The contribution of 25 Years of GGP operation to gravimetric measurements

David Crossley

St. Louis University

Department of Earth and Atmospheric Sciences

GGP = Global Geodynamics Project

Anniversaries are getting much longer!

What	Who	When
Plate tectonics	Ewing (1953), Runcorn (1956), Hess (1962), Vine-Matthews-Morley (1963), Wilson (1963)	60 yr
Dynamo theory	Bullard & Gellman (1954), Elsasser (1956)	60
Free oscillations	Alterman-Jarosch-Pekeris (1959) Chile (1960)	55
Deep sea vessels	Alvin first Dive 1964	50
SGs	Prothero-Goodkind (1972), Warburton et al. (1975-78)	40
PREM	Dziewonski-Anderson (1981)	33
GGP	Smylie, Rochester, Merriam, Aldridge, (Canada 1989)	25

Life with GGP

started in late 1980's:

1987 At the IUGG General Assembly in Vancouver several connections were made (e.g. Hinderer-Crossley)

•1988 Tuzo Wilson suggested Canadian geoscientists should get together to add knowledge of the deep interior to bear on the problems of plate tectonics

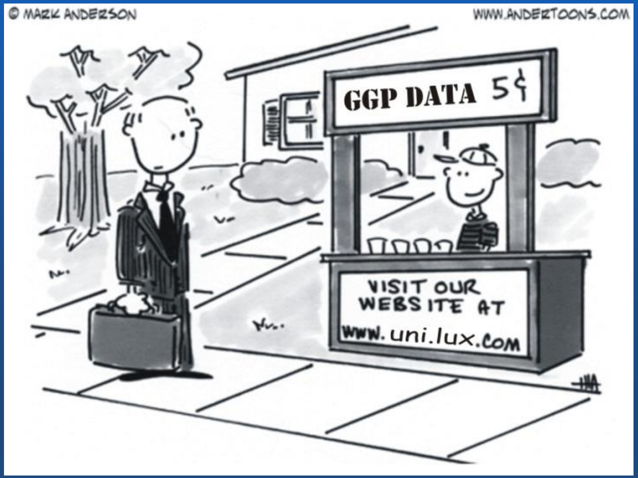
•1988 SEDI meeting Blanes, Spain. Some Canadian theoreticians thought that the core spectrum could be determined by recording internal gravity waves using SGs.

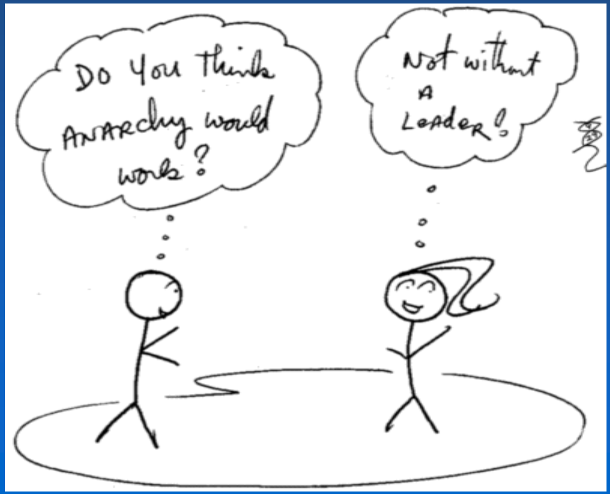
•1989 The crazy Canucks (who were not experimentalists) bought and installed an SG at Cantley, Quebec – but had no idea about SGs

•1990 First international letter went out inviting participation in GGP

Life without GGP?

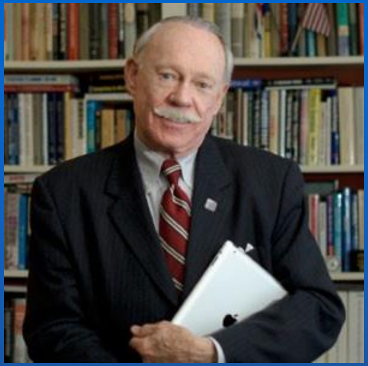
… could have been otherwise…





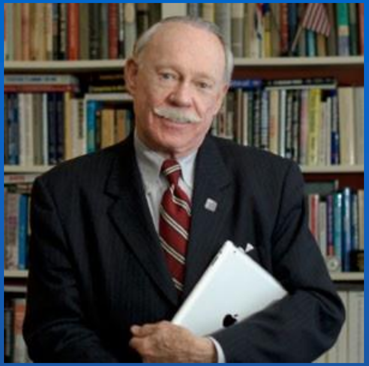
The 6 phases of a project

Ephraim McLean
(1972)



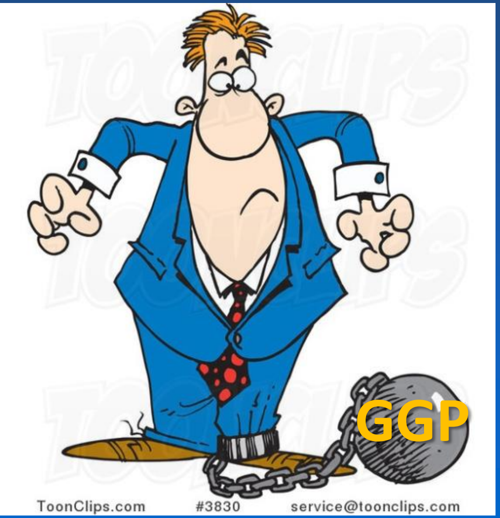
1. **Wild uncritical enthusiasm** (when the project is launched)
2. **Disillusionment** (as goals are perceived as unattainable)
3. **Panic, hysteria, confusion** (as project gets underway)
4. **Disaster and search for the guilty** (when things go wrong)
5. **Punishment of the innocent** (for leading the project)
6. **Praise and rewards for the non-participants** (“I told you so”)

The 6 phases of a project

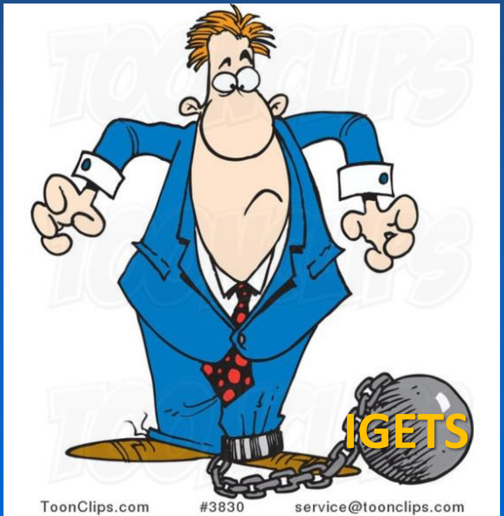


Ephraim McLean (1972)

1. **Wild uncritical enthusiasm** (when the project is launched)
2. **Disillusionment** (as goals are perceived as unattainable)
3. **Panic, hysteria, confusion** (as project gets underway)
4. **Disaster and search for the guilty** (when things go wrong)
5. **Punishment of the innocent** (for leading the project)
6. **Praise and rewards for the non-participants** ("I told you so")



But they don't tell you about the effect of long-term projects on your scientific career …. (pay attention JPB)

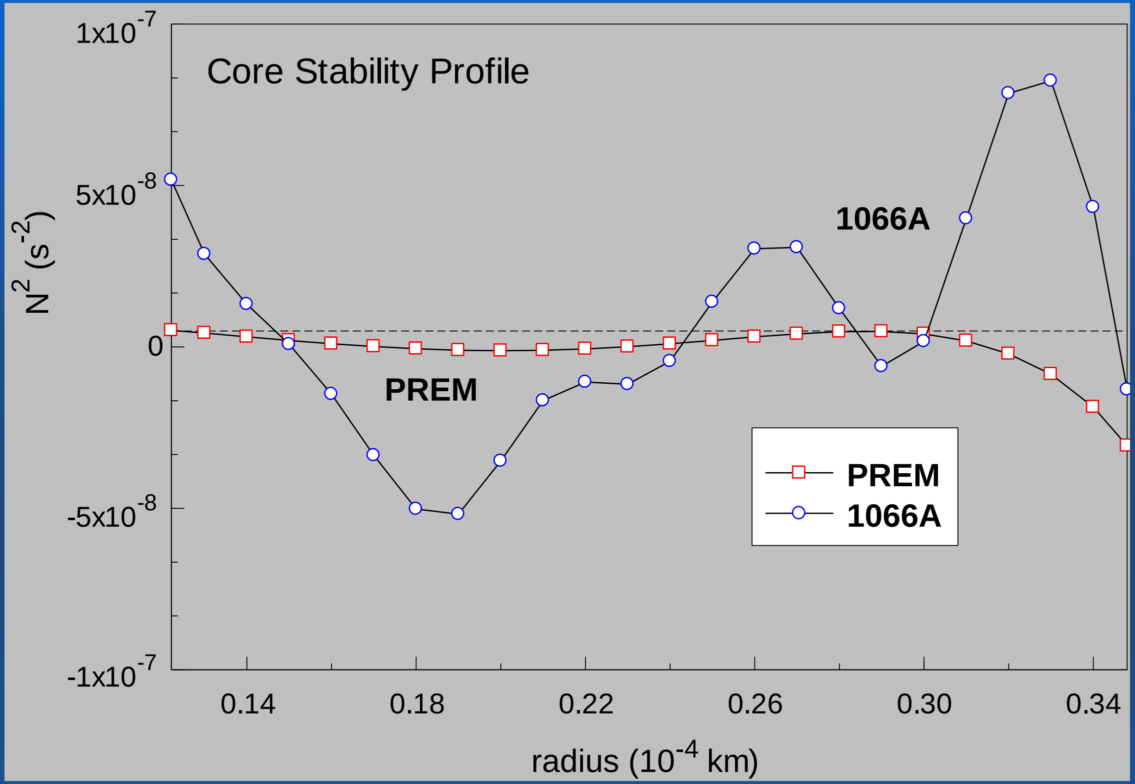


GGP early environment – Canada 1985-90

some theoreticians wanted to look for core modes to determine the liquid core stability profile for dynamo theory

the big idea was "Core Undertones" – analog of elastic Normal Modes - giving rise to a spectrum of inertial-gravity waves from the core

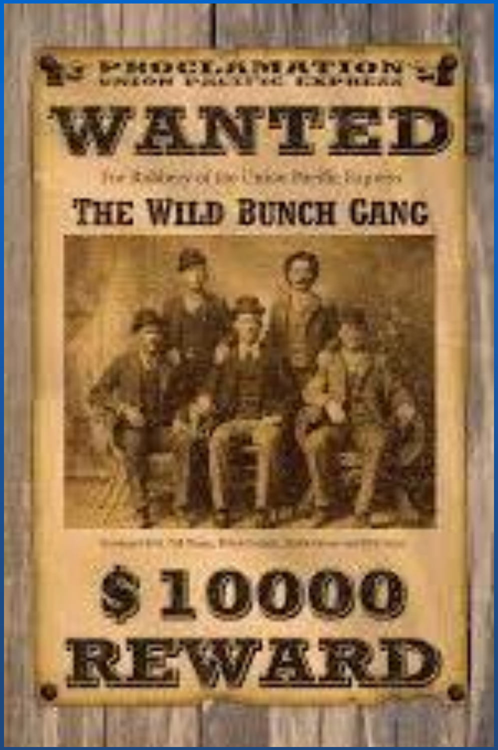
and "Slichter Triplet" was to be found for ICB density contrast



SG data in late 80's was difficult to obtain – different Data Acquisition Systems and Data Formats – we had to write (beg, plead, cajole, bargain) for access to use data

Canadian efforts to obtain funding for a global data center failed – so (a) we got our own instrument, and (b) we turned to the data producers for a community solution

SEDI, Bonn, and GGP



We started GGP as a SEDI project because it focused on the core and the initial promise was high

eventually it became stand-alone (more or less), and lawless, not subject to any agency oversight - except our own

important early venues for meetings during the 1990's were **the Bonn Meetings** - High Precision Gravimetry, Tidal Potential, Environmental Effects in gravity, etc. organized by **G. Jentzsch**

and the **Walferdange Workshops** on Intercomparisons of AGs and SGs, organized by **B. Ducarme, C. Poitevin** and others at ROB and Luxembourg

