The absolute gravity reference system and its contribution to geoid determination

H. Wziontek, R. Falk, H. Wilmes
Federal Agency for Cartography and Geodesy (BKG)
Development of Gravity Reference Systems

Potsdam Gravity System: Single station

Absolute gravity measurements with reversion pendulums from 1898 – 1904 at station Telegrafenberg (Potsdam) by Helmert, Kühnen und Furtwängler

\[ g = (981274 \pm 3) \text{ mGal} \text{ too large by } \sim 140 \text{ µm/s}^2 \]

F. Kühnen and Ph. Furtwängler 1906: Bestimmung der absoluten Größe der Schwerkraft zu Potsdam mit Reversionspendeln
Potsdam Gravity System

Potsdam reversion pendulums (1898)

F. R. Helmert
1843 - 1917
Development of Gravity Reference Systems

Potsdam Gravity System: Single station

Absolute gravity measurements with reversion pendulums from 1898 – 1904 at station Telegrafenberg (Potsdam) by Helmert, Kühnen und Furtwängler

\[ g = (981274 \pm 3) \text{ mGal} \] too large by \( \sim 140 \mu\text{m/s}^2 \)

F. Kühnen and Ph. Furtwängler 1906: Bestimmung der absoluten Größe der Schwerkraft zu Potsdam mit Reversionspendeln

International Gravity Standardization Net 1971 (I.G.S.N.71)

Based upon the first free fall absolute gravimeter measurements
Relative measurements by spring gravimeters and pendulums
Systematic error of the Potsdam System corrected
approx. 500 central stations, accuracy \( \pm 1 \mu\text{m/s}^2 \) (\( \pm 100 \mu\text{Gal} \))
The International Gravity Standardization Net 1971

Official gravity reference system of IAG

Accuracy of a single station:

±1 µm/s² (±100 µGal)

IGSN71 reference network (after Morelli)

- Adopted 1971, XXV. IUGG Gen. Assembly Moscow
- Correction models and conventions have been developed further since 1971 and need to be updated (tides, atmosphere...)
- Treatment of permanent tide inconsistent with other products of IAG (e.g. World Height System)
- Today, I.G.S.N.71 neither fulfils requirements of metrology nor of geodesy and geosciences!
Development of Gravity Reference Systems

Potsdam Gravity System: Single station

Absolute gravity measurements with reversion pendulums from 1898 – 1904 at station Telegrafenberg (Potsdam) by Helmert, Kühnen und Furtwängler

\[ g = (981274 \pm 3) \text{ mGal} \text{ [too large by } \sim 140 \text{ µm/s}^2] \]

F. Kühnen and Ph. Furtwängler 1906: Bestimmung der absoluten Größe der Schwerkraft zu Potsdam mit Reversionpendeln

International Gravity Standardization Net 1971 (I.G.S.N.71)

Based upon the first free fall absolute gravimeter measurements
Relative measurements by spring gravimeters and pendulums
Systematic error of the Potsdam System corrected
approx. 500 central stations, accuracy \(\pm 1 \text{ µm/s}^2\) (\(\pm 100 \text{ µGal}\))

Today: Ballistic free-fall instruments establish a de-facto standard

Accuracy: a few µGal

Gravity reference realized by each absolute gravimeter independently

\(\rightarrow\) International comparisons essential

Modern Gravity Reference System: Absolute Gravimeters + Comparisons
Permanent Tide in Gravimetry

- IGSN71: Mean tide system, both, gravitational potential and deformation effect restored by Honkasalo-correction ($\delta = 1.20$, not 1.16 !)
- IAG resolution Canberra 1979: Conventional tide free

Official gravity reference system of the IAG still mean tide!

Space geodetic techniques:
Conventional tide free, in conflict with 1983 resolution too, which “recommends that:
3. the indirect effect due to the permanent yielding of the Earth be not removed.”

The latitude depend correction according to Honkasalo (1964) ranges $\sim 120 \mu$Gal
Reference System in Gravimetry

- **Reference System:** Mathematical definition of the coordinate system to describe (geometric) position and position changes.

- **Reference Frame:** Physical materialization of the reference system by the entirety of geodetic sites

- Magnitude and direction of gravity is physically present and observable at every point in space (natural coordinates) → In gravimetry: reference system == reference frame!

