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GUIDE07 GUIDELINES FOR FIELD WORK AND GRAVIMETRIC MEASUREMENTS PROCESSING

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GENERAL INFORMATION

The purpose of this document is to guide users in the measurement and processing of gravimetric data, especially those who are starting to work with gravimetric data. In addition to reading this guide, the user should always consult the documents of the mapping agency or the institute responsible for gravimetry in their country. The document is divided into three parts: "Introduction to Gravimetry" which deals with basic concepts on the subject; "Fieldwork" which deals with practical aspects of the instruments used in the field and measurement methodologies; and finally, the section on "Processing of gravimetric measurements" which develops a step-by-step guide on how it is recommended to process the data measured in the field.

INTRODUCTION TO GRAVIMETRY

1. GRAVIMETRY

The set of techniques and procedures intended to measure the acceleration of gravity is called Gravimetry, which etymologically means measurement of weight (in Latin, *gravis* is weight, and *metron* is measure in Greek). In practice, when a gravimetric measurement is made, the magnitude of the acceleration of gravity g ($g = |\vec{g}|$) on or near the Earth's surface is usually measured.

The unit of measurement of gravity in the International System of Measurement (SI) is m/s^2. On the other hand, in Geodesy, the most commonly used unit is the Gal (in honour to Galileo Galilei) and the subunits, the *mGal* and the *μGal*. The *mGal* is defined as:

$$1\,mGal \;=\; 10^{-3}\,Gal \;=\; 0{,}001\,cm/s^2 \;=\; 10^{-5} m/s^2$$

and *μGal* as:

$$1\,\mu Gal \;=\; 10^{-6}\,Gal \;= 10^{-8} m/s^2.$$

In Geodesy, Gravimetry aims to determine the Earth's gravity field as a function of position and time by gravity measurements made on or near the Earth's surface. Terrestrial gravity measurements are classified as absolute and relative.

In absolute gravity measurements, the value of g at a point is determined by direct observation of the two fundamental quantities of acceleration: distance and time (Torge, 1989). In the most commonly used absolute gravity meters, g is determined through a test mass in free-fall. In relative gravity measurements, only one fundamental quantity of acceleration is observed: distance. In this case, the variations of this quantity are measured from the spring-mass principle, either between two stations (A and B) or its variations in time at a fixed station. In the first case, to know the gravity acceleration at station B, g must be known at station A established with an absolute gravimeter. Only the difference in gravity between the two stations can be known with relative gravimeters. In the second case, temporal variations of the Earth's gravity field at a given station are studied.

1.1. GRAVITY METERS

Gravity measurements are performed with gravimeters. For absolute gravity measurements, free-fall and "rise and fall" principles are used (pendulum gravity meters are no longer in use). Today, the most commonly used **absolute gravity meters** are free-fall and correspond to the A-10 and FG5 series manufactured by Micro-g LaCoste™. These devices are sensitive and bulky, making them difficult to transport. In laboratories, measurements are carried out in very stable locations, at specific temperature and humidity conditions, and preferably on well-monumented pillars. In the field, locations with specific stability, easy access to the vehicle, and sheltered from sun, rain, and wind are chosen. Generally, hundreds of measurements are made to obtain the absolute value of the acceleration of gravity, with prior processing of the observations. **Relative field gravimeters** are less precise than absolute gravimeters but are generally lighter, more portable, and considerably less expensive. Modern relative gravity meters use the spring-mass principle. The force of gravity causes a variation in spring elongation, and by measuring the variations in spring elongation, it is possible to deduce the g variation. This gravity variation is obtained from the computation of station length differences (Tocho et al., 2020). For studies of temporal variations of gravity at a given station, superconducting gravimeters are very sensitive and highly stable gravimeters. These are of the spring-mass type, but the mechanical spring is replaced by a virtual spring that employs the principle of magnetic levitation of the test mass. In general, these gravimeters are found in laboratories and geodetic observatories.