Very influential supporters of GGP at that time were (and many others …) :

Jacques Hinderer, Paul Melchior, Bernd Richter, Houtse-Hsu, Tadahiro Sato, Yoshiaki Tamura, Hans-Georg Wenzel , Manfred Bonatz

Early concerns within GGP

Who will benefit from the distribution of data? (everyone)

How much effort will this require? (initially - a lot, but today – very little)

Someone will use our data first!! (didn't happen)

We don't want government intervention! (Republicans)

What kind of data formats and metadata are suitable? (Preterna)

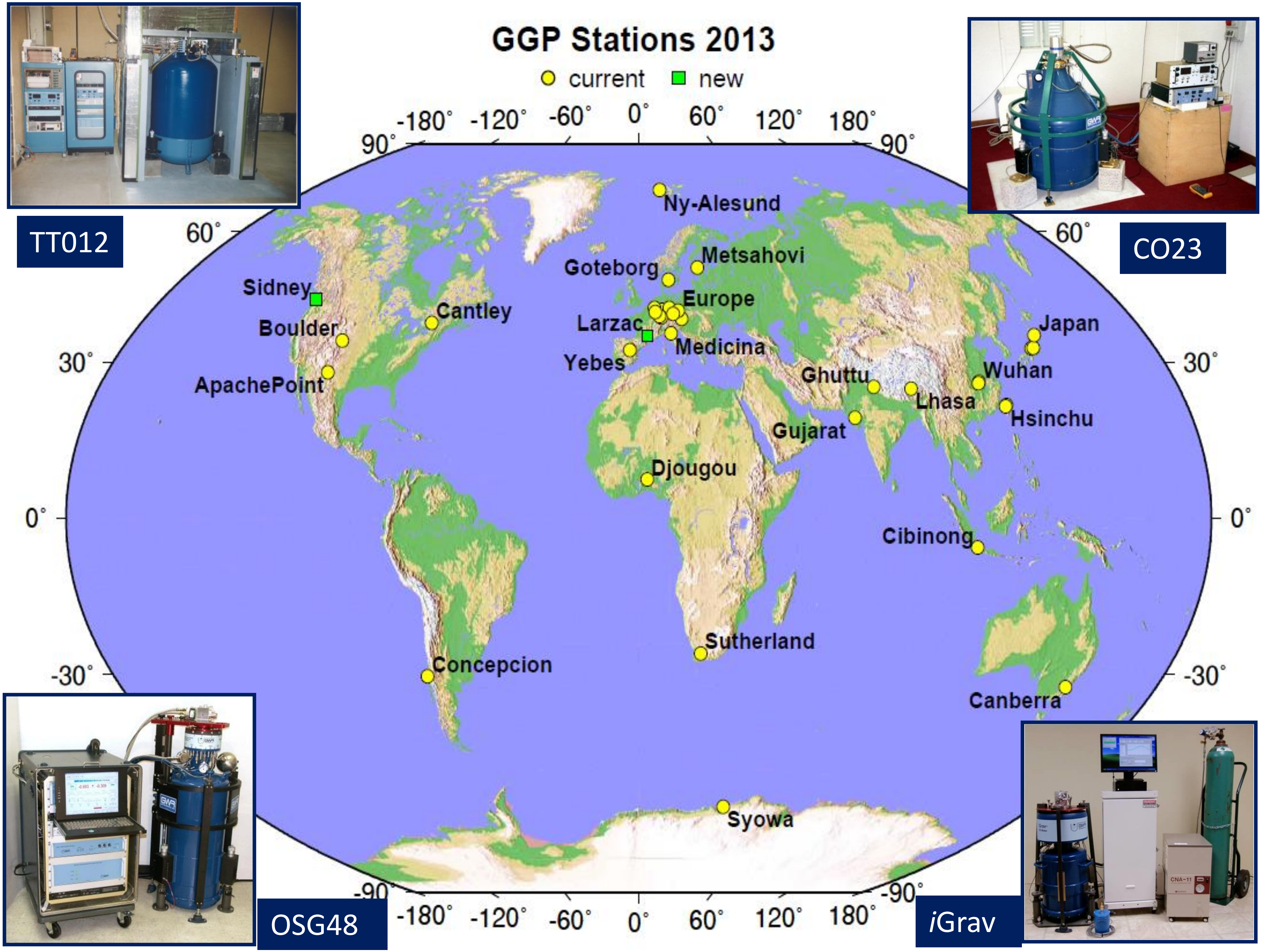
But my site may be only temporary! – (OK, data still valuable, e.g. large earthquakes)

How should we treat raw data? ("don't tamper with the data – that's forbidden and illegal!" - Brussels ETC 1997)

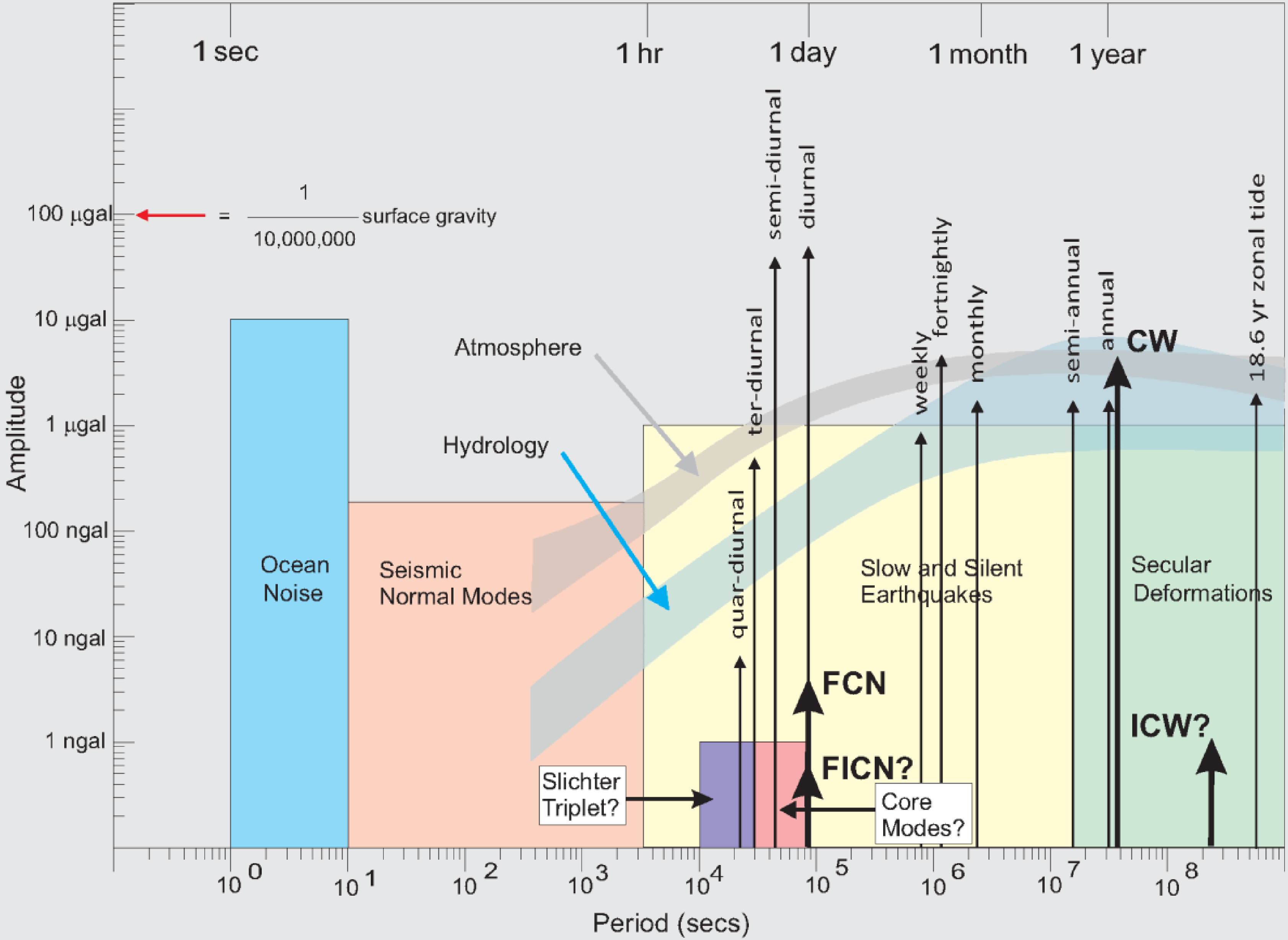
Parallels and contrasts with AGs

The SG project (GGP) and database took > 10 years to develop but (until AGrav) achieved a much more extensive data exchange than AG data

	AG	SG
inventor / first results	J. Faller (1965)	J. Goodkind / Prothero and Goodkind (1968) Warburton et al. (1975-78)
commercial instrument	T. Niebauer (1986)	R. Warburton (1981)
data collection	BGI	GGP/ICET (1997-2014)
modern database	AGrav (Wilmes et al. 2009)	proposed IGETS (2015)
commercially made	Micro-g, Boulder, CO	GWR Instruments, San Diego, CA


TT012
CO23
GGP Stations 2013
current
new
-180° -120° -60° 0° 60° 120° 180°
90° 60° 30° 0° -30° -90°
Ny-Alesund
Metsahovi
Goteborg
Sidney
Europe
Cantley
Boulder
Larzac
Japan
Medicina
Yebes
Wuhan
Ghuttu
ApachePoint
Lhasa
Hsinchu
Gujarat
Djougou
Cibinong
Sutherland
Concepcion
Canberra
Syowa
OSG48
iGrav

Geophysical Effects on Gravimeters



Most of GGP's organizational goals have been realized

Agreements on standards for SG sites and preparation, data types, formats and specifications

Cooperation with GWR in establishing a standardized data acquisition system

global database 1997 – 2014 (17 years)

the main data generator for the International Centre for Earth Tides (ICET)

ICET supported SG data with a large effort to manually pre-process it for tidal analysis

developed a geodetic sub-community, a website, and produced 21 Newsletters of SG information on the GGP website

enjoyed support by a large proportion of the scientific community

GGP Goals 1995

- <u>1. Earth tides and the nearly diurnal free wobble</u>
  - the estimation of precise tidal parameters
- <u>2. core modes</u>
  - the search for internal gravity waves in the Earth's liquid core
- <u>3. atmospheric interactions</u>
  - stacking global gravity and pressure data is essential for evaluating the effects of global atmospheric surface pressure and mass redistribution on the Earth's gravity field.
- <u>4. Earth rotation and polar motion</u>
  - the measurement of the gravity effect of polar motion (orientation of the Earth's rotation axis) requires a global coverage of stations
- <u>5. gravity changes due to tectonic motions</u>
  - the monitoring of long-term changes due to tectonic motions, sea-level changes affecting the survival of coastal cities, post-glacial uplift and the deformation associated with active tectonic events.
- <u>6. enhancing absolute gravity measurements</u>
  - SGs are a valuable aid to international programs for the determination of absolute gravity values on a global scale as they provide a short-term, relative gravity reference level.
- <u>7. general research tool</u>
  - a high quality, continuous global data set will be a valuable resource for future geodetic and geophysical studies that involve the Earth's gravity.