- Realization only limited by measurement accuracy, not by station distribution nor temporal changes.
Absolute gravity reference system: Requests for a from Metrology

- Metrological objectives
  - Conformity with International Meter Convention
  - Traceability to SI units
  - Metrological equivalence
  - Uncertainty estimates
  - Supporting
    - Kilogram definition (Watt balance)
    - Kelvin redefinition (Boltzmann and Planck constants)
    - Verification of new instruments (Atom interferometer, optical clocks) etc.
  - BIPM is responsible for the equivalence of national standards

(BIPM: International Office for Weights and Measures)
Absolute gravity reference system: Requests from Geodesy and Geosciences

- Basis for precise gravity field determination
  - Geoid / Geodetic height reference surface
  - Contributes to the Realization of a Global Height System

- Quantify smallest temporal changes
  - Geodynamics
  - Isostasy, height changes
  - Mass transports (glaciology, hydrology)
  - Sea level rise etc.

- Requirement for a precise global gravity reference system
  - Ensure consistent results for more than 100 absolute gravimeters

Measured gravity residuals and corresponding water storage change
Creutzfeldt et al. (2012), J. Geophys. Res., 117, D08112

International Project:
- FGI (Finland)
- NGS / NOAA (USA)
- BKG (Germany)
- Statens Kartverk (Norway)
- Lantmäteriet (Sweden)
Comparison of Changes in Gravity and Height

GPS uplift rates 10 mm / year (BIFROST 2001)

GPS uplift rates 10 mm / year (Kaniuth/Vetter 2004)

Gravity changes -2 μGal / year

[1 μGal = 10 nm/s²]
Changes in Gravity in Fennoscandia 1993-2005

Engfeldt et. al. 2008
Gravity at Geodetic Observatory Wettzell

\[ g_{WTZ} = 9.808356954 \text{ [m/s}^2\text{]} \]

Figure of the Earth, Centrifugal force
Mass-Anomalies
Earth's Tides
Atmosphere, Ocean, Polar Motion, Hydrology, Height changes
State of the Art: Ballistic Absolute Gravimeter

Gravity acceleration obtained from free fall experiments

Principle:
- Acquisition of length and time during free fall of a test mass

Instrumental Properties:
- based on physical standards for time and length
- no drift
- accuracy: ca. ± 2 µGal

Construction:
- evacuated dropping chamber
- stabilised laser as length reference
- Rb – oscillator as time reference
- inertial reference (superspring)
- interferometer
Absolute Ballistic Gravimeter: Principle
(Michelson Interferometer)

Test-Mass: moving mirror

Photo-diode

Interference pattern

Laser

Inertial Reference: fixed mirror

Frequency-change (sweep) of fringe pattern during acceleration.

Fringe-signal contains time and distance:
- Fixed wavelength using stabilized Laser
- Zero-crossings are referenced to oscillator (counter) after conversion into TTL-signal

Wave 1 + Wave 2 = Constructive Interference
Wave 1 + Wave 2 = Destructive Interference

Max. Int. → Max. Int.
Min. Int. → Min. Int.
A10 Absolute Field Gravimeter

Manufacturer Specifications:
- **Accuracy:** ± 10 µGal
- **Precision:** ± 10 µGal
- **in 10 Minutes (‘at a quiet site’)**
Mobile Atom Interferometer
GAIN (Gravimetric Atom Interferometer)

- Mobile setup
- Atomic fountain
  \( h \approx 0.7 \text{m} \)
  \( T' \leq 0.3 \text{s} \)
- Rubidium 87
- Diode Laser System @ 780nm

Targeted Performance:

Sensitivity
\( 10^{-8} \text{ g/} \sqrt{\text{Hz}} \)

Accuracy:
\( 5 \times 10^{-10} \text{ g} \)
Absolute Gravity Reference: Interrelations

- International Comparisons of Absolute Gravimeters (4 years interval)
- Regional Comparisons of Absolute Gravimeters
- Continuous Monitoring of temporal gravity changes
- International Gravity Reference System (AGrav database)
- National Gravity Standard
- National Gravity Reference Networks
- Absolute gravity field observations ~10 µGal (independent)
- Relative gravity surveys (network) ~ 20 µGal

Absolute gravity field observations ~10 µGal

Relative gravity surveys (network) ~ 20 µGal

µGal
Cooperation of Metrology and Geodesy

International comparisons of Absolute Gravimeters (AG)

• Held since 1981 in 4-yearly sequence at the BIPM, since 2013 under CIPM
• Determine Degree of Equivalence (offsets and uncertainty estimates)
• Ensure traceability and link to SI units
• Key Comparisons since 2009
• International comparisons determine the absolute gravity reference!
International Comparisons of Absolute Gravimeters

