y pole coordinates in rad
$\omega = 7\,292\,115 \times 10^{-11}\,\mathrm{rad\,s^{-1}}$ mean angular velocity
$a = 6\,378\,136.6\,\mathrm{m}$ equatorial radius of the Earth[8]
φ, λ geodetic coordinates of the observation point, (longitude positive east of Greenwich).
$\delta = 1.164$ is the amplitude factor for the elastic response of the Earth.

The pole coordinates should be taken from the EOP data as released by IERS[9]. At present, a reduction for angular velocity (length of day) variations is not recommended.

3.5 Atmosphere

The lumped effects of direct gravitation of air mass changes and indirect effect via deformation of the solid Earth have been determined empirically from air pressure variations. It is recommended to reduce these effects through (IAG 1983 Resolution No. 9)

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[5] http://holt.oso.chalmers.se/loading/.

[6] https://igppweb.ucsd.edu/~agnew/Spotl/spotlmain.html.

[7] http://holt.oso.chalmers.se/hgs/ttimm/index.html.

[8] The small difference to the value of a as given in Boedecker (1988) has no impact on this correction.

[9] https://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html.

$$\Delta g = 0.3 \cdot \Delta p \; 10^{-8}\,\mathrm{m\,s^{-2}} \tag{6}$$

$$\Delta p = (p_a - p_n)\ \mathrm{hPa} \tag{7}$$

with

p_a actual observed air pressure
p_n normal air pressure

The normal air pressure is referred to the ISO 2533:1975 (DIN 5450) Standard Atmosphere

$$p_n = 1013.25\,(1 - 0.0065 \cdot H/288.15)^{5.2559}\ \mathrm{hPa} \tag{8}$$

where H is the physical height of the station in meters. The applied value of p_n needs to be documented for each measurement.

The use of more advanced models, e.g., based on numerical weather models as provided by the EOST Loading Service[10] (Boy et al. 2009) or Atmacs[11] (Klügel and Wziontek 2009), must be documented. It is particularly important to ensure that no constant contributions from these models have an impact to ensure the compatibility with Eq. (6).

3.6 Hydrology

Hydrological phenomena may have a large influence on absolute gravity, and repeated measurements of absolute gravity can in turn be used to study hydrology. However, the magnitude of hydrological corrections on absolute gravity cannot be quantified because an absolute reference for water storage changes is currently not uniquely accessible, e.g., by global models of continental hydrology. Furthermore, the largest impact originates from local water storage changes in the vicinity of the station. The characterization is complex and highly site dependent and requires extensive supplemental in situ instrumentation (Creutzfeldt et al. 2008, 2010). Large-scale water storage changes are also significant and reach up to several $10^{-8}\,\mathrm{m\,s^{-2}}$, in terms of both Newtonian attraction and the deformation due to surface loading (Boy and Hinderer 2006) but their quantification depends strongly on the choice of the global hydrology model (Creutzfeldt et al. 2010). Due to a missing normal reference, its complexity and uncertainty, corrections for local or large-scale water storage changes are currently not recommended to be applied to gravity values submitted to the IGRF.

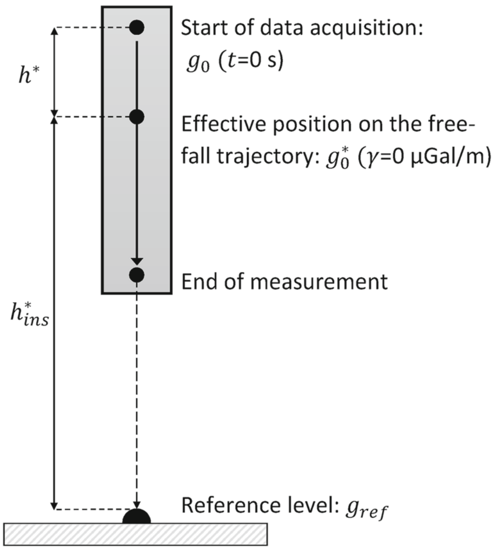

Fig. 1 Schematic representation of the effective position on the free-fall trajectory, where the determined g is independent of the constant VGG γ used within the observation equation of corner-cube gravimeters. The effective measurement height h^* has its origin within the gravimeter itself (start of data acquisition) and depends on the processed section of the zero crossings. The effective instrumental height h^*_{ins} depends also on the setup of the gravimeter and has to be known to transfer the gravity value to a reference level (usually top of the benchmark) by using a VGG that can differ from γ

3.7 Absolute gravity height reference

The results of absolute gravity measurements are presented usually at a specific height above the station marker that mainly depends on the gravimeter type. The absolute gravity value should be referred to the effective position on the free-fall trajectory (Pálinkáš et al. 2012). At this position, the gravity value is invariant under changes of the constant vertical gravity gradient (VGG) used in the observation equation of corner-cube gravimeters (Niebauer et al. 1995). Hence, the evaluation of absolute gravity measurements and the transfer of the gravity value to a given height above the benchmark (Sect. 3.8) can be handled separately.

In order to associate the measured gravity value with a specific height above the marker (reference: highest point of the marker), it is recommended to provide the distance between the effective position on the free-fall trajectory and the marker, labeled as the “effective instrumental height” in Fig. 1. It allows for a correct transfer of the gravity value to any other height above or on top of the benchmark. In contrast, the “effective measurement height” as introduced, e.g., by Niebauer (1989) or Timmen (2003), refers to the same position but has its reference inside the gravimeter at the start of the data acquisition ($t = 0$ s, Fig. 1) or at the position $z = 0$ m, respectively.

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[10] http://loading.u-strasbg.fr/.

[11] http://atmacs.bkg.bund.de/.

