Remarks on the Combined Use of Absolute and Superconducting Gravimeters for GGOS and the NA Geoid Project

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GGOS
Global Geodetic Observing System

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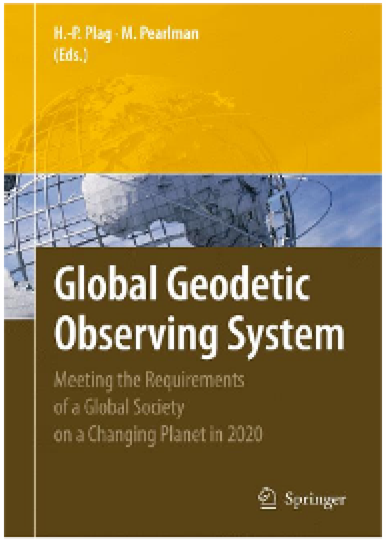

Hans-Peter Plag, University of Nevada, Reno, NV, USA; Michael Pearlman, Harvard Smithsonian Center for Astrophysics, Cambridge, MA, USA (Eds.)

Global Geodetic Observing System

Meeting the Requirements of a Global Society on a Changing Planet in 2020

With the provision of accurate reference frames and observations of changes in the Earth's shape, gravity field and rotation, modern geodesy takes a fundamental role for improved understanding of geodynamics, geohazards, the global water cycle, global change, atmosphere and ocean dynamics, and it supports many societal applications that depend on accurate geo-referencing. To advance geodetic theory, methods and infrastructure for Earth system science and applications, the International Association of Geodesy (IAG) has established the Global Geodetic Observing System (GGOS). This book provides a comprehensive overview of geodesy's contribution to science and society at large, and it identifies user needs and requirements in terms of geodetic observations and products. Specifications for a global geodetic observing system that would meet these requirements lead to considerations of system design and implementation.

Contents: Executive Summary.- 1 Introduction.- 2 The goals, achievements, and tools of modern geodesy.- 3 Understanding a dynamic planet: Earth science requirements for geodesy.- 4 Maintaining a modern society.- 5 Earth observation: Serving the needs of an increasingly global society.- 6 Geodesy: Foundation for exploring the planets, the solar system and beyond.- 7 Integrated scientific and societal user requirements and functional specifications for the GGOS.- 8 The future geodetic reference frame.- 9 The future Global Geodetic Observing System.- 10 Towards GGOS in 2020.- 11 Recommendations.- References.- Acronyms and abbreviations.- Index.

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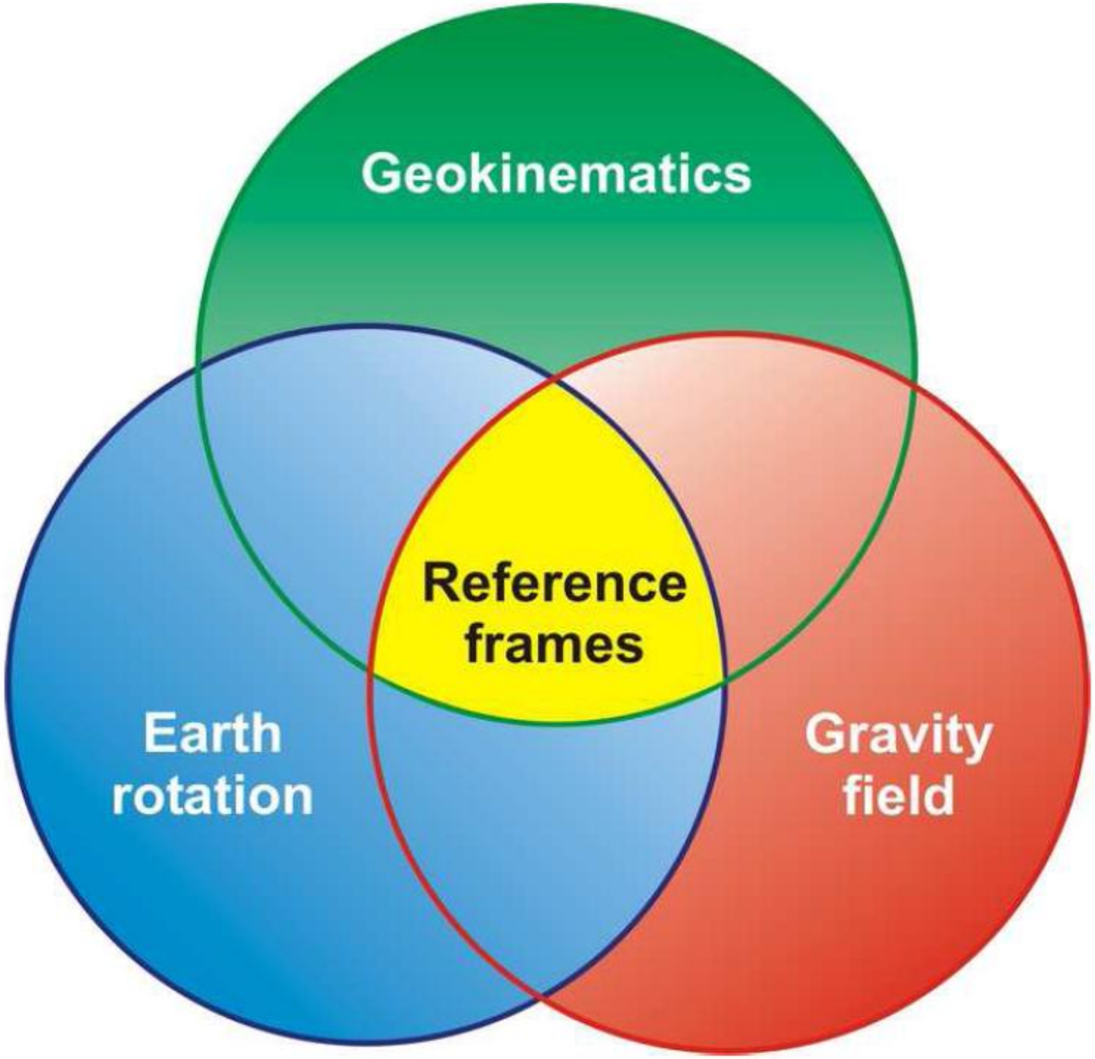


AG
SG

Fig. 1.1. Constituents of an integrated geodetic monitoring system. The “three pillars” of geodesy provide the conceptual and observational basis for the reference frames required for Earth observation. These three pillars are intrinsically linked to each other as they provide different observation related to the same Earth system processes.

“User requirements for geodetic observations and products are demanding:

In order to have a frame at least an order of magnitude more accurate than the signal to be monitored, the terrestrial reference frame should be accurate at a level of 1 mm and be stable at a level of 0.1 mm/yr.

The most demanding applications of the geoid are likely to be the determination of the mean sea surface topography for oceanic general circulation models, and the GNSS determination of the height of surface points at the millimeter level.
These applications require the static geoid to be accurate

at a level of 1 mm and to be stable at a level of 0.1 mm/yr;

consistent with the accuracy and stability of the terrestrial reference frame.

For the time variable geoid, the monitoring of the water cycle at sub-regional to global scales appears to be the most demanding applications requiring the geoid variations to be monitored accurate

to 1 mm, stable to 0.1 mm/yr, with a spatial resolution of 50 km and a time resolution of 10 days.”

What does this mean for Gravity?

Table of Gravity / Height Ratios [after de Linage et al. (2007)]

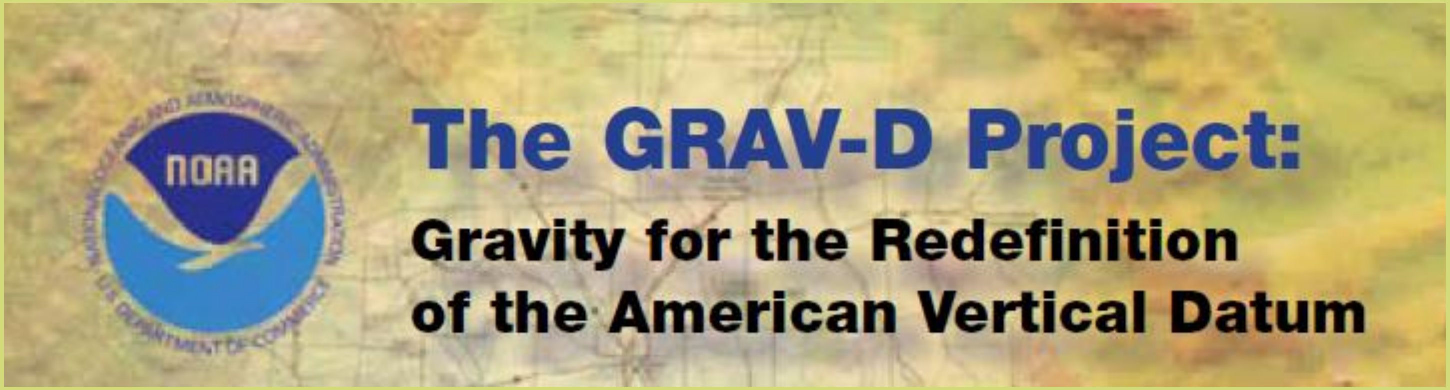
application	**(μGal / mm)**
long wavelength free-air gradient (FAG)	− 0.308
elastic incompressible layer ($\rho = 2500\ \mathrm{kgm}^{-3}$) with attraction + FAG	− 0.203
elastic compressible layer ($\rho = 2500\ \mathrm{kgm}^{-3}$) with attraction + FAG	− 0.235
mean value outside load area, no local attraction; also tidal loading	− 0.26
hydrology loading in basins, depends on area	- 0.74 to - 1.73
atmospheric loading, IB hypothesis, varies with latitude and coastline	+0.30 to +0.47
soil moisture	- 0.28

So for GGOS the static geoid, and the geoid variations, need to be

accurate to 0.3 μGal and stable at a level of 0.03 μGal/yr

with a spatial resolution of 50 km and a time resolution of 10 days

[AG fails all 3, SG fails spatial, and GRACE fails short wavelength spatial+accuracy]



The GRAV-D Project:

Gravity for the Redefinition of the American Vertical Datum

Role of Gravity

Geoid: The equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level.

GRAV-D is a proposal by the National Geodetic Survey to re-define the vertical datum of the US by 2017.

Campaign # 2. A low-resolution "movie" of gravity changes:

- This is primarily a terrestrial campaign and will mostly encompass episodic re-visits of absolute gravity sites, attempting to monitor geographically dependent changes to gravity over time

- This will allow time-dependent geoid modeling and thus time dependent orthometric height monitoring through GNSS technology.

