Two Decades of High Precision Gravimetry, GGP, and Prospects for the Future

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Thank you …

- Cheinway Hwang,
- CW Lee,
- Ricky Kao, and other workshop organizers,
- and financial sponsors

for the opportunity to participate in the Workshop and visit Hsinchu

Outline

SG beginnings 1967-80

Early installations 1981-89

GGP activities 1990-96

GGP accomplishments 1997-2007 covered in Workshop:

- seal level,
- general geophysics and geodynamics
- earthquakes
- ocean tides
- data fusion
- calibration
- hydrology
- AGs
- GRACE
- geoid height

Prospects for the future

SG beginnings 1967-80

40 yr

Prothero, W. A., 1967. A cryogenic gravimeter, Ph. D. thesis, Univ. of Calif. at San Diego, La Jolla.

Prothero, W. A., and Goodkind, J. M., 1968. A superconducting gravimeter, *Rev. Sci. Instrum.,* **39**, 1257-1262.

Prothero, W. A., and Goodkind, J. M., 1972. Earth tide measurements with the superconducting gravimeter, *J. Geophys. Res.,* **77**, 926-932

SG beginnings … Prothero and Goodkind (1972)

tide removal (no pressure correction)

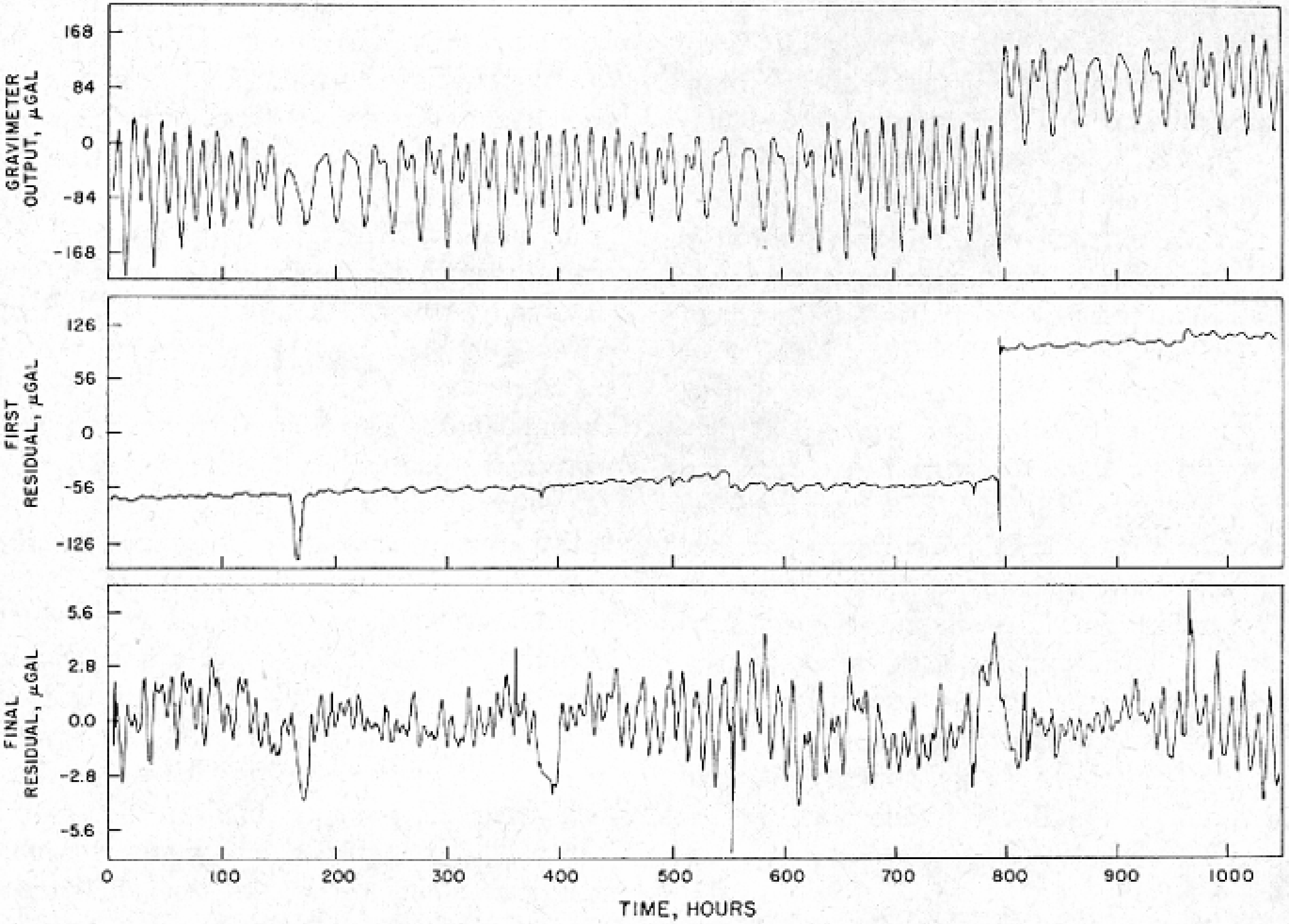


Fig. 3. Plots of the data from run 2 at three stages of analysis. The large offset near 800 hours was deliberately introduced to change the zero of the output. The middle plot is the data after the first subtraction of diurnal and semidiurnal tides. The lower plot shows the data after the lowest-order long-period, diurnal, and semidiurnal tides and offsets have been fit and subtracted. Large spikes have also been removed by linear interpolation.

Prothero and Goodkind: first SG analysis

the tides!

EARTH-TIDE MEASUREMENTS

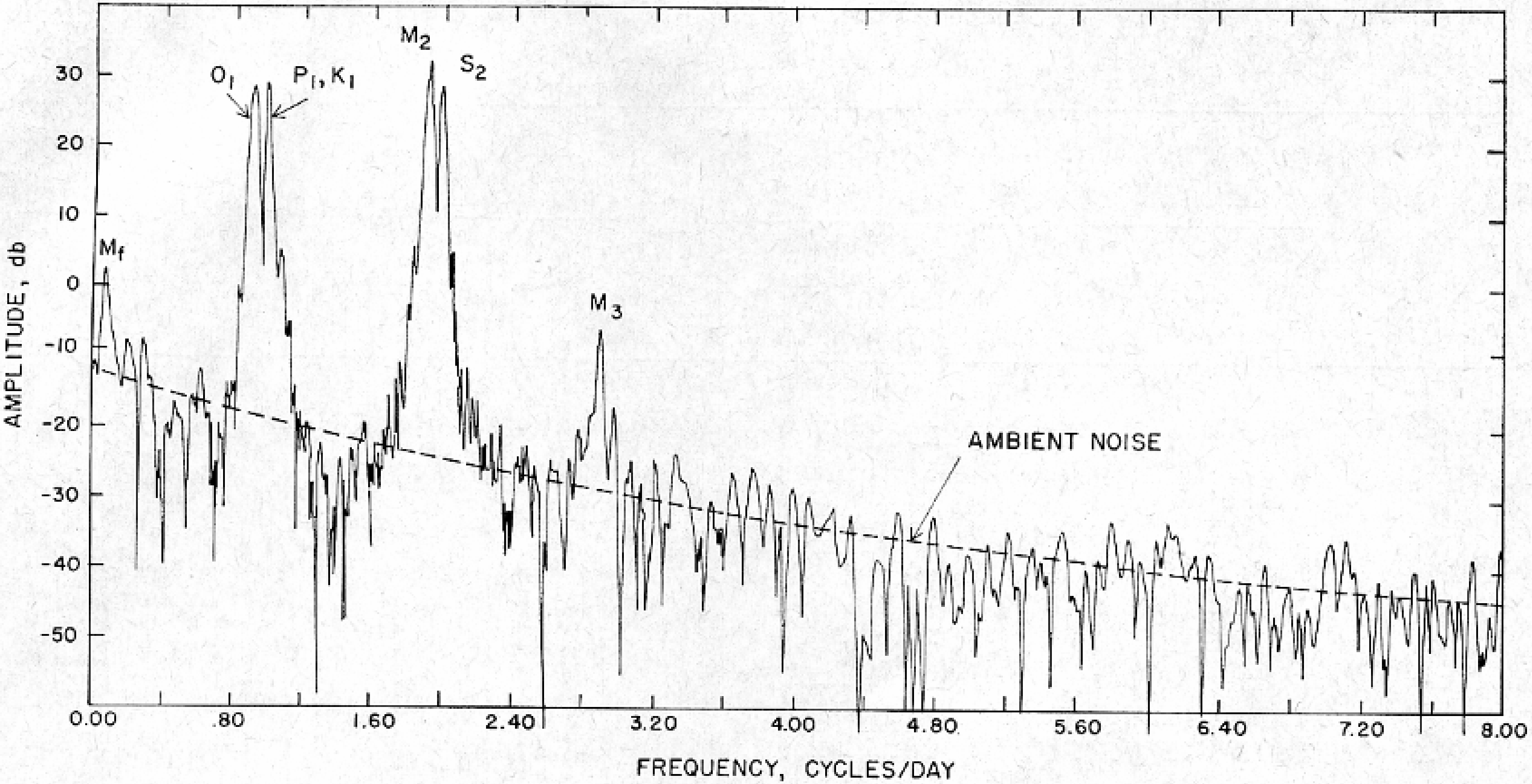


Fig. 4. Fourier spectrum of the data of run 2. Here 0 db corresponds to approximately 2 μgal^2 or a power spectral density of 10^{+3} μgal/cph.