“ … additionally, GGP will be used for valuable local studies”

- <u>8. seasonal effects</u>
  - long-period seasonal (annual, semi-annual) components have been observed in gravity variations at some single SG stations. These variations cannot be successfully modeled without comparisons with other SG stations. √
- <u>9. earthquakes</u>
  - a SG with a bandwidth of 1 second to several years is the only instrument capable of monitoring both earthquake activity and tectonic motions. At intermediate time scales the SG is the ideal instrument for detecting slow and silent earthquakes.
- <u>10. seismic normal modes</u>
  - the SGs have excellent noise characteristics for the observations of the Earth's normal mode spectrum following a moderate to large earthquake √
- <u>11. geodesy</u>
  - single SGs, if located at strategic geodetic sites, can considerably enhance local models used to reduce VLBI and other precise measurements and if located near the coast, would provide data for estimating true local sea level

The more problematic goals

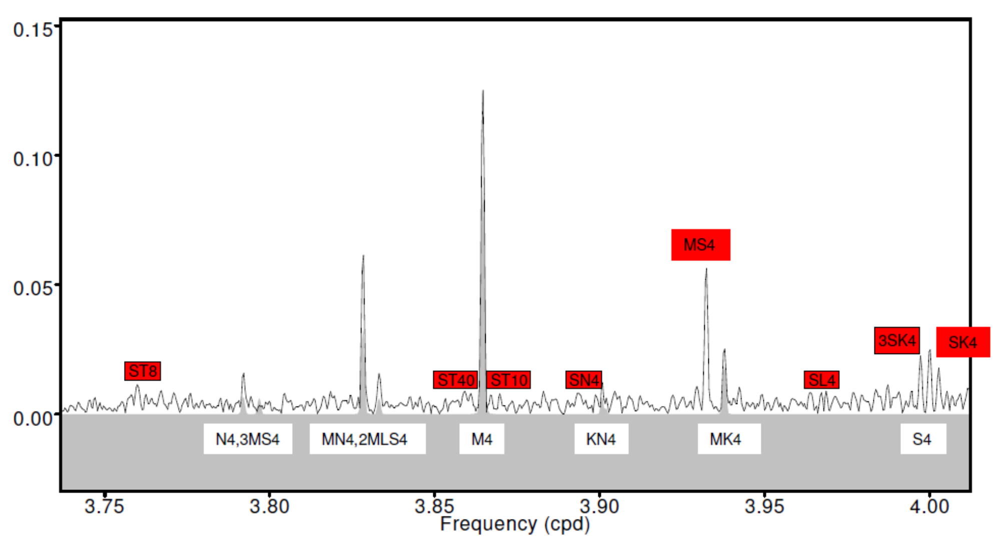
- 2. core modes
  - the search for internal gravity waves in the Earth's liquid core
- 5. gravity changes due to tectonic motions
  - the monitoring of long-term changes due to tectonic motions, sea-level changes affecting the survival of coastal cities, post-glacial uplift and the deformation associated with active tectonic events
- 11. geodesy
  - single SGs, if located at strategic geodetic sites, can considerably enhance local models used to reduce VLBI and other precise measurements and if located near the coast, would provide data for estimating true local sea level

Unexpected developments

- metrology – interest in Instrument characteristics
  - noise and performance levels in various frequency ranges
- Hydrology!
  - applications of SGs to hydrological signals at all scales from local to regional, and global

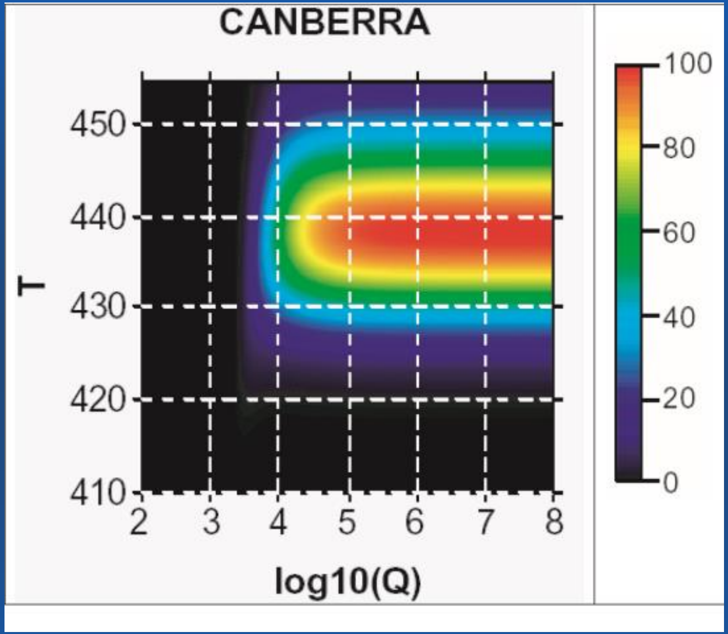
Success stories
#1. Earth tides and the nearly diurnal free wobble FCN

spectrum of M4 residuals at Sutherland



Ducarme & Chinese colleagues (2007)

T and Q of FCN from SGs



contribution of K_1^+ lunar nodal wave to FCN

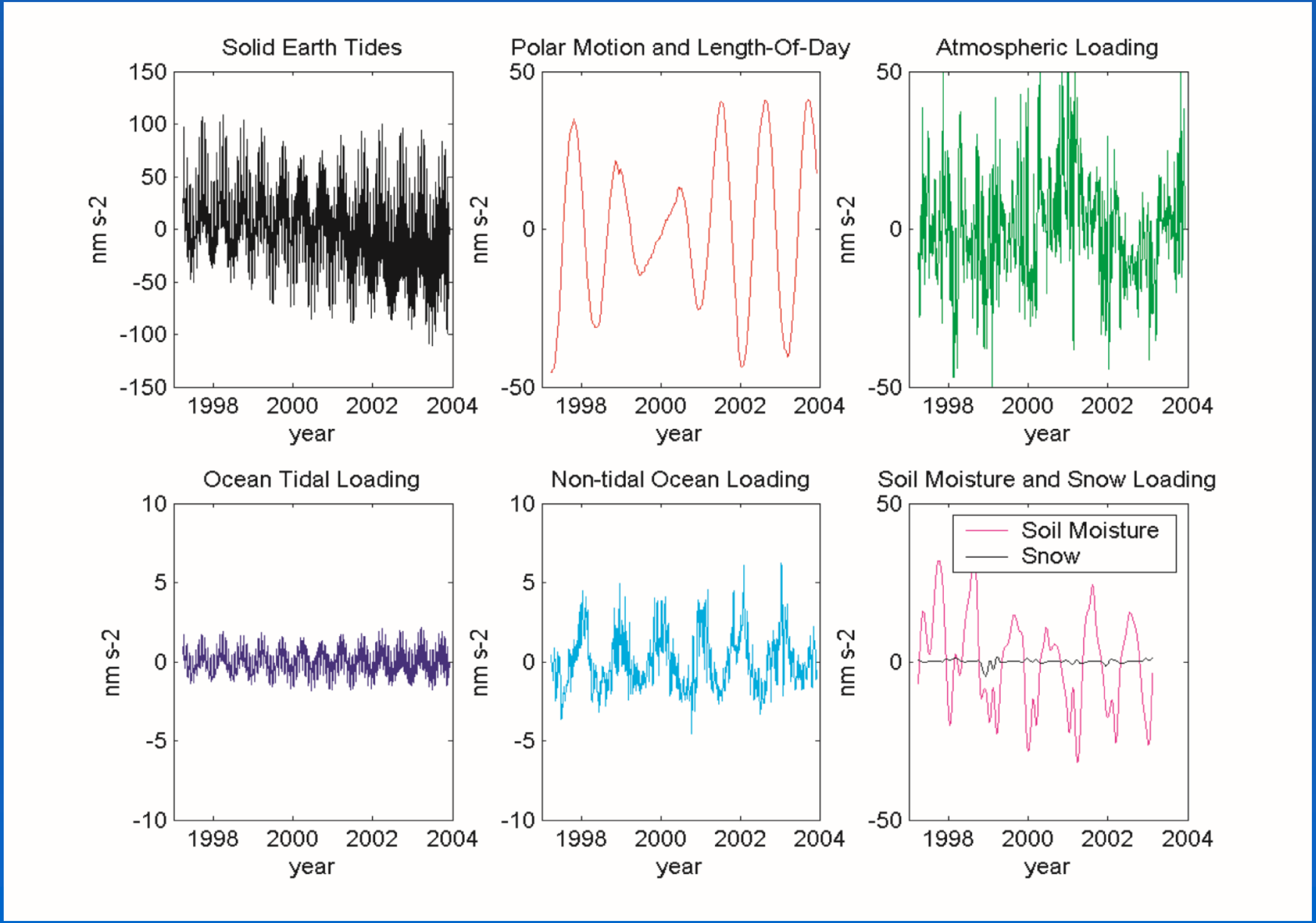
Florsch, Hinderer, Rosat, Sato, Ducarme ..

“the mean relative difference ρ^+ between K_1 and K_1^+ (0.113%±0.022%) is very close to the values 0.124% and 0.116% predicted respectively by the DDW99NH (Dehant et al., 1999) and the MAT01NH (Mathews, 2001) models … the nodal wave K_1^+ should be included in the determination of the FCN parameters, besides O1, P1, K1, PSI1 and PHI1”

Ducarme (2013)

#3. atmospheric and long term effects

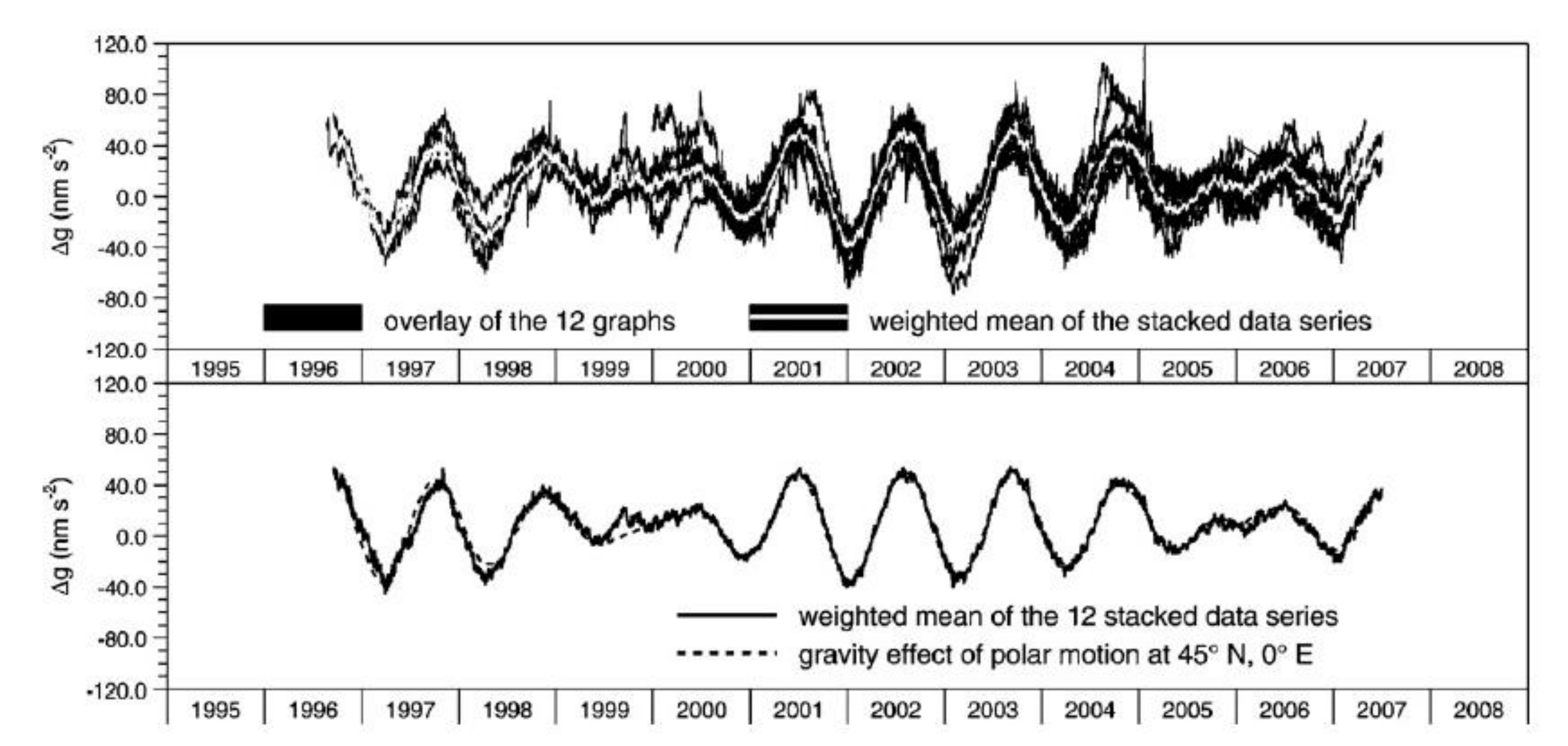
evaluating global atmospheric surface pressure, tides, ocean loading, polar motion, hydrological loading, height studies