Conterminus US data points

It will be necessary to have a broad coverage of points well spaced, but with essential locales covered.

For example, in order to model known height changes, there must be points near the Great Lakes, Southern California, and Louisiana.

Additionally, NGS has a long historical re-survey record in Arizona and should make use of that site.

Finally, NGS has been running a superconducting gravimeter at Table Mountain Gravity Observatory in Boulder, Colorado for many years.

Such a site represents excellent gravity velocity tracking which should be calibrated relative to repeated absolute gravity measurements episodically.

Nonetheless, the exact number and location of all other sites remains open for exact mission planning sessions.

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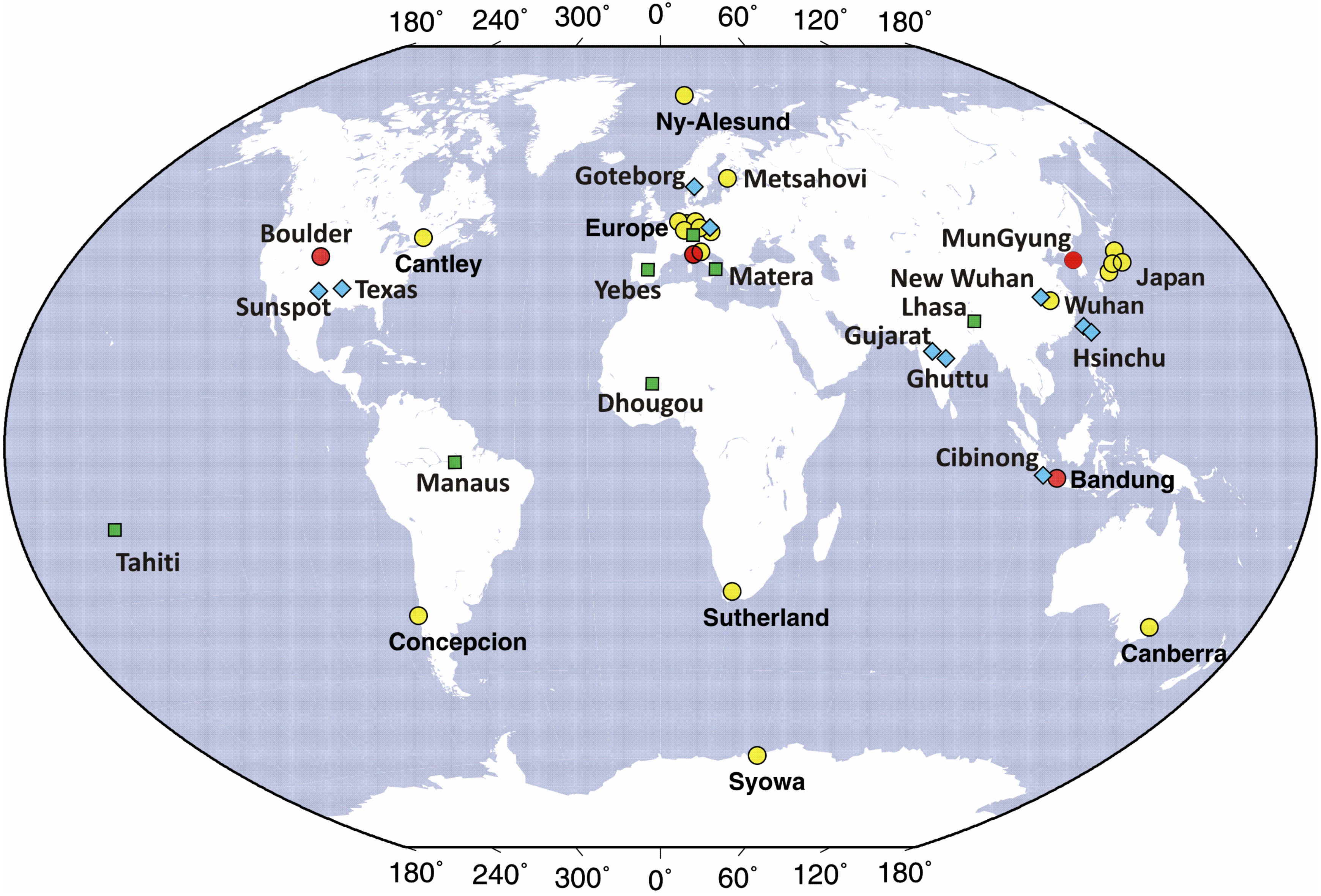
GGP
Global Geodynamics Project

Superconducting Gravimeters

GGP Stations - Past 🔴 Current 🟡 Recent 🔷 and Planned 🟩



Two Recently Installed US SG Sites

1. Sunspot Lunar Laser Ranging Facility

Apache Point Observatory, New Mexico

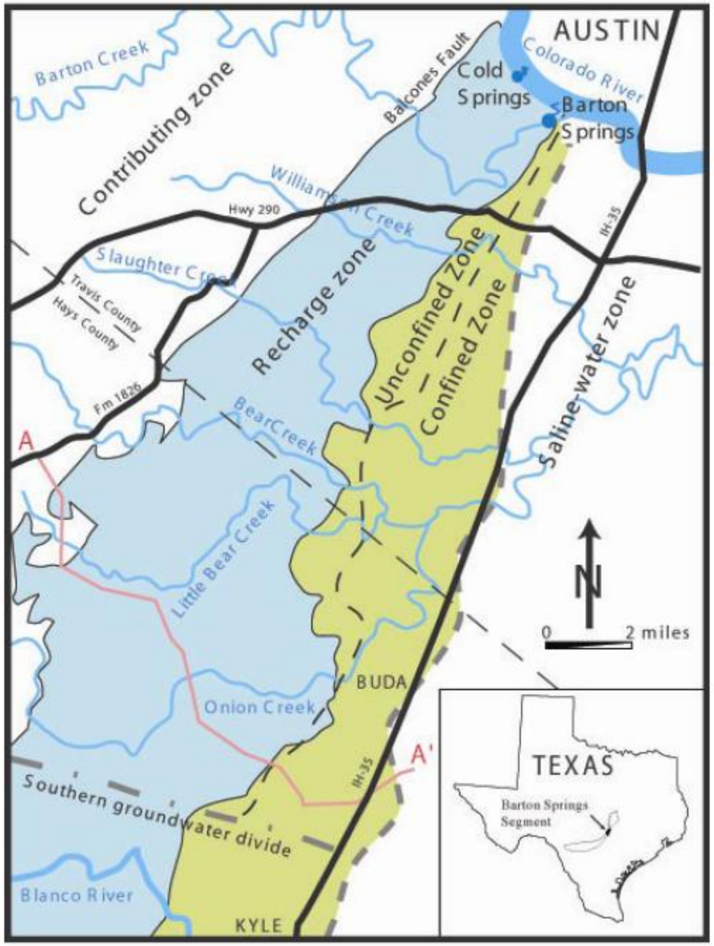
The gravimeter is located in the large dome at lower right. It is situated on a massive (15-foot-square) concrete pier that goes deep into bedrock and is isolated from the building. Low noise when the earth is quiet. We do see gravity signals from the moving dome, but the dome position is logged and removable.

Tom Murphy, UC San Diego

2. Texas Aquifer Monitoring Project

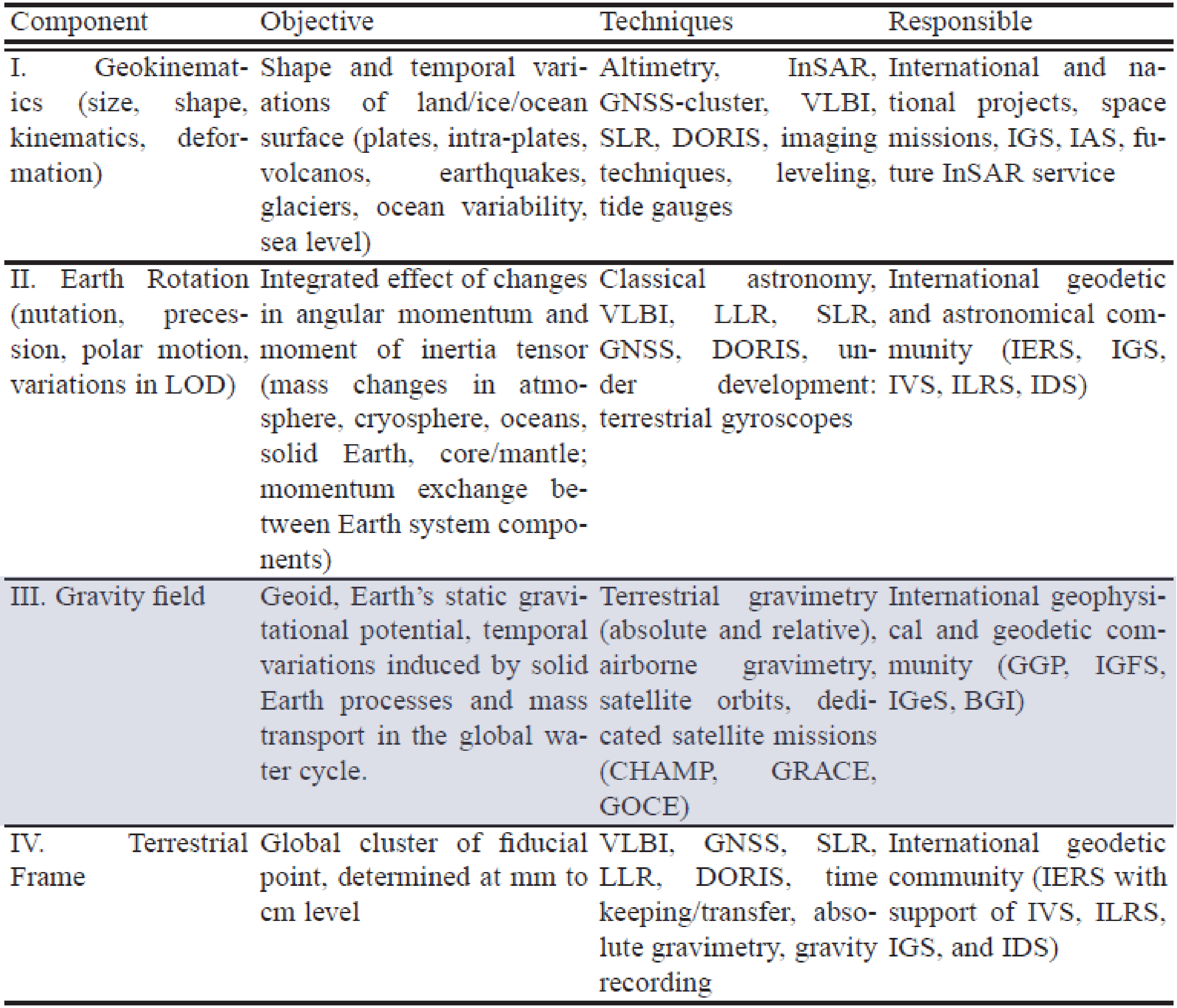
-initially Barton Springs portion of Edwards karst aquifer, Central Texas

C. Wilson, U. Texas Austin



The gravimeter enclosure contains a standard SG, with rack mounted instruments. Transport requires locking the gravimeter dewar to the frame with brackets, and lifting off the gravimeter pillars. Relocations is accomplished with the proof mass suspended.