the second topic

normal modes analysis!
Kamchatka 7.1

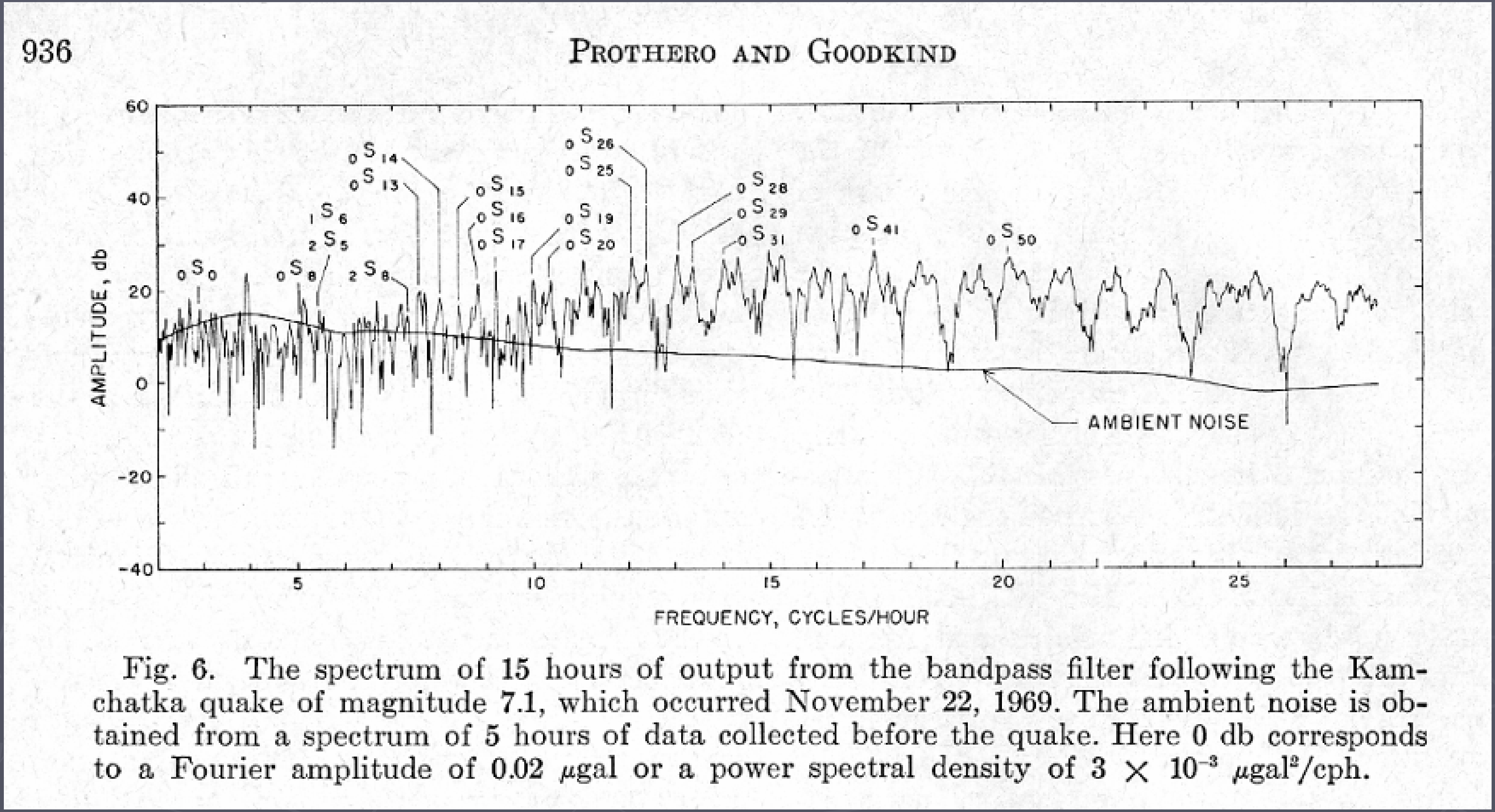


Fig. 6. The spectrum of 15 hours of output from the bandpass filter following the Kamchatka quake of magnitude 7.1, which occurred November 22, 1969. The ambient noise is obtained from a spectrum of 5 hours of data collected before the quake. Here 0 db corresponds to a Fourier amplitude of 0.02 μgal or a power spectral density of 3×10^{-3} μgal^2/cph.

SG beginnings - GWR

Warburton, R. J., Beaumont, C., and Goodkind, J. M., 1975. The effect of ocean tide loading on tides of the solid earth observed with the superconducting gravimeter, *Geophys. J. R. astr. Soc.,* **43**, 707-720.

30 yr

Warburton, R. J., and Goodkind, J. M., 1977. The influence of barometric-pressure variations on gravity, *Geophys. J. R. astr. Soc.,* **48**, 281-292.

Warburton, R. J., and Goodkind, J. M., 1978. Detailed gravity-tide spectrum between one and four cycles per day, *Geophys. J. R. astr. Soc.*, **52**, 117-136.

(these 3 papers should be on the reading list of all SG researchers)

The Gamblers

formed GWR in 1979 as a commercial venture

John Goodkind

- the inventor

Richard Warburton

– the innovator

Richard Reineman

– the backroom wizard

The Pioneers

purchased and installed instruments

Paul Melchior (1981)
Bernd Richter (1981,85)

Hou-Tse Hsu (1986)
Jacques Hinderer (1987)

Shanghai Observatory 1981

Visite du Roi Baudouin
à l'Observatoire de Shanghai en 1981.

Early SG Installations 1981-89

- Richter – first SG installed at Bad Homburg (near Frankfurt), former wine cellar of castle

Models TT40 (1981) and TT60 (1985)

and the first parallel recording over a period of 10 months, showing agreement to a few 0.1 uGal

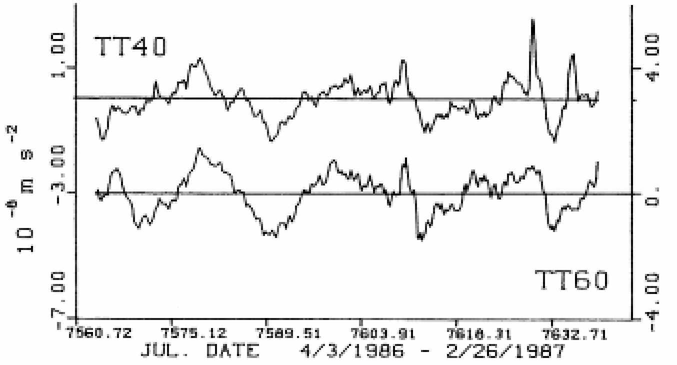


Fig. 4. Residuals of the analysis of parallelregistration of SCG TT40 and SCG TT60 .

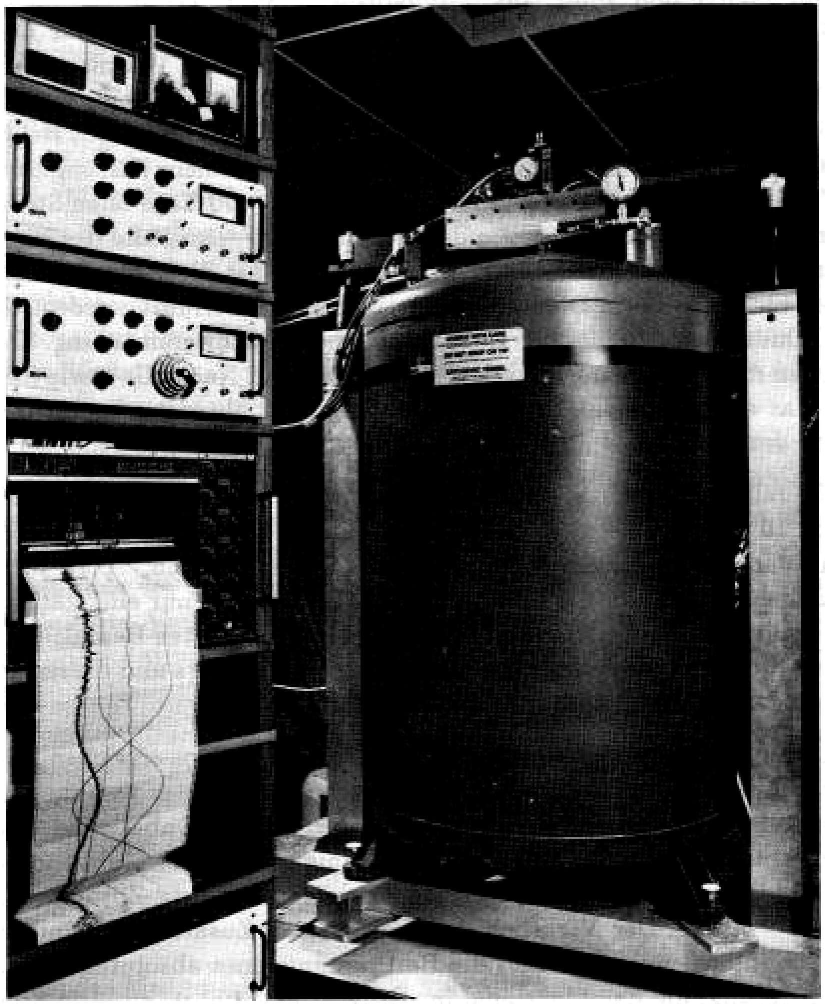
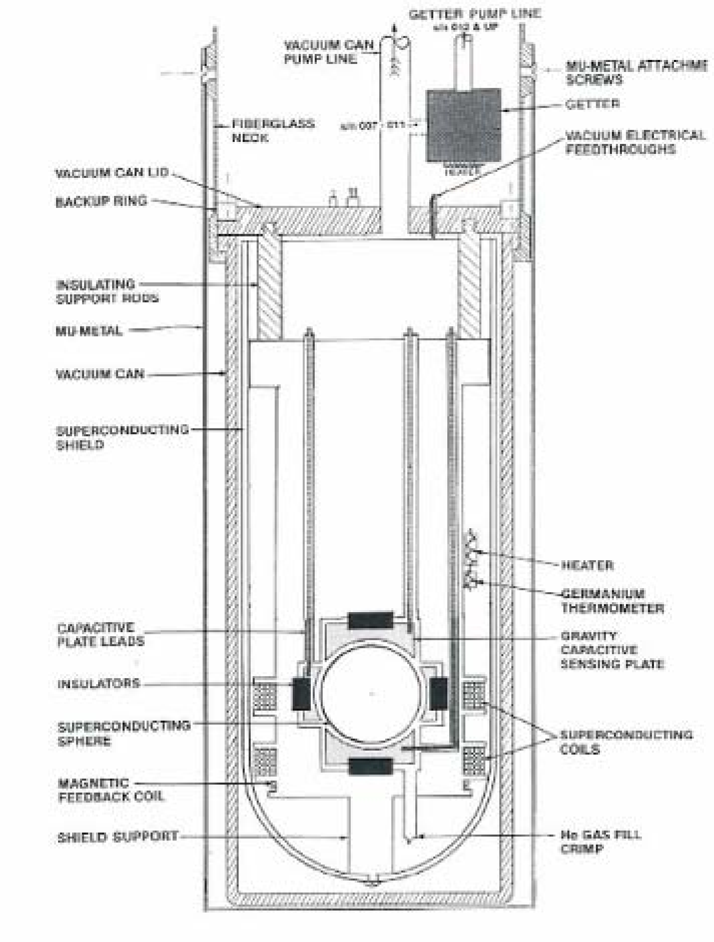