Boy, Hinderer, de Linage, …

Stacking 12 stations for polar motion transformed to a single point (45°N,0°E) Harnisch & Harnisch (2009)

BH(2), CA, CB, MB, MC, ME, MO (2), ST, SU(2), TC, VI



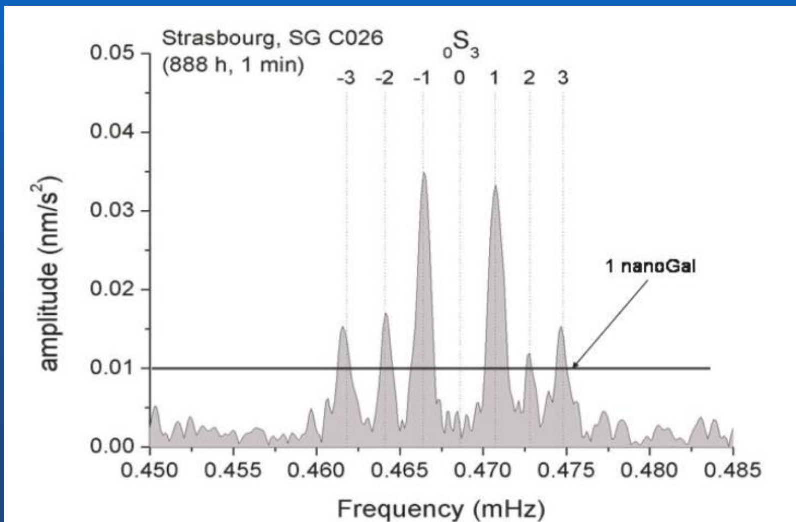
total PM δ=1.13 ± 0.05 (weighted mean W/O annual removed)

Annual alone: δ=1.11 ± 0.14, Chandler alone: δ=1.15 ± 0.02

(2000-2005) Annual: δ=1.183 ± 0.01 Chandler: **δ=1.168 ± 0.01**

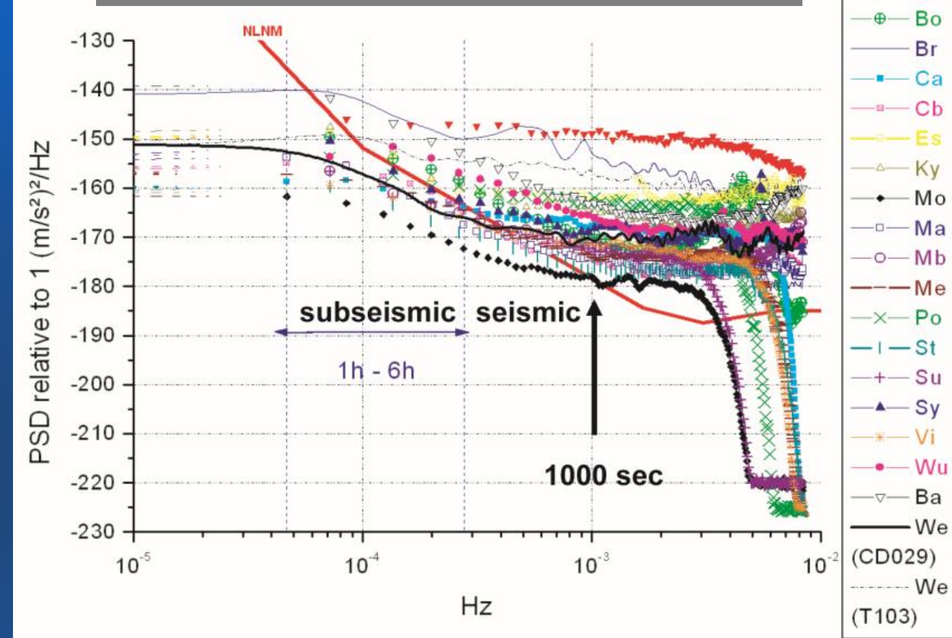
10. seismic normal modes

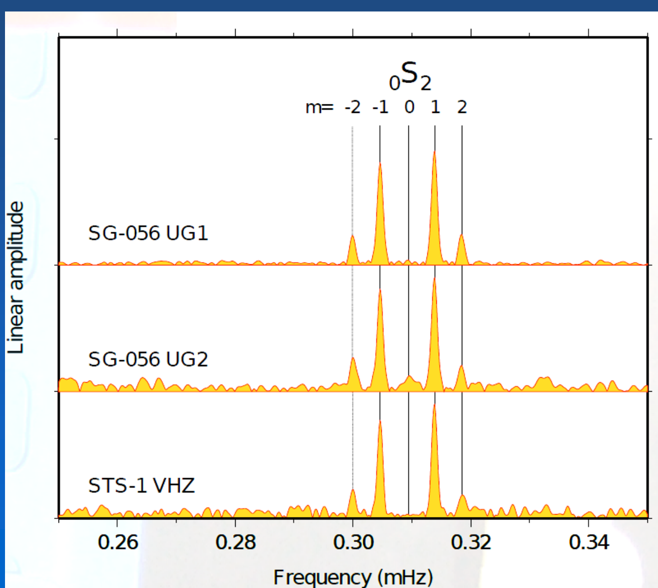
the SGs have excellent noise characteristics for the observations of the Earth's normal mode spectrum following a moderate to large earthquake



splitting of $_0S_2$ Rosat et al. (2005)

noise studies (Banka, Rosat, Palinkas)





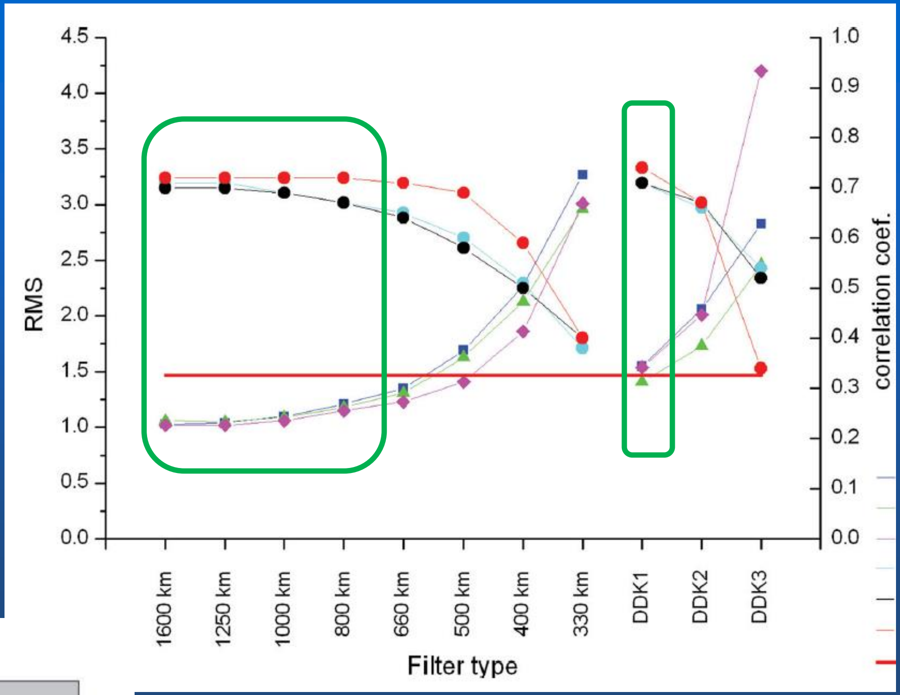
Singlet	Frequency [µHz]	1·σ [µHz]	Q	1·σ
-2	299.928	0.038	530	73
-1	304.613	0.011	463	15
0	-	-	-	-
1	313.836	0.010	488	15
2	318.411	0.038	524	71

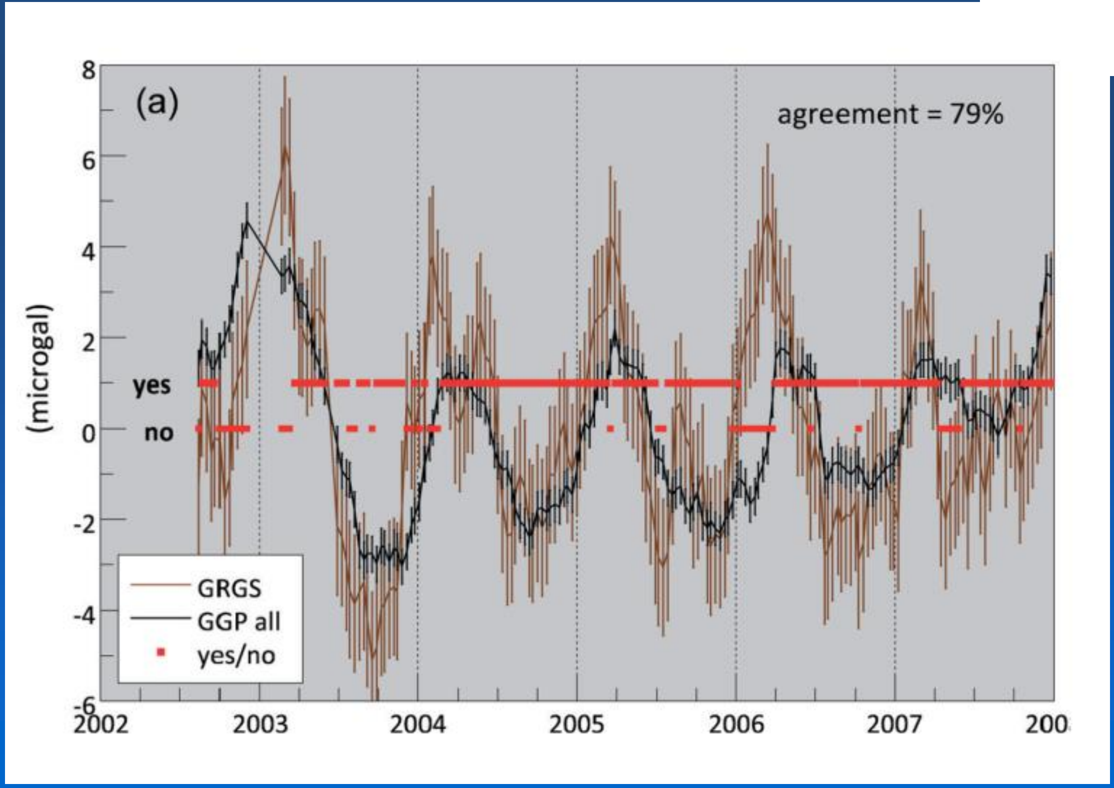
the dual sphere splitting of $_0S_2$ at BFO Widmer-Schnidrig (2012)

Use of GGP for regional comparison of ground gravity with GRACE satellite data

highest correlation (70%) of GGP and GRACE data achieved with an isotropic Gaussian averaging of 800-1600 km and non-isotropic Kusche-type filter DDK1

Abe et al (2012)

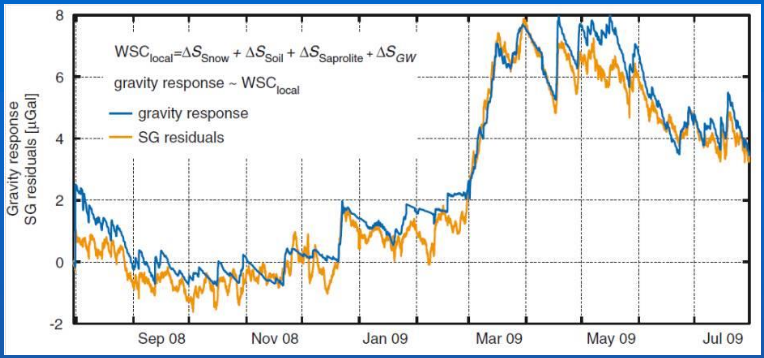




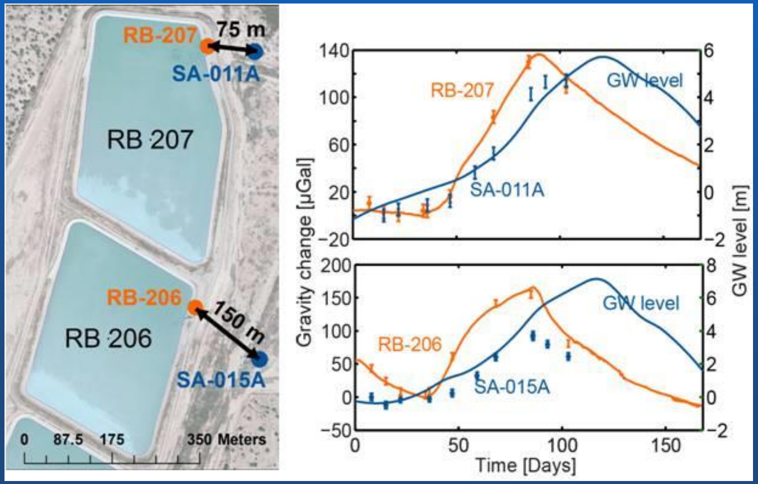
Agreement between EOF mode 1 for GRACE (GRGS) and GGP reached 79% within data error bars, even better (90%) using only surface stations

