The International Gravity Reference System

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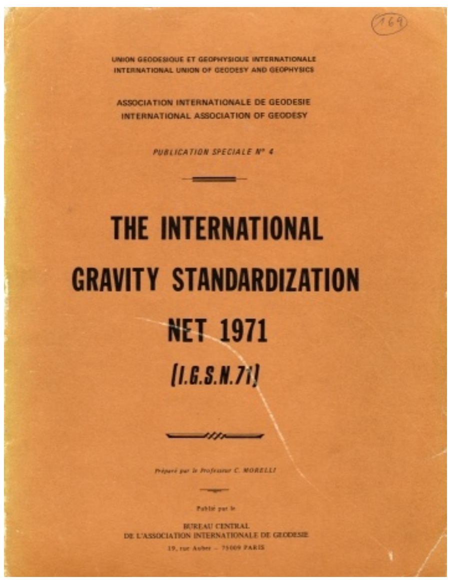
International workshop for the
Implementation of the Global Geodetic Reference Frame (GGRF) in Latin America
Buenos Aires, Argentina, Sep 16 - 20, 2019

The International Gravity Standardization Net 1971

Adopted 1971, XXV. IUGG General Assembly (Moscow)

- ✓ Based upon the first **4 free fall absolute gravimeter** measurements
- ✓ Relative measurements by **spring gravimeters and pendulums**
- ➢ Objective : Worldwide reference (datum & scale) – Accuracy : ± 0.1 mGal



Morelli, IAG Bulletin n°4, Paris, 1971

IGSN71 is still the official gravity reference

IGSN 71 instruments and data

Instrument	*Type instrument*	*N° instruments*	*Surveys*
Absolute	Cook	1	1 station
	Sakuma	1	1 "
	Faller-Hammond	1	9 "
Pendulum	Gulf	2	23 trips
	Cambridge	1	12 "
	IGC	2	4 "
	USCGS	2	2 "
	DO	1	1 "
	GSI	1	8 "
Gravimeter	LaCoste-Romberg	53	98 trips
	Worden	14	12 "
	Askania	2	6 "
	North American	2	5 "
	Western	3	2 "

The International Gravity Standardization Net 1971

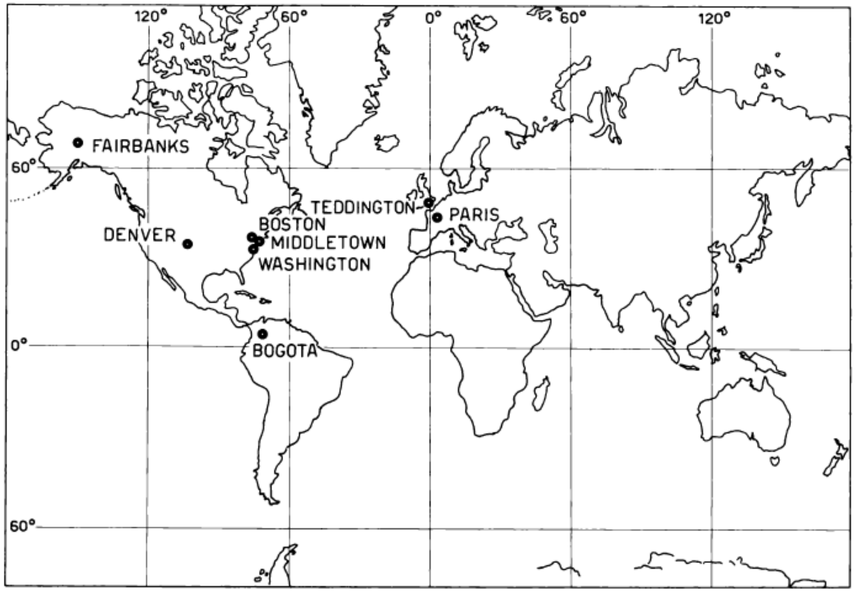


Fig. 7 : Location of Absolute Stations


Fig. 4.1 : MAIN GRAVIMETER CONNECTIONS IN IGSN 71

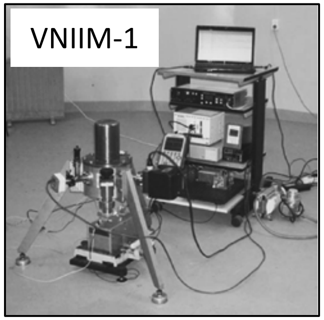
- **Limited number of AG stations** (<10)
- **Airborne and shipborne connections** with relative meters
- **Network adjusted globally**
- Subject to **densifications in all continents** for decades

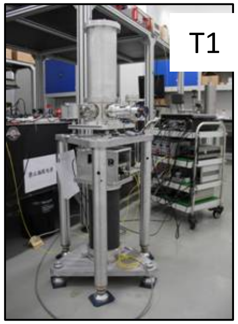
GGRF Workshop IUGG IASPEI IAG

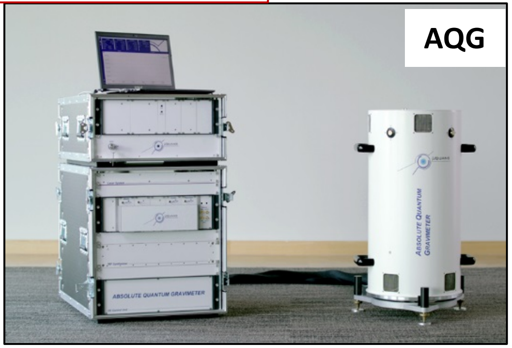
Diversity & Accuracy of gravity meters

Absolute gravity meters (corner cube, cold-atoms) → few µGal level

AG : independent measurements
(no network adjustment required)







Super-conducting
gravity meters
→ nGal level

Enables field AG surveys
(10 µGal or better)

IAG Resolution N°2 (2015)

26th IUGG General Assembly 2015, International Union of Geodesy and Geophysics, Union Géodésique et Géophysique Internationale. Prague, Czech Republic, Prague Congress Centre, June 22 - July 2, 2015. Earth and Environmental Sciences for Future Generations. Visit the website: www.iugg2015prague.com