Abbildung 1.1: Das GWR supraleitende Gravimeter TT60 mit Steuerelektronik

… and inside


GETTER PUMP LINE
s/n 012 & UP
VACUUM CAN
PUMP LINE
MU-METAL ATTACHME
SCREWS
GETTER
FIBERGLASS
NECK
s/n 007 - 011
VACUUM ELECTRICAL
FEEDTHROUGHS
VACUUM CAN LID
BACKUP RING
INSULATING
SUPPORT RODS
MU-METAL
VACUUM CAN
SUPERCONDUCTING
SHIELD
HEATER
GERMANIUM
THERMOMETER
CAPACITIVE
PLATE LEADS
GRAVITY
CAPACITIVE
SENSING PLATE
INSULATORS
SUPERCONDUCTING
SPHERE
SUPERCONDUCTING
COILS
MAGNETIC
FEEDBACK COIL
SHIELD SUPPORT
He GAS FILL
CRIMP

… compare to modern version 2007

MunGyung,
Hsinchu …

a notable publication of this era by B. Richter

DEUTSCHE GEODÄTISCHE KOMMISSION
bei der Bayerischen Akademie der Wissenschaften

Reihe C: Dissertationen — Heft Nr. 329

Mitteilung Nr. 176
DES INSTITUTS FÜR ANGEWANDTE GEODÄSIE
(Abt. II des Deutschen Geodätischen Forschungsinstituts)
ISSN 0071—9196

DK 528.563.089.6
528.026.3.06
537.312.62(043.3)

Das supraleitende Gravimeter

Anwendung, Eichung und Überlegungen zur Weiterentwicklung

Inauguraldissertation
zur Erlangung des Grades
Doktor-Ingenieur
(Dr.-Ing.)
der
Hohen Landwirtschaftlichen Fakultät
der
Rheinischen Friedrich-Wilhelms-Universität
zu Bonn

vorgelegt von
Dipl.-Ing. Bernd Richter
aus Rückingen

1987

VERLAG DES INSTITUTS FÜR ANGEWANDTE GEODÄSIE
FRANKFURT AM MAIN

Start of 20 yr retrospective

Variation of local pressure admittance

amplitude and phase variations with frequency

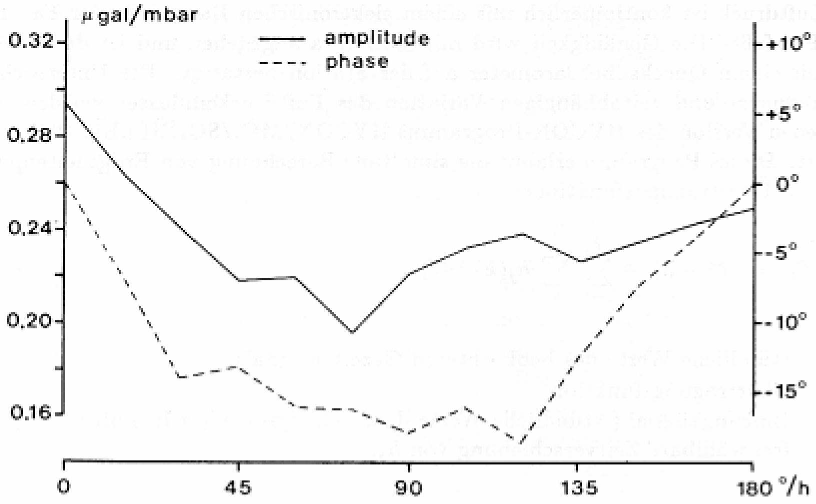


Abbildung 5.12: Frequenzabhängiger Luftdruckregressionskoeffizient

amplitude variation with time

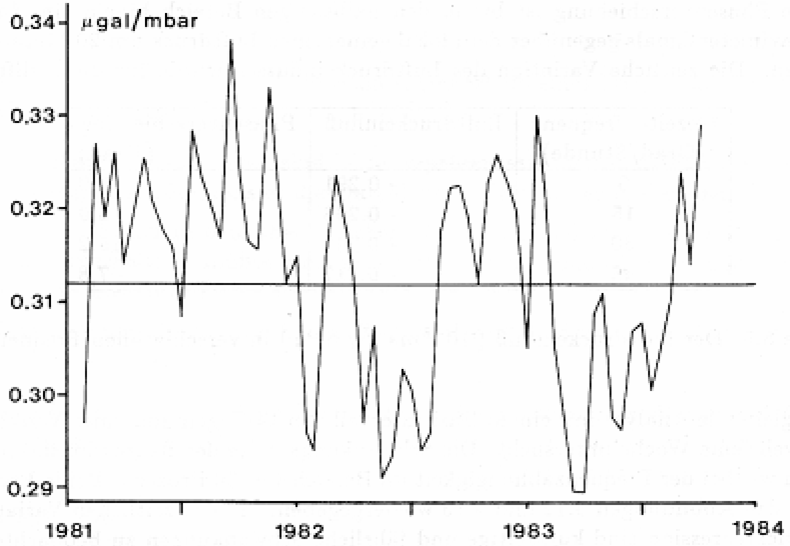
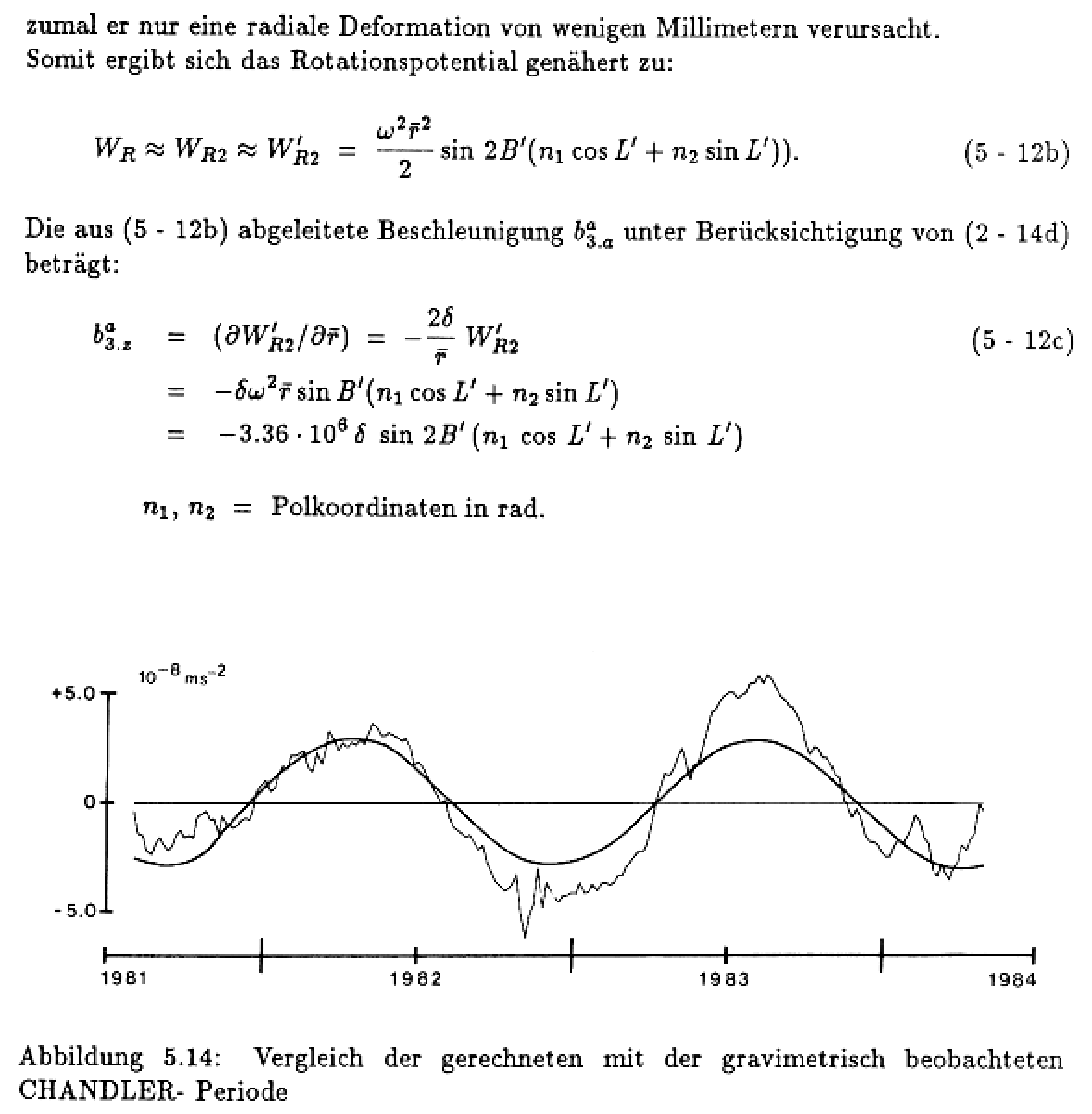


Abbildung 5.13: Zeitabhängiger Luftdruckregressionskoeffizient

... and the famous variation of gravity due to polar motion



zumal er nur eine radiale Deformation von wenigen Millimetern verursacht. Somit ergibt sich das Rotationspotential genähert zu:

$$W_R \approx W_{R2} \approx W'_{R2} = \frac{\omega^2 \bar{r}^2}{2} \sin 2B'(n_1 \cos L' + n_2 \sin L')). \qquad (5 - 12b)$$

Die aus (5 - 12b) abgeleitete Beschleunigung $b^a_{3.a}$ unter Berücksichtigung von (2 - 14d) beträgt:

$$\begin{aligned} b^a_{3.z} &= (\partial W'_{R2}/\partial \bar{r}) = -\frac{2\delta}{\bar{r}} W'_{R2} \qquad (5 - 12c) \\ &= -\delta \omega^2 \bar{r} \sin B'(n_1 \cos L' + n_2 \sin L') \\ &= -3.36 \cdot 10^6 \, \delta \, \sin 2B' \, (n_1 \, \cos \, L' + n_2 \, \sin \, L') \end{aligned}$$

n_1, n_2 = Polkoordinaten in rad.