Crossley et al. (2012)

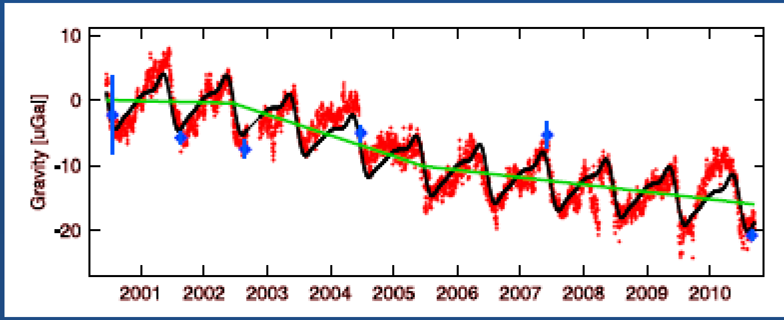
Local studies using SGs (gravity and GPS, effects of **hydrology** on gravity, gravity and reservoir levels, episodic slip at subduction zones)



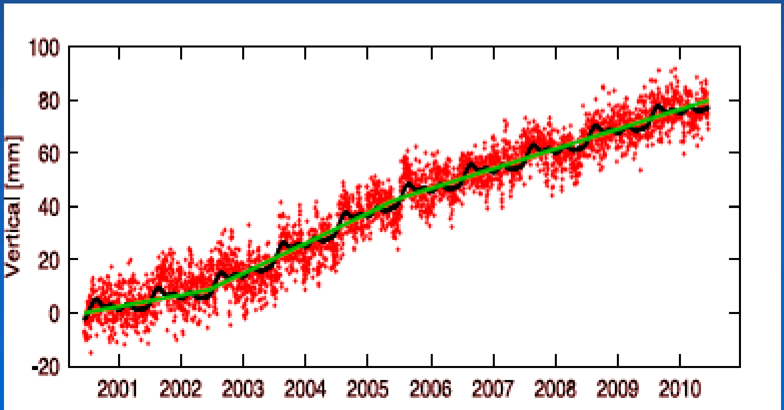
spectacular agreement – hydrology vs gravity (Creutzfeldt et al. 2010)

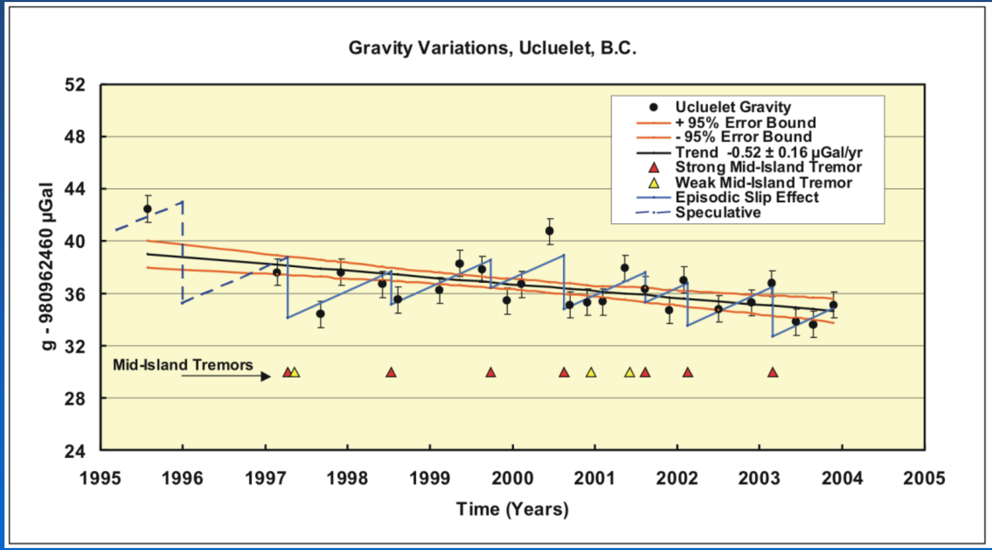


SAVSARP, Arizona reservoir monitoring, 2 SGs vs hydro model (Kennedy et al 2013)



Ny Alesund ice melting/GIA – gravity and GPS measurements (Omang et al. 2011)

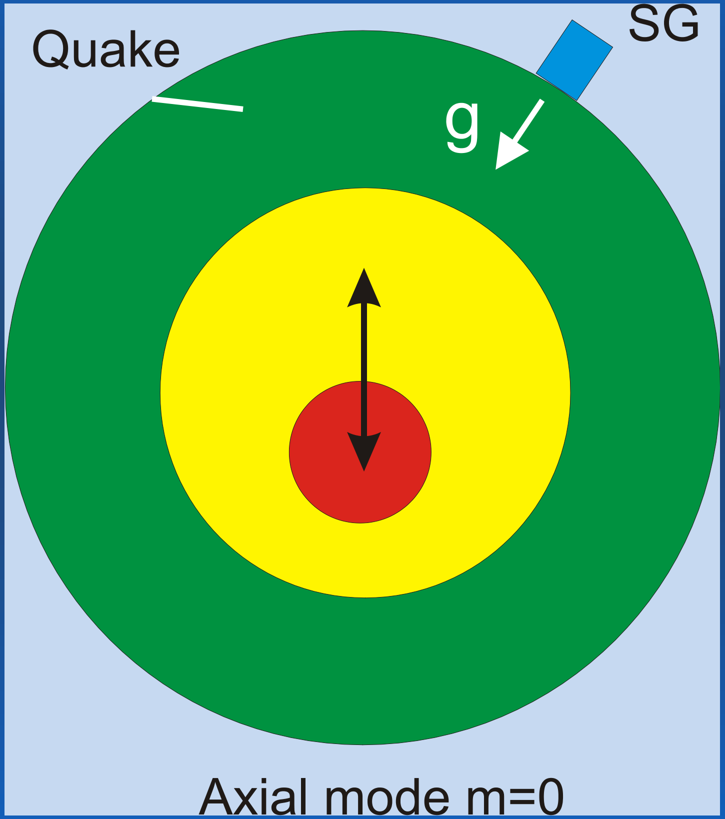


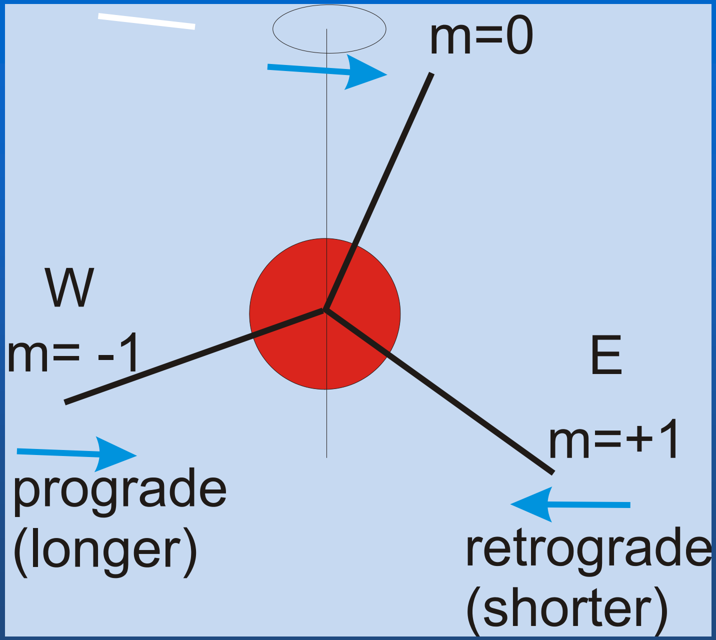


episodic gravity (AG; SG expected), Cascadia subduction

So, what about the core?

Slichter Triplet $_1S_1^m$





Mechanisms:

earthquake

surface atmospheric pressure

external meteor strike

core fluid turbulence

volcanic eruption

Detection:

SG global array (e.g. GGP)

Current Situation

- SGs are best instrument but no confirmed observations; earthquake excitation predicts:

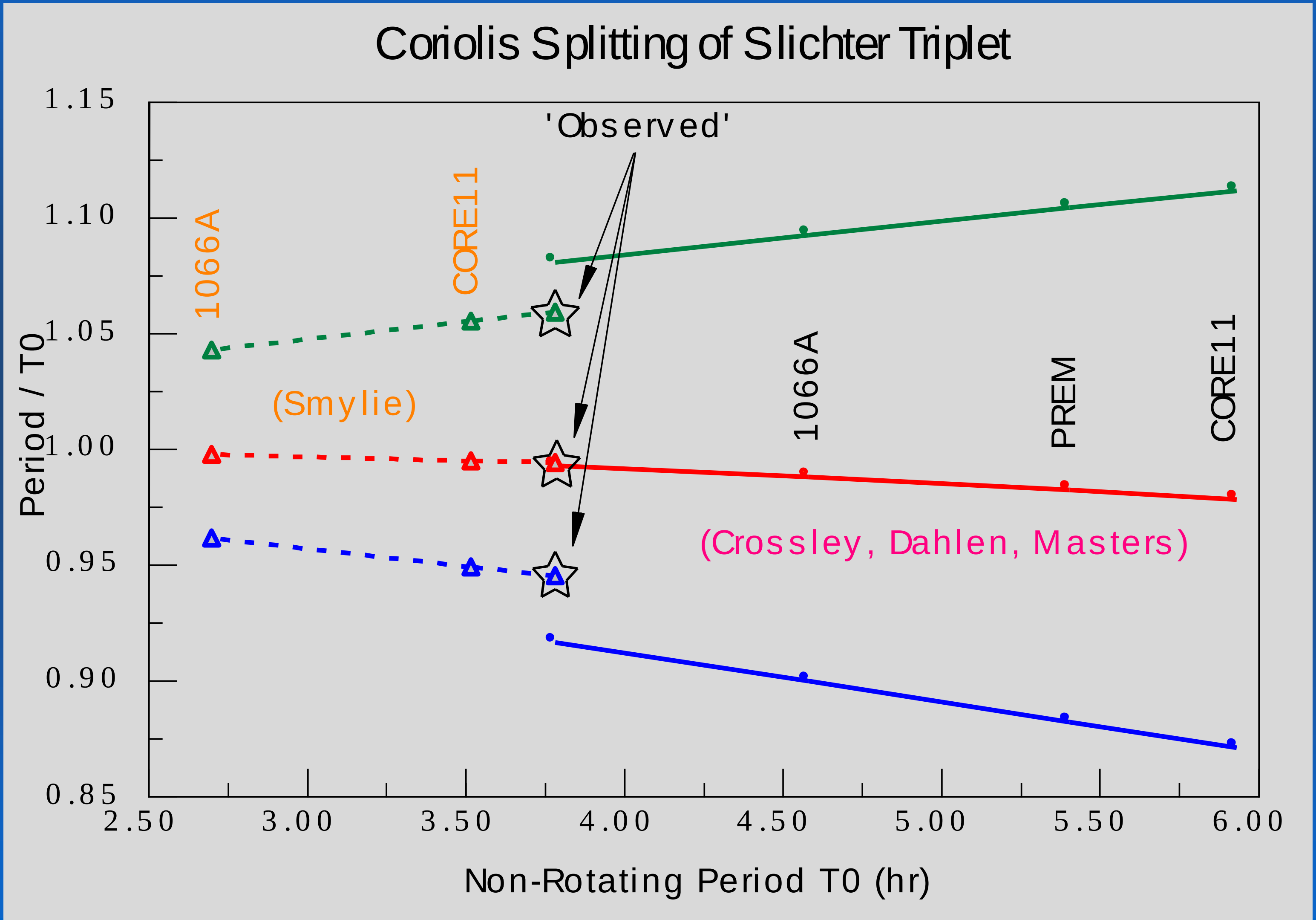
triplet ${}_1S_1^m$	$m = -1, 0, 1$
period range	5 - 8 hr
amplitude	~ 1 nanogal (10^{-12}g)