Establishment of a global absolute reference system

Resolution 2: Establishment of a global absolute gravity reference system

The International Association of Geodesy,

Considering

- That the time variable gravity field is one of the keys to understanding the changing Earth,
- That the accuracy of modern absolute gravimeters has significantly improved,
- That absolute gravity observation has become a valuable tool for monitoring crustal deformations and mass transports,
- That new observation principles and instruments like cold atom interferometers and ultra-precise clocks are in preparation and testing,
- That modern gravity observations need to be based upon the International Metre Convention and the relevant measurement standards,
- That international comparisons of absolute gravimeters under the auspices of International Committee for Weights and Measures (CIPM) define the best metrological realization,
- That absolute gravity observations are archived and distributed at global scale according to international standards by the International Gravimetric Bureau (BGI) jointly with the Federal Agency for Cartography and Geodesy (BKG) under the auspices of International Association of Geodesy (IAG);

Acknowledging

- that the Strategy Paper between Metrology and Geodesy (see note 1) has been accepted by the IAG Executive Committee;

Noting

- That the International Gravity Standardization Net 1971 (IGSN71) no longer fulfills the requirements and accuracy of a modern gravity reference thus requiring replacement by a new global gravity reference system,
- That measurement accuracies have improved from the "100 µGal" to the "few µGal" level,
- That only with an improved gravity reference system time-dependent gravity variations can be determined with high reliability,
- That the use of consistent standards and conventions is necessary for the comparison of geometric and gravimetric observations in the framework of the Global Geodetic Observing System (GGOS);

Resolves

- To adopt the Strategy Paper as the metrological basis for absolute gravimetry,
- To initiate a working group to compile standards for the definition of a geodetic gravity reference system based upon the international comparisons of absolute gravimeters,
- To establish a gravity reference frame by globally distributed reference stations linked to the international comparisons of absolute gravimeters where precise gravity reference is available at any time,
- To link the reference stations to the International Terrestrial Reference System by co-location with space-geodetic techniques,
- To initiate the replacement of the International Gravity Standardization Net 1971 (IGSN71) and the latest International Absolute Gravity Base Station Network by the new Global Absolute Gravity Reference System.

Note 1: Report of Commission 2: CCM – IAG Strategy for Metrology in Absolute Gravimetry, Role of CCM and IAG. In: IAG Reports 2011-2015 (Travaux de l'AIG Vol. 39 (http://iag.dgfi.tum.de/index.php?id=329).

Drewes, H., Kuglitsch, F. G., Adám, J., Rózsa, S. The Geodesist's Handbook (Journal of Geodesy, 2016)

Key points

- **IGSN71 no longer fulfills the requirements and accuracy** for the understanding of the Earth's System, metrology…
- **Measurement accuracy have improved** from the 100 µGal to « few µGal » level
- Needs for **consistent standards & conventions** of geometric and gravimetric observations (GGOS framework)

> - Network of globally distributed stations where precise gravity reference is available at any time
> - Link to ITRS
> - Initiate the replacement of IGSN71 and IAGBN

Definitions of System and Frame

Reference System	Reference Frame
The fundamental principles	**The realization of the system**

The definition of gravity must be stable over time

- Instantaneous **acceleration of free fall** traceable to the International System of Units (SI)
- Set of conventional corrections for the **time independent components** of gravity effects
  - ✓ **Permanent tide** (zero tide system)
  - ✓ Standard **atmosphere** (~ height)
  - ✓ Earth rotation axis **IERS reference pole**

Numbers actually obtained
(subject to model improvements or updated requirements)

- **Observations with absolute gravimeters** (epoch, gravity, gravity as a function of height, ref. height)
- **Comparisons of absolute gravimeters** Common level, traceability, compatibility of the observations and processing, assessment of systematic effects
- **Set of conventional models** for correction of temporal changes (tides, ocean loading, atmosphere, polar motion)
- **Compatible infrastructure** (markers, points) and documentation (database)

Update of the IAGBN Processing Standards

International Absolute Gravimeter Base Network (IAGBN) Processing Standards, Boedecker (1988)

- Tides:
  Zero-tide system for the permanent tide *and*
  Tide generating potential: Tamura (or higher development); Elastic response: Observed tidal parameters or *Earth model of Dehant, Defraigne and Wahr (1999) (DDW)*
- Atmosphere:
  Standard Atmosphere: DIN 5450 (ISO 2533:1975),
  Temporal variations*: Single admittance of 0.3 µGal/hPa*
- Polar motion:
  IERS reference pole with *elastic gravimetric factor 1.164*
- Ocean tide loading:
  FES2004 or best fitting model
- Gravity as a function of height:
  Linear approximation, measurement at 3 levels,
  Evaluation of equation of motion at effective height

Legend: fixed | improved | system | *frame*

IAGBN: Absolute Observations Data Processing Standards

(1992 collection)

As far as possible the basis for the following recommendations were taken from IAG/
resolutions.

- Light travel time correction is based on c = 299 792 458 [ms^{-1}] (IAG 1983 resolution no. 1) Each individual time value should be corrected by

  $$\delta t = -\frac{z}{c}$$

  where z is the distance from the pre-drop resting position.

- Earth tides reduction: It is recommended to apply the Cartwright-Tayler-
  development supplemented by the ICET to yield a total of 505 tidal constituents or a
  recognized development like Tamura, Büllesfeld or Xi. For the tidal parameters (amp
  factors and phase lags) values deduced from observations or from a recognized
  model like Wahr-Dehant should be used, which seems better; else, an amplitude fac
  1.164 may be applied. The details must be reported as part of the observation docume

  The tidal reduction generally includes the M_0S_0 tide. Because the direct contribution of this tide, consta
  time, should be attributed an amplitude factor of 1 instead of about 1.164 for the tides varying with ti
  difference can be corrected using

  $$\delta g\,(M_0S_0) = -4.83 + 15.73 \cdot \sin^2\psi - 1.59 \cdot \sin^4\psi\ [10^{-8}ms^{-2}]$$

  where
  ψ geocentric latitude

  (c.f. IAG 1983 resolution no. 9 and no. 16; details see Rapp 1983).