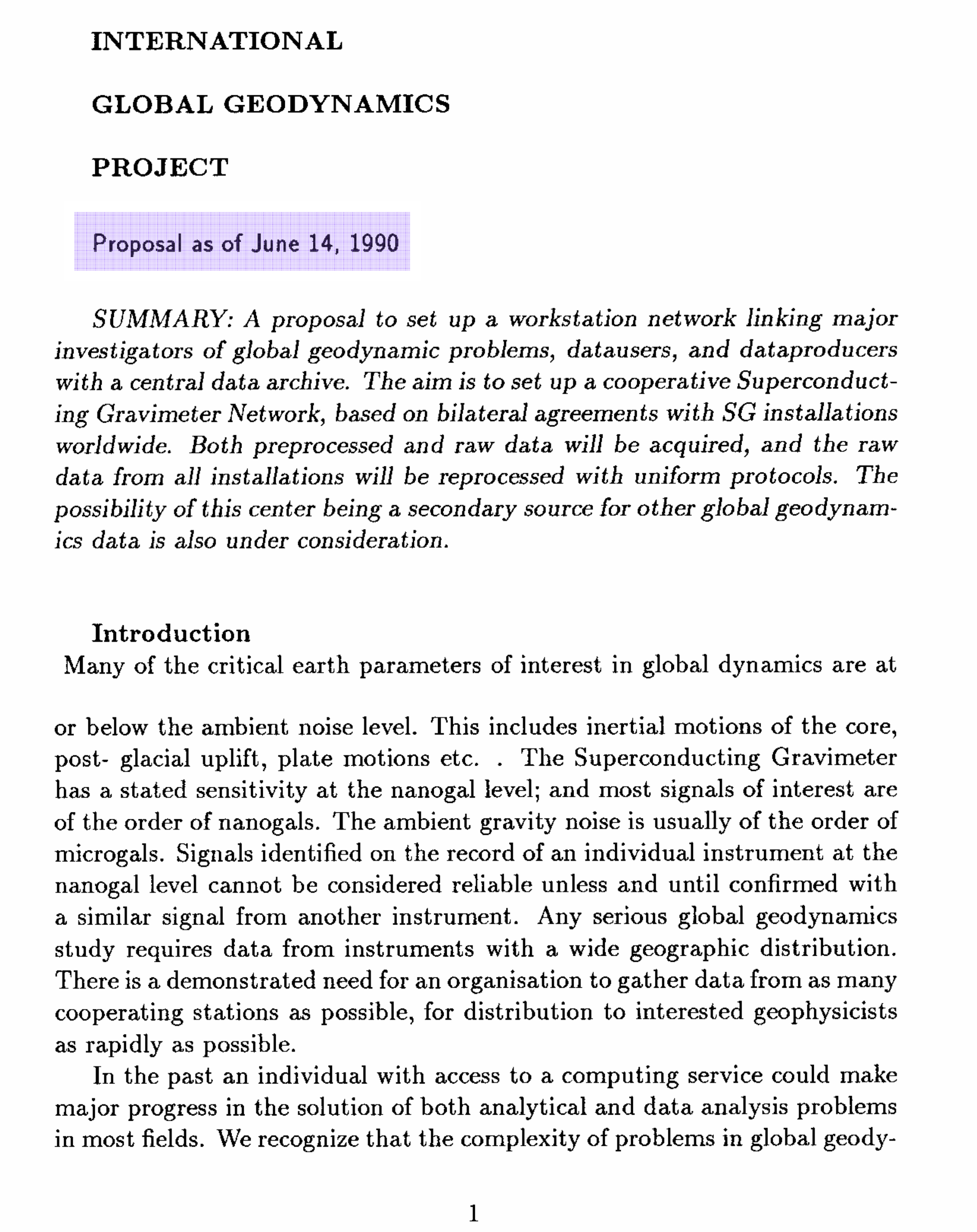
Abbildung 5.14: Vergleich der gerechneten mit der gravimetrisch beobachteten CHANDLER- Periode

Canadian SG (Cantley, 1989)

- delicate electronics in humidity controlled rack
- gravimeter and levellers surrounded by styrofoam insulation (here partially removed) to protect from room temperature changes (± 3º C)
- yes there is air conditioning

Reinstallation 1995

1990-96, start of GGP



INTERNATIONAL

GLOBAL GEODYNAMICS

PROJECT

Proposal as of June 14, 1990

SUMMARY: A proposal to set up a workstation network linking major investigators of global geodynamic problems, datausers, and dataproducers with a central data archive. The aim is to set up a cooperative Superconducting Gravimeter Network, based on bilateral agreements with SG installations worldwide. Both preprocessed and raw data will be acquired, and the raw data from all installations will be reprocessed with uniform protocols. The possibility of this center being a secondary source for other global geodynamics data is also under consideration.

Introduction

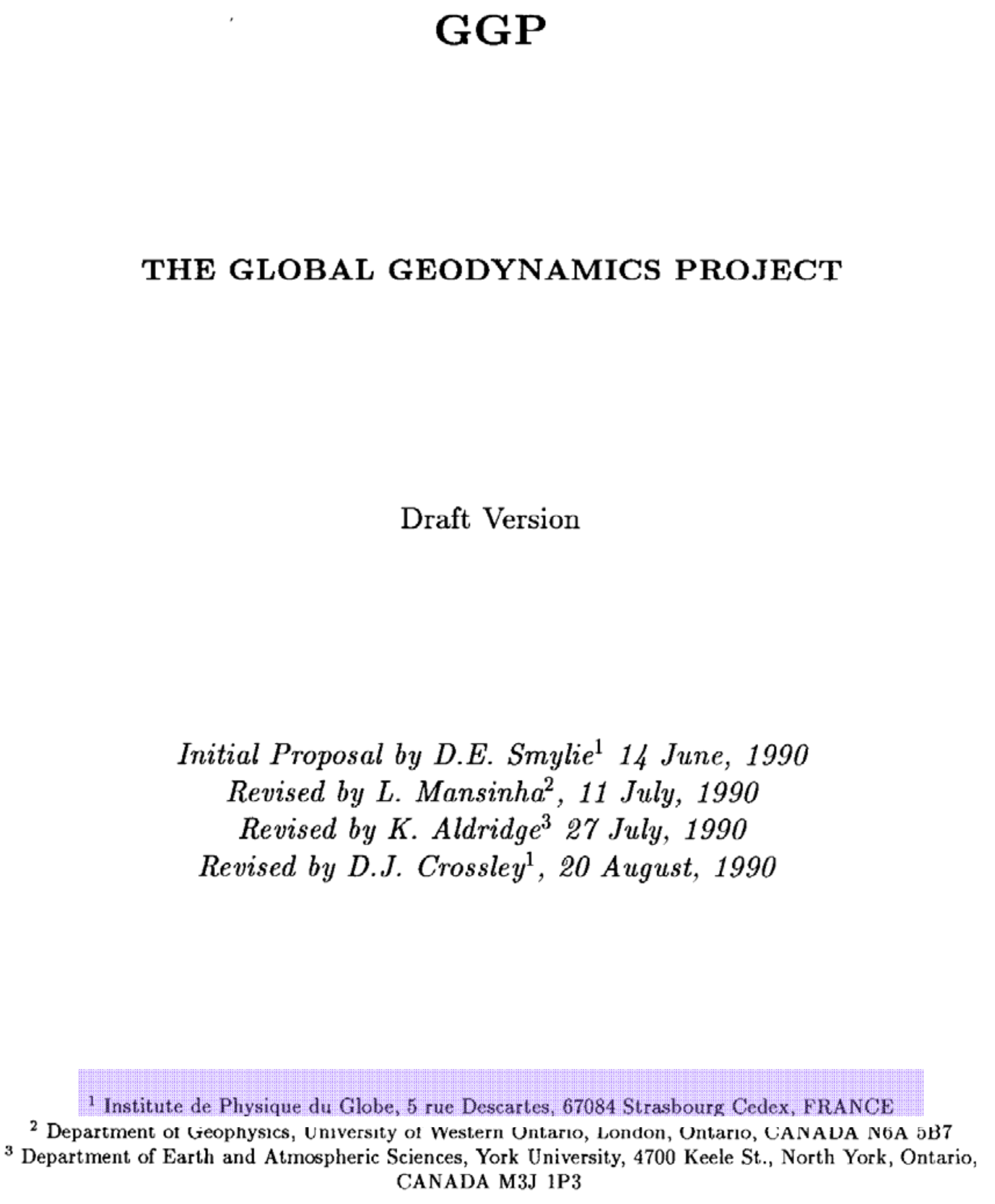
Many of the critical earth parameters of interest in global dynamics are at

or below the ambient noise level. This includes inertial motions of the core, post- glacial uplift, plate motions etc. . The Superconducting Gravimeter has a stated sensitivity at the nanogal level; and most signals of interest are of the order of nanogals. The ambient gravity noise is usually of the order of microgals. Signals identified on the record of an individual instrument at the nanogal level cannot be considered reliable unless and until confirmed with a similar signal from another instrument. Any serious global geodynamics study requires data from instruments with a wide geographic distribution. There is a demonstrated need for an organisation to gather data from as many cooperating stations as possible, for distribution to interested geophysicists as rapidly as possible.

In the past an individual with access to a computing service could make major progress in the solution of both analytical and data analysis problems in most fields. We recognize that the complexity of problems in global geody-

2 months later …

… at Strasbourg!