The effective instrumental height depends on the type of absolute gravimeter, its actual setup and the processed section of the zero crossings. For the FG5, FG5–X and A10 gravimeters, it ranges around 1.21 m, 1.27 m and 0.68 m, respectively. The effective position on the free-fall trajectory should be determined individually following, e.g., the simple empirical approach as given in Pálinkáš et al. (2012), allowing for an accuracy better than 0.1 mm.

A transfer from the effective instrumental height to any other height above the marker requires additional information about the VGG and is increasing the uncertainty of the absolute gravity value. Therefore, for highest accuracy it is preferred to provide the gravity value at the effective instrumental height which should be determined with an accuracy of about 1 mm. Alternatively, it is possible to report the gravity value at any height of the user's choice, however, by applying the same constant vertical gravity gradient γ as used in the observation equation of absolute gravimeters. This allows to restore the gravity value to the effective instrumental height and further apply a more precise/actual vertical transfer according to Sect. 3.8.

The following set of information has to be reported along with the gravity value referred to the height above the marker:

1. The effective instrumental height (preferably the same as reported with the gravity value). If missing, the height based on gravimeter type can be used.
2. The VGG used in the observation equation.

In case that the gravity value was evaluated exactly at the effective instrumental height, the VGG is not strictly necessary but should nevertheless be reported.

3.8 Vertical gravity gradient

In order to transfer the absolute gravity value from the effective instrumental height to a common reference height, e.g., to harmonize results by different instruments or to refer the result to the marker on the benchmark, the actual vertical gravity gradient above the benchmark should be used. This gradient can be different from those used within the observation equation of free-fall (Sect. 3.7) and can be also approximated by higher order polynomials. It is recommended to include any available information about the gradient determination along the vertical (constant value, polynomial model, etc.) in the report of absolute gravity measurements.

At the reference and comparison stations, it is recommended to determine gradients from measurements of relative gravimeters carried out at least at three levels above the benchmark, covering the range of typical instrument heights. If no information about the vertical gravity gradient can be obtained, the normal vertical gravity gradient of $-308.6 \times 10^{-8}\ \mathrm{s}^{-2}$ should be applied.

4 Infrastructure

The main infrastructure of the IGRF is formed by gravity stations of three different types:

- **Reference stations** are essential to ensure a long-term stable absolute gravity reference. Here, a gravity reference function provides the mean absolute level and residual gravity variations after reduction of time-dependent gravity effects as given in Sect. 3. It can be derived from continuous operation of a superconducting gravimeter (SG) in combination with repeated absolute gravity observations or a continuously operated absolute quantum gravimeter. If a continuous monitoring is not possible, repeated absolute gravity observations every two months are recommended to capture annual variations, mainly of hydrological origin. For stations operating a SG, it is recommended to perform absolute gravity observations every two years for the determination of the SG instrumental drift. Stations of the International Geodynamics and Earth Tide Service (IGETS) (Boy et al. 2020) with long-term SG records should become an essential part of the IGRF.
- **Comparison stations** are reference stations as described above with extended facilities to check the compatibility of instruments, either based on continuous gravity monitoring or by simultaneous measurements of at least two absolute gravimeters. Calibration may serve as a tool to document significant systematic deviations in order to improve or restore the compatibility and should follow the "CCM – IAG Strategy for Metrology in Absolute Gravimetry".
- **Core stations** provide a link to the ITRF where at least one space geodetic technique is established and GGOS core sites play an essential role. A GGOS core site is a geodetic observatory that defines terrestrial reference points in the space and time domain and in the presence of the Earth's gravity field permanently by delivering decadal time series. Observational data from complementary co-located instruments are used in a synergistic way, to obtain the most accurate global reference frame (Appleby et al. 2015). In accordance with the GGOS requirements for core sites, it is therefore recommended to continuously monitor temporal gravity variations and to repeat absolute gravity observations at all GGOS core sites.

In order to guarantee sustainability of the gravity reference frame, all stations of the IGRF need to be indicated by a permanent marker. All measurements at these stations should be documented and archived in the IAG absolute gravity database (AGrav) operated by BGI (Bureau Gravimétrique

International[12]) and IGETS (International Geodynamics and Earth Tide Service[13]) for static and time variable measurements respectively. By this, the basis for the further development of compatible infrastructure on the national level is provided.

5 Conclusions and Outlook

A concept for the gravity reference system and the frame as its realization is described, based on the instantaneous acceleration of free-fall as the measurand, the traceability to the International System of Units (SI) and sets of conventional gravity corrections for time-invariant and time-dependent components of gravity effects. While the system must remain stable over time, the frame is realized by observations with absolute gravimeters corrected for temporal gravity changes by models which may be adapted to future improvements. A set of models along with well-established standards are proposed, representing minimum requirements.

The IGRF is realized by measurements with absolute gravimeters at any time. These instruments need to be compared at different levels, from international comparisons under guidance of the CIPM to additional comparisons for users in geosciences. This is an essential part of the concept and underlines the need to continue the common efforts of metrology and geodesy. To ensure their stability, the instruments should be further monitored at reference stations where a gravity reference function is available.

To make the IGRF accessible to users and to finally replace the previous IGSN71 network, an adequate infrastructure based on absolute gravity measurements needs to be built up. This requires the support of international and national institutions, agencies and governmental bodies in charge of geodetic infrastructure which are encouraged to establish compatible first order gravity networks and to provide information about existing absolute gravity observations. This was acknowledged by IAG with Resolution No. 4 of 2019 and provides the frame for activities IAG Joint Working Group 2.1.1. to establish the IGRF.

A modern and precise absolute gravity reference system will serve as a long-term and precise gravity reference for IAG's Global Geodetic Observing System and will contribute to the establishment of the Global Geodetic Reference Frame (GGRF) of UN-GGIM.

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