- Earth rotation changes: The geometric position of the Earth's body relative to its spi
  has to be referenced to mean position. It is recommended to use (e.g. Wahr 1985)

  $$\delta g = -1.164 \cdot 10^8 \cdot \omega^2 \cdot a \cdot 2\sin\phi \cdot \cos\phi\,(x \cdot \cos\lambda - y \cdot \sin\lambda)\ [10^{-8}ms^{-2}]$$

  where
  x, y pole coordinates in IERS system in radian (publ. IERS–Bull.)
  ω = 7 292 115 · 10^{-11} [rad · s^{-1}] angular velocity
  a = 6 378 136 [m] semimajor axis
  ϕ, λ geographic coordinates of the observation station, referred to CIO pole (longitude positive east of Greenwich)

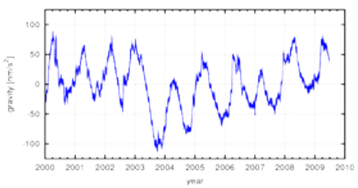
  If real time evaluation is desired, an appropriate prediction may be used (e.g. Sheng 1
  At present, a reduction for angular velocity variations is not recommended.

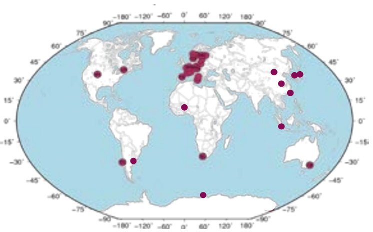
- Air pressure: The lumped effects of direct gravitation of air mass changes and in
  effect via deformation of the solid earth have been determined empirically.
  recommended to reduce these effects through (IAG 1983 resolution no. 9)

Definition/Concept for a stable AG Reference

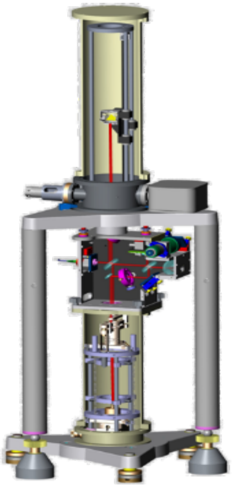
Gravity reference stations

- with continuous comparison reference function monitored by SG, QG or repeated AG



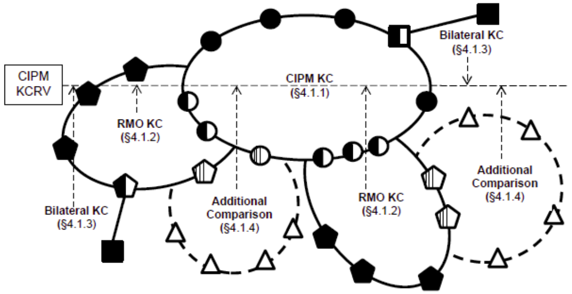


Absolute Gravimeters



Intercomparisons

- CCM-KC, RMO-KC Geodetic Comparisons *with linked CRF*



Standard correction models
Tides, Atmosphere, Polar Motion

Central Inventory (Database)

GGRF Workshop IUGG IASPEI IAG

Long term stability and traceability of Absolute Gravimeters

Long lasting cooperation between metrology and geosciences in Absolute Gravimetry (>30 years)

between

- **BIPM :** Consultative Committee for Mass and Related Quantities (CCM)
- **IAG Commission 2 & IGFS (BGI, IGETS)**

  ✓ **Traceability to International System of Units** (SI)

  ✓ **International Keys Comparisons** (subset of AG)

  ✓ **Regional and Additional Comparisons** (to document agreement between different AG)

Update 2014 (Strategy paper)

Urs Marti, President of the International Association of Geodesy (IAG) Commission 2 «Gravity Field»
Philippe Richard, President of the Consultative Committee for Mass and related quantities (CCM)
Alessandro Germak, Chairman of the CCM working group on gravimetry (WGG)
Leonid Vitushkin, President of IAG SC 2.1
Vojtech Pálinkáš, Chairman of IAG JWG 2.1
Herbert Wilmes, Chairman of IAG JWG 2.2

11 March 2014

CCM – IAG Strategy for Metrology in Absolute Gravimetry
Role of CCM and IAG

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http://www.bipm.org/wg/CCM/CCM-WGG/Allowed/2015-meeting/CCM_IAG_Strategy.pdf
and Travaux of IAG 2011 - 2015

Long term stability and traceability of Absolute Gravimeters

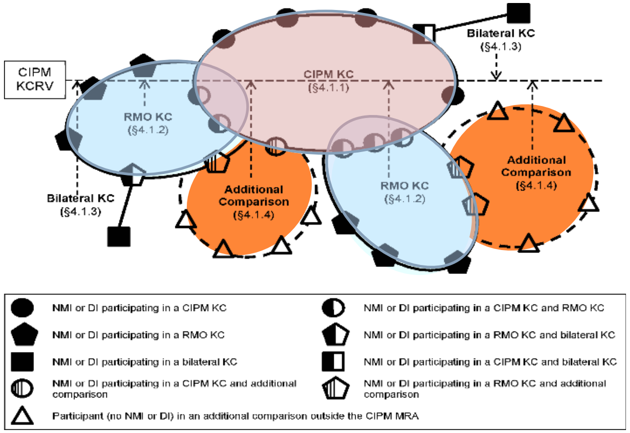
Comparisons of Absolute Gravimeters at different levels

CIPM Level
CCM.G-K2.2017
Key Comparison (KC) and Pilot Study (PS)
Beijing, China

RMO linked to CIPM by means of common participants:
Stability of mean absolute level!