GGP

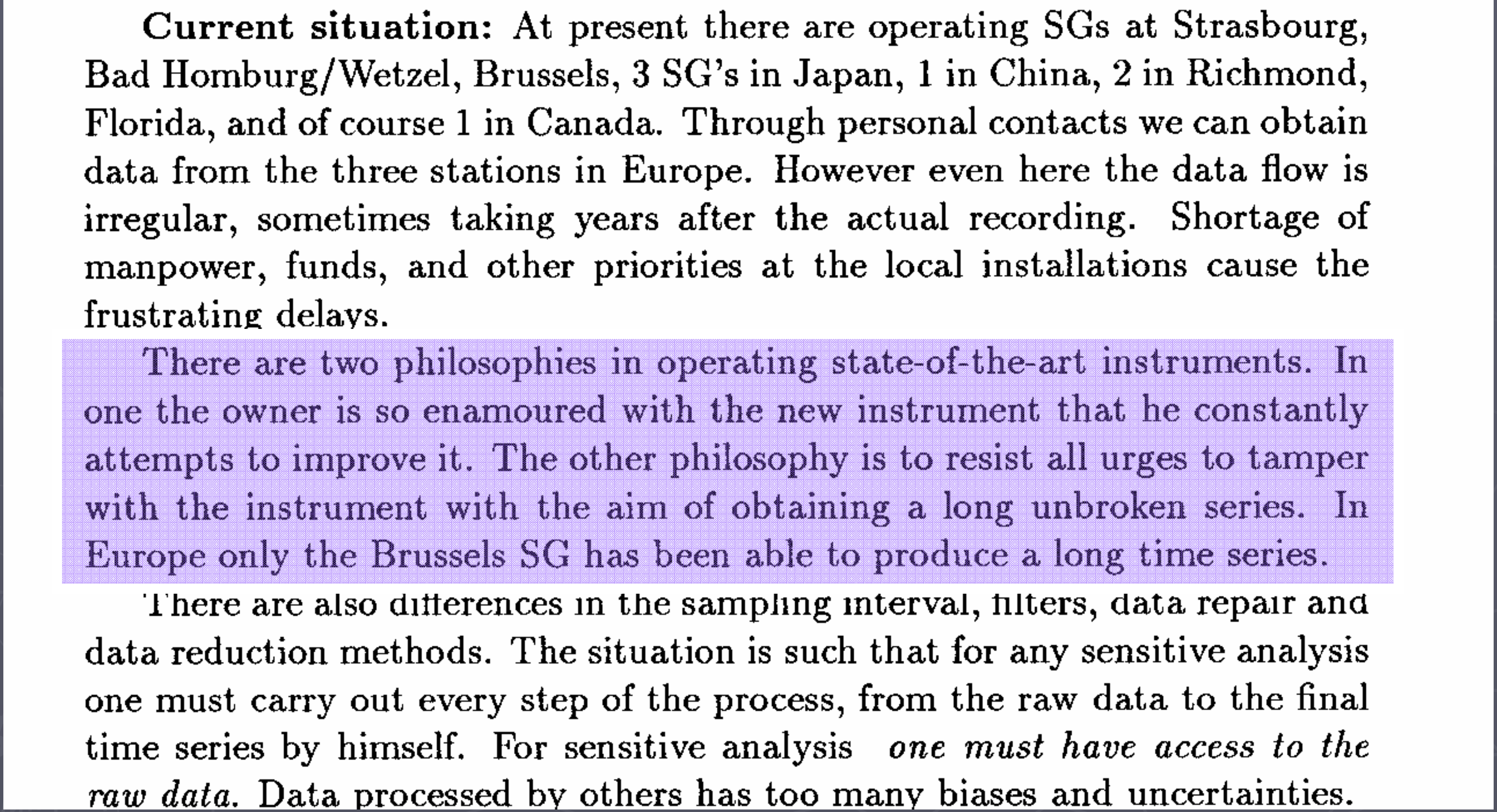
THE GLOBAL GEODYNAMICS PROJECT

Draft Version

Initial Proposal by D.E. Smylie[1] *14 June, 1990*
Revised by L. Mansinha[2]*, 11 July, 1990*
Revised by K. Aldridge[3] *27 July, 1990*
Revised by D.J. Crossley[1]*, 20 August, 1990*

[1] Institute de Physique du Globe, 5 rue Descartes, 67084 Strasbourg Cedex, FRANCE
[2] Department of Geophysics, University of Western Ontario, London, Ontario, CANADA N6A 5B7
[3] Department of Earth and Atmospheric Sciences, York University, 4700 Keele St., North York, Ontario, CANADA M3J 1P3

some of the rationale …

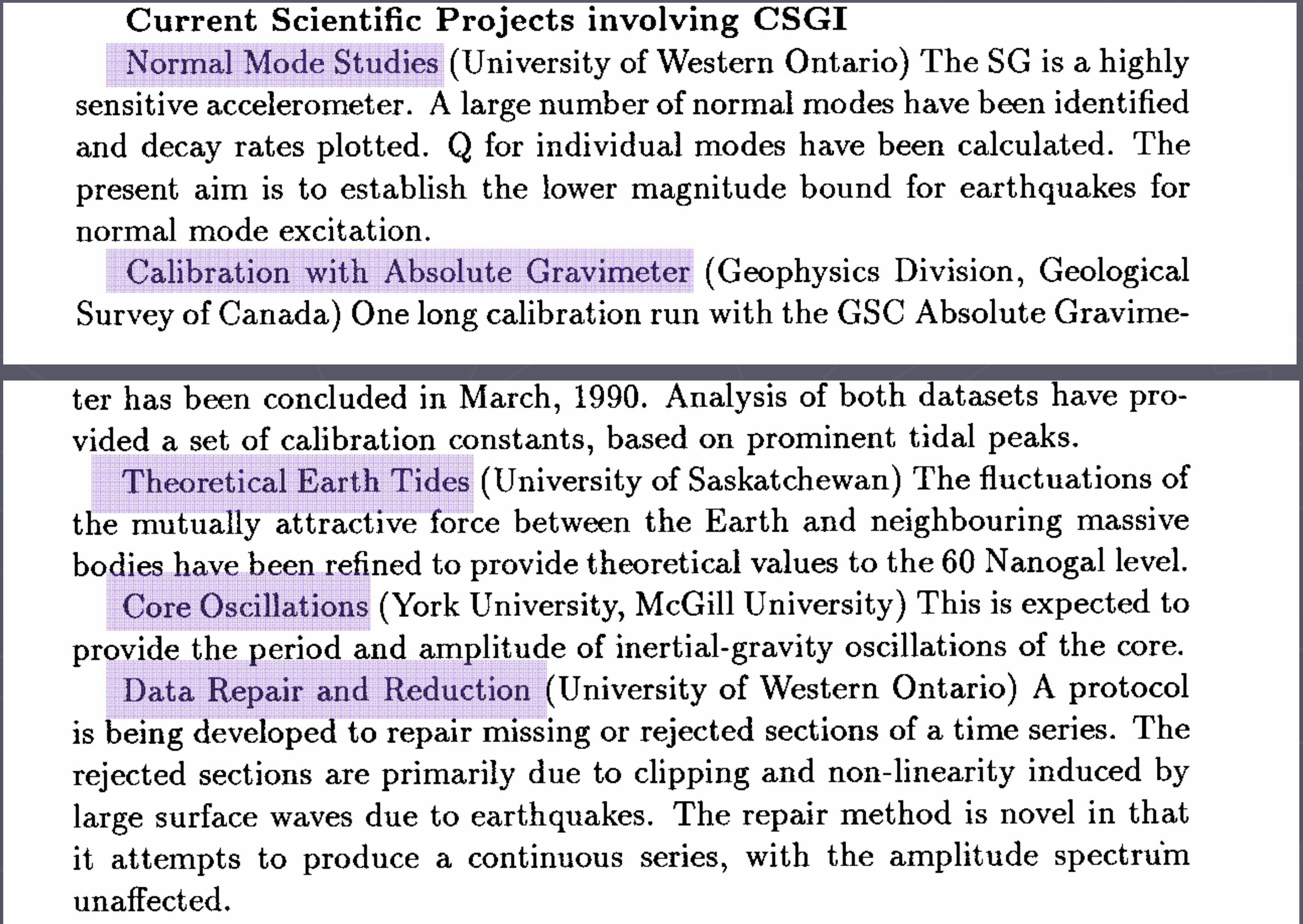


Current situation: At present there are operating SGs at Strasbourg, Bad Homburg/Wetzel, Brussels, 3 SG's in Japan, 1 in China, 2 in Richmond, Florida, and of course 1 in Canada. Through personal contacts we can obtain data from the three stations in Europe. However even here the data flow is irregular, sometimes taking years after the actual recording. Shortage of manpower, funds, and other priorities at the local installations cause the frustrating delays.

There are two philosophies in operating state-of-the-art instruments. In one the owner is so enamoured with the new instrument that he constantly attempts to improve it. The other philosophy is to resist all urges to tamper with the instrument with the aim of obtaining a long unbroken series. In Europe only the Brussels SG has been able to produce a long time series.

There are also differences in the sampling interval, filters, data repair and data reduction methods. The situation is such that for any sensitive analysis one must carry out every step of the process, from the raw data to the final time series by himself. For sensitive analysis *one must have access to the raw data*. Data processed by others has too many biases and uncertainties.

initial studies



Current Scientific Projects involving CSGI

Normal Mode Studies (University of Western Ontario) The SG is a highly sensitive accelerometer. A large number of normal modes have been identified and decay rates plotted. Q for individual modes have been calculated. The present aim is to establish the lower magnitude bound for earthquakes for normal mode excitation.

Calibration with Absolute Gravimeter (Geophysics Division, Geological Survey of Canada) One long calibration run with the GSC Absolute Gravimeter has been concluded in March, 1990. Analysis of both datasets have provided a set of calibration constants, based on prominent tidal peaks.

Theoretical Earth Tides (University of Saskatchewan) The fluctuations of the mutually attractive force between the Earth and neighbouring massive bodies have been refined to provide theoretical values to the 60 Nanogal level.

Core Oscillations (York University, McGill University) This is expected to provide the period and amplitude of inertial-gravity oscillations of the core.

Data Repair and Reduction (University of Western Ontario) A protocol is being developed to repair missing or rejected sections of a time series. The rejected sections are primarily due to clipping and non-linearity induced by large surface waves due to earthquakes. The repair method is novel in that it attempts to produce a continuous series, with the amplitude spectrum unaffected.

GGP today

GGP is now an Inter - Commission Project of IAG (like WEGENER)

reports to:

Commission 3 – Earth Rotation and Geodynamics
Commission 2 – The Gravity Field
(Inter Commission Project 3.1)

until IUGG 2007:

Chair: D. Crossley
Secretary: J. Hinderer

activities:

Meetings: 1 per year (next - IUGG Perugia)
Workshops: 1 every year or two (Hsinchu)
Newsletters: as needed

GGP mission

- maintain standards for SG instrument siting and data recording
- provide means for data exchange and accessibility
- foster discussion of scientific issues

Scientific goals have not changed

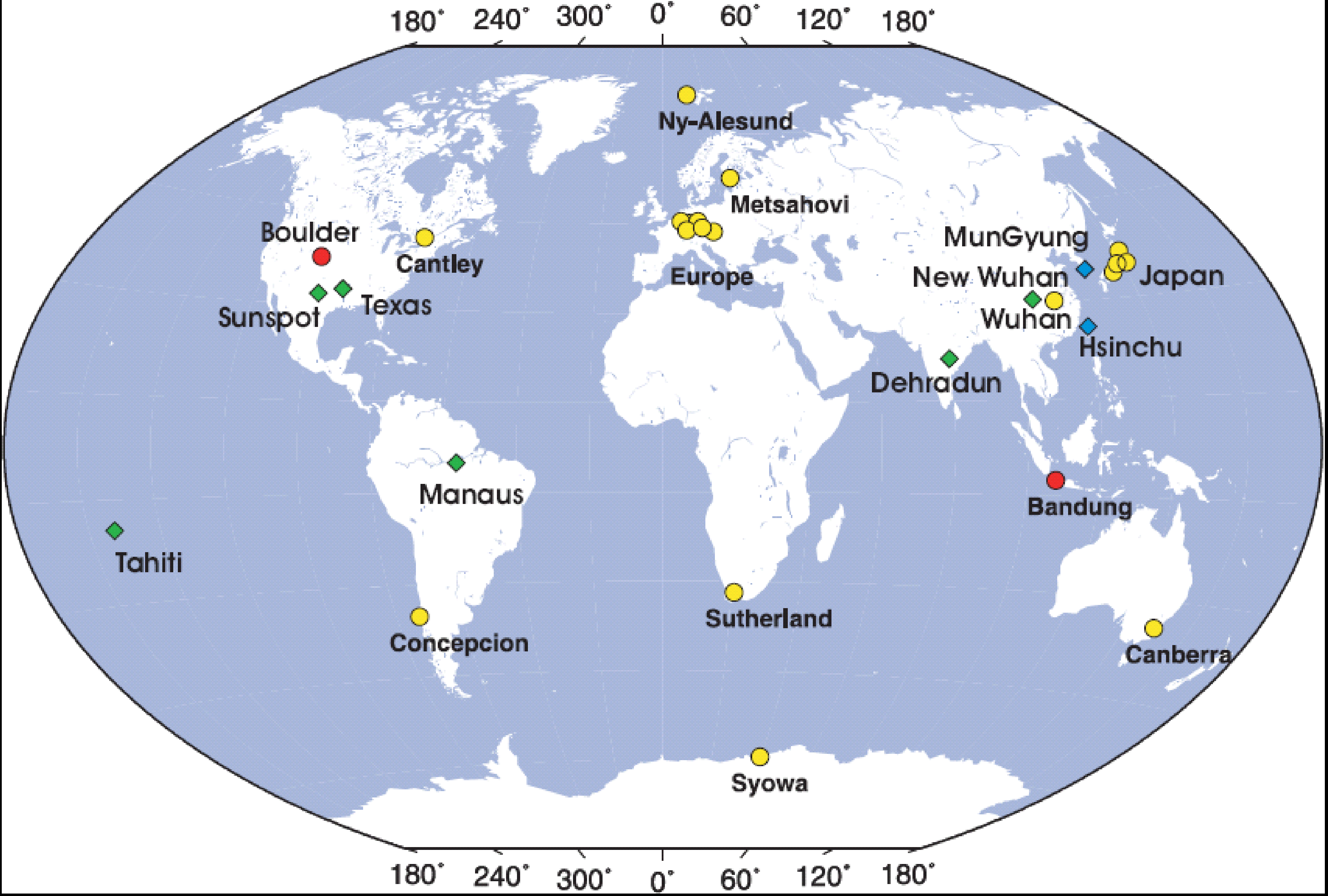
- studies of solid earth and ocean tides and tidal loading
- atmospheric pressure changes to gravity
- earthquakes and normal modes
- geodynamics processes, e.g. sea level changes
- hydrology at various length and time scales
- seasonal variations, and long-term tectonics