Table 2.1. The Global Geodetic Observing System (GGOS). For acronyms, see the list in Appendix 11.



Component	Objective	Techniques	Responsible
I. Geokinematics (size, shape, kinematics, deformation)	Shape and temporal variations of land/ice/ocean surface (plates, intra-plates, volcanos, earthquakes, glaciers, ocean variability, sea level)	Altimetry, InSAR, GNSS-cluster, VLBI, SLR, DORIS, imaging techniques, leveling, tide gauges	International and national projects, space missions, IGS, IAS, future InSAR service
II. Earth Rotation (nutation, precession, polar motion, variations in LOD)	Integrated effect of changes in angular momentum and moment of inertia tensor (mass changes in atmosphere, cryosphere, oceans, solid Earth, core/mantle; momentum exchange between Earth system components)	Classical astronomy, VLBI, LLR, SLR, GNSS, DORIS, under development: terrestrial gyroscopes	International geodetic and astronomical community (IERS, IGS, IVS, ILRS, IDS)
III. Gravity field	Geoid, Earth's static gravitational potential, temporal variations induced by solid Earth processes and mass transport in the global water cycle.	Terrestrial gravimetry (absolute and relative), airborne gravimetry, satellite orbits, dedicated satellite missions (CHAMP, GRACE, GOCE)	International geophysical and geodetic community (GGP, IGFS, IGeS, BGI)
IV. Terrestrial Frame	Global cluster of fiducial point, determined at mm to cm level	VLBI, GNSS, SLR, LLR, DORIS, time keeping/transfer, absolute gravimetry, gravity recording	International geodetic community (IERS with support of IVS, ILRS, IGS, and IDS)

GGOS 2020 - Plag et al. (2009)

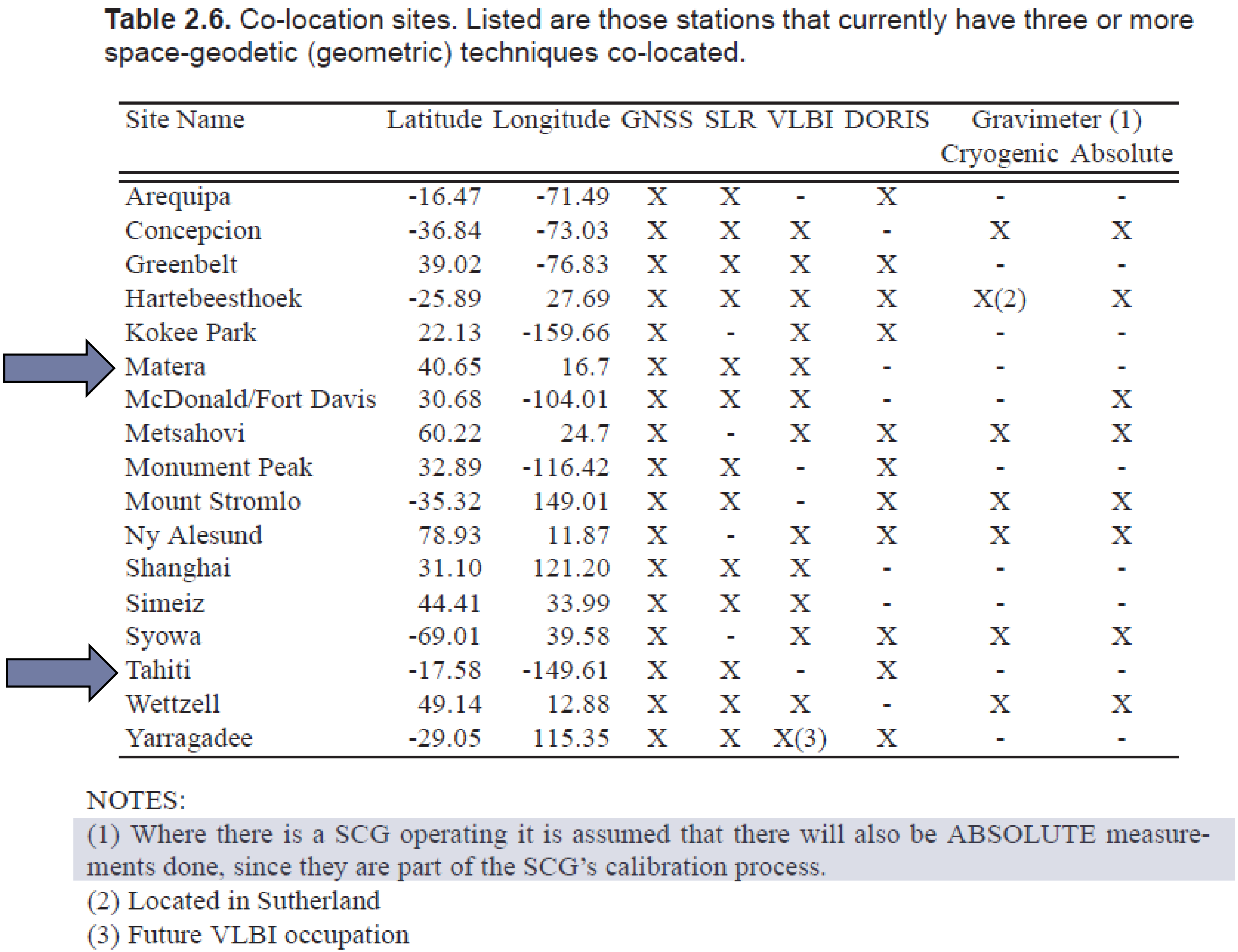


Table 2.6. Co-location sites. Listed are those stations that currently have three or more space-geodetic (geometric) techniques co-located.

Site Name	Latitude	Longitude	GNSS	SLR	VLBI	DORIS	Gravimeter (1)	
							Cryogenic	Absolute
Arequipa	-16.47	-71.49	X	X	-	X	-	-
Concepcion	-36.84	-73.03	X	X	X	-	X	X
Greenbelt	39.02	-76.83	X	X	X	X	-	-
Hartebeesthoek	-25.89	27.69	X	X	X	X	X(2)	X
Kokee Park	22.13	-159.66	X	-	X	X	-	-
Matera	40.65	16.7	X	X	X	-	-	-
McDonald/Fort Davis	30.68	-104.01	X	X	X	-	-	X
Metsahovi	60.22	24.7	X	-	X	X	X	X
Monument Peak	32.89	-116.42	X	X	-	X	-	-
Mount Stromlo	-35.32	149.01	X	X	-	X	X	X
Ny Alesund	78.93	11.87	X	-	X	X	X	X
Shanghai	31.10	121.20	X	X	X	-	-	-
Simeiz	44.41	33.99	X	X	X	-	-	-
Syowa	-69.01	39.58	X	-	X	X	X	X
Tahiti	-17.58	-149.61	X	X	-	X	-	-
Wettzell	49.14	12.88	X	X	X	-	X	X
Yarragadee	-29.05	115.35	X	X	X(3)	X	-	-

NOTES:

(1) Where there is a SCG operating it is assumed that there will also be ABSOLUTE measurements done, since they are part of the SCG's calibration process.

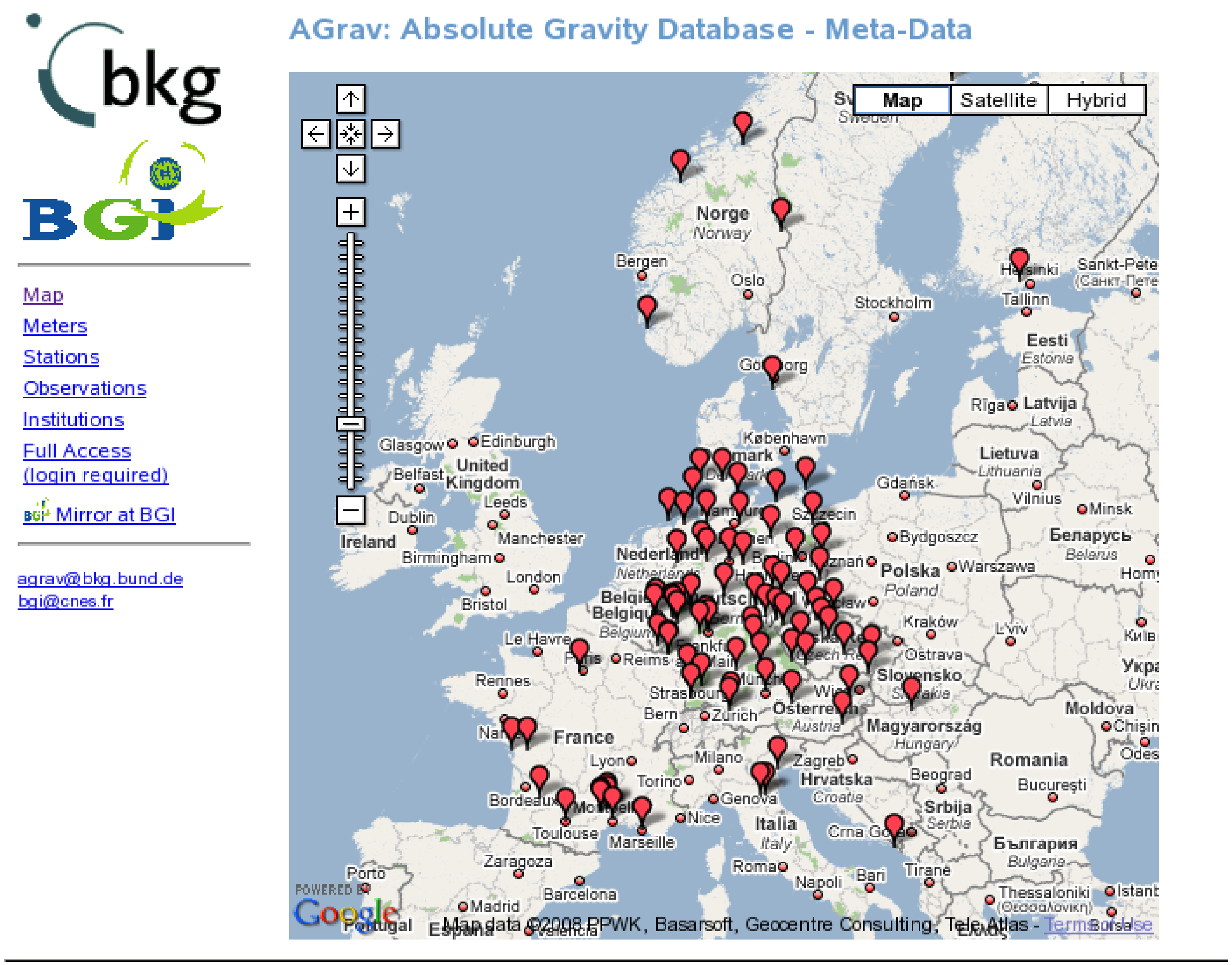
(2) Located in Sutherland

(3) Future VLBI occupation

GGOS 2020 - Plag et al. (2009)