In the case of relative gravimeters, some definitions are important. The **scale factor** of an instrument is the transformation factor that allows to transform an instrumental reading to *mGal* units. The **instrumental drift** is related to the wear and tear of the mechanical components, and other factors such as transport, temperature changes, and age. These factors directly influence the reading and is seen as a short-term (hour) variation in the observations of a gravimeter if it is observed at a fixed station. There are two types of drift. **Static drift** exists even when the gravimeter remains stationary for a while. In general, in a circuit, when the gravimeter remains stationary for more than two hours, static drift becomes significant and must be corrected. **Dynamic drift** occurs when the gravimeter is moving as, for example, in transport from one station to another. How the instrumental drift can be corrected, and a detailed description of the most commonly used gravimeters is presented in Guide 2 - Fieldwork.

1.2. MARINE, AIRBORNE AND SATELLITE GRAVIMETRIC MEASUREMENTS

In addition to measuring gravity on the Earth's surface, there are other ways to obtain the value of gravity. In the sea, there are two ways to measure gravity. The first consists of lowering a gravimeter to the bottom of the ocean in a waterproof container. This process is time-consuming, but the measurement is accurate (0.1 mGal) (MicrogLacoste, 2024). The second way is to place the gravimeter on a moving ship on a leveled platform. In airborne gravimetry, the instruments are placed in airplanes or helicopters, where the gravimeter must be on a gyroscopically stabilized platform. Another way to study the gravity field is through satellite measurements. Since the early 2000s, three satellite gravity field missions have been carried out: CHAMP (Reigber et al., 1996), GRACE (GRACE, 2008), and GOCE (ESA, 2006). Since 2018, the GRACE-FO mission (Landererer et al., 2020) was launched to continue GRACE.

1.3. GRAVIMETRIC DATA REPOSITORIES

It is recommended that gravimetric data collected in the field be available in repositories open to the community. The International Association of Geodesy makes the *Bureau Gravimétrique International* (BGI[1]) service available to the community. The BGI is intended to ensure the data inventory and long-term availability of gravity measurements acquired over the Earth's surface. Its main task is collecting, validating, and archiving all types of gravity measurements acquired from land, marine or airborne surveys and disseminating the data and derived products to various users for various purposes. In addition, the AGrav repository (Absolute Gravity Database[2]) is the absolute gravity data collection service of the International Gravity Field Service (IGFS). This repository

[1] https://bgi.obs-mip.fr/

[2] https://bgi.obs-mip.fr/data-products/gravity-databases/absolute-gravity-data/
https://agrav.bkg.bund.de/

was officialized to document the International Terrestrial Gravity Reference Frame (ITGRF, see Section 4) and is maintained jointly by the BGI and the German Federal Agency for Cartography and Geodesy (BKG).

2. MAIN APPLICATIONS

Gravity observations are used for various applications, from geoid modeling to natural resource exploration. These applications are generally divided into geodetic applications and geophysical applications.

Geodetic applications relate to the study of the physical shape and dimension of the Earth, which is modeled by its gravity field. On the other hand, the geoid, the most commonly used reference surface for height determination, can only be determined from gravity observations.

As for geophysical applications, gravity observations provide information on the internal structure of the Earth, as well as on the distribution of densities. In this sense, the study of the gravity field contributes to the exploration of natural resources and the description of geological structures underneath the Earth's surface. In addition, the study of temporal variations of the gravity field has contributed to the study of hydrological effects, mean sea-level variations, glacio-isostatic and geodynamic adjustment effects, among others.

3. IMPORTANCE IN THE ESTABLISHMENT OF VERTICAL NETWORKS

Gravimetry is important for establishing physical height systems linked to the International Height Reference Frame (IHRF). Gravity values measured around an IHRF station are the primary data for calculating gravity potential values and heights. In this sense, the quality and standards of the measurements must be considered. The WG-III has prepared a technical guide on the performance of gravity measurements around IHRF[3] stations. In this document, the user will find general information on how to proceed with gravimetric measurements.

4. INTERNATIONAL TERRESTRIAL GRAVITY REFERENCE FRAME

Nowadays, one of the main objectives of the International Association of Geodesy (IAG) is to establish a gravity reference frame to replace the actual one, the International Gravity Standardization Net 1971 (IGSN71). IGSN71 was adopted during the XV General Assembly of the International Union of Geodesy and Geophysics (IUGG) in 1971. This global network accounted for about 1900 stations and was obtained from a network adjustment including relative gravity measurements performed with spring gravimeters and pendulums, and linked to the first absolute gravity observations measured with free-fall absolute gravimeters. This network aimed for a global coverage (Figure 1) and had a precision of 0.1 mGal (Morelli et al., 1972).

