

COMBINATION OF ABSOLUTE AND SUPERCONDUCTING GRAVITY OBSERVATIONS AT THE ARGENTINEAN-GERMAN GEODETIC OBSERVATORY (AGGO)

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Combination of Absolute and Superconducting gravity observations at the Argentinean-German Geodetic Observatory (AGGO)

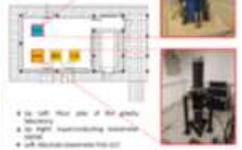
Horstmut Wziontek¹⁾, Ezequiel D. Antokletz²⁾, Reinhard Fell³⁾, Claudia Teicher⁴⁾ and Claudio Brunini⁵⁾

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⁵⁾ Federal Agency for Cartography and Geodesy (BKG), Germany



Argentinean-German Geodetic Observatory (AGGO)

- AGGO is a fundamental geodetic observatory located close to the Rio de La Plata, Argentina.
- It is a non-commercial, cooperative project between the National Scientific and Technical Research Council (CONICET) from Argentina and the Federal Agency for Cartography and Geodesy (BKG) from Germany.
- All main space geodetic techniques are to be used together with a superconducting gravimeter (SGM) (Wziontek et al., 2017) and an absolute gravimeter (AG).



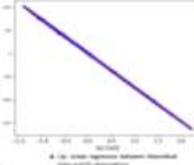
- Absolute gravity measurements are monthly available since January 2018.
- Continuous gravity record from the superconducting gravimeter (SGM) since December 2015.
- Reference station of the International Gravity Reference Frame (IGRF).
- Link between IGRF and the International Height Reference System (IHRS) (Wziontek).

First Scale Factor estimation: Theoretical Tides

- Linear regression between gravity time series of the SGM and theoretical tides, including:
 - Theoretical tides computed by Tisserand's catalogue of 1300 values (Tisserand, 1907) and synthetic Earth tide parameters (Dobson et al., 1999).
 - Ocean Tide Loading (OTL) effect on gravity now computed using IUGG19 model (Cannon et al., 2014) with parameters provided for the ocean tide loading provider of IAGG, Sea and Ice-02 Software (<http://ftp.cea.fr/pub/seasoft/ice02/ice02v2/>).
 - Atmospheric effects were modelled with a simple air pressure algorithm using a constant value of 2.77 mmHg/2kPa.
 - Air tide tides take into account using EOP 04C series of IERS and a gravimetric factor of 1.5.
 - Mean values of the tide (Dobson et al., 2007).

$$g(t_{AG}) = g(t_{SG}) + g_{\text{OTL}}(t) + g_{\text{ATL}}(t) + g_{\text{ATM}}(t) + g_{\text{AIR}}(t) + P + \beta_0 + \beta_1 SG(t)$$

- where:
 - g_{OTL} : Ocean Tide Loading effect;
 - g_{ATL} : atmospheric effect;
 - g_{ATM} : air tide;
 - g_{AIR} : ocean tides of the air;
 - P : residual;
 - β_0 : constant that represents the mean value of tide;
 - β_1 : calibration factor;
 - $SG(t)$: SG measurement in m/s².



Scale Factor estimation: combination of Absolute and Superconducting gravity observations

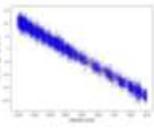
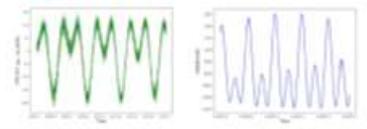
- Absolute gravity measurements are monthly available since January 2018. Three absolute gravity measurements were developed during periods of high tide variability for the Scale Factor determination:
 - May 10, 2018 (11760 individual drops)
 - July 12, 2018 (11888 individual drops)
 - August 9, 2018 (10512 individual drops)

All data are treated as error free because of the distinct resolution from AG data. Every drop from the set of AG observations is assigned to a SG value. The SG data are filtered before to suppress environmental background noise. The adjustment is well established (e.g. Francis, 1998) and the observation equations for the AG data are simple:

$$g(t_{AG}) = P + \beta_0 + \beta_1 SG(t)$$

- where:
 - $g(t_{AG})$: raw AG drops;
 - P : residual;
 - β_0 : constant that represents the mean AG value;
 - β_1 : calibration factor;
 - $SG(t)$: SG measurement in m/s², corresponding to the AG drop.

AGGO			
Date	# of Drops	β_1 [mm/s ²]	Std. Dev. [mm/s ²]
May 10, 2018	11760	-717.8	1.7
July 12, 2018	11888	-717.8	1.6
August 9, 2018	10512	-717.8	1.5



Has the Scale Factor of the Superconducting Gravimeter changed from TGO to AGGO?