RMO North America 2016
SIM.M.G-K1 KC and PS
Table Mountain, Boulder, CO, USA

RMO Europe 2018
EURAMET.M.G-K3 KC and PS
Wettzell, Germany



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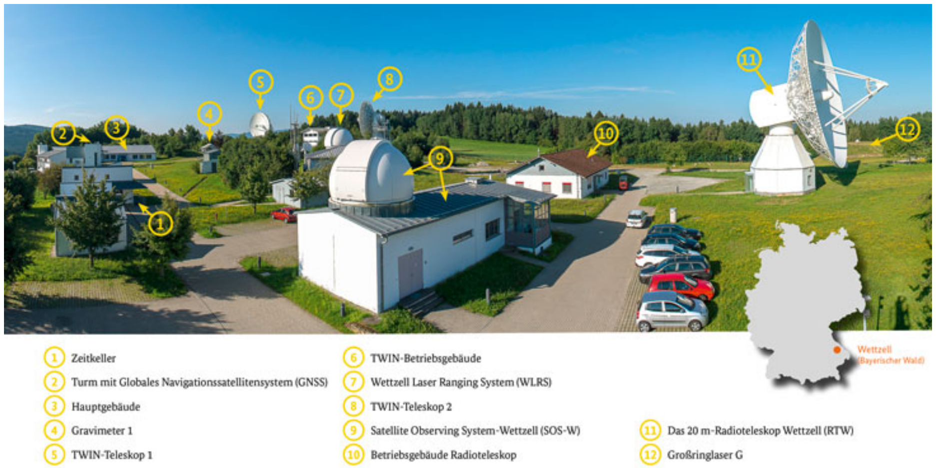
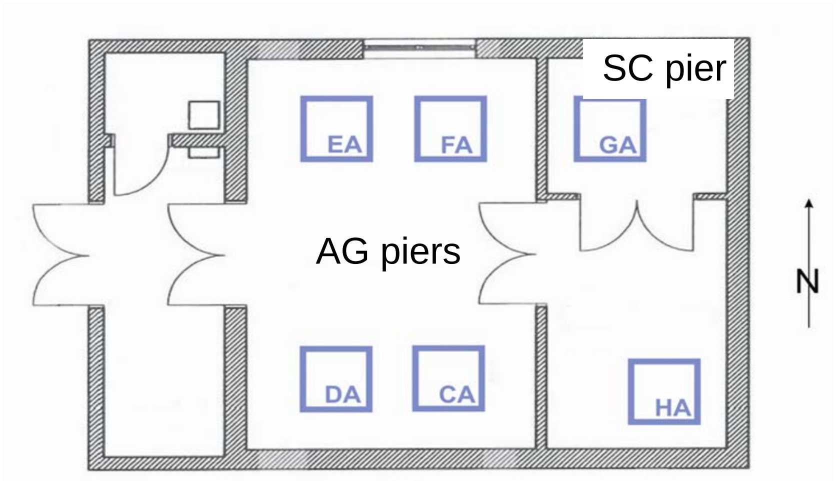
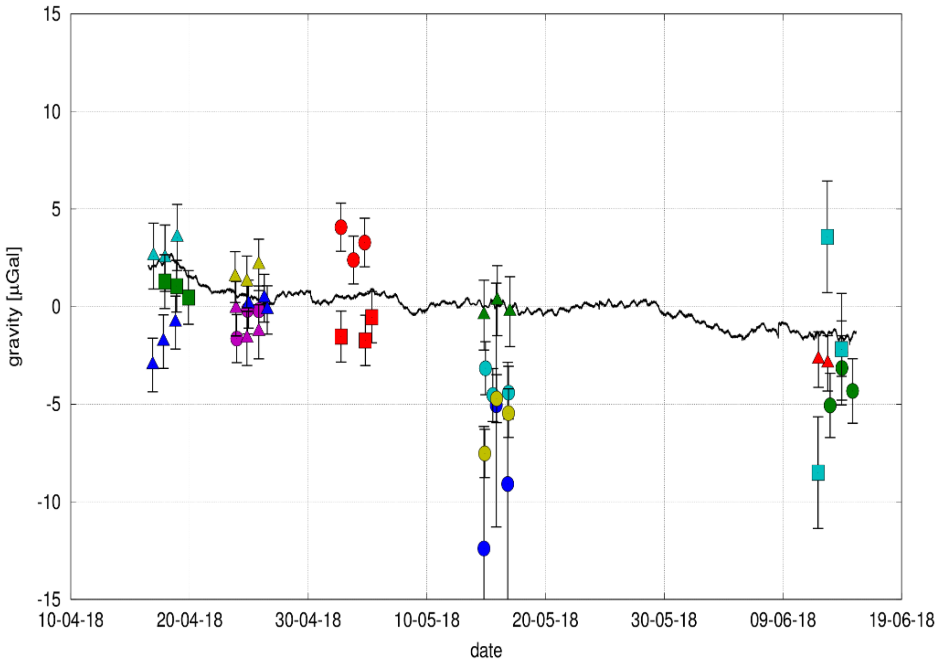
Gravimetric Reference and Comparison Station Geodetic Observatory Wettzell





2018 EURAMET.M.G-K3 Key Comparison and Pilot Study of Absolute Gravimeters

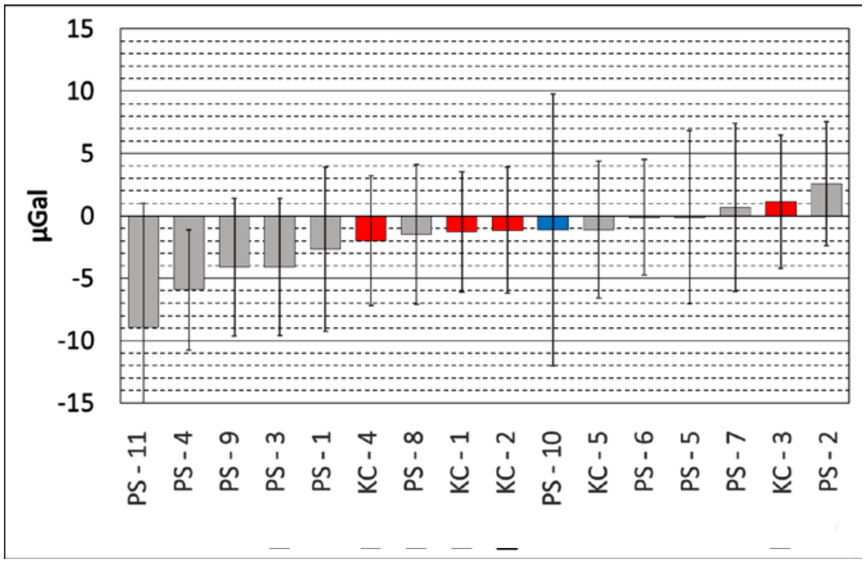
- Regional Key Comparison and Pilot Study
- Organized by BKG and the pilot laboratory VÚGTK/RIGTC, Czech Republic at Geodetic Observatory Wettzell (V. Pálinkáš)
- 16 instruments from 12 countries including 5 instruments for KC
- 5 observation sessions between April 16th and June 15th 2018