Table 1. SG stations of the GGP Network, as of 5 March 2007
Most recent coordinates are given

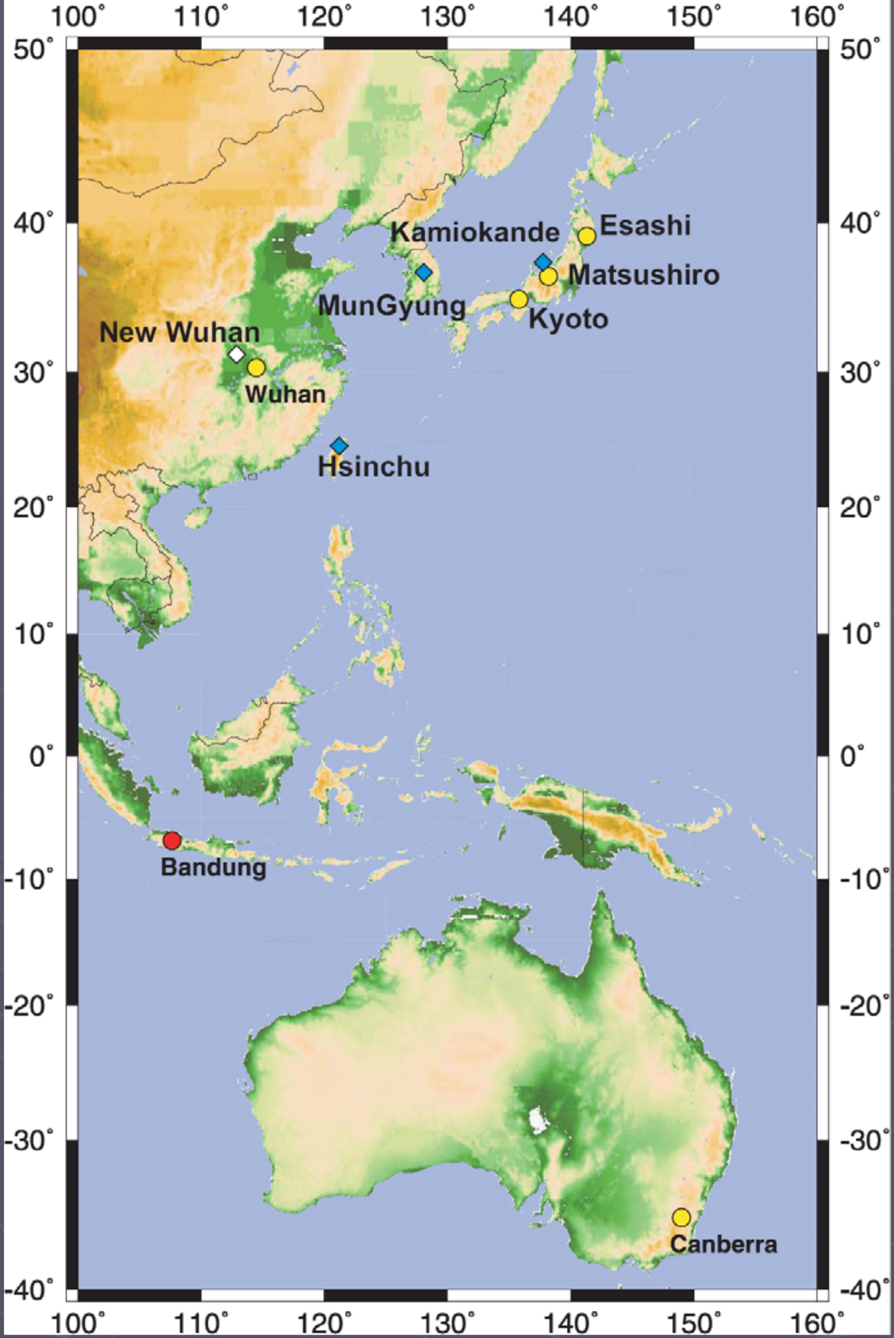
						installed	
						2006	**2007**
#	**Code**	**Location**	**Country**	**Responsible**	**Institute**	**Latitude**	**Long**
						+N, -S	+E, -W
1	**BA**	Bandung	Indonesia	Y. Fukuda	Kyoto U.	-6.8964	107.6317
2	**BH**	Bad Homburg	Germany	H. Wilmes	BKG Frankfurt	50.2285	8.6113
3	**CA**	Cantley	Canada	J. Liard	GSC Ottawa	45.5850	284.1929
4	**CB**	Canberra	Australia	T. Sato	NAO Mizusawa	-35.3206	149.0077
5	**ES**	Esashi	Japan	T. Sato	NAO Mizusawa	39.1511	141.3318
6	**HS**	Hsinchu	Taiwan	C. Hwang	Nat. Chiao Tung U.	24.7890	120.9710
7	**KA**	Kamioka	Japan	T. Sato	NAO Mizusawa	36.4250	137.3100
8	**KY**	Kyoto	Japan	Y. Fukuda	Kyoto U.	35.0278	135.7858
9	**MA**	Matsuchiro	Japan	Y. Imanishi	U. Tokyo	36.5430	138.2070
10	**MB**	Membach	Belgium	M. van Camp	ROB Brussels	50.6093	6.0066
11	**MC**	Medicina	Italy	H. Wilmes	BKG Frankfurt	44.5219	11.6450
12	**ME**	Metsahovi	Finland	H. Virtanen	FGI Masala	60.2172	24.3958
13	**MG**	MunGyung	S. Korea	J.-W. Kim	Sejong U.	36.6402	128.2147
14	**MO**	Moxa	Germany	C. Kroner	FSU Jena	50.6447	11.6156
15	**NY**	Ny-Alesund	Norway	T. Sato	NAO Mizusawa	78.9306	11.8672
16	**ST**	Strasbourg	France	J. Hinderer	EOST Strasbourg	48.6217	7.6838
17	**SU**	Sutherland	S. Africa	J. Neumeyer	GFZ Potsdam	-32.3814	20.8109
18	**SY**	Syowa	Antarctica	K. Shibuya	NIPR Tokyo	-69.0067	39.5857
19	**TC**	Concepcion	Chile	H. Wilmes	BKG Frankfurt	-36.8437	286.9745
20	**VI**	Vienna	Austria	B. Meurers	U. Vienna	48.2493	16.3579
21	**WA**	Walferdange	Luxembourg	O. Francis	MNH Walferdange	49.6650	6.1530
22	**WE**	Wettzell	Germany	H. Wilmes	BKG Frankfurt	49.1440	12.8780
23	**WU**	Wuhan	China	H.-P. Sun	IGG Wuhan	30.5159	114.4898
24	**PE?**	Pecny	Czech Rep.		Geodetic Obs. Pecny	49.9170	14.7830
26		Derhadun	India		Wadia Inst. Himal. Geol.	30.3170	78.0660
25		Wuhan	China		China Earthquake Admin.	30.5100	114.4900
27		Manaus?	Brazil		GFZ Potsdam	-3.0100	-60.0000
28		Austin	USA	C. Wilson	U. Texas at Austin	30.2900	-97.7400
29		Sunspot NM	USA		Lunar Laser Ranging	32.7660	-105.8200
30		Tahiti	France	J. Hinderer	EOST Strasbourg	-17.5769	-149.6063