The SG was previously located with TGO at Comares, Cádiz. The SG was re-located transported over 3000 km by truck. The sphere was re-centred at the new location. The Scale Factor was obtained at TGO by using all AG observations developed after we upgrade of the electronic system of the SG in December, 2016.

TGO	β_1 [mm/s ²]	Std. Dev. [mm/s ²]
Mean Scale Factor from all AG observations	-716.8	1.6

Conclusion: Although the actual Scale Factor differs by about 1.5 ‰, the change is not significant!

First Estimate of the SG Instrumental Drift at AGGO

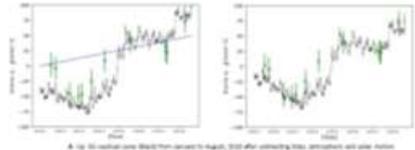
In combination of all AG and SG observations, the instrumental drift can be separated from long term geophysical trends in gravity. Raw (uncorrected) gravity data are used to avoid the impact of models used to correct inorganic gravity changes which are not phase-consistent between AG and SG processing. Instrumental drift was adjusted following the equation:

$$g(t_{AG}) = P + \beta_1 [SG(t_{AG}) + d(t)]$$

- where:
 - $g(t_{AG})$: raw AG drops;
 - P : residual;
 - β_1 : calibration factor;
 - $SG(t_{AG})$: SG measurement in m/s², corresponding to the AG drop;
 - $d(t)$: instrumental drift, assumed to be linear.

The instrumental drift was determined with 7.7 $\mu\text{m/s}^2/\text{year}$. The Scale Factor was simultaneously estimated with $-717.9 \pm 0.4 \text{ mm/s}^2/(\text{m/s}^2)$.

Conclusion: First estimation of SG Instrumental Drift after eight month of AG data: 7.7 $\mu\text{m/s}^2/\text{year}$.



Acknowledgments

We thank A. M. Castro, M. Hahn, N. Hain, A. Löffelmann, A. Poupard and A. Reinhold for setup and operation of the absolute gravimeter and maintenance of the superconducting gravimeter.

Francis, J., 1998. *Gravity: Theory and Observation*. Cambridge University Press, Cambridge, 478 pp.
 Wziontek, H., 2017. *Superconducting Gravimetry*. Springer, Berlin, 300 pp.
 Wziontek, H., 2018. *Superconducting Gravimetry*. Springer, Berlin, 300 pp.
 Wziontek, H., 2019. *Superconducting Gravimetry*. Springer, Berlin, 300 pp.
 Wziontek, H., 2020. *Superconducting Gravimetry*. Springer, Berlin, 300 pp.
 Wziontek, H., 2021. *Superconducting Gravimetry*. Springer, Berlin, 300 pp.

La gravedad depende de la ubicación de la estación en la Tierra, del tiempo, de la posición relativa de la Luna, del Sol y de otros planetas, del sistema climático, de la rotación terrestre y de la distribución de masas. Por ejemplo, los cambios de las masas de hielo, los movimientos de los fluidos en los volcanes influyen en el valor de la gravedad así como en las deformaciones terrestres y en la redistribución de masas asociadas a grandes terremotos.



(Van Camp et al., 2017)

El campo de gravedad de la Tierra, incluidas sus variaciones temporales, es un parámetro clave para comprender el sistema Tierra.

Gravimetría Terrestre

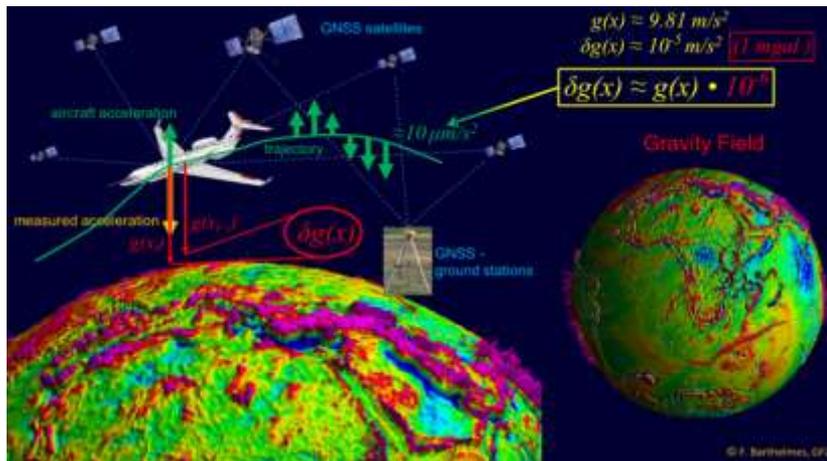
En la actualidad, existen dos principios de medición terrestre:

- Mediciones de gravedad absolutas (g)
 - Principio de caída libre
 - Gravímetros Absolutos: Micro-g LaCoste™ FG5 y A10
- Mediciones de gravedad relativas (Δg)
 - Principio masa-resorte
 - Gravímetros relativos: LaCoste & Romberg™ y Scintrex™
 - Gravímetros Superconductores

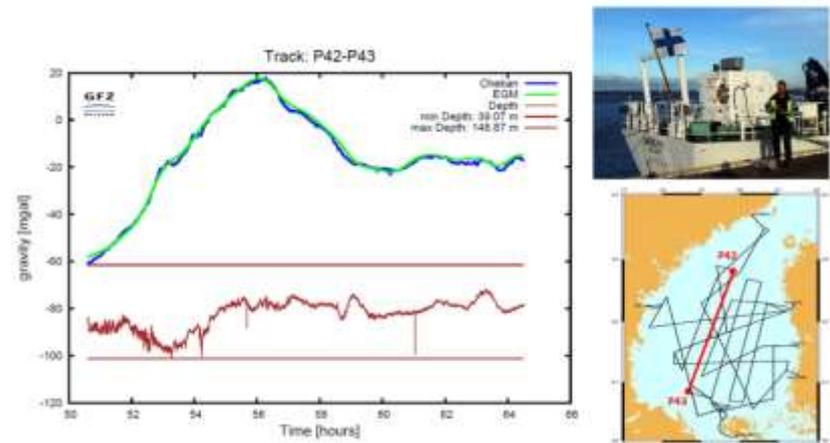
Gravímetros



Gravimetría aérea



Gravimetría marina



Observatorio Argentino Alemán de Geodesia (AGGO)

Observatorio Fundamental de Geodesia ubicado en las cercanías de la ciudad de La Plata. surge de una iniciativa conjunta del Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) de la Argentina y de la Agencia Federal de Cartografía y Geodesia (Bundesamt für Kartographie und Geodäsie - BKG) de Alemania.



Observatorio Argentino Alemán de Geodesia



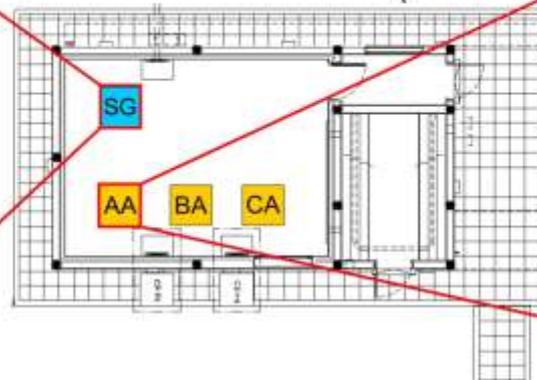
Múltiples técnicas geodésicas co-localizadas

- VLBI (Interferometria de Base Muy Larga)
- SLR (Laser a Satélite)
- GNSS/GPS
- Tiempo
- Gravimetría
- Sismómetro
- Sensores meteorológicos e hidrológicos

Se define una estación fundamental como aquel sitio en donde haya al menos tres técnicas geodésicas espaciales independientes co-localizadas.

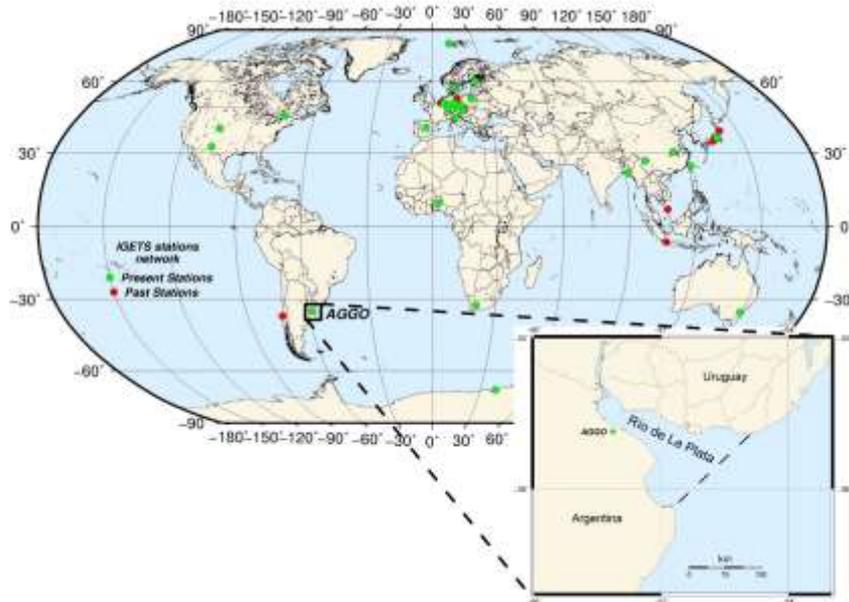
Adicionalmente, si es posible que haya observaciones de AG y SG y mareógrafos.