AGrav – the New International Absolute Gravity Database of BGI and BKG and its Benefit for the Global Geodynamics Project (GGP)

H. Wilmes, H. Wziontek, R. Falk, S. Bonvalot



AGrav: Absolute Gravity Database - Meta-Data

agrav@bkg.bund.de
bgi@cnes.fr

SG – AG Comparisons

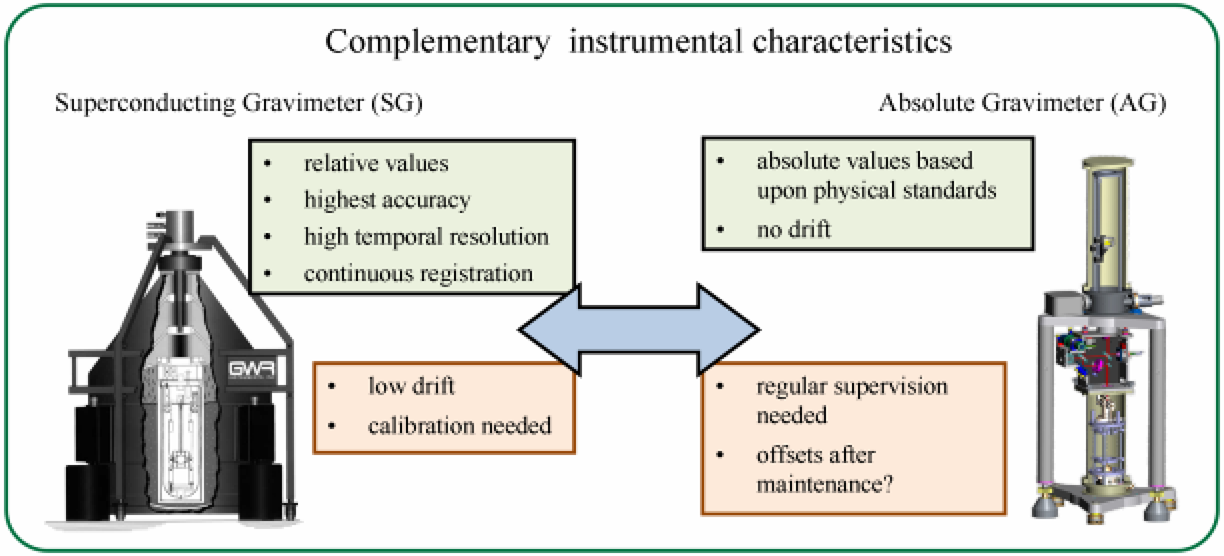


Table 1. Comparison of Gravity Instruments (1 μGal = 10^{-9} g).

	Absolute Gravimeter AG (Transportable type, e.g. Micro-g Solutions Inc. FG5)	Relative Superconducting Gravimeter (Observatory and Transportable type: GWR)	Relative Spring Gravimeter (Field type: Scintrex CG-3M)
Precision	μGal	0.0001 μGal	3 μGal
Accuracy	1-3 μGal	0.1 μGal	3~10 μGal
Drift	0 (by definition)	1-5 μGal / yr	~400 μGal / day
Stabilization Time	1 hr (setup only)	days to weeks or longer	10 min (setup only)
Operation	Usually 1-3 days of continuous operation per measurement location, maximum period 2 weeks	Continuous unlimited measurement, with 2 x per year AG monitoring and calibration	Continuous unlimited measurement, with repeated ties every few hours to a reference site
Accuracy limited by	microseismic noise	environmental effects	instrument drift, elevation, environmental effects, calibration changes

Mythconception

- The AG is limited to long periods, whereas the SG is limited to short periods

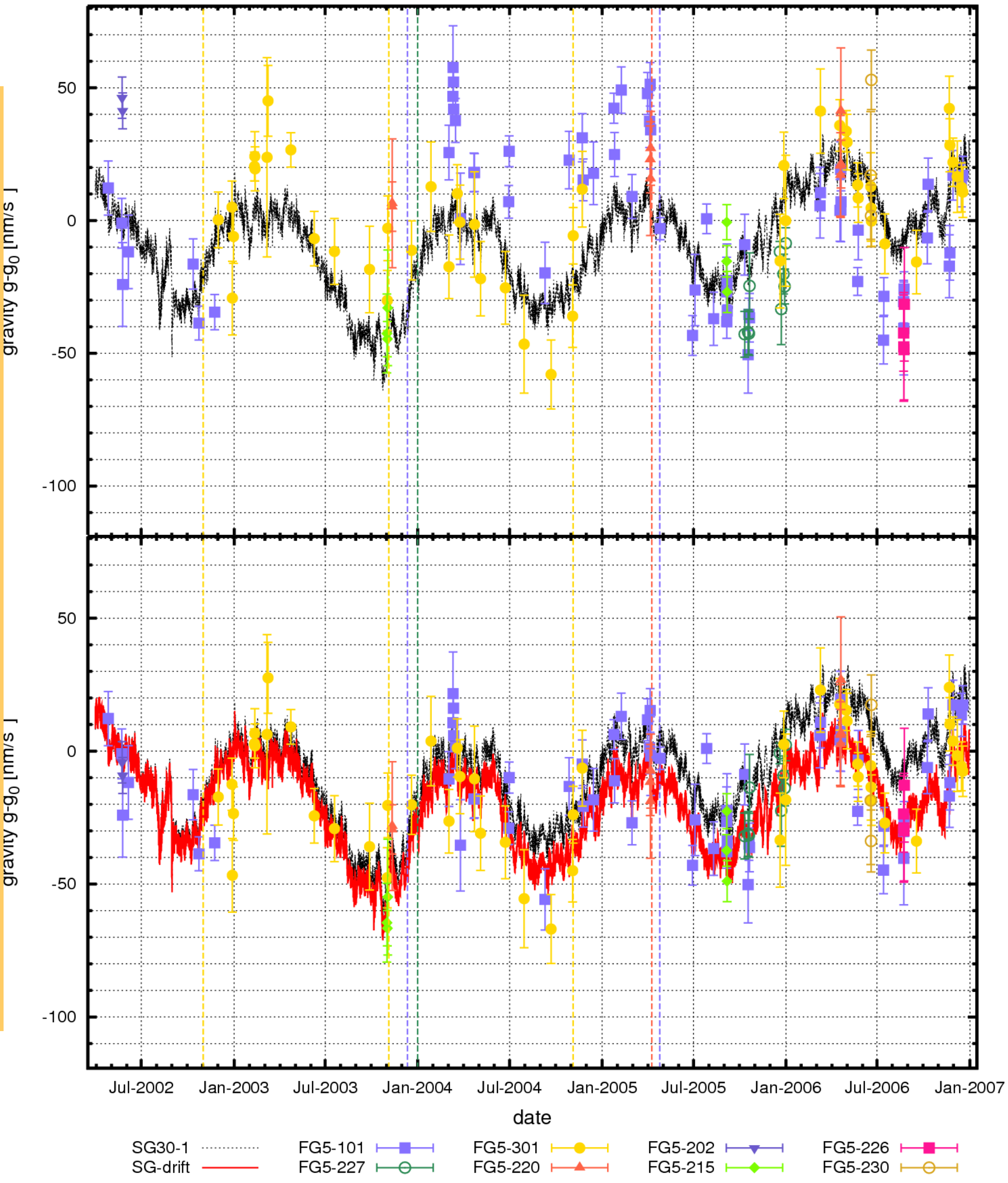
Not true – the division is not primarily about sampling rate, but about capabilities.