- **Gravity standard:** realized by all absolute gravimeters – no independent reference!
- ICAG supported by BIPM from 1981 until 2009, repeat cycle: 4 years
  First CIPM Key Comparison in 2009,
- Intermediate comparisons at Walferdange/Luxembourg since 2003, shifted by 2 years, first ICAG in 2013,
- Link to SI quantities by application of standards for time and distance (e.g. Rb-oscillator and stabilized laser),
- Consistency checks by repeated comparisons,
- **Applications in Geosciences / Geodesy:** Gravity changes over time → temporal stability of an AG most important (repeatability),
- Complementary regional comparisons, but compatibility to ICAGs needed.
The global gravity reference system is realized by a network of "gravity gauges" connected by AG comparisons.
Absolute Gravity Reference: Interrelations

- International Comparisons of Absolute Gravimeters (4 years interval)
- Regional Comparisons of Absolute Gravimeters
- Continuous Monitoring of temporal gravity changes
- International Gravity Reference System (AGrav database)
- National Gravity Standard
- National Gravity Reference Networks
- Absolute gravity field observations ~10 μGal (independent)
- Relative gravity surveys (network) ~ 20 μGal
Station Walferdange (Luxembourg)
Gravity reference and comparison site

- 15 AG piers
- SG site

European comparison of absolute Gravimeters in Walferdange (ECAG2011) under responsibility of Swiss National Metrological Institute (METAS)
Gravity reference station for AG comparisons

Example site TMGO in Boulder, CO, USA
- 10 AG piers
- SG
Realization of the national gravity reference: Wettzell (DE)

- Individual piers for 4 (5) AG
- Superconducting Gravimeter (SG) is part of the comparison
- SG contributes to gravity reference function
Realization of the national gravity reference: Wettzell (DE)

RICAG2010 Wettzell - Neues Gravimeterhaus
in µgal, bezogen auf WETT_FA@125cm
\( (g_0 = 980\,836\,960\ \mu\text{Gal}) \)
Realization of the national gravity reference: Wettzell (DE)

Gravimetrische Zeitsreihe Wettzell - Neues Gravimeterhaus

Schwerewerte in µgal bezogen auf WETT_FA@125cm

\[ g_0 = 980,836,960 \, \mu\text{Gal} \]
Realization of the national gravity reference: Wettzell (DE)

Gravimetrische Zeitreihe Wettzell - Neues Gravimeterhaus (SG030-1 Residuen) in µgal bezogen auf WETT_FA@125cm

($g_0 = 980\,836\,960\,\mu\text{Gal}$)
Realization of the national gravity reference: Wettzell (DE)

Gravimetrische Zeitreihe Wettzell - Neues Gravimeterhaus (SG030-1 Residuen) in μgal bezogen auf WETT_FA@125cm

\( g_0 = 980 \, 836 \, 960 \, \text{µGal} \)
Link to International Intercomparisons

Regional comparisons (e.g. Wettzell) will complement international intercomparisons.
Combination of instruments with complementary characteristics

Superconducting Gravimeter (SG)
- relative values
- precision < 0.1 nm/s²
- continuous registration
- high temporal resolution

Absolute Gravimeter (AG)
- based upon physical standards
- no drift
- uncertainty: ± 20 nm/s²
- observation epochs
Combination of instruments with complementary characteristics

Superconducting Gravimeter (SG)
- relative values
- precision < 0.1 nm/s²
- continuous registration
- high temporal resolution

Absolute Gravimeter (AG)
- based upon physical standards
- no drift
- uncertainty: ± 20 nm/s²
- observation epochs

Combination includes:
- SG drift determination
- Check of calibration
- AG: Test for offsets

Gravity reference function with highest resolution and long-term stability

Residual gravity time series

Comparison Reference Function
Superconducting Gravimeter

Most precise relative Gravimeter (stationary)

- **Principle:**
  - Superconducting sphere (Niobium), floating in the magnetic field of superconducting coils
  - Position changes compensated by a feedback controlled additional magnetic field

- **Instrumental Properties:**
  - Sensitivity higher than 0,1 nm/s²
  - High signal to noise ratio
  - Long term stability
  - Low, almost linear instrumental drift: a few µgal/year
  - Broad spectral range: from normal modes to secular gravity changes

- **Construction:**
  - Dewar filled with liquid helium (4.2 K)
  - Temperature inside sensor unit stabilised to a few µK
  - Feedback system, registration system
Superconducting Gravimeter Sensor Unit (TT 60)
Modern Superconducting Gravimeters