Laboratorio de Gravimetría



Gravímetro Superconductor SG038

Gravímetro Absoluto (AG) FG5-227



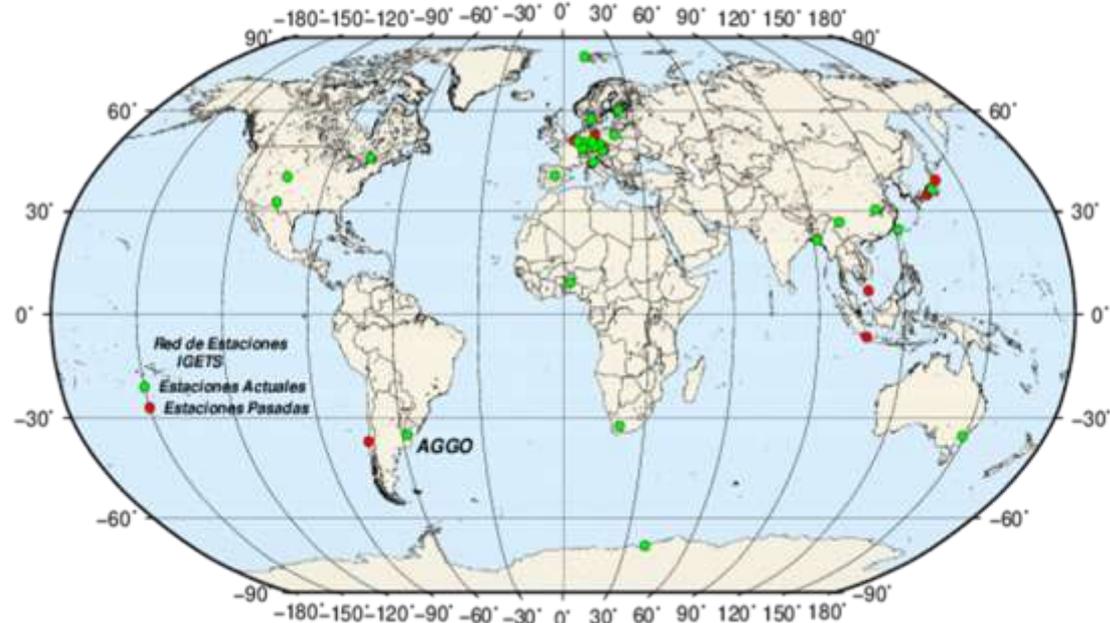
- ▶ Absolute gravity measurements are monthly available since January, 2018;
- ▶ Continuous gravity record from the Superconducting Gravimeter SG038 since December, 2015.



- ▶ Reference station of the International Gravity Reference Frame (IGRF);
- ▶ Link between IGRF and the International Height Reference System/Frame (IHRF/IHRF).

Proyectos Internacionales en el que SG de AGGO forma parte

Red **International Geodynamics and Earth Tide Service (IGETS)** que es una red de gravímetros superconductores dispersos por todo el mundo y su objetivo es medir el campo de gravedad terrestre con mucha precisión para realizar estudios geodésicos y geofísicos.