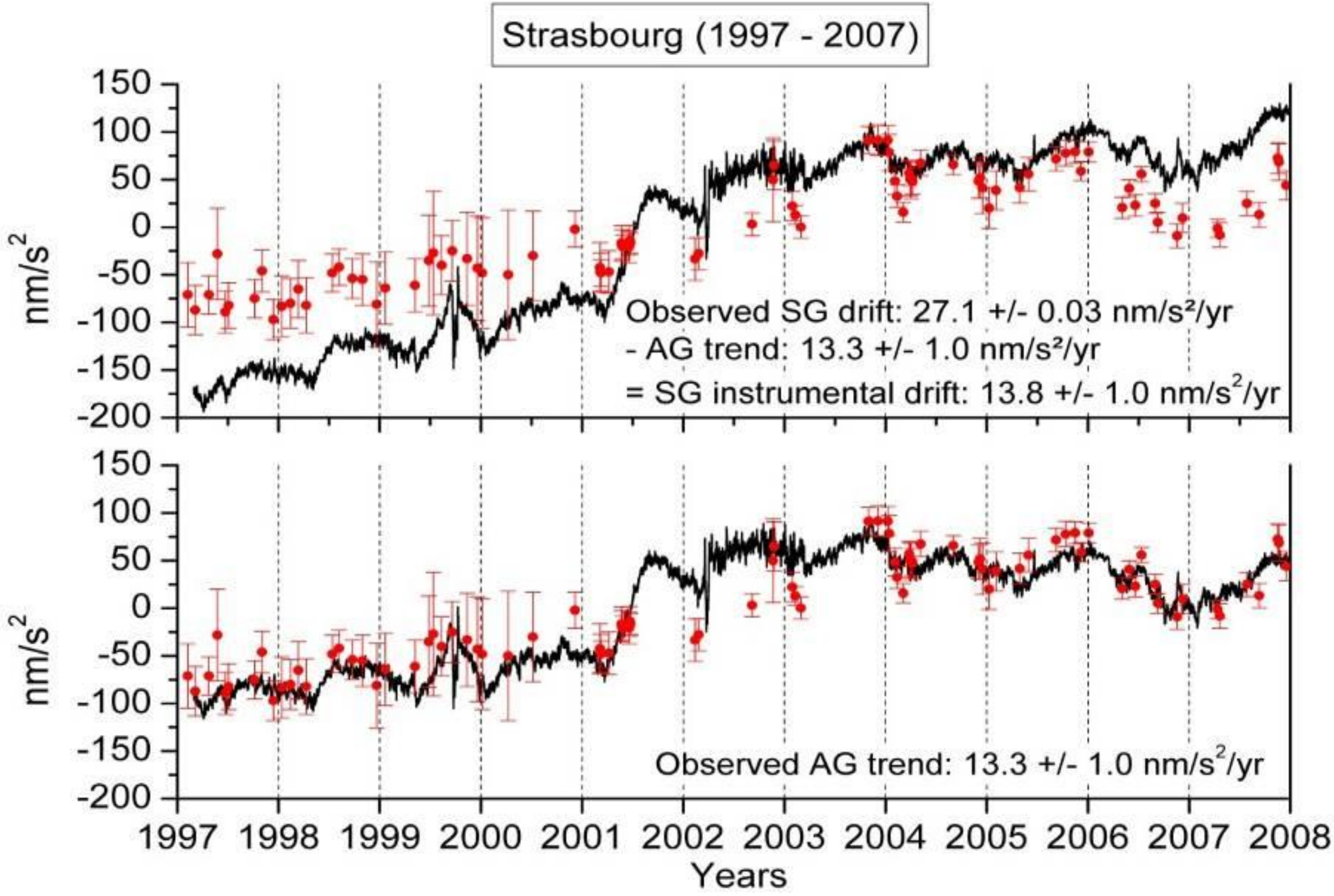
Combination of AG and SG observations at the station Bad Homburg (Germany);

upper graph: SG-30 residual gravity function (black) and AG measurement results of 8 AG, symbols in selected colours;

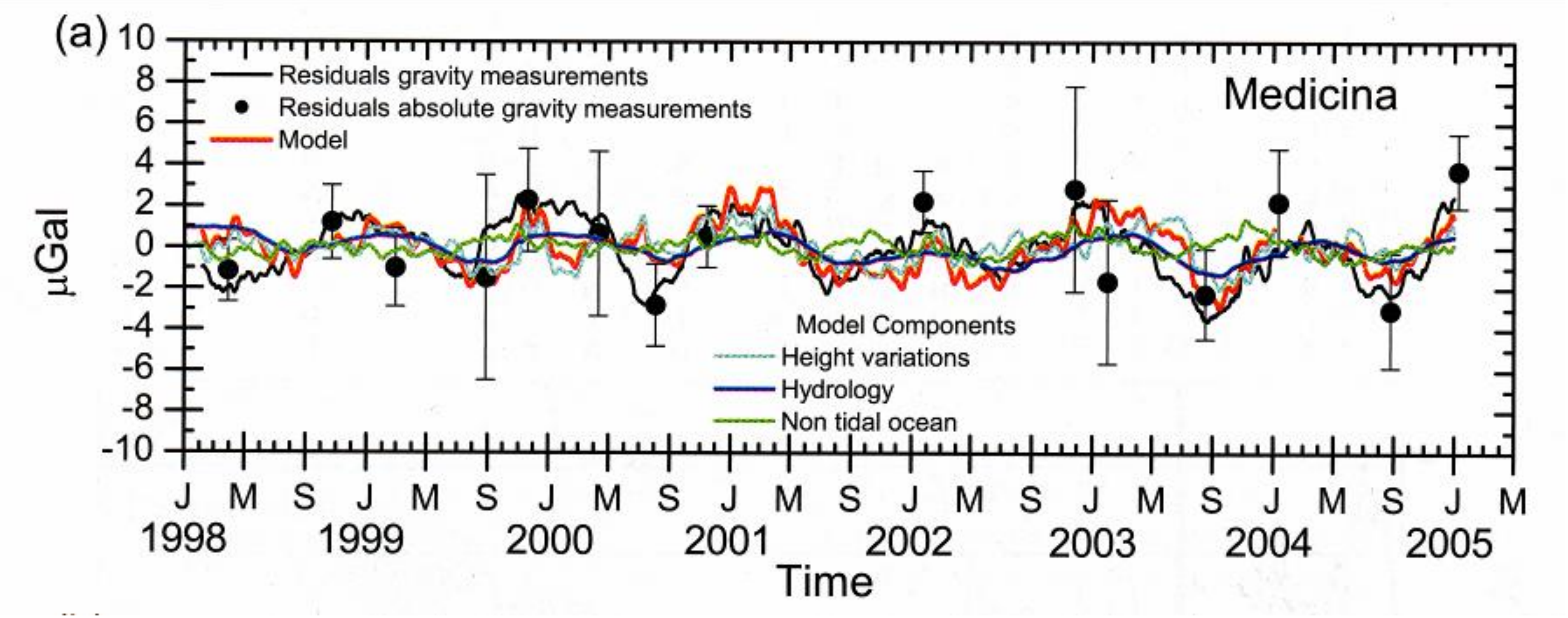
lower graph: SG and AG observations prior (black/upper curve) and after combination (red/lower curve);

AG measurement results show smaller residuals after offset determination for the individual AG [after Wilmes et al. (2009)].



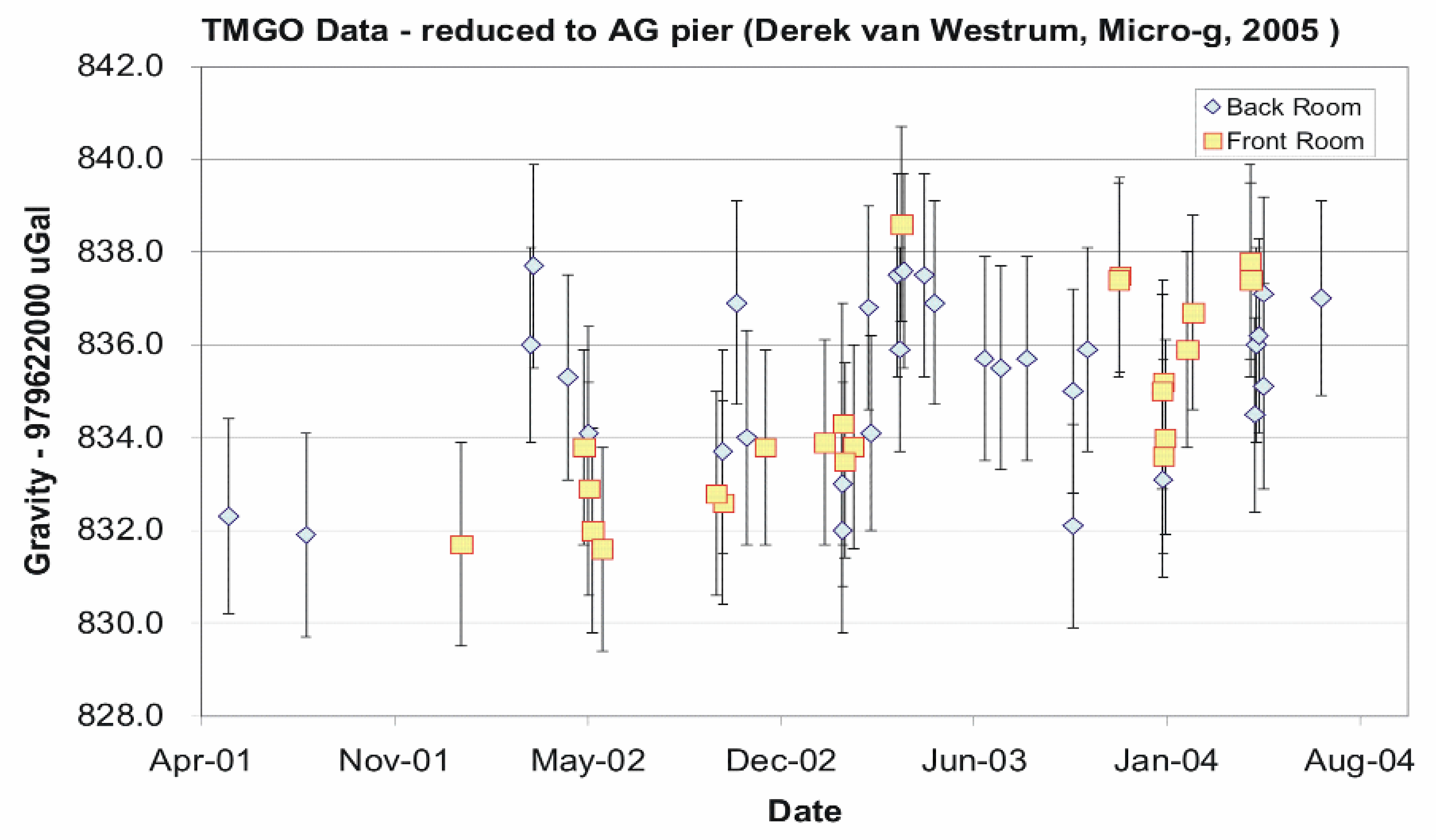


Superposition of AG FG5#206 measurements and SG GWR-C026. The upper plot represents the SG time-varying gravity without correction of the SG instrumental drift and the lower plot represents the superposition after removing the instrumental part from the SG trend. [after Rosat et al., 2009)].