- Motion of inner core, outer core, and mantle

IC displacement	~ mm
$\Delta\rho$ (ICB) range	0.3 – 0.6 gm cm^{-3}

- Elasticity of IC, mantle contribute 10%

Observed splitting claimed from only one study, never repeated, agreed theoretically with only the Bolt-Urhammer Earth model



We see that many IC seismic modes are not observed: there is insufficient excitation by a near-surface event, and high elastic damping (only 1 week to detect) for most modes (except ${}_0S_0$ and ${}_1S_1$)

Classification of Modes (based on region having > 25% KE)

Group 1: IC Modes

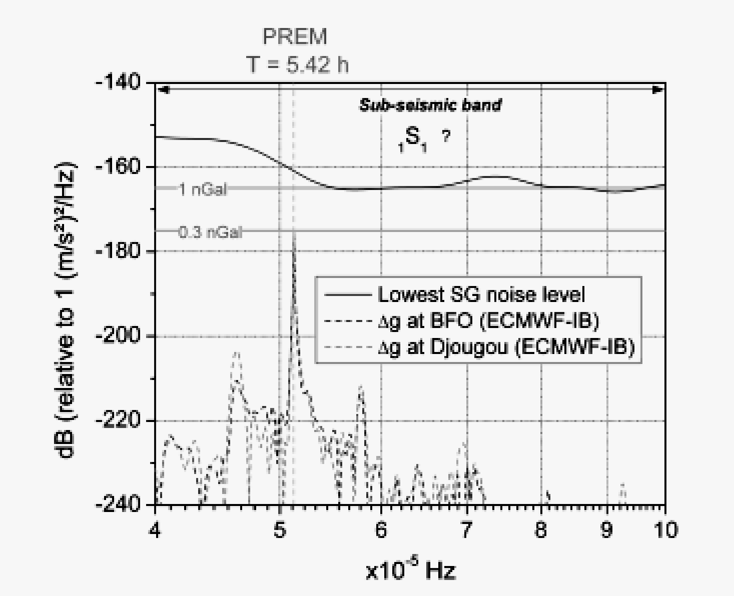
n	*l*	*Period (s)*	*Observed?*
5	1	583.259	-
10	1	294.529	-
14	1	202.966	-
6	2	414.676	-
11	2	246.323	-
7	3	324.328	-
12	3	213.446	-
8	4	269.978	-
9	5	231.146	-
10	6	203.431	-

Classification of Modes (based on region having > 25% KE)

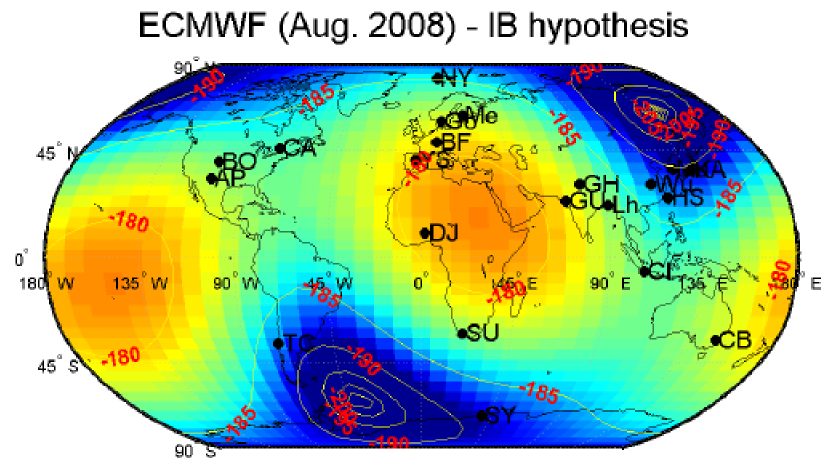
Group 2: IC+OC Modes

n	*l*	*Period (s)*	*Observed?*
1	1	19514.268	–
2	2	1065.853	–
3	3	705.338	–
3	4	545.251	–
3	5	447.353	–
4	6	380.537	–
4	7	331.712	–
4	8	294.288	–
5	9	264.619	–
5	10	240.483	–
6	11	220.443	–
6	12	203.526	–

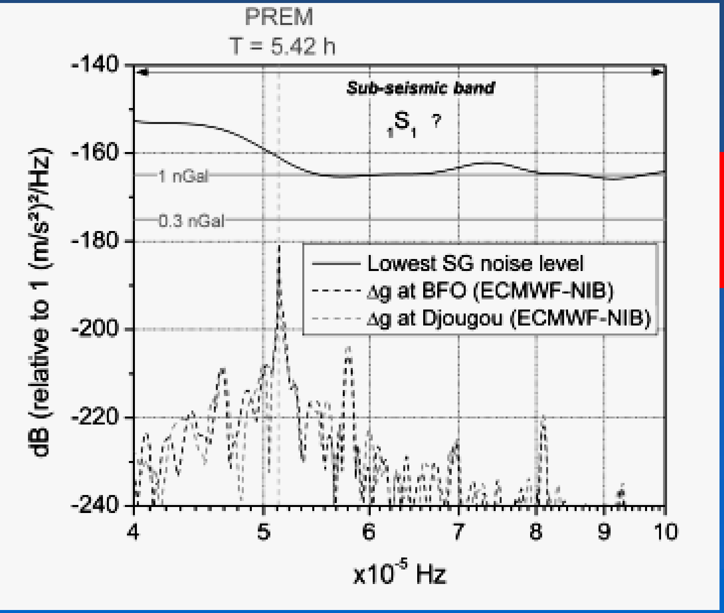
surface pressure excitation



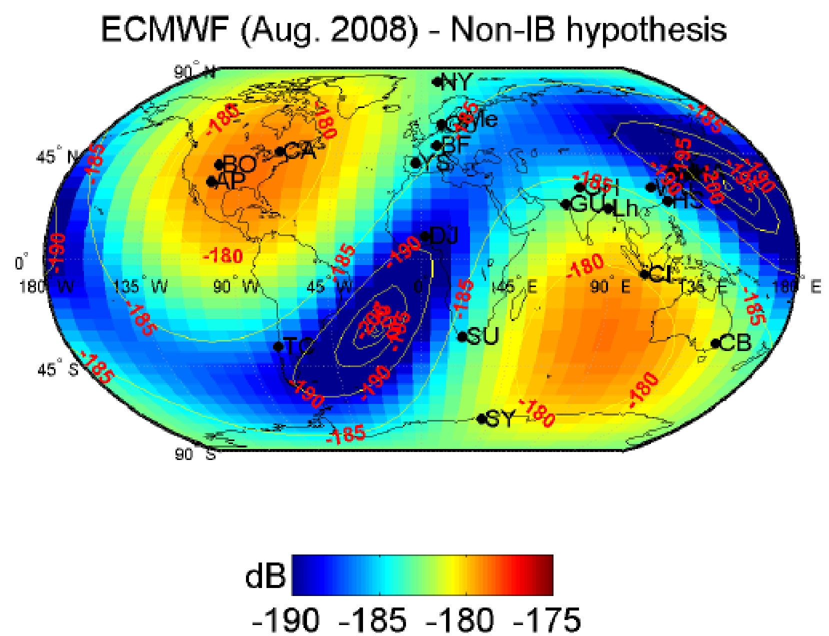
IB response



rosat et al. (2014)



non-IB response



Rosat, Rogister

Wavelet non-detection

- "The peaks attributed to the Slichter triplet by Courtier et al. (2000) *do not appear in our data set*, as well as the predicted frequencies of the Slichter triplet (e.g. Rieutord 2002; Rogister 2003).
- The candidates detected by Guo *et al. (2007) that have passed their test for at least two data sets* have not been detected by our CDW analysis.
- The possible candidates detected by Rosat *et al. (2006) based on the same stacked data sets* have not been detected by our CDW method.
- So we may conclude that they were much [more] probably a noise effect, or due to the presence of the spike, the origin of which is unknown"

Rosat et al. (2007)

Additional excitation effects such as external impact, volcanic eruption and internal fluid impulses from core fluid

Meteroid Impact requires a body at least as large as that causing the Chicxulub crater (>17 km) or equivalent to Mw = 9.7

Another possibility is internal pressure acting from the fluid on the ICB, best when impulse is 0.25 T (=1.3 hr) then excitation may be possible to 1 nGal level

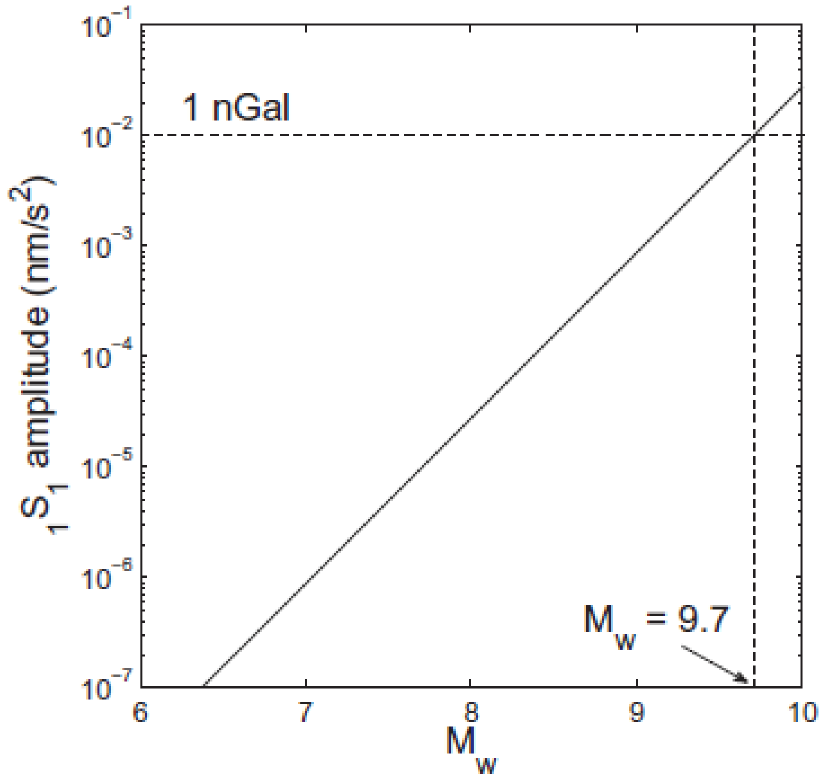


Fig. 7. Surface gravity perturbation induced by the Slichter mode as a function of the moment magnitude of a superficial energy release (explosion or object impact).

Rosat et al. (2012)

IC translation probably not excited to observable levels

Arguments in "Core modes and Slichter modes: fact and fancy" (Crossley BIM 117, 1993)

Excitation No mechanism to date, except possibly the internal fluid pressure, seems capable of exciting the ${}_1S_1$ mode to more than 1 nGal level. Random excitation may also scramble the phase of the motion to below threshold

Detection lowering that threshold will take considerable SG data processing skills, and a very light damping mechanism if the excitation is continuous or episodic

Damping

The effect of latent heat of fusion at the ICB fails to change the standard IC translation on two counts:

(a) freezing/melting on opposite sides of the core cannot possibly redistribute heat across IC in 5 hr, and

(b) growth of dendrites is much too slow to change the dynamics of the IC motion

Thermodynamics? effect of mushy zone as a transition layer between OC and IC was found not to perturb the periods of the PREM modes by more than 1% (Peng and Rochester, 1997)

For core modes (gravity inertial waves) fluid motion is not favorable

inviscid fluid motion has characteristic surfaces that become tangential to ICB at long periods (T-P theorem)

shear planes develop in a rotating container with excitation

in the limit of zero viscosity, the shear is infinite, so there is a singularity in the variables and thus in the spectrum

this behavior should be reflected in the solutions for dynamics within the rotating core

In addition, OC is probably adiabatic throughout, except for thin stable layer near ICB – only very weak gravity modes!