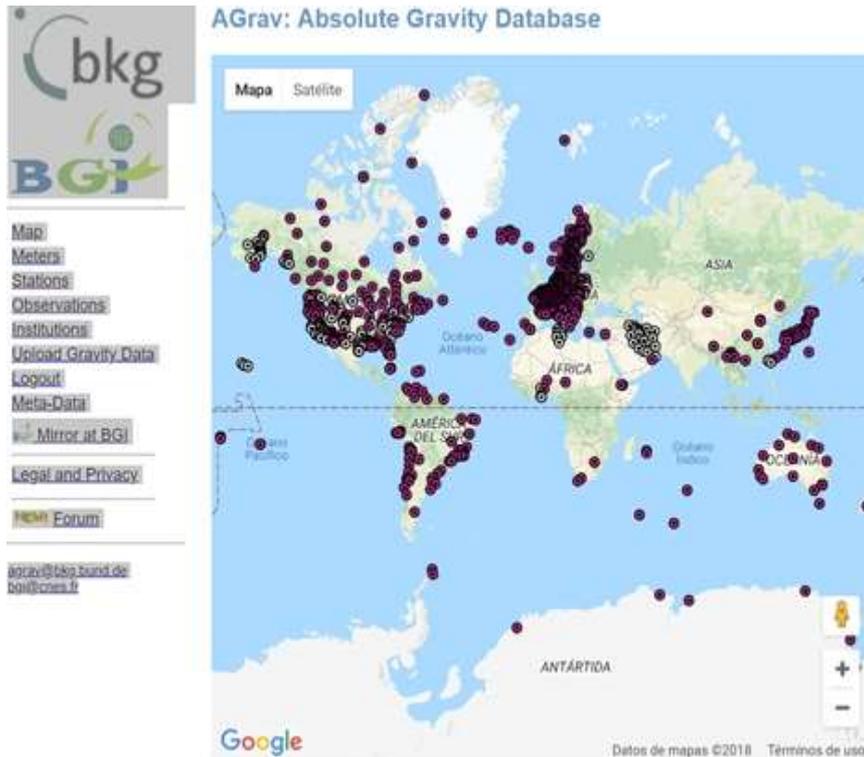
La base de datos se encuentra en

<https://isdc.gfz-potsdam.de/igets-data-base/>

Los objetivos científicos de la IGETS cubren el estudio de fenómenos geofísicos en un amplio rango de períodos (de un segundo a varios años), cubriendo tópicos como modos normales, reología del manto, mareas, interacción atmósfera-océanos-Tierra sólida, hidrología y rotación terrestre.

Proyectos Internacionales en el que AG de AGGO forma parte

AGrav: International Absolute Gravity Database del BGI y BKG



Legend:

- Station with meta data (station location)
- Station with gravity information



<http://bgi.omp.obs-mip.fr>

<http://agrav.bkg.bund.de>

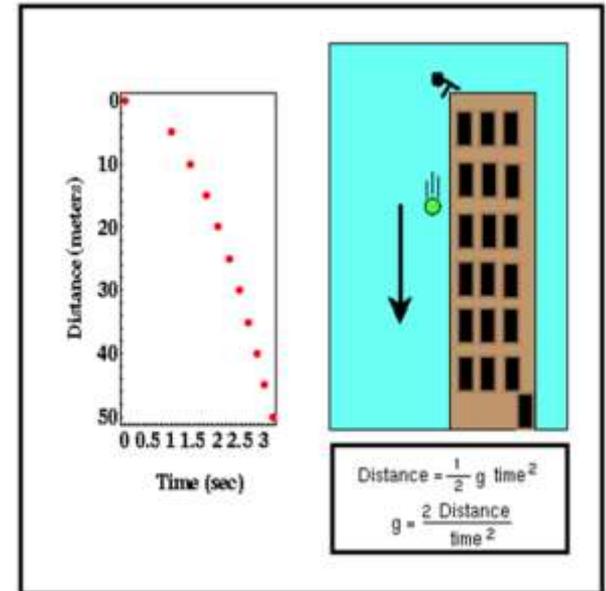
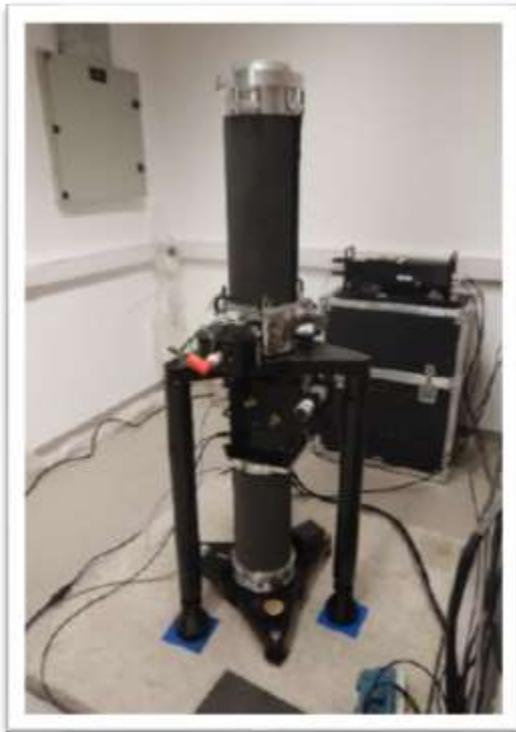


Mediciones absolutas de la gravedad: Gravímetros absolutos de Micro-g LaCoste™.

FG5

A10

Principio de caída libre



Gravímetros absolutos de Micro-g

LaCoste™

Características:

Principales ventajas

- Son transportables, miden la componente vertical de la gravedad.
- **Sin drift.**
- Proporcionan valores de gravedad absolutos precisos.
- A10 es aproximadamente 10 veces menos preciso y exacto que el FG5.