[3] https://sirgas.ipgh.org/en/resources/guidelines/

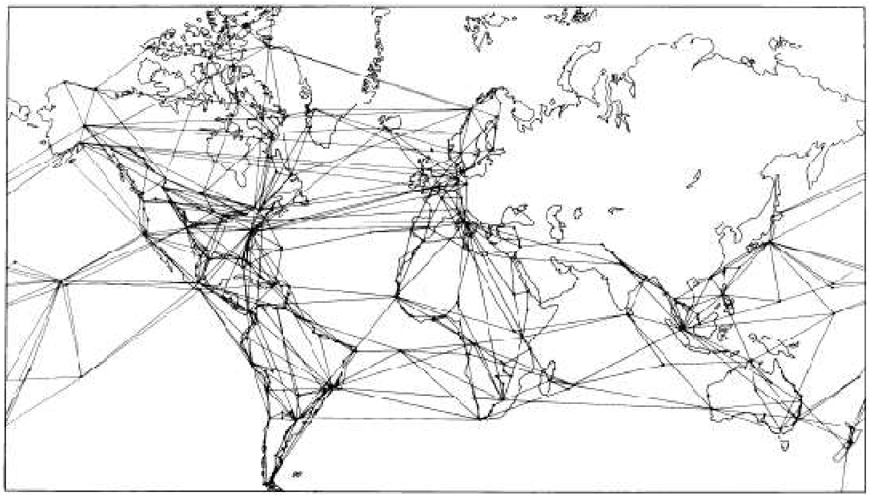

Figure 1 IGSN71 network (Morelli et al., 1972).

Over many years, IGSN71 provided a global reference used for different applications. However, the development and availability of absolute gravimeters capable to reach precisions as high as a few µGal, made it obsolete. Moreover, many IGSN71 stations were destroyed and, therefore, the reference frame is not accessible anymore. For this reason, the IAG started to develop a new reference frame based on absolute gravity observations to replace the IGSN71. This was formally stated through the IAG Resolution N° 2 (Drewes et al., 2016) adopted during the XXVI IUGG General Assembly in 2015, and the establishment of the *Joint Working Group* JWG2.1.1: *Establishment of the International Gravity Reference Frame*. The JWG2.1.1 has intensively worked towards the definition of a gravity reference system and its global and stable realization, allowing the monitoring of the gravity field and its variations over time. Some years later, the IAG Resolution N° 4 (Poutanen y Rózsa, 2020) adopted in 2019 recognizes that the establishment of such reference system and its realization is only possible through the cooperation between national, regional and international institutions that perform absolute gravity observations.

The International Terrestrial Gravity Reference System (ITGRS) brings together the fundamental principles and conventions that allow the definition of gravity (Figure 2). This is defined as the instantaneous acceleration of the free-fall experiment, measured on the International System of Units (SI) and a collection of conventions given by the ITGRS Conventions (Wziontek et al., 2021). These conventions establish a set of time-independent corrections:

- The zero-tide concept (Mäkinen, 2021) for the treatment of the permanent tide;
- A standard atmosphere as reference for the atmospheric corrections;
- The orientation of the rotation axis of the Earth, as defined by the *International Earth Rotation and Reference Systems Service* (IERS).

These definitions were officially adopted by the IAG as the definition of the ITGRS through the IAG Resolution N° 1, during the XXVIII IUGG General Assembly in 2023[4].

[4] https://www.iag-aig.org/doc/651bd7f2e3cbf.pdf

Reference System **Fundamental principles**	**Reference Frame** **System realization**
Stable definition of gravity over time	Measurements

Reference System – Fundamental principles

- **Instantaneous acceleration of free-fall,** measured in the International System of Units (SI)
- **Set of conventional time-independent corrections:**
  - Permanent tides (zero-tide concept);
  - Standard atmosphere;
  - Rotation axis of the Earth defined by the IERS.