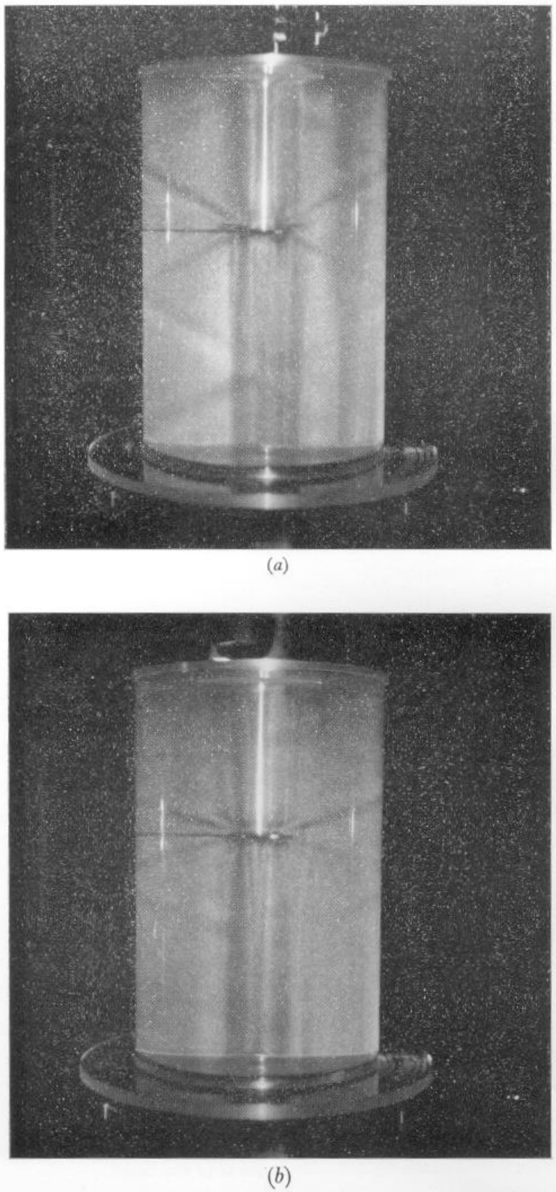
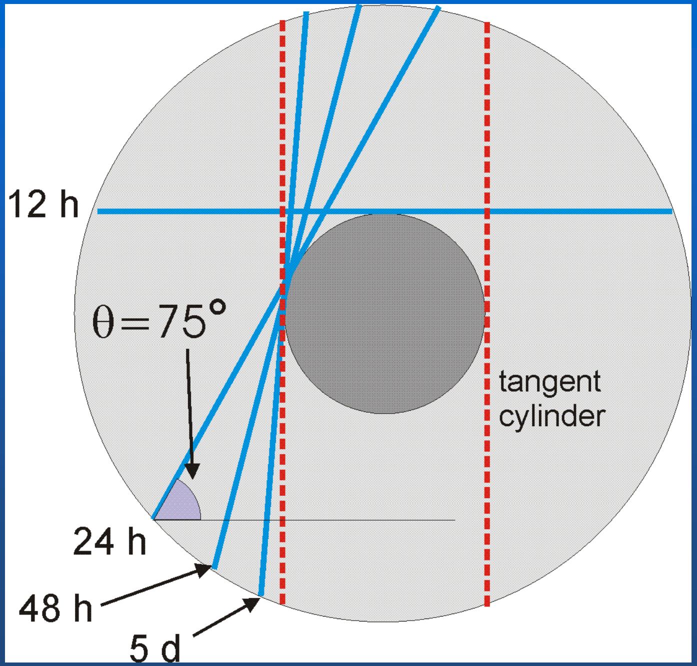
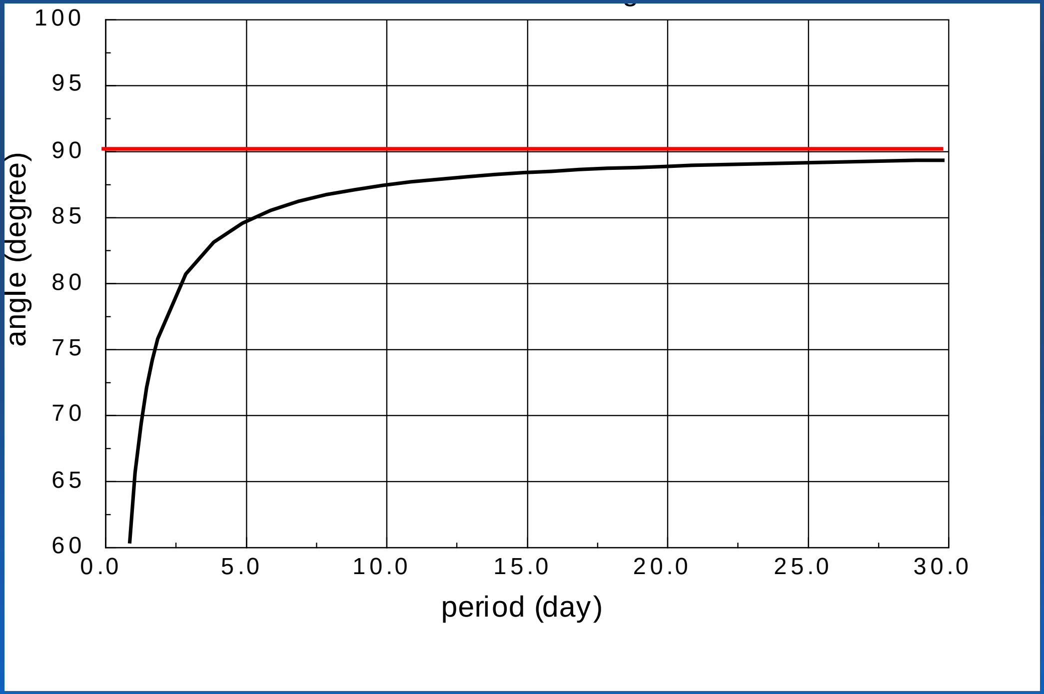


Fig. 1.3. (a) Waves produced by an oscillating disk with $\omega/\Omega = 1{\cdot}75$. The half apex angle is 59° and the theoretical value is 56°. (b) The apex angle increases for a larger value of ω/Ω.

Shear plane geometry means that SH expansions are unsuited to represent cylindrical motion at periods > 12 hr





Rieutord has managed to get convergent solutions, but by increasing viscosity to high levels

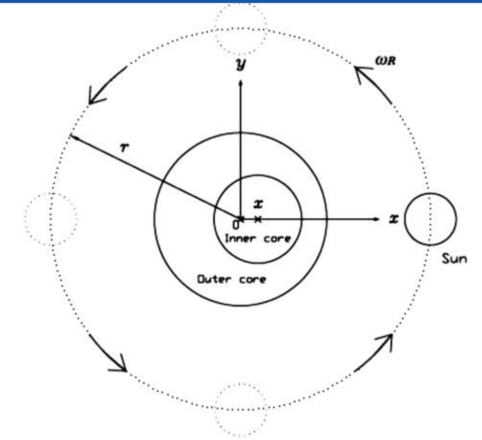
but the core is difficult, even in spherical shell geometry!

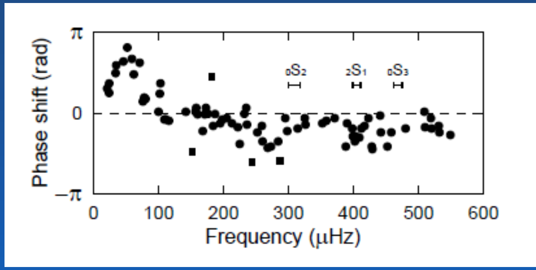
There is a graveyard wherein will lie the bones of those seeking the Slichter triplets and core modes …

GGP goal #7: general research tool

“a high quality, continuous global data set will be a valuable resource for future geodetic and geophysical studies that involve the Earth's gravity”

- Sashi Shiomi (2006)
  - geophysical test of the universality of free-fall (Phys. Rev. D74, 2006)
- Gustav Shved and colleagues (2009, ongoing)
  - want to use SGs for studies of short period (1-8 hr) atmospheric waves e.g. “Steady-frequency waves at intradiurnal periods from simultaneous co-located microbarometer and seismometer measurements: a case study, Ann Phys 29 (2011)”
- Gerard Fonte and colleagues (2010, ongoing)
  - using SG data to test the speed of gravity, solar tides vs lunar tides
- Coughlin and Harms (2014)
  - using SGs to constrain gravitational wave radiation levels





PHYSICAL REVIEW D **90,** 042005 (2014)

Constraining the gravitational wave energy density of the Universe using Earth's ring

Michael Coughlin[1] and Jan Harms[2]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*INFN, Sezione di Firenze, Sesto Fiorentino 50019, Italy*

These limits were set by: pulsar timing observations, Doppler-tracking measurements of the Cassini spacecraft, monitoring Earth's free-surface response with seismometers ("Seismic") , and correlating data from the first-generation, large-scale GW detectors LIGO.

The new limits resulting from normal-mode measurements are shown as crosses.

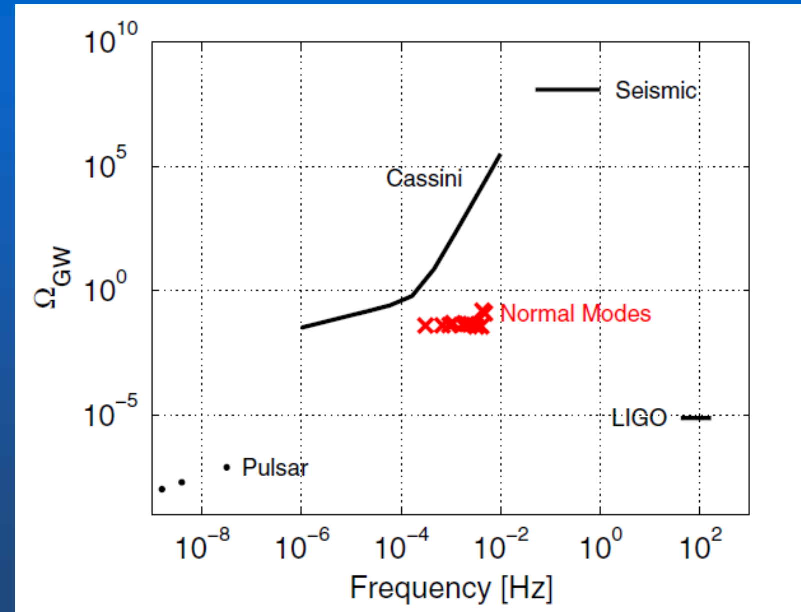


FIG. 1 Current upper limits on GW energy density.