Principales desventajas

- Los AGs son instrumentos complejos y delicados.
- Las medidas dependen de la calibración del láser, de la calidad del sitio (nivel de ruido microsísmico, estabilidad térmica, ruido humano, etc.).
- AGs no se usan frecuentemente para monitoreo continuo.

Aplicaciones

- **Redes y estaciones de referencia**
 - Establecimiento de redes de referencia gravimétricas
 - Líneas de calibración
- **Metrología**
 - **Calibrar gravímetros relativos**
- **Estudio de las variaciones temporales del campo de gravedad**
 - Recuperación de redes (vulcanología , hidrología , el rebote post-glacial, terremotos)
 - Observaciones semipermanentes (mareas terrestres)

Gravímetro Superconductor

1^{er} Gravímetro Superconductor (Prothero y Goodkind, 1968) → en 1979, GWR Instruments Inc.

Principales ventajas:

- El gravímetro superconductor funciona como un gravímetro relativo con una alta sensibilidad y alta estabilidad en el tiempo;
- Mediciones temporales locales de la gravedad en forma continua (1 seg);
- Muy baja deriva o drift ($\sim 2-6 \mu\text{Gal/año}$), que puede modelarse y corregirse;
- Su muy alta sensibilidad permite detectar señales con periodos de 1 segundo a varios años.

Principales desventajas:

- Instrumento relativo (requiere calibración), no es transportable y requiere mantenimiento;
- Muy baja temperatura de funcionamiento (helio líquido);
- Se requiere aislamiento térmico (Dewar criogénico).

- First Scale Factor estimation: Theoretical Tides

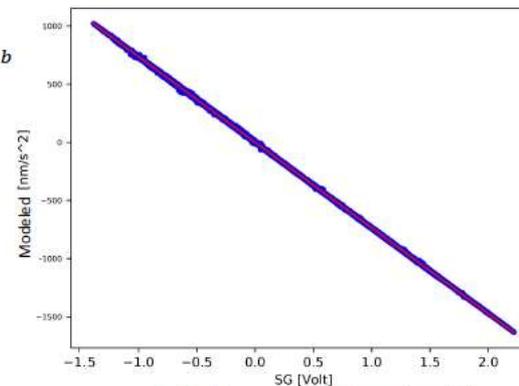
- Linear regression between gravity time series of the SG038 and theoretical tides.

$$g_{\{tides\}} + g_{\{OTL\}} + g_{\{atm\}} + g_{\{pole\}} + g_{\{ODT\}} + v = b_0 + b_1 SG_{\{ob\}}$$

where:

- $g_{\{tides\}}$: theoretical tides;
- $g_{\{OTL\}}$: Ocean Tide Loading effect;
- $g_{\{atm\}}$: atmospheric effect;
- $g_{\{pole\}}$: pole tides;
- $g_{\{ODT\}}$: storm surges of the river;
- v : residuals;
- b_0 : constant that represents the mean value of tides;
- b_1 : **calibration factor**;
- $SG_{\{obs\}}$: SG measurement in Volts.

➔ $b_1 = -735.98 \text{ nm/s}^2/\text{Volt}$



▲ Up: Linear regression between theoretical tides and SG observations.

- Scale Factor estimation: combination of Absolute and Superconducting gravity observations.

- Absolute gravity measurements are monthly available since January, 2018. Three absolute gravity measurements were developed during periods of high tides variability for the Scale Factor determination:

May 16, 2018 (11786 individual drops)

July 12, 2018 (11808 individual drops)

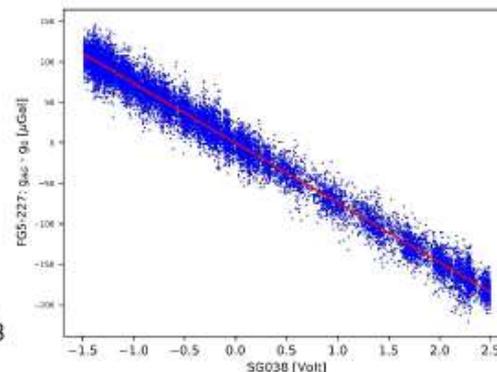
August 8, 2018 (14532 individual drops)

$$AG_{\{obs\}} + v = b_0 + b_1 SG_{\{obs\}}$$

where

- $AG_{\{obs\}}$ are raw AG values (drops)
- $SG_{\{obs\}}$ are the corresponding filtered SG values
- v are the residuals
- b_1 is the calibration factor
- b_0 is a constant representing the mean AG value

Right: Correlogram of AG and SG observations in August 2018



Date	# Drops	Tide Var	Scale	Prec
		μGal	$\text{nm/s}^2/\text{V}$	$\text{nm/s}^2/\text{V}$
16-May-18	11786	274	-735.3	2.7
12-Jul-18	11808	303	-737.8	2.1
8-Aug-18	14532	294	-737.8	2.5

Has the Scale Factor of the Superconducting Gravimeter changed from TIGO to AGGO?