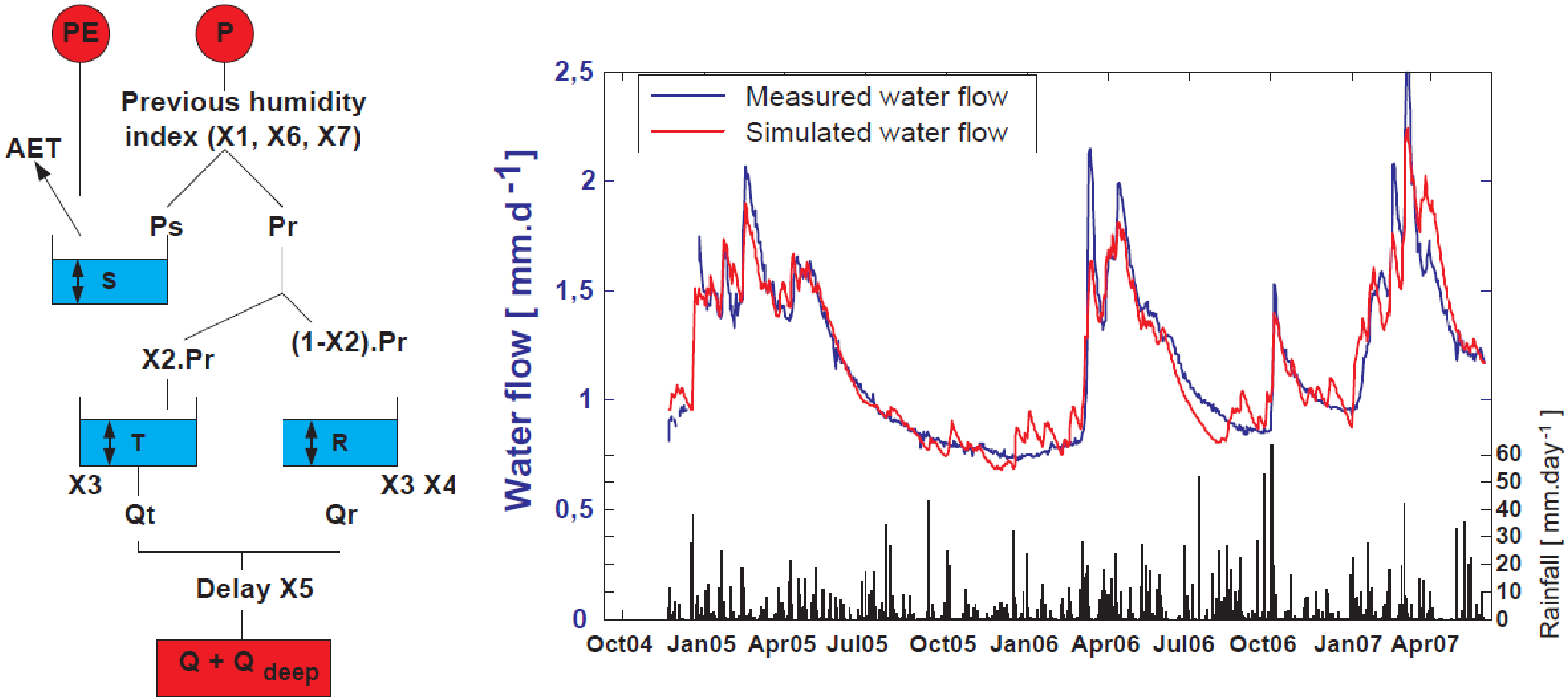


Comprehensive model of SG, AG, CGPS. and hydrology data from the Medicina fiducial station (which includes VLBI). Note the good agreement between AG and SG, but occasional disparities with the model [after Zerbini et al. (2007)].

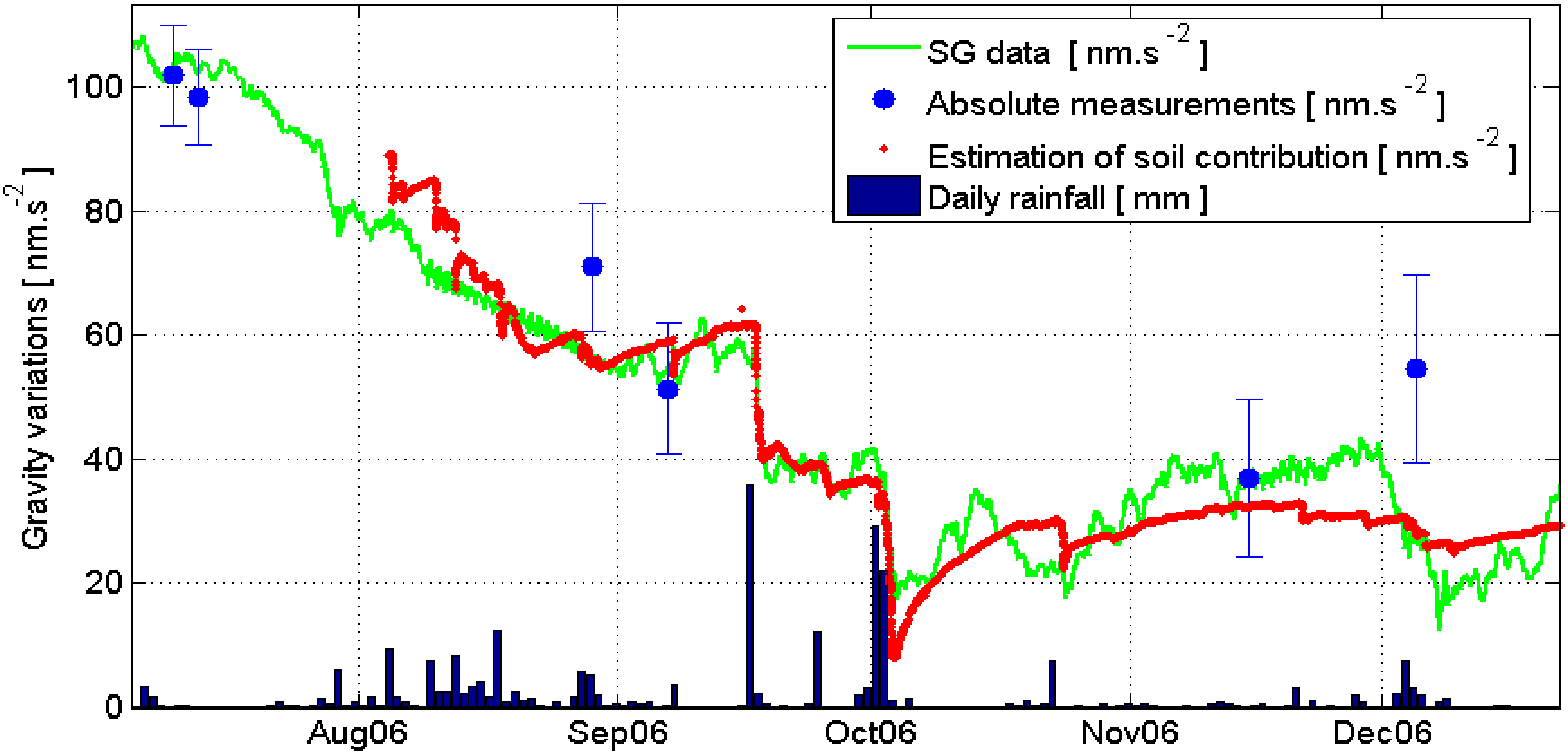
AG, SG, and Hydrology



TMGO Data - reduced to AG pier (Derek van Westrum, Micro-g, 2005)

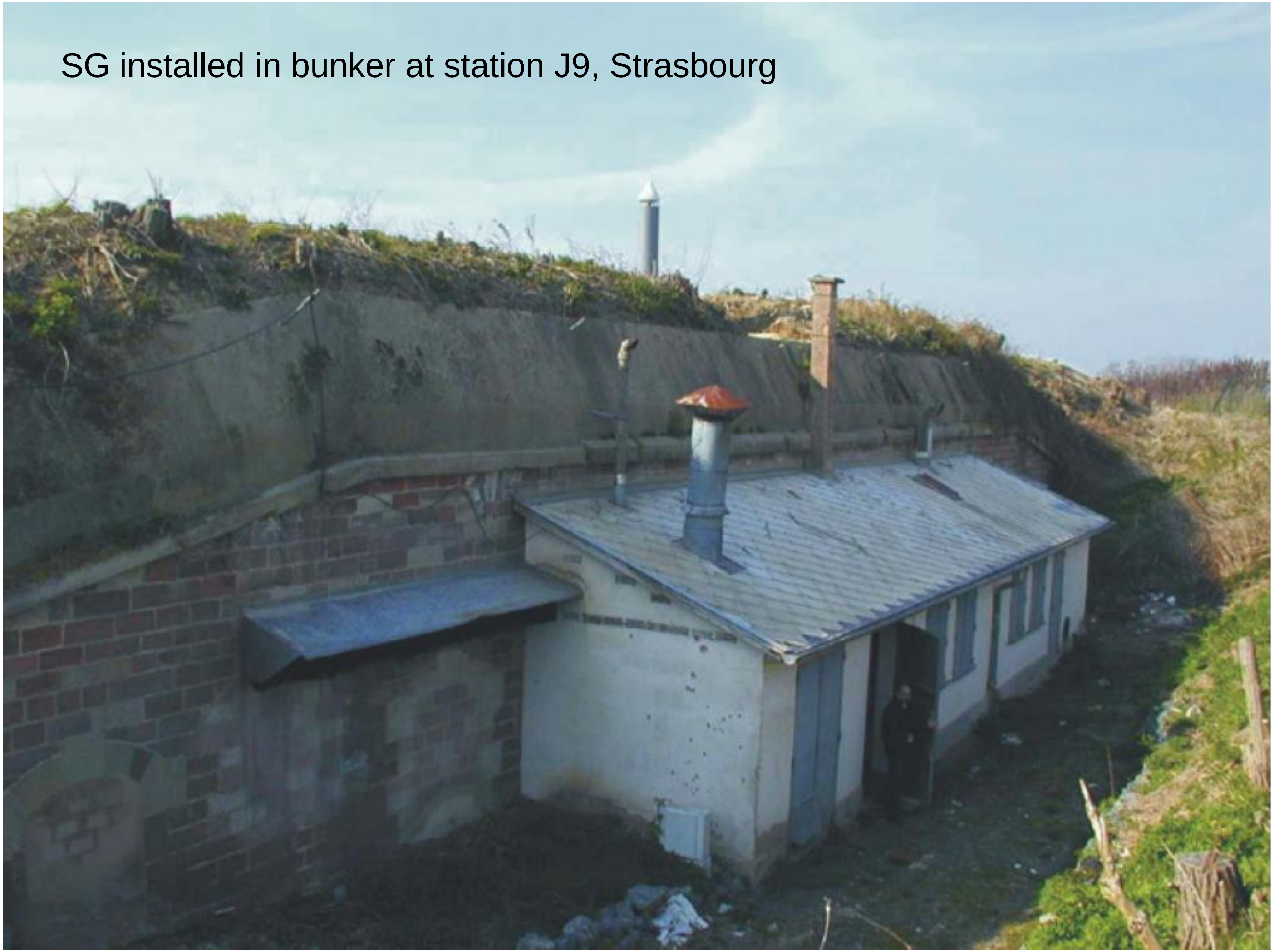


Modified IHAC lumped model based on 7 parameters (X1-X7). In red, forcing data, *PE*, *P*, *Q* and *Qdeep* are potential evapotranspiration, precipitation, runoff out of the mine and deep runoff respectively. In blue, S, T, R correspond to modeled water-height in the 3 reservoirs, respectively soil, quick and slow storage. R store level variations are used to estimate water height variations [after Longuevergne, 2008)].