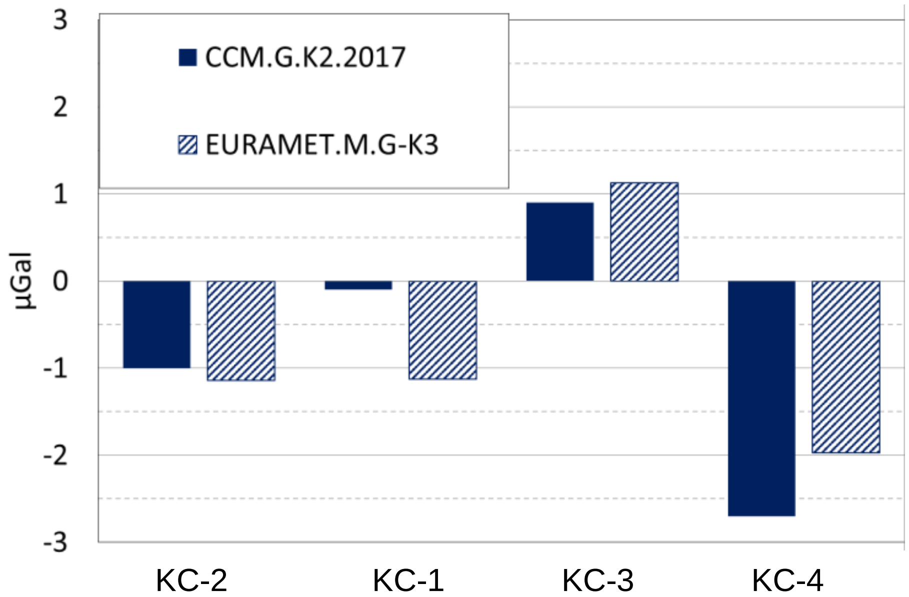


Objectives:

- Validation of the Calibration and Measurement Capabilities (CMCs) published in the Key Comparison Database (KCDB)
- Link of European gravimeters to CCM.G-K2.2017, Changping, China

2018 EURAMET.M.G-K3 Key Comparison and Pilot Study of Absolute Gravimeters

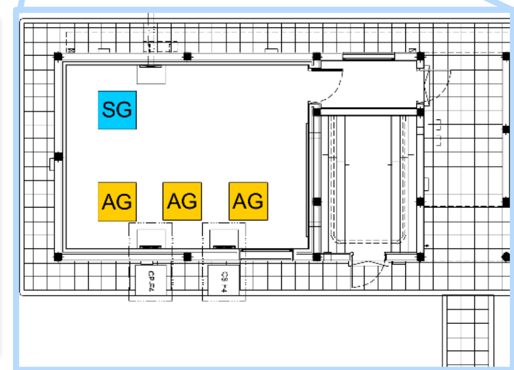




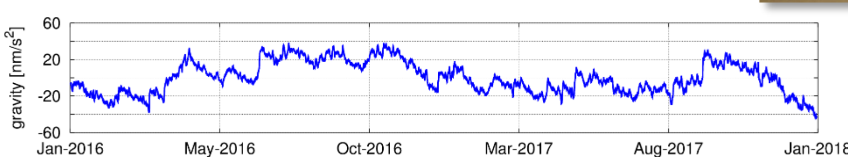
Falk et. al: The 2018 EURAMET.M.G-K3 Key Comparison and Pilot Study of Absolute Gravimeters in Wettzell, Germany. Poster presentation at 27th IUGG General Assembly, 8-18 July 2019, Montréal

AGGO
Argentine-German Geodetic Observatory

- Development of AGGO to a Gravimetric Reference Station for South America
- Gravimeter lab (5.3 x 7m) with 4 piers with 1.10 m side length, usable for all FG5
- Superconducting Gravimeter SG038: since Dec 2015
- Absolute gravimeter FG5-227: since Jan 2018