First Estimate of the SG Instrumental Drift at AGGO

By combination of all AG and SG observations, the instrumental drift can be separated from long term geophysical trends in gravity. Raw (uncorrected) gravity data was used to avoid the impact of models used to correct temporal gravity changes which are not always consistent between AG and SG processing. Instrumental Drift was adjusted following the equation:

$$AG_{\{obs\}} + v = b_1[SG_{\{obs\}} + d(t)]$$

where:

- $AG_{\{obs\}}$: raw AG drops;
- v : residuals;
- b_1 : calibration factor;
- $SG_{\{obs\}}$: SG measurement in Volts, corresponding to the AG drop;
- $d(t)$: instrumental drift. Assumed to be linear.

¿ Cual fue el drift instrumental estimado?

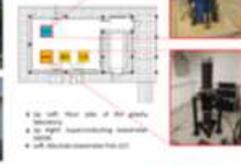
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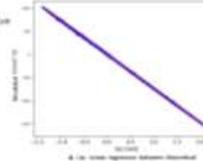
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 - Theoretical tides computed by Tides99 catalogue of IERS (Fesenko, 1997) and synthetic Earth tide parameters (Dobson et al., 1999).
 - Ocean Tide Loading (OTL) effect on gravity now computed using IUGW10 model (Cannon et al., 2010) with parameters provided for the ocean tide loading procedure of M2, J2, and its 10 harmonics (<http://ftp.cea.fr/pub/cesium/otl/otl10.txt>).
 - Atmospheric effects were modelled with a simple air pressure algorithm using a constant value of 2.37 mm/s²/hPa.
 - Tide tides taken into account using IERS C04 series of IERS and a gravimetric factor of 1.5.
 - Mean values of the error (Wziontek et al., 2017).

$$g(t)_{AG} = g(t)_{SGM} + g(t)_{OTL} + g(t)_{ATM} + g(t)_{P} + P + B_0 + B_1 SG_{OTL}$$

- where:
 - $g(t)_{OTL}$: Theoretical tides;
 - $g(t)_{OTL}$: Ocean Tide Loading effect;
 - $g(t)_{ATM}$: atmospheric effect;
 - $g(t)_{P}$: pole tides;
 - $g(t)_{P}$: ocean tides of the sea;
 - P : residual;
 - B_0 : constant that represents the mean value of tides;
 - B_1 : calibration factor;
 - SG_{OTL} : SG measurement in mV, corresponding to the AG drop.



Scale Factor estimation: combination of Absolute and Superconducting gravity observations

Absolute gravity measurements are monthly available since January 2018. These absolute gravity measurements were developed during periods of high tides variability for the Scale Factor determination.

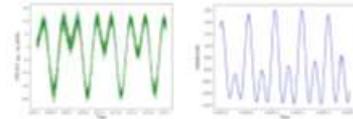
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- August 9, 2018 (14512 individual drops)

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$$\Delta g_{(AG)} + P = B_0 + B_1 SG_{(AG)}$$

- where:
 - $\Delta g_{(AG)}$: raw AG drops;
 - P : residual;
 - B_0 : constant that represents the mean AG value;
 - B_1 : calibration factor;
 - $SG_{(AG)}$: SG measurement in mV, corresponding to the AG drop.

AGGO			
Date	# of Drops	B_1 [mm/s ²]	Std. Dev. [mm/s ²]
May 10, 2018	11760	-715.1	1.7
July 12, 2018	13308	-717.8	1.4
August 9, 2018	14512	-717.8	1.5



- to AGGO AGGO calibration factor, $B_1 = -715.1 \text{ mm/s}^2/\text{mV}$
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TGO		
Mean Scale Factor from all AG observations	B_1 [mm/s ²]	Std. Dev. [mm/s ²]
-716.1	-716.1	1.3

Conclusion: Although the actual Scale Factor differs by about 1.5 ‰, the change is not significant!

First Estimate of the SG Instrumental Drift at AGGO

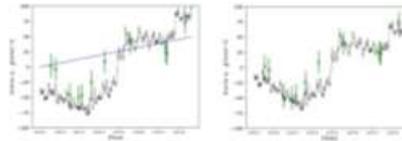
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$$\Delta g_{(AG)} + P = B_1 [SG_{(AG)} + d(t)]$$

- where:
 - $\Delta g_{(AG)}$: raw AG drops;
 - P : residual;
 - B_1 : calibration factor;
 - $SG_{(AG)}$: SG measurement in mV, corresponding to the AG drop;
 - $d(t)$: instrumental drift, assumed to be linear.