Comparison of SG and AG measurements with rainfall and soil moisture for the Strasbourg site J9. Because the gravimeter is under the soil moisture horizon, gravity decreases with rainfall [after Longuevergne (2008)].

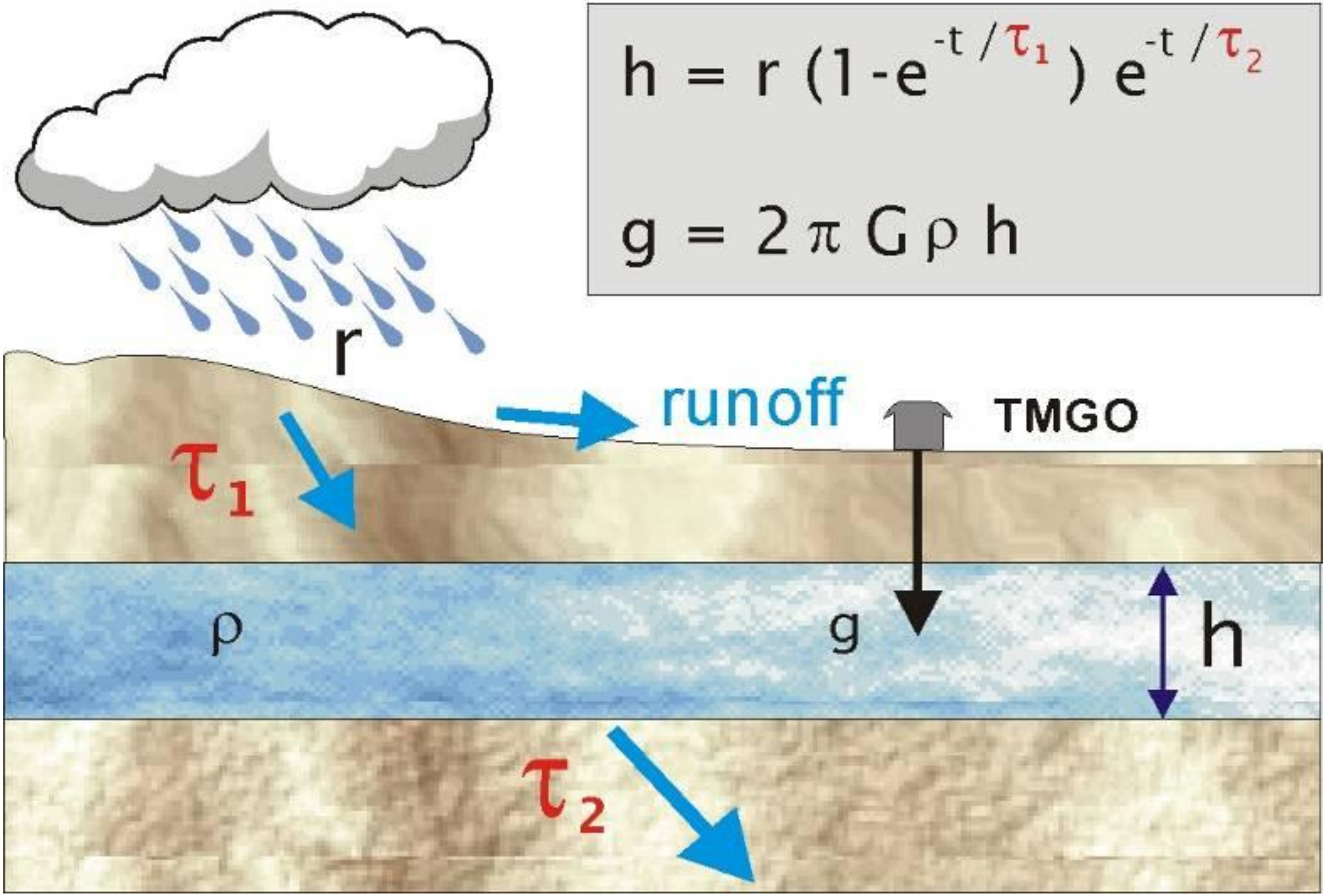
SG installed in bunker at station J9, Strasbourg



Spring Rains in Boulder, 1995

$$h = r\,(1-e^{-t/\tau_1})\,e^{-t/\tau_2}$$

$$g = 2\pi G \rho h$$



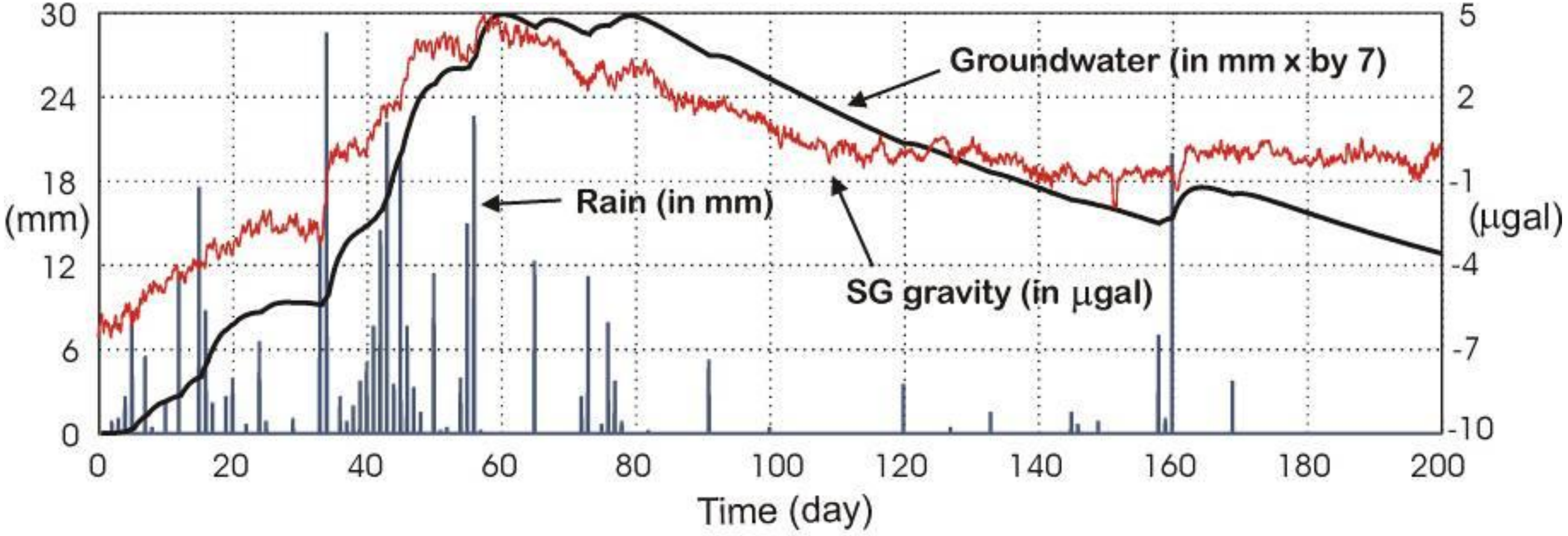
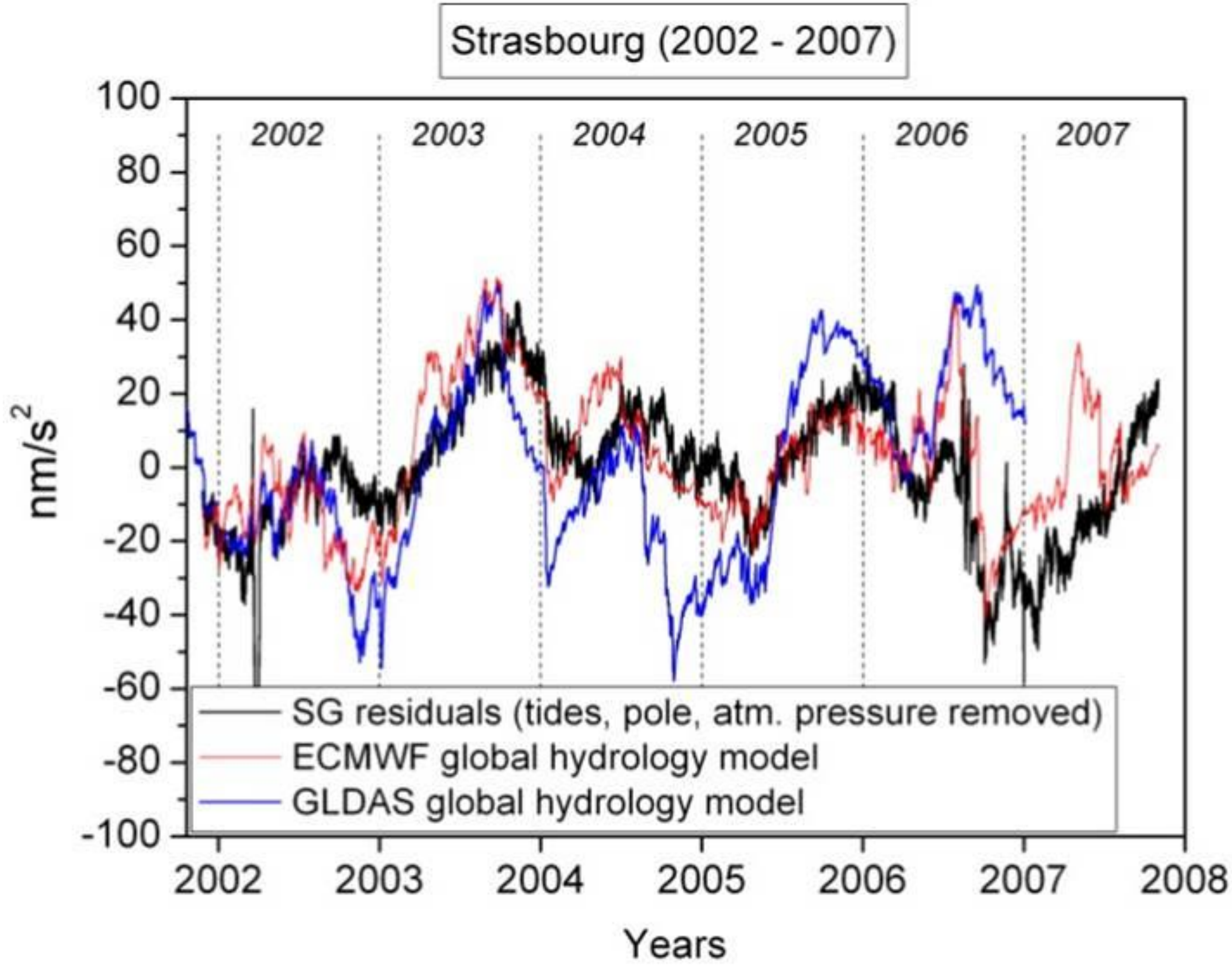
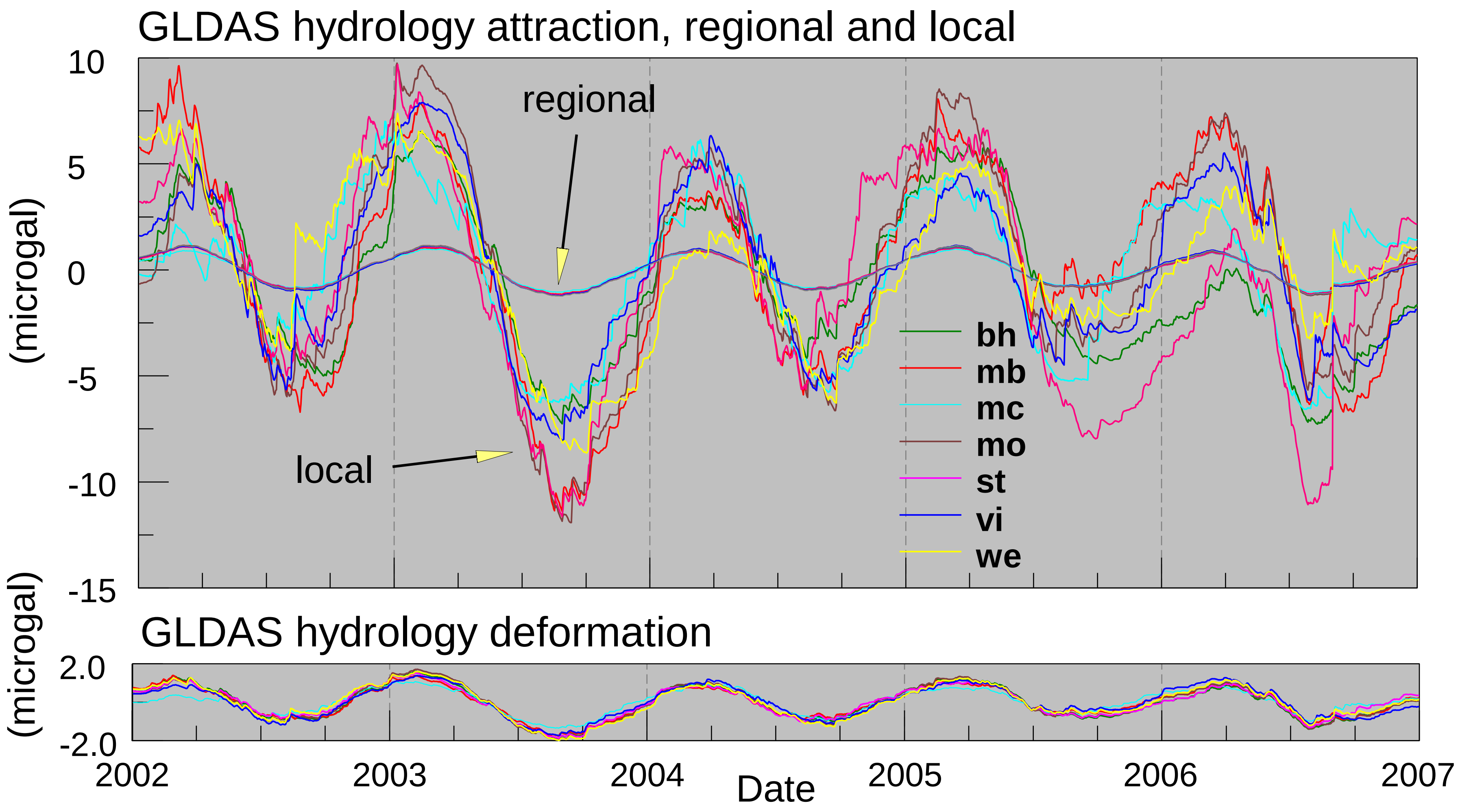