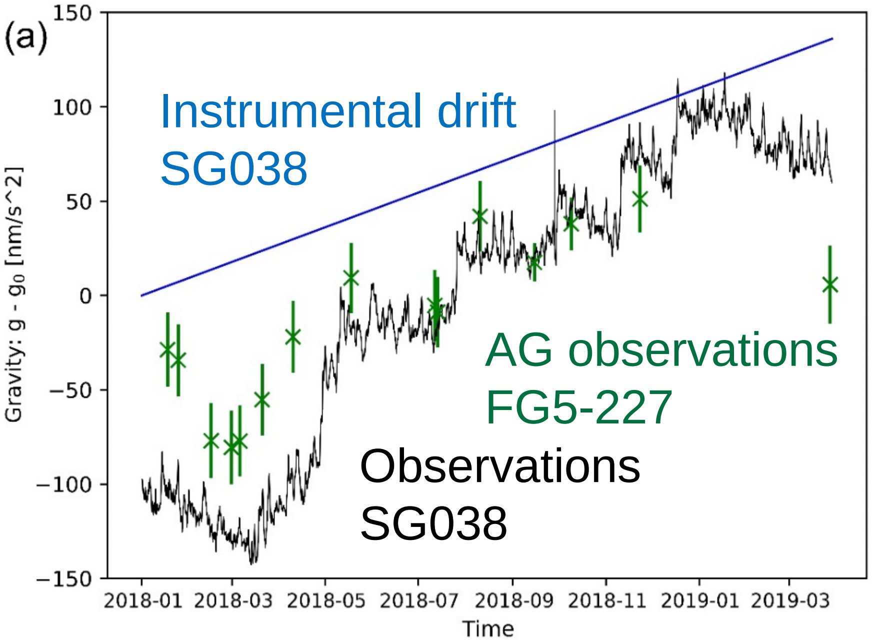


Residual Signal SG after drift correction

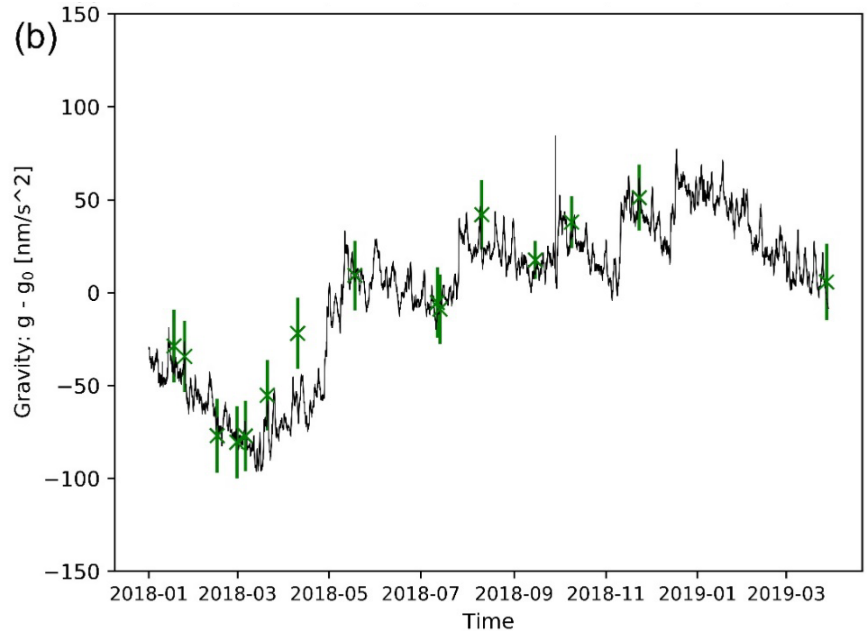


Combination of SG and AG observations
Example: AGGO

SG038 observations



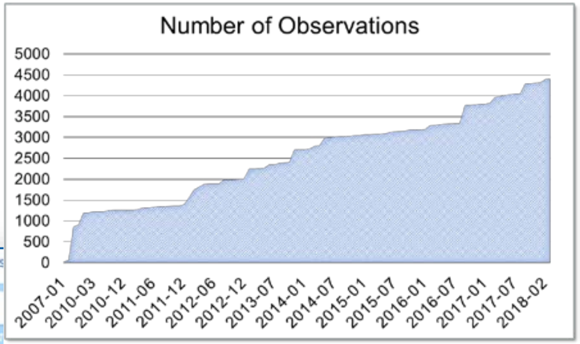
SG038 observations after correction due to instrumental drift, atmosphere, and polar motion



Antokoletz et al. (2019). Calibration of SG038 at the Argentinian-German Geodetic Observatory (AGGO) by co-location with absolute measurements. Journal of Geodesy, in preparation

Central Inventory: AGrav database

www.agrav.bkg.bund.de



Operational since 2008

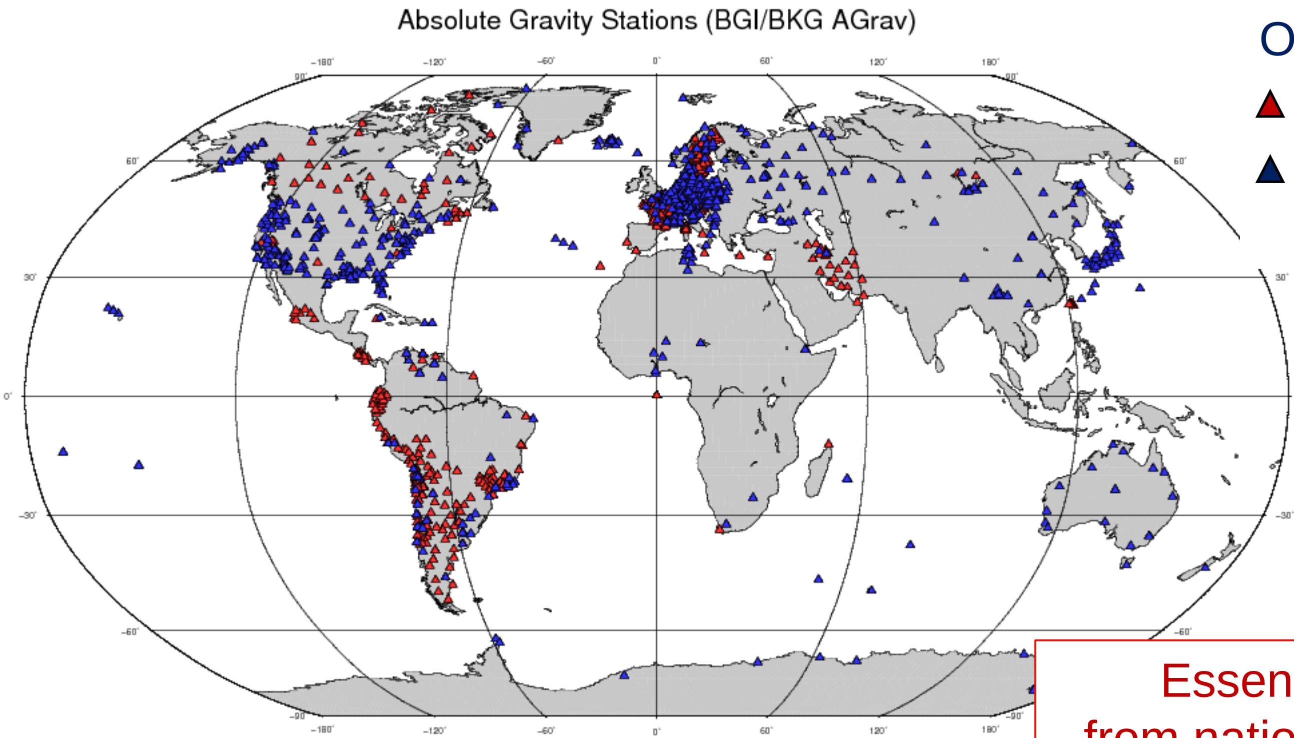
- Operated by BKG and BGI
- Increasing number of contributors
- DOI (Digital Object Identifiers)

Upgrade planned in 2019 (ex of new features)

- **Time series plots** in common reference height
- **Documentation** of comparison results
- **Overview about IGETS** observations

+ Joint collaboration with new IAG JWG 2.1.2
Unified file formats and processing software for high-precision gravimetry"
(Chair: Ilya Oshchepkov, Russia)

Present Status: AG observations (AGrav Database)



Over 1200 stations

▲ AG field measurements

▲ AG lab. & ref. measurements

Essential contribution from national agencies & AG contributors

GGRF Workshop IUGG IASPEI IAG

IAG Resolution No. 4 of 2019

Resolution 4: Establishment of the Infrastructure for the International Gravity Reference Frame