Reference Frame – System realization

- **Observations with absolute gravimeters** (epoch, gravity, gradient, reference height)
- **Comparison between absolute gravimeters** (common level, compatibility of observations and processing, systematic errors detection)
- **Set of conventional time-dependent corrections** (tides, ocean tide loading, atmosphere, polar motion)
- **Infrastructure and documentation** (marcs, data base)

Figure 2 Main components of the International Terrestrial Gravity Reference System and Frame (ITGRS/ITGRF). Modified from Wziontek et al. (2021).

The International Terrestrial Gravity Reference Frame (ITGRF), as a realization of the ITGRS, is established through measurements carried out with absolute gravimeters on reference stations (Figure 2) with a relative accuracy of 10^{-8} or better (Wziontek et al., 2021). Each observation must be documented with additional information as observation epoch, gravity value, applied corrections, reference height and vertical gravity gradient.

Given that the absolute gravimeters define a self-reference level for each instrument, one of the key components of the Frame is the comparison of absolute gravimeters. These are measurement campaigns where several instruments participate with the aim of defining a common reference level and ensure the compatibility between their observations. These comparisons are periodically organized on a regional or international level and are essential so that the observations of an instrument can be integrated into the ITGRF. This also allows to address the compatibility between different processing methodologies, corrections applied and detect systematic errors.

Within the *ITGRS Conventions* a set of recommendations and models for temporal corrections is also proposed (Wziontek et al., 2021). Earth tides should be accounted using a spherical harmonic expansion with coefficients given by the Tamura (1987) tidal catalogue of 1200 coefficients or better, and elastic parameters provided by Dehant et al. (1999). It is also possible to use a local tidal model if this is available. Ocean tide loading effects should be accounted the FES2004 ocean model (Lyard et al. 2006) or any other that provides good precision in the region where the measurement takes place. Effects due to polar motion should be corrected based on Wahr (1985) and using (as established in the ITGRS) polar coordinates as published by the IERS. Finally, atmospheric effects should be accounted for through the measured atmospheric pressure at the station and an admittance factor of $3\ \mu Gal/hPa$. Moreover, the conventions establish recommendations about the reference height of the gravity value and the way to measure the vertical gravity gradient. For more details, please refer to Wziontek et al. (2021).

The infrastructure of the ITGRF is divided into three categories, which of them has different characteristics:

- Reference stations: those stations that account for a gravity reference function established through at least one of the following options: (a) periodic absolute gravity observations (at least one every two months); (b) combination of absolute gravity observations and continuous operation of a superconducting gravimeter to account for temporal gravity changes; (c) continuous measurements with a quantic gravimeter. In any case, the gravity reference function must provide a direct access to the reference frame at any time.

- Comparison stations: these are reference stations (i.e. they account for a gravity reference function) that have facilities to perform absolute gravimeters comparison campaigns.

- Core-stations: reference stations also linked to the International Terrestrial Reference Frame (ITRF), to the IHRF and the Global Geodetic Observing System (GGOS). In this sense, core-stations of the ITGRF are also core-sites of GGOS and are co-located with other geodetic techniques.

Finally, observations, results from comparison campaigns and the infrastructure of the ITGRF has to be documented and information should be accessible to the user. This is done through the Absolute Gravity Database (AGrav) of the IAG (see Section 1.4).

In South America, there are two proposed stations to integrate the ITGRF: the Argentinean-German Geodetic Observatory (AGGO) and the National Observatory of Brazil. AGGO is a fundamental geodetic station that accounts for the continuous monitoring of temporal gravity changes and absolute gravity observations performed with a FG5 absolute gravimeter. The combination of both observables has allowed to establish a continuous and stable gravity reference function (Antokoletz et al., 2020). In combination with the infrastructure to perform absolute gravimeters comparisons, AGGO has the capabilities to be a core-station of the ITGRF, also linked to the ITRF and the IHRF (Tocho et al., 2020). On the other hand, the National Observatory of Brazil accounts for periodic measurements of a FG5 absolute gravimeter and several pillars that allows for comparison campaigns at the station.

5. TERRESTRIAL GRAVITY NETWORKS

Traditionally, the establishment of gravity stations is done through networks, which may have local, regional, national, or global coverage. In this context, it is ultimately desirable to adopt a single and sufficiently precise reference that allows adequate interoperability between the existing systems and networks, as with other geodetic reference frames. This single reference with global coverage will be provided by the ITGRF, as mentioned in the previous chapter, which points to the growing efforts of the entire global geodetic community in establishing this framework in the coming years.