Figure 2. Gravity Variations Due to Rainfall, Boulder TMGO

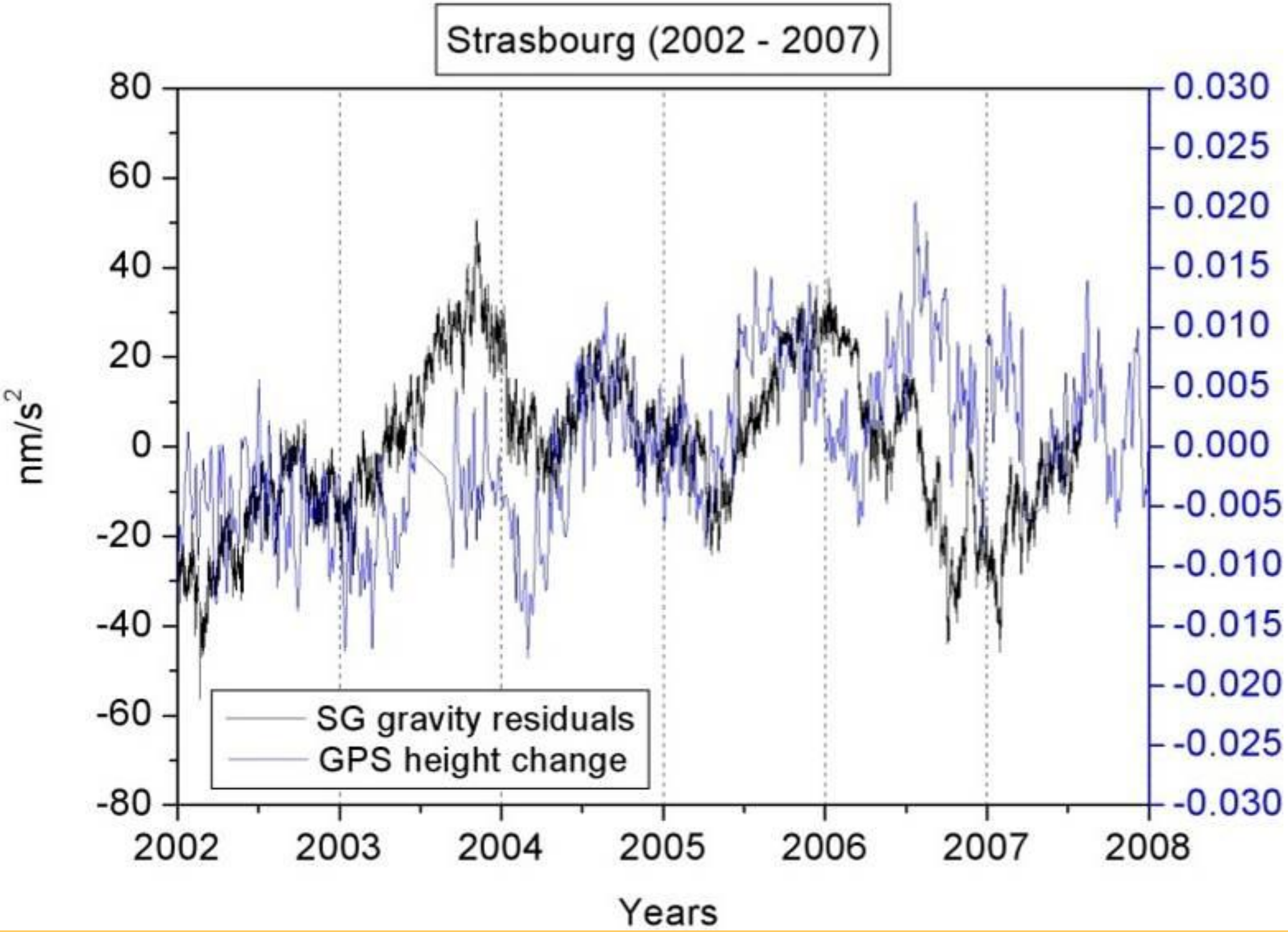
Using the first 200 days of data (where the correlation is strongest), we find that τ_1 = 4 hrs, the recharge time constant, and τ_2 = 91 days, the discharge time constant. The groundwater/gravity admittance from the first 200 days gives 0.0414 μgal / mm; for the whole record it is 0.00925 μgal mm−1. The value calculated for the Bouguer slab is 0.0419 μgal / mm.



SG gravity residuals and global hydrology effects at Strasbourg. In blue is the continental water content effect using GLDAS global model and in red using the ECMWF model of soil moisture and snow [after Rosat et al., 2009)].


GLDAS hydrology attraction, regional and local
(microgal)
10
5
0
-5
-10
-15
regional
local
bh
mb
mc
mo
st
vi
we
GLDAS hydrology deformation
(microgal)
2.0
-2.0
2002
2003
2004
2005
2006
2007
Date

SG and GPS



SG gravity residuals (in black) and GPS height changes (in blue) observed at Strasbourg, J9 site from 2002 to late 2007. Note the positive correlation between both signals due to the fact that the local hydrological masses dominate and are located above the SG [after Rosat et al. (2009)]. (Conversion = -0.267 µGal / mm)

Main Points

1. A stable reference system for gravity ideally requires combined AG and SG instruments

1. AG’s alone are good to 1-2 μGal, but subject to
    (a) unknown offsets
    (b) time-dependent hydrology (may or may not be known)

3. SG’s can accurately determine time-dependent hydrology, but require periodic measurements with AGs

4. Fiducial stations, as conceived by T. Flinn* in the 1970’s will form a set of core stations with collocated (space geodetic + AG + SG + …) instruments for GGOS and perhaps a subset of the reference stations for GRAV-D.

*Fiducial Laboratory for an International Natural Science Network (FLINN) was part of NASA’s crustal dynamics project in the late 1980’s.

What is the site importance: $N or $2N?

1. Start with AG measurements
   a) install hydrological instrumentation (rainfall, groundwater, soil moisture, …)
   b) generate hydrological model
   c) validation of hydrological model → buy SG

2. Start with SG measurements
   a) buy (borrow, or share) AG for calibration and drift estimates
   b) install hydrological instrumentation (rainfall, groundwater, soil moisture, …)
   c) generate hydrological model
   d) validation of hydrological model with SG