The International Association of Geodesy,

Considering,

- The IAG Resolution No. 2 for the establishment of a global absolute gravity reference system released at the 26th IUGG General Assembly in July 2015;

Acknowledging,

- The achievements of
  - JWG 2.1.1 "Establishment of a global absolute gravity reference system",
  - Sub-Commission 2.1 "Gravimetry and Gravity Networks",
  - International Gravity Field Service (IGFS)
- in realizing this resolution;

Noting,

- That the realization of the International Gravity Reference System (IGRS), the International Gravity Reference Frame (IGRF), is based on measurements with absolute gravimeters (AG) monitored at reference stations and during international comparisons, which needs the support of national and international institutions;

Urges,

- International and national institutions, agencies and governmental bodies in charge of geodetic infrastructure to
  - Establish a set of absolute gravity reference stations on the national level,
  - Perform regular absolute gravity observations at these stations,
  - Participate in comparisons of absolute gravimeters to ensure their compatibility,
  - Make the results available open access.

27th IUGG General Assembly / Assemblée Générale de l'UGGI — IUGG UGGI

July 8 – 18 2019, Montréal, Canada

GGRF Workshop — IUGG — IASPEI — IAG

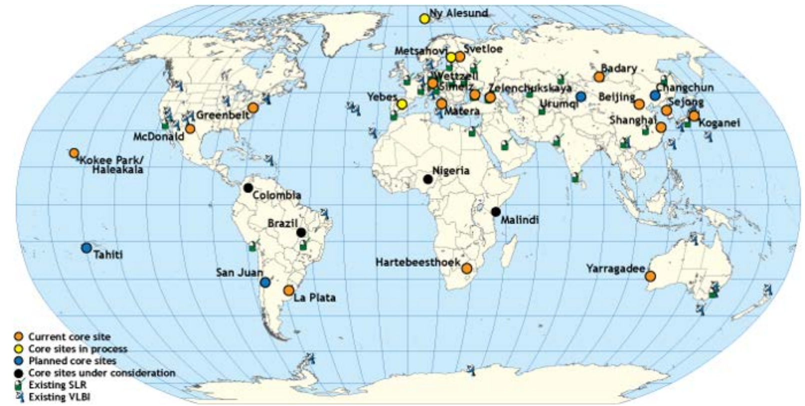
Potential Reference stations

Reference Station according to IGRS

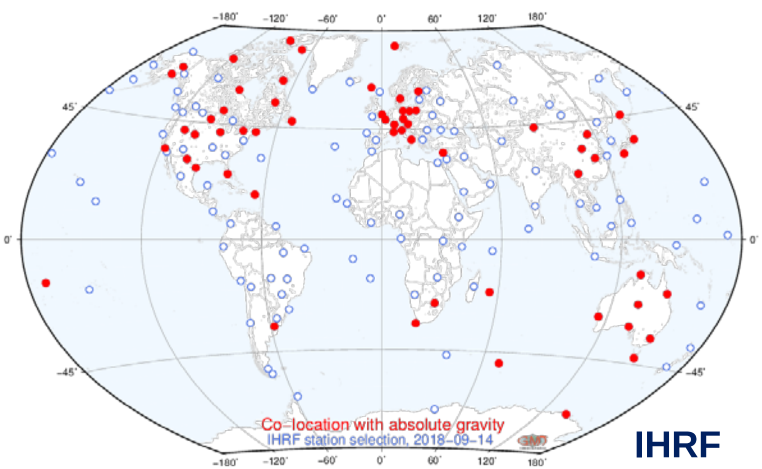
- Continuous reference function by SG (relative) or Quantum gravimeter (absolute)
- Regular AG measurements (rep. rate: two years, less than two month (w/, w/o SG resp.))

Co-Location with other global reference networks

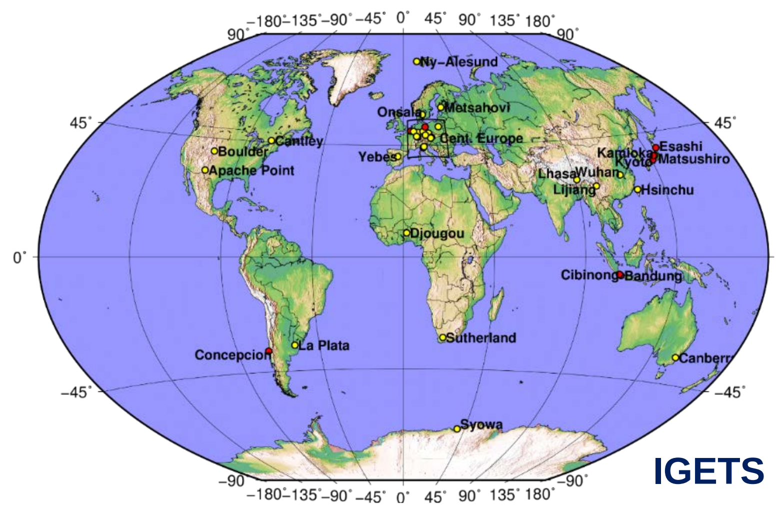
- Global Geodetic Observing System (GGOS)
- International Height Reference Frame
  IAG Joint Working Group 0.1.2.
- International Geodynamics and Earth Tides Service (IGETS)