GW radiation (from binary pulsar) has periods from 1 kHz to billions of years

causes oscillations of planetary and stellar bodies

coupling coefficient α_n depends on ${}_nu_\ell$, ${}_nv_\ell$, and $|d\mu/dr|$ at internal boundaries (esp. ICB, CMB)

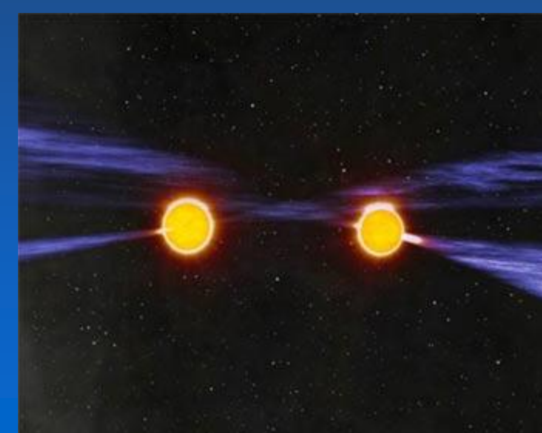
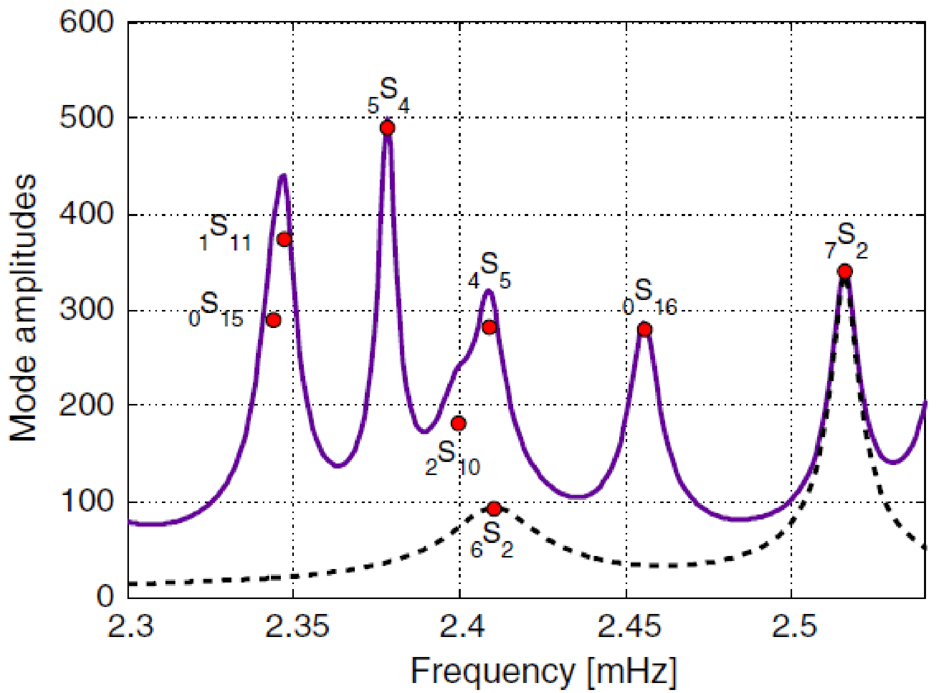


FIG. 2. Simulated spectrum of spheroidal normal modes around ${}_6S_2$. The curves are sums of harmonic oscillator response functions (solid: all spheroidal modes, dashed: all spheroidal quadrupole modes). The values of the red markers correspond to the modes' Q values.



analysis is done on overtones of S_2^m, excited by quadrupole radiation

α_n is GW-mode coupling parameter

p_n is surface gravity effect

TABLE I. Summary of mode parameters: mode frequencies f_n, quality factors Q_n, coupling strengths α_n, radial surface displacement u_n, perturbation of gravity surface potential p_n (both normalized to the same, but arbitrary unit). The last row shows the upper limits on the energy density Ω_{GW} as plotted in Fig. 6.

${}_nS_2$	0	1	2	3	4	5	6	7	8	9	10	11	12	13
f_n [mHz]	0.309	0.679	0.938	1.11	1.72	2.09	2.41	2.52	3.21	3.23	4.03	4.06	4.33	4.84
Q_n	510	310	95.9	365	433	317	92.9	340	316	445	203	126	229	878
α_n	−0.645	−18.3	−1.78	−0.696	−18.9	13.3	4.31	−34.5	−3.97	−6.54	15.8	−16.9	12.7	3.12
u_n	0.74	−0.14	−0.06	−0.19	−0.18	−0.11	−0.019	−0.086	−0.050	0.13	0.073	0.057	−0.021	0.086
p_n	−0.43	0.028	5.7e-5	−4.9e-4	2.1e-4	4.7e-5	−3.1e-6	1.7e-5	5.3e-6	3.6e-6	2.0e-7	7.4e-7	1.0e-6	1.9e-8
Ω_{GW}	0.039	0.039	0.040	0.048	0.041	0.045	0.042	0.044	0.035		0.036		0.15	0.12

Study made extensive use of GGP network data

FIG. 3 Earth quadrupole oscillation. The red and blue shapes correspond to the maxima of a quadrupole oscillation separated by half an oscillation period. The green balls mark locations of some of the gravimeters of the GGP network. Here the oscillation is induced by a GW propagating along the northsouth axis.

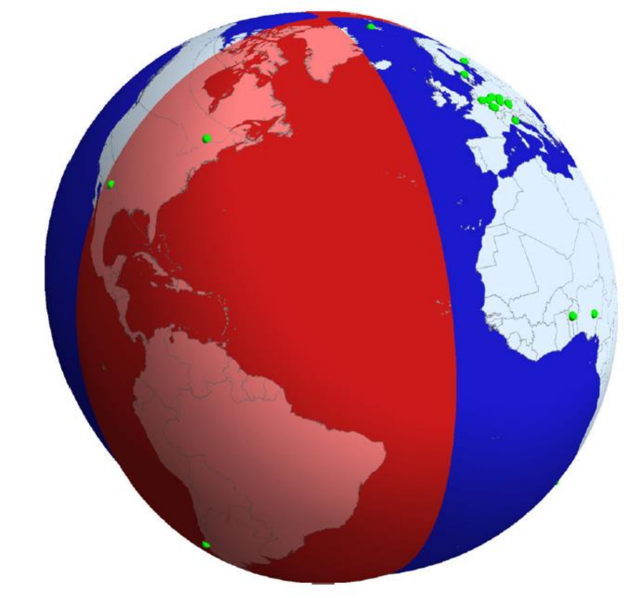
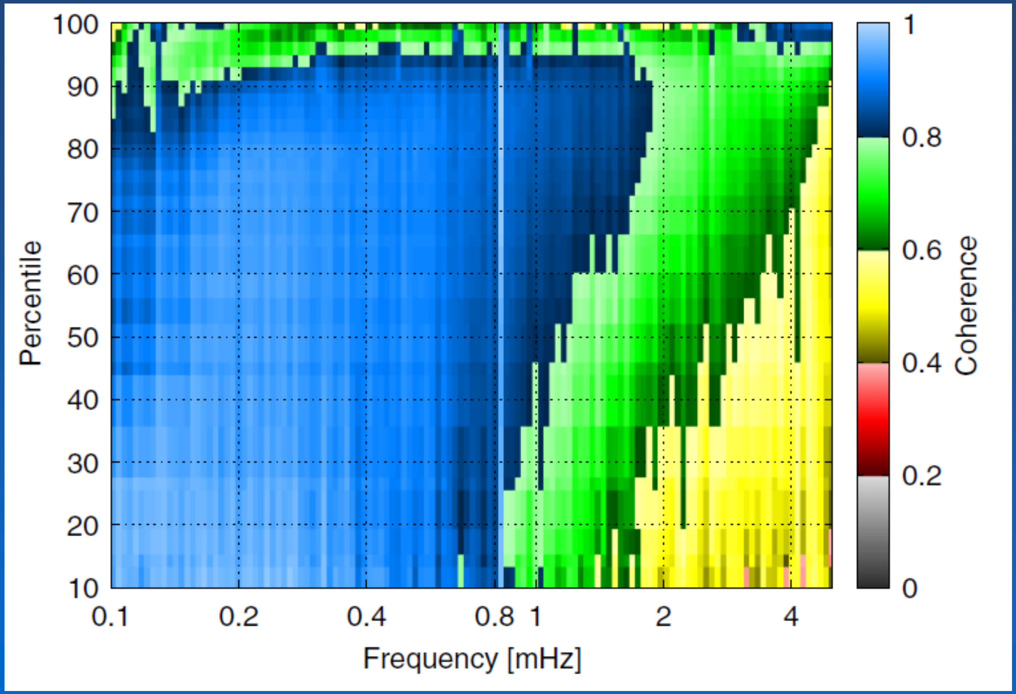
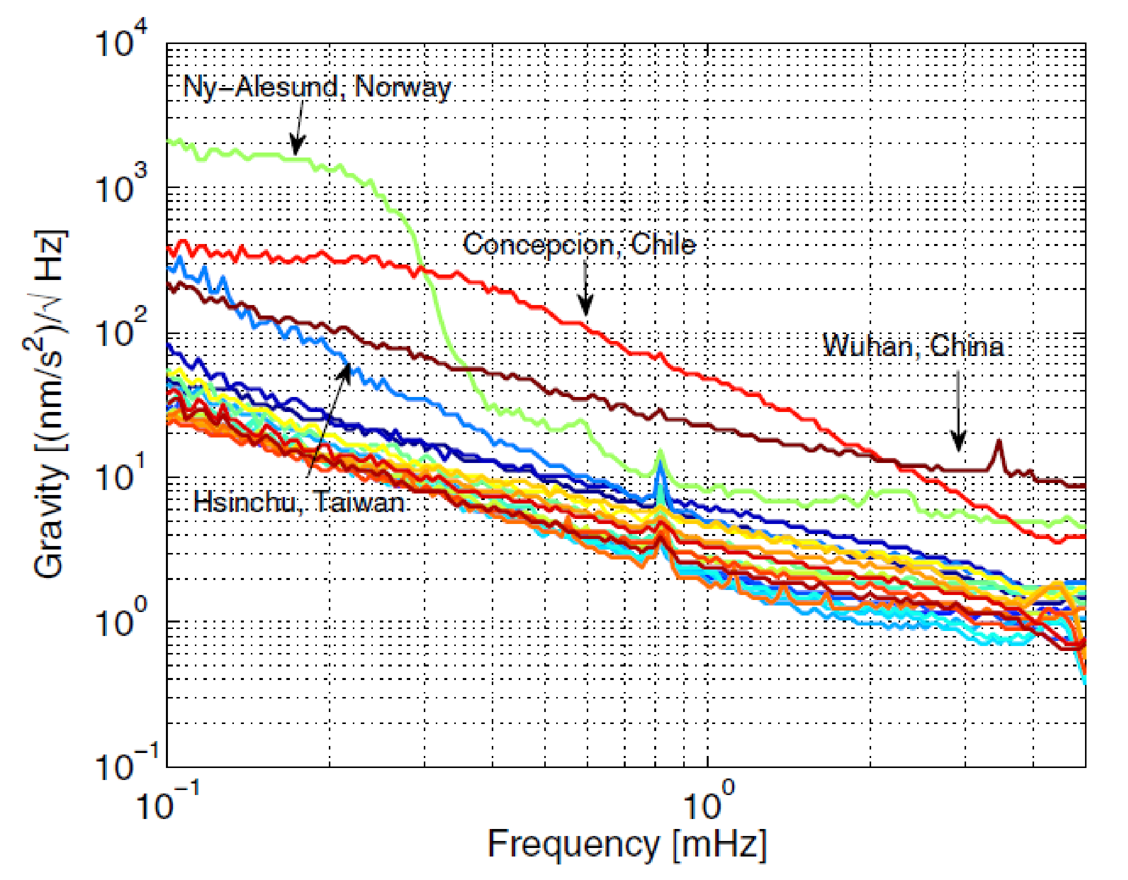


FIG. 5 Coherence of signals from two levitated spheres in the same gravimeter at Wettzell, Germany. The result is shown as a function of percentile of gravimeter noise excluded from the coherence measurement. A percentile of 90 means that 10% of the loudest spectra were excluded from the coherence measurement. Only the high-Q radial normal mode 0S0 at about 0.81 mHz contributes significantly to coherence for all times.



… including their estimate of the gravity noise (SG+site) independently of authors from GGP

FIG. 4 Medians of gravimeter spectra measured in 2012. All gravimeters used in this study show a comparable level of stationary background noise represented by their spectral medians, except for the four gravimeters highlighted in the plot.




GGP ACT II
is
IGETS
International Gravity and Earth Tides Service
IUGG Prague 2015
Enhanced GGP 1 min files
New Level 2 Data – processed for standard corrections and ready for global use
Raw SG 1 sec data to GFZ/IRIS
ICET archives and services incorporated
improved GFZ support

Conclusions …

not all applications of SGs were foreseen in GGP (, esp.hydrology)

some topics seem to have reached a plateau, or ‘essentially solved in principle’

FCN, tides, IC translation, atmospheric corrections, ocean tide loading

… and new goals

as a service, IGETS must remain faithful to its mandate (global gravity series for long period studies)

management must maintain personal contact with scientists

new stations, and temporary deployments, should be made welcome in IGETS

don’t stop the GGP spirit – meetings and collegiality!

thanks to Jacques Hinderer for all the good collaboration and leadership in Strasbourg