Superconducting Gravimeters

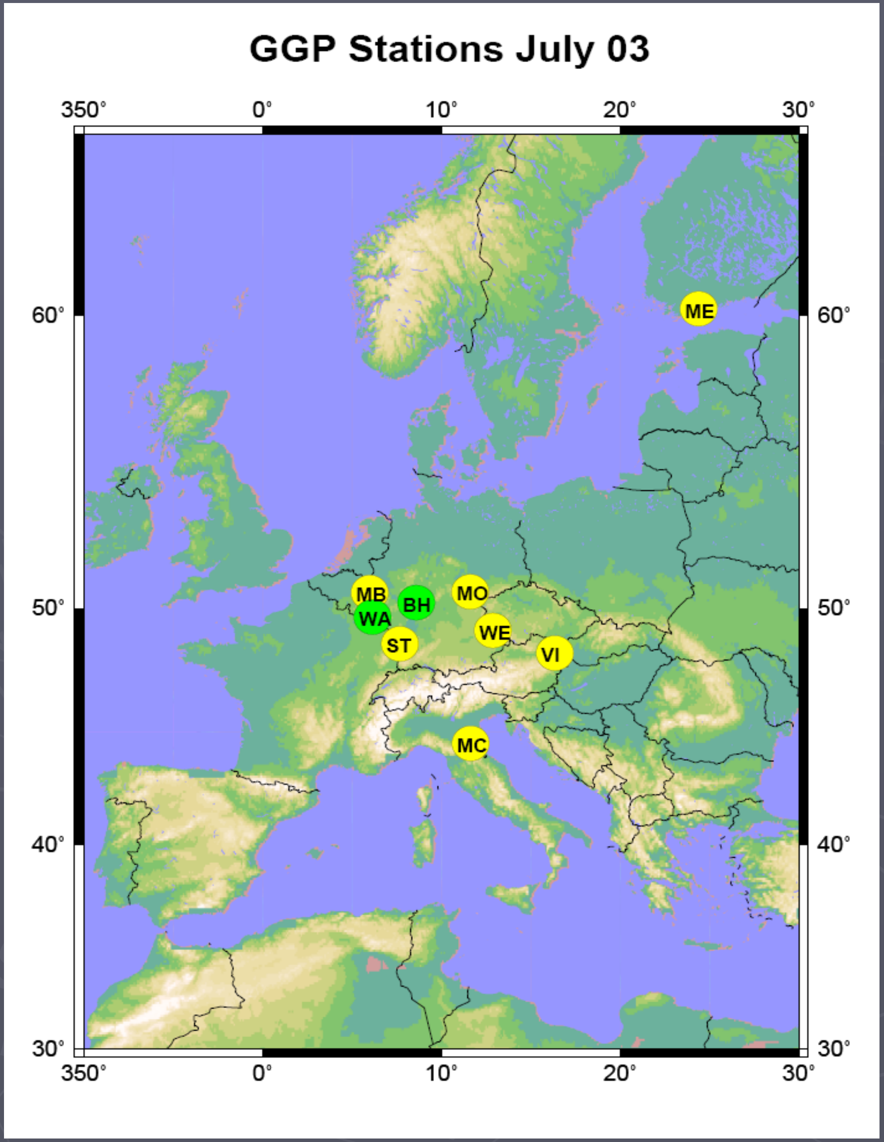
GGP Stations - Current and Planned

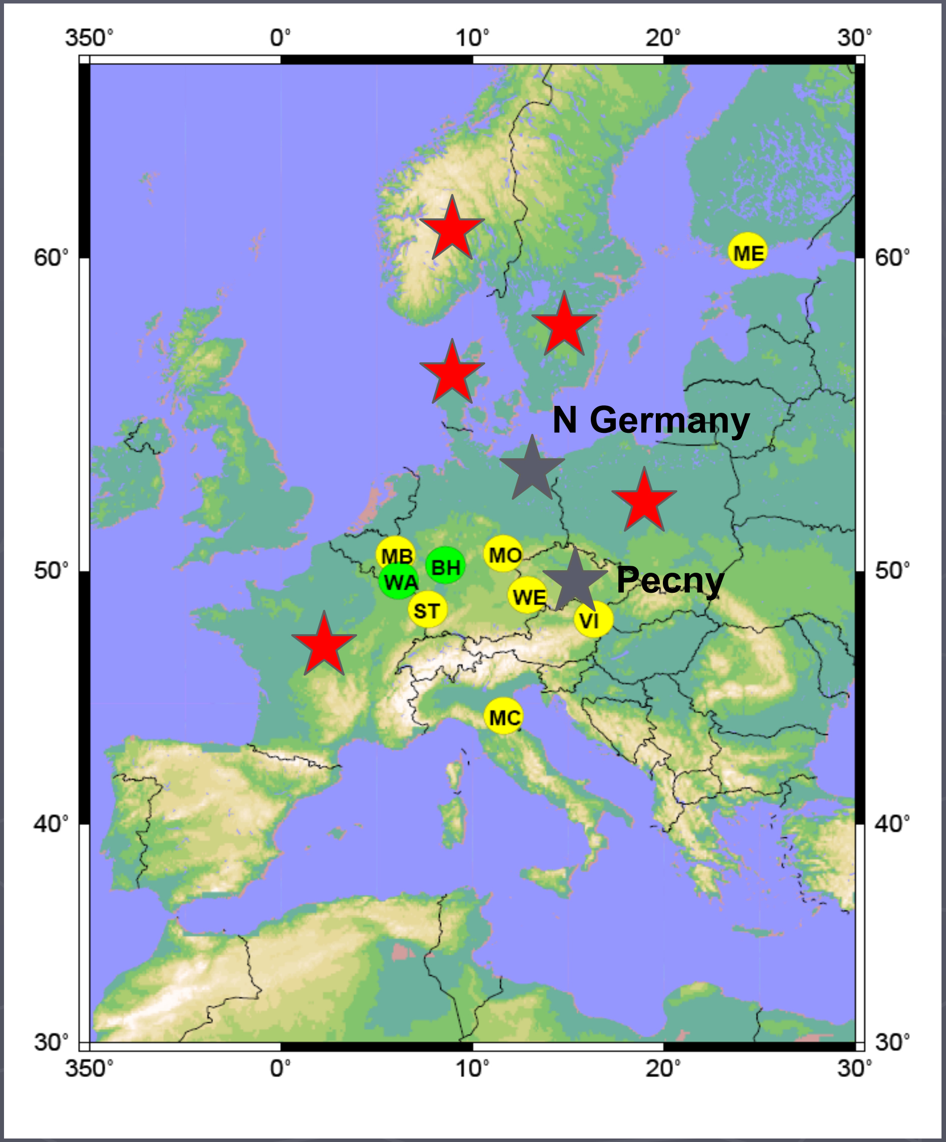


GGP Stations in Asia

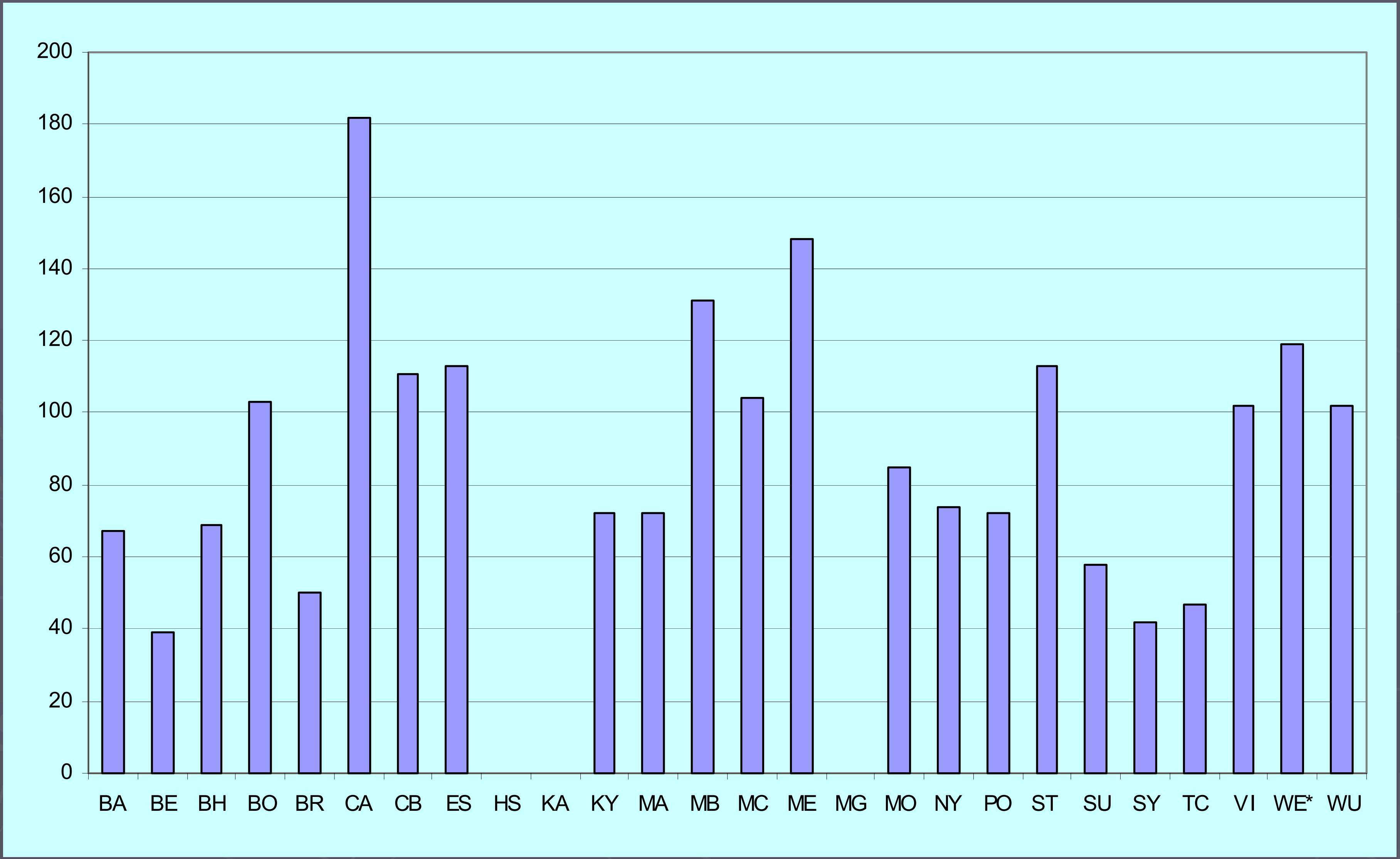


Current European SGs, and possible network extensions

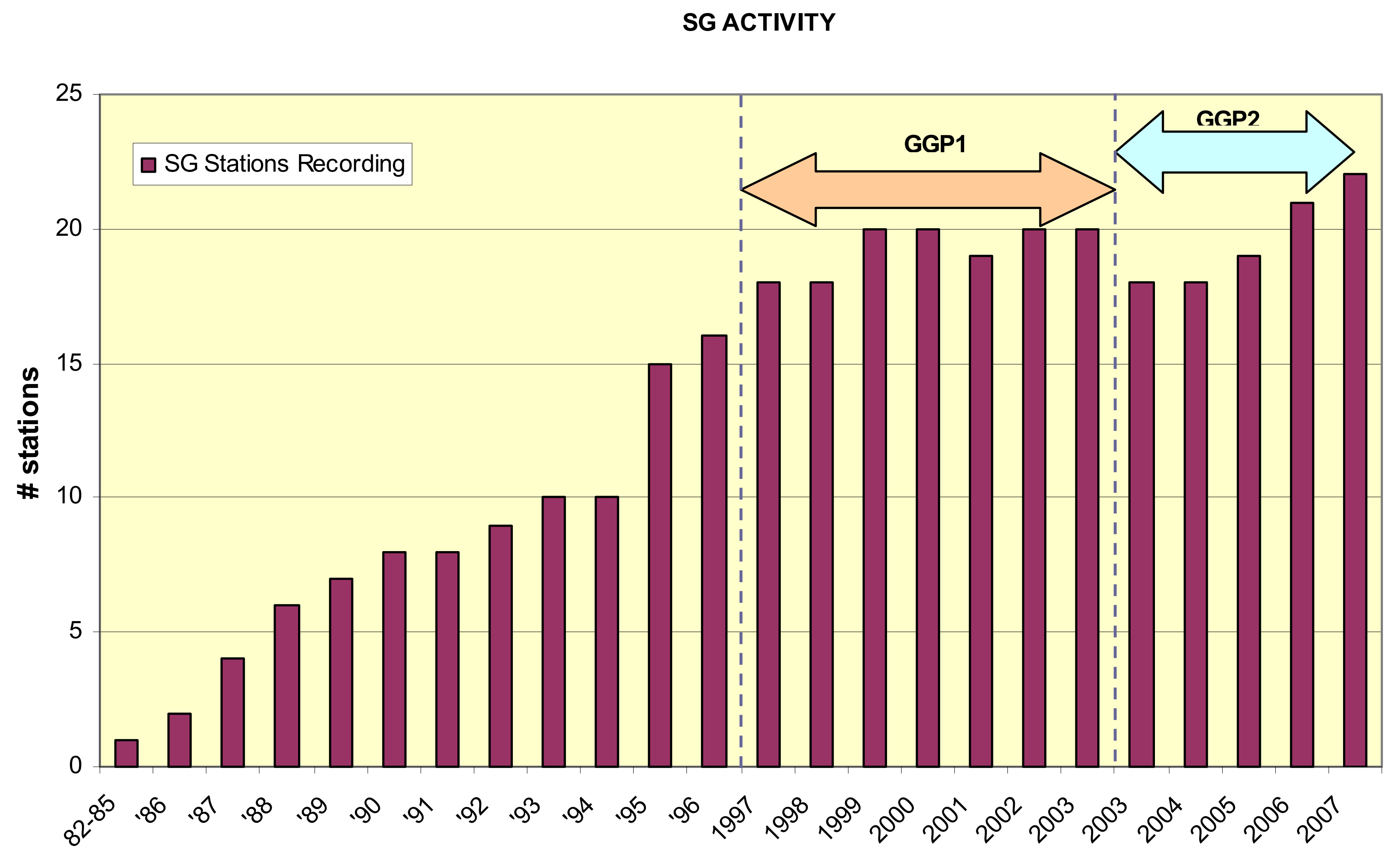




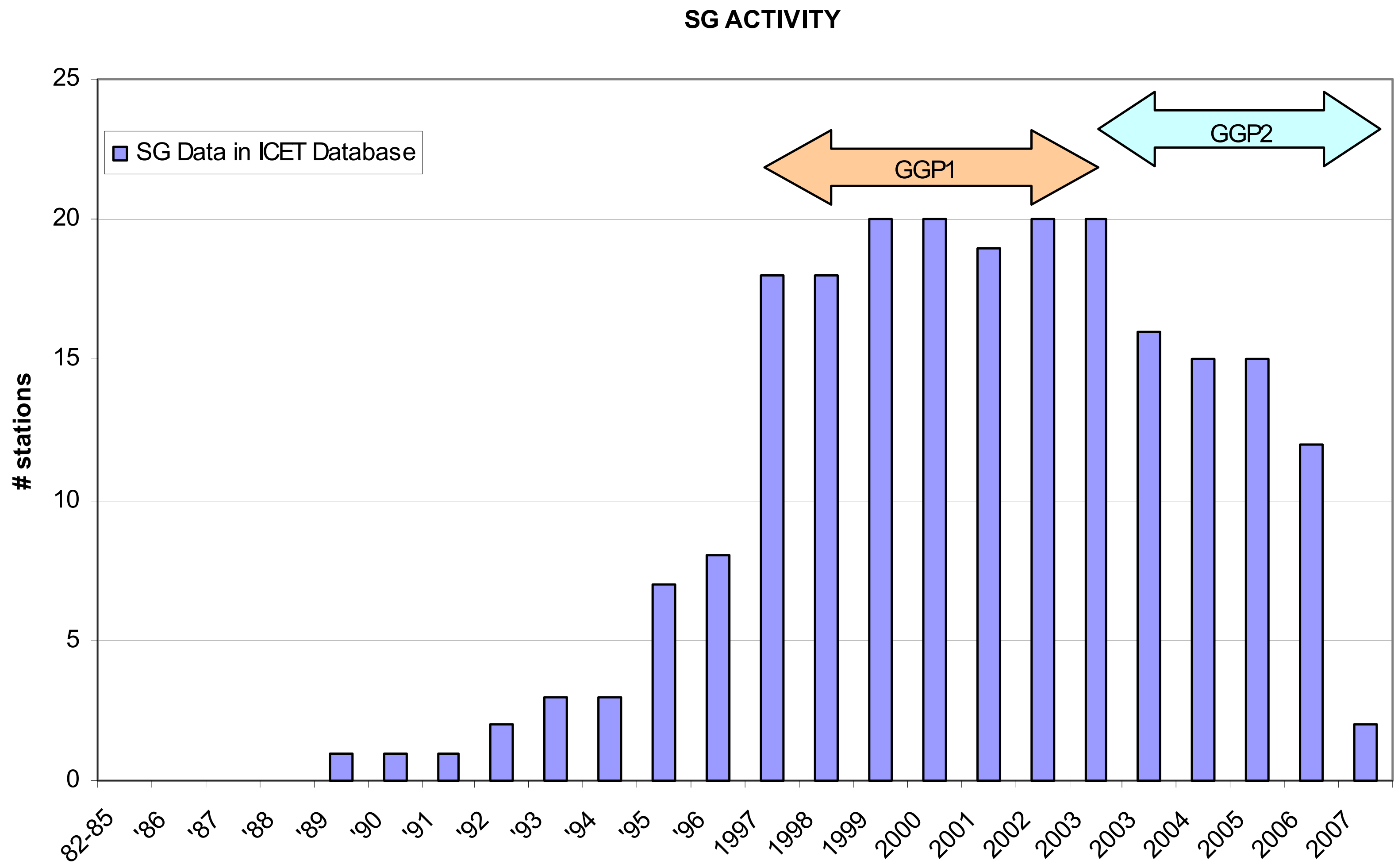
Months of data at ICET for GGP stations



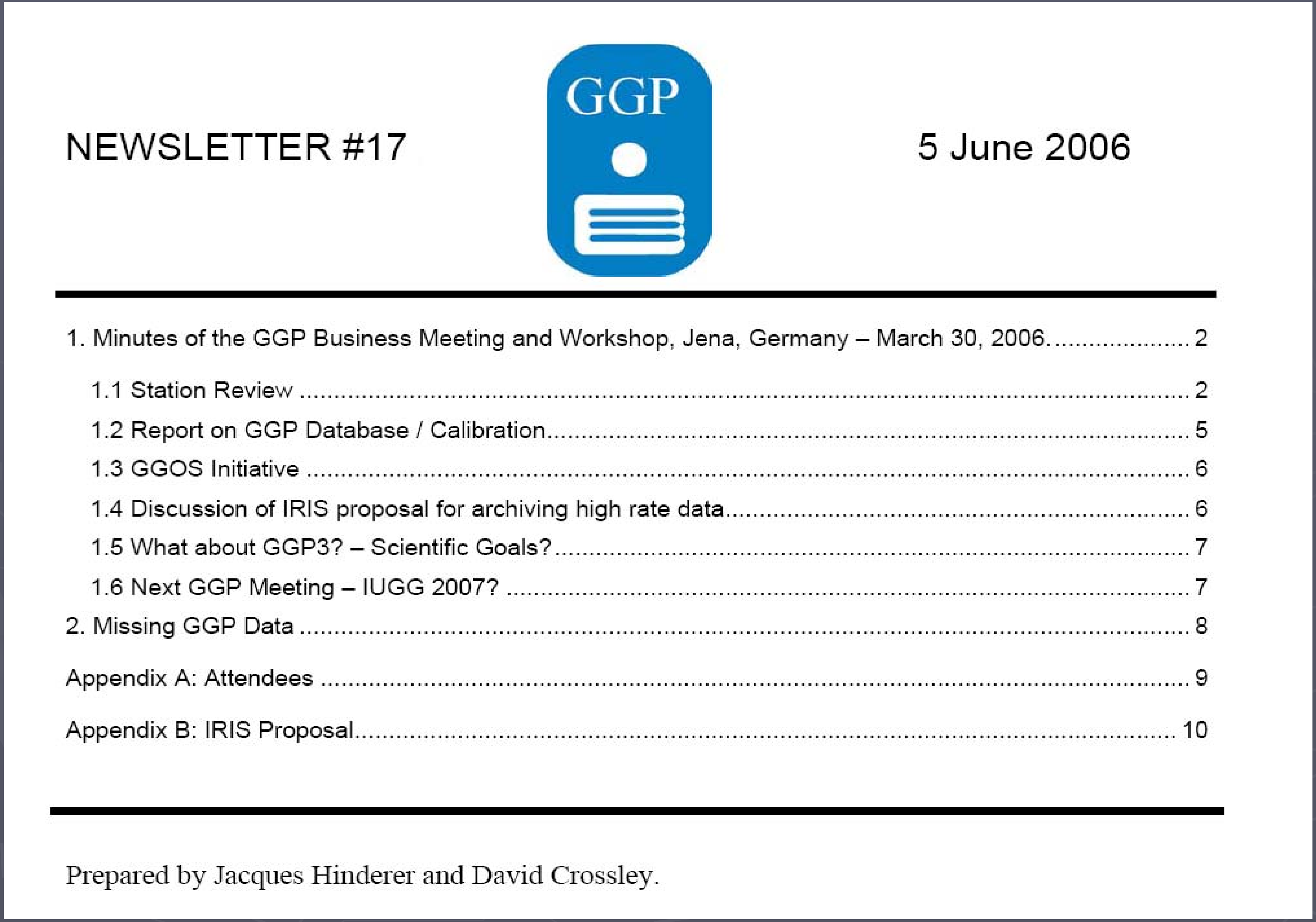
SG station recording history



SG station reporting



newsletters …



NEWSLETTER #17

5 June 2006

Prepared by Jacques Hinderer and David Crossley.

GGP & GGOS (Global Geodetic Observing System)

1. Provide access to GGP database – expand GGP mailing list to GGOS representatives (Newsletters etc.)
2. Undertake a project within GGP to record and report on all GPS measurements at the stations – these are necessary anyway to account for height variations that contribute to gravity variations
3. Undertake a project within GGP to record and report all Absolute Gravity measurements made at the GGP sites – these would be benchmark measurements (one point with error bar and supplementary information)
4. Assist in the coordination of future Absolute Gravimeter Intercomparisons at a site (or sites), where there is an SG
5. Be receptive to joint initiatives in geodesy or tectonics where the use of an SG would significantly improve the interpretation of measurements from other instruments.

Earthquake studies