The instrumental drift was determined with 7.7 $\mu\text{m/s}^2/\text{year}$. The Scale Factor was simultaneously estimated with $-717.9 \pm 0.4 \text{ mm/s}^2/\text{mV}$.

Conclusion: First estimation of SG Instrumental Drift after eight month of AG data: 7.7 $\mu\text{m/s}^2/\text{year}$.



to AGGO AGGO calibration factor, $B_1 = -717.9 \text{ mm/s}^2/\text{mV}$

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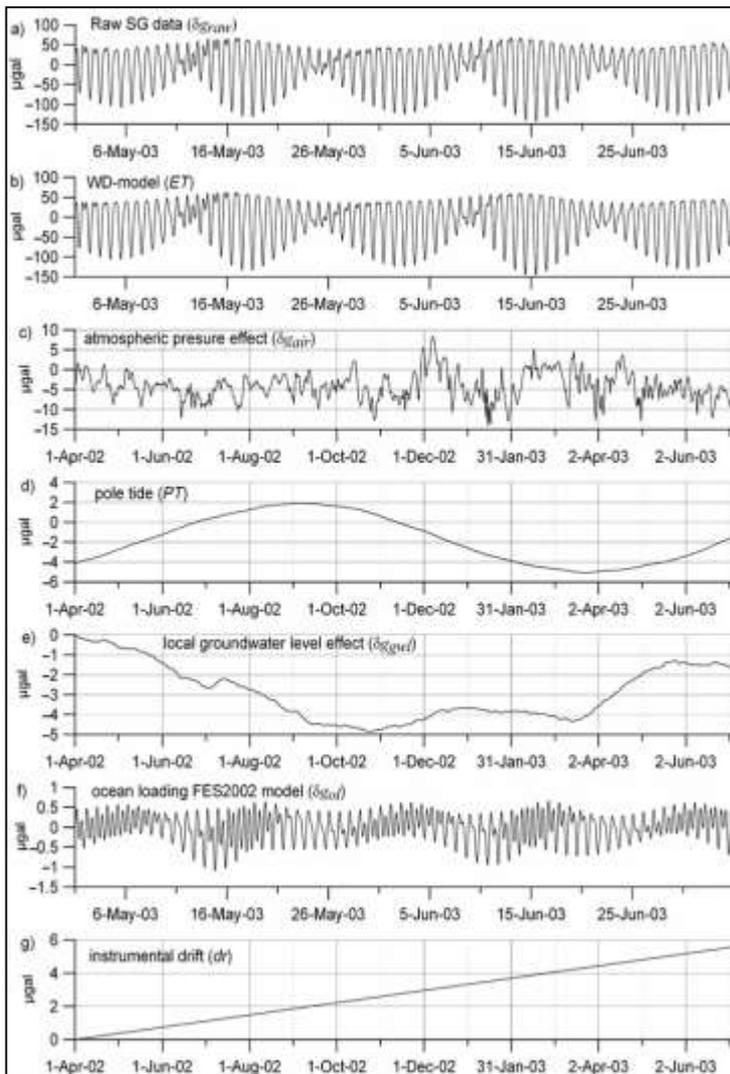
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 Wziontek, H., 2018. The International Gravity Reference Frame (IGRF) and the International Height Reference System (IHRS). *Journal of Geodesy*, 92, 1-10.
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Muchas Gracias!



Señal gravimétrica y sus principales constituyentes (Estación Metsahovi, Finlandia)



- (a) Señal gravimétrica registrada por un SG (δg_{raw}). Amplitud máxima: 213.12 μGal . Incluye:
- (b) efectos del modelo WD de mareas terrestres teóricas (ET); Amplitud máxima: 210.08 μGal .
- (c) efectos debidos a la presión atmosférica (δg_{air}); Amplitud máxima: 22.45 μGal .
- (d) efectos debidos al movimiento del polo (PT) utilizando datos del IERS (δg_{pol}). Amplitud máxima: 4.85 μGal .
- (e) efectos de los niveles de aguas subterráneas local (δg_{gwl}) en las cercanías del SG; Amplitud máxima: 4.85 μGal .
- (f) efectos debidos a la carga oceánica basada en modelo FES2002 (δg_{ol}); Amplitud máxima: 1.94 μGal
- (g) drift instrumental (dr) de 4.2 $\mu\text{Gal/año}$.