GGOS



IHRF

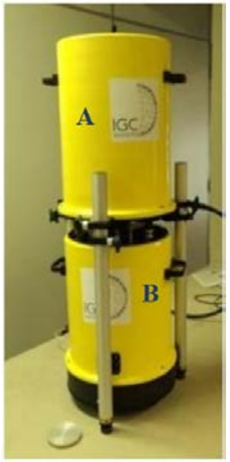


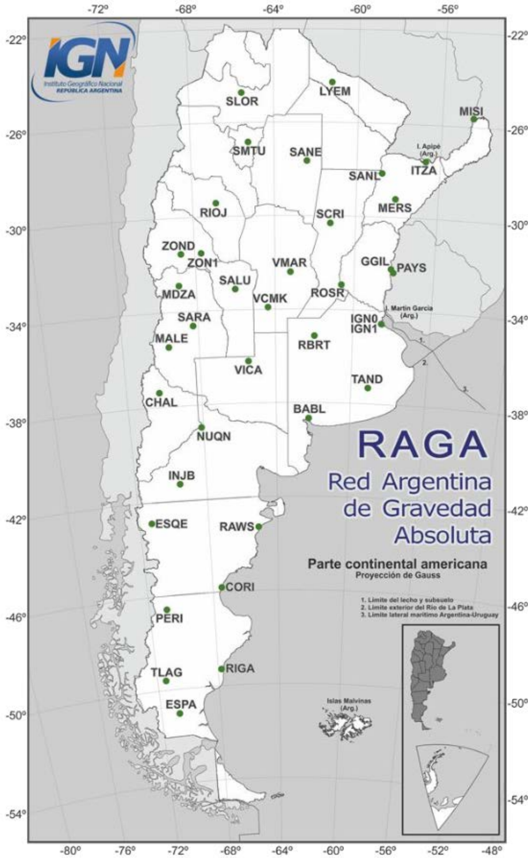
IGETS

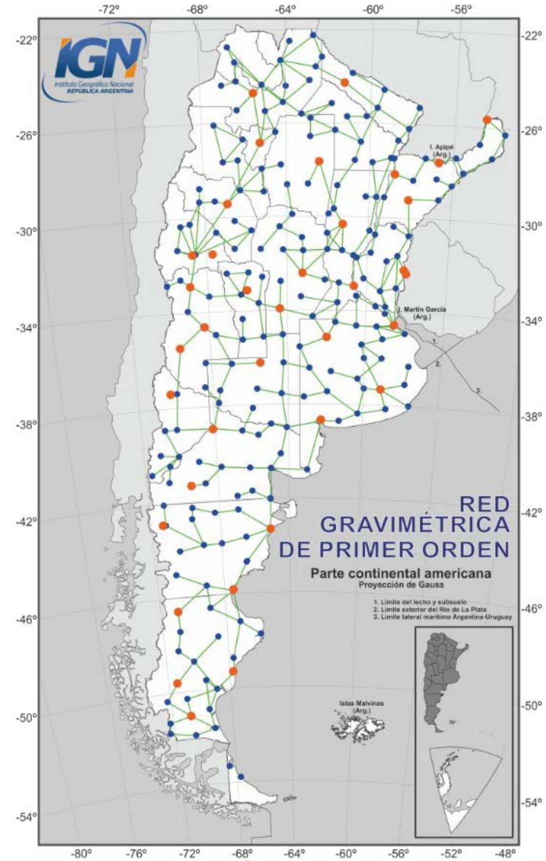
National gravimetric networks Argentina

Red Argentina de Gravedad Absoluta (RAGA)

- Collaboration between IGN, UNR, São Paulo University, IRD, UNSJ, UNLP
- Observations by A10#14, A10#32 in 2013 and 2014

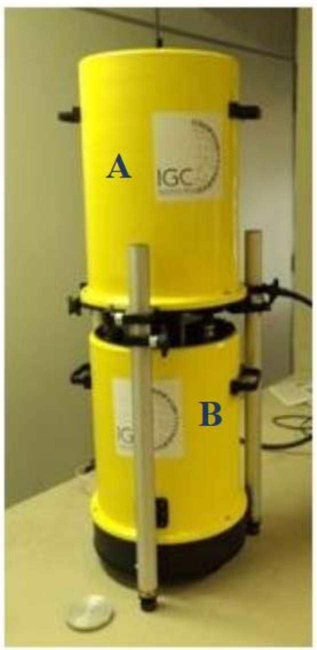


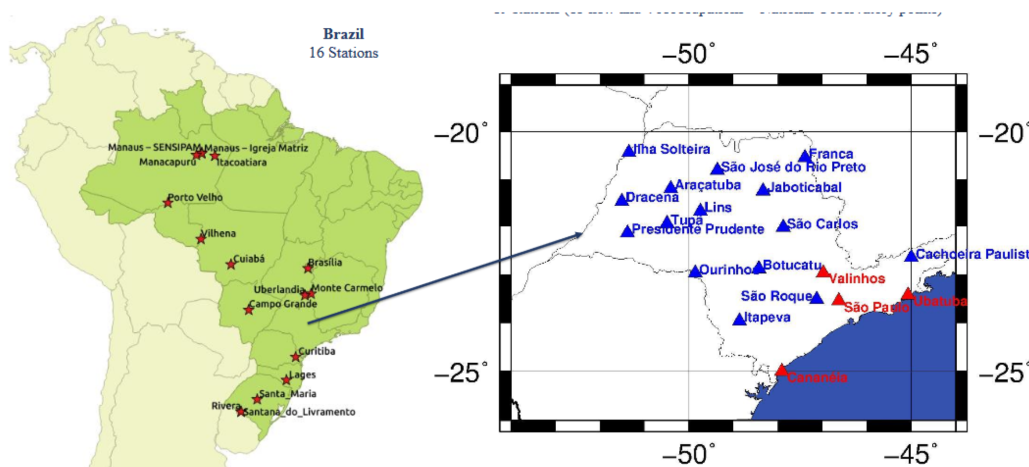




National gravimetric networks
Brazil, Venezuela, Equador

D. Blitzkow et al. (2018) Absolute gravity network in South America – Comparisons. EGU General Assembly 2018, Vienna.





Summary

- Transition from 100µGal range of IGSN71 to a new international gravity reference system/frame (IGRS/IGRF) in the few µGal range started
- System defined as *instantaneous acceleration of free fall* based on SI and a *set of constant corrections*
- Frame defined by observations with *validated absolute meters* and a set of models to correct for temporal gravity changes
- *Gravity reference stations* for quality assessment of absolute meters,
- *Comparisons of absolute meters* essential part of the concept, link to metrology,
- Link to GGOS, IGETS and IHRF,
- Update of *models for correcting temporal gravity variations*,
- *AGrav database* as a central archive for absolute gravity observations (both, reference and infrastructure level) and comparison results, including referencing datasets with DOI
- New IGRS/IGRF will provide absolute, metrologically secured, homogeneous gravity values with on the accuracy level of $(2..3)*10^{-9}$, which also allows to document gravity changes with time