To better facilitate the implementation of these gravimetric stations, each country is responsible for establishing its networks within the most convenient methodologies and disseminating the respective results. At a later stage, gravimetric information should be centralized in national gravimetric databases. The WG-III is interested in supporting these initiatives, with suggestions for standardized procedures and promoting the exchange between international organizations and institutions with the appropriate technology and instruments for establishing gravimetric stations.

Therefore, given the availability of gravimetric stations already established around the world, from various equipment and methodologies, WG-III presents a proposal for a simplified classification of gravimetric networks, considering the instruments used and the methods considered in the measurements of the respective gravimetric stations: absolute network, relative network, and densification network. Countries that already use their nomenclature should continue to use it. This section aims to clarify concepts about the different types of gravimetric networks that a country may have.

5.1. ABSOLUTE GRAVITY NETWORK

As the name suggests, the gravimetric stations that comprise the absolute network would be established only with absolute gravimeters. This type of stations has gradually became more famous due to the increasing availability of absolute gravimeters. The accuracy of the stations depends on the instruments used and the stability of the station; however, something better than 20 μGal is expected.

All absolute stations should be installed in stable, secure, and durable locations over time and materialized by nameplates or identification monuments. In addition to having a proper name, through an acronym or numerical ID, each station should have a description containing the detailed location and information considered relevant.

These stations will be in charge of densifying the ITGRF to serve as a reference for local gravimetric surveys.

5.2. RELATIVE GRAVITY NETWORK

For decades, gravimetric stations established from relative gravity measurements have been the most widely used methodology to satisfy the gravimetric needs of each country. This is essentially due to the diffusion of mechanical gravimeters since the 1930s, which offered promising prospects to the techniques and instruments used until then to determine gravity.

The relative network must be linked to the absolute gravity network and meet specific criteria of accuracy in its establishment. This type of network consists of stations with accuracies around 50 *μGal*. Apart from accuracy, the instruments used are the major difference concerning the absolute gravity network. In this context, ideally, gravimetric stations should be established through observations with more than one relative gravimeter to minimize observation errors and systematic errors and evaluate the convergence of the results.

Similar to what is recommended for the absolute network, gravimetric stations should have descriptions of markings and be monumented in stable and secure locations.

In addition, an essential aspect in relative networks should be considered: the need for re-adjustment to existing gravimetric stations. According to best practices, it is recommended that these adjustments be made periodically, depending on the new stations that are eventually added to the absolute gravity network. From these procedures, it is possible to provide users with information on the accuracy of each station, in addition to the values of *g*.

5.3. DENSIFICATION GRAVITY NETWORK

Denser than the absolute and relative networks, the densification gravity network generates detailed knowledge of the Earth's gravity field. Typically, densification gravimetric stations are set up in circuits or lines through daily measurement days based on the infrastructure provided by existing reference networks. Although using more than one relative gravimeter simultaneously to establish densification networks is desirable, as a rule, only one equipment is used to determine the respective gravimetric stations. It is unnecessary to materialize densification networks, so the vast majority of the stations have only identification through a license plate and are not materialized in the field.

The accuracy of each densified station is estimated to be better than 0.1 *mGal*. The spacing between densification stations may vary depending on the objectives and required accuracy. However, to calculate geoid/quasi-geoid models or gravity potential values (for IHRF heights), the denser and more homogeneous the distribution of gravity stations, the better. For example, in large countries such as Canada, a densification scheme of at least one observation in areas of 5 minutes of arc has been generated, while in some European countries, it has been possible to have an observation every kilometer of distance. It is important to emphasize that in this type of network, each station must be geolocated with the highest possible or feasible accuracy of terrain height information (generally determined through GNSS positioning).

5.4. CALIBRATION LINES

The purpose of the calibration lines is to serve as a standard for calibrating the relative gravimeters used in the measurements. It is recommended that lines with absolute gravimeters be established in stable, safe, and durable sites that allow quick access and ease of making observations. A calibration line should be established with a criterion of coverage in geographical latitude and variation in altitude. Further information on calibration lines can be found in Escobar et al., (1996), Pastorino et al., (2003), INEGI (2015), and Guimarães et al., (2020).

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