Development:

- Small Dewar, only 35 l Helium
- Coldhead enables He-reliquification
- Closed system, no Helium loss, icing problems minimized
- Efficient air-cooled compressor (1.6 kW power consumption)
- Data acquisition system: 7½ digits for gravity signal, 40 channels, 16-bit for auxiliary data
- GPS/DCF time keeping
- Remote controlled over network
Absolute Gravity Reference: Interrelations

- International Comparisons of Absolute Gravimeters (4 years interval)
- Regional Comparisons of Absolute Gravimeters
- Continuous Monitoring of temporal gravity changes
- International Gravity Reference System (AGrav database)
- National Gravity Standard
- National Gravity Reference Networks

Absolute gravity field observations ~10 μGal (independent)

Relative gravity surveys (network) ~ 20 μGal
Modern gravity network based on 35 absolute gravity observations (30 points: FG5-101, BKG, 5 points: JILAG-3, IfE)

Observation period: 1993 to 1995

Accuracy: ± 5 µGal

Backbone of gravity networks of the German Federal States
German Primary Gravity Network 1996 (DHSN 96)

Consistent basis for (relative) gravity surveys, nationwide coverage

Basis:
• DSGN94 and updated observations of German Federal States
• Old States: Readjustment of previous network DHSN82, Bias: -19 µGal
• New States: Adjustment of 1st order relative observations 1996/97 and connection to 15 points of DSGN94
Validation of DHSN96 by Field Absolute Gravimeter A10

Reobservation of 1/3 of DHSN96 proofs both,

- reliability of A10 absolute field gravimeter
- no systematic deviation of DHSN96

Founded by BMBF project „Geotechnologien Projekt“, No.03F0422A
Calibration of the A10 Field Absolute Gravimeter

Monitoring Unit for the physical standards at BKG

- Caesium frequency standard
- Iodine-stabilised Laser WEO100 (control electronics)
- Modified laser heterodyne system, Winters Electro Optics Inc., USA
- Laser beam adapter and fibre optics interferometer in cooperation with Darmstadt Technical University, Germany
- Iodine-stabilised Laser WEO100 (laser head)
A10 Messungen in der gravimetrischen Referenzstation Bad Homburg
Absolute Gravity Reference: Interrelations

- International Comparisons of Absolute Gravimeters (4 years interval)
- Regional Comparisons of Absolute Gravimeters
- Continuous Monitoring of temporal gravity changes
- International Gravity Reference System (AGrav database)
- National Gravity Standard
- National Gravity Reference Networks

- Absolute gravity field observations ~10 µGal (independent)
- Relative gravity surveys (network) ~ 20 µGal

Federal Agency for Cartography and Geodesy

Tutorial Height and Gravity
EUREF Symposium 2015, Leipzig, Germany, June 2, 2015 i Page 44
Gravity observations in Germany with A10 Field Absolute Gravimeter

- 100 Stations measured for the renewal of the German first order leveling network
- > 200 additional points as requested by German Federal States:
  - homogeneous gravity reference, improvement of geoid modeling
  - Integrated geodetic reference
Conclusions

- International absolute gravity reference with an accuracy of 5 µGal established by
  - Modern absolute gravimeters (AG)
  - Intercomparisons based on continuous reference function by Superconducting gravimeters (SG)
- Regional comparisons ensure temporal stability of absolute gravimeters
- National gravity reference by combination of AG - SG
- Field absolute gravimeters enables spatially distributed gravity measurements with an accuracy ~ 10 µGal
- Homogenous gravity references basis for consistent global gravimetric geoid
- Up-to-date geoid models allow already gravity prediction < 500 µGal
- Future gravity data should be more precise than current geoid models

Precise absolute gravity reference system is the basis for high precision geoid models, regional and globally.
Thank you for your kind attention!

Contact:

Federal Agency for Cartography and Geodesy
Section G4 Gravity Metrology
Karl-Rothe-Straße 10-14
04105 Leipzig

Hartmut Wziontek
hartmut.wziontek@bkg.bund.de
www.bkg.bund.de
Tel. +49 (0) 341 56 34 - 256

Richard-Strauss-Allee 11
60598 Frankfurt/Main

Reinhard Falk, Herbert Wilmes
reinhard.falk@bkg.bund.de
herbert.wilmes@bkg.bund.de
www.bkg.bund.de
Tel. +49 (0) 69 6333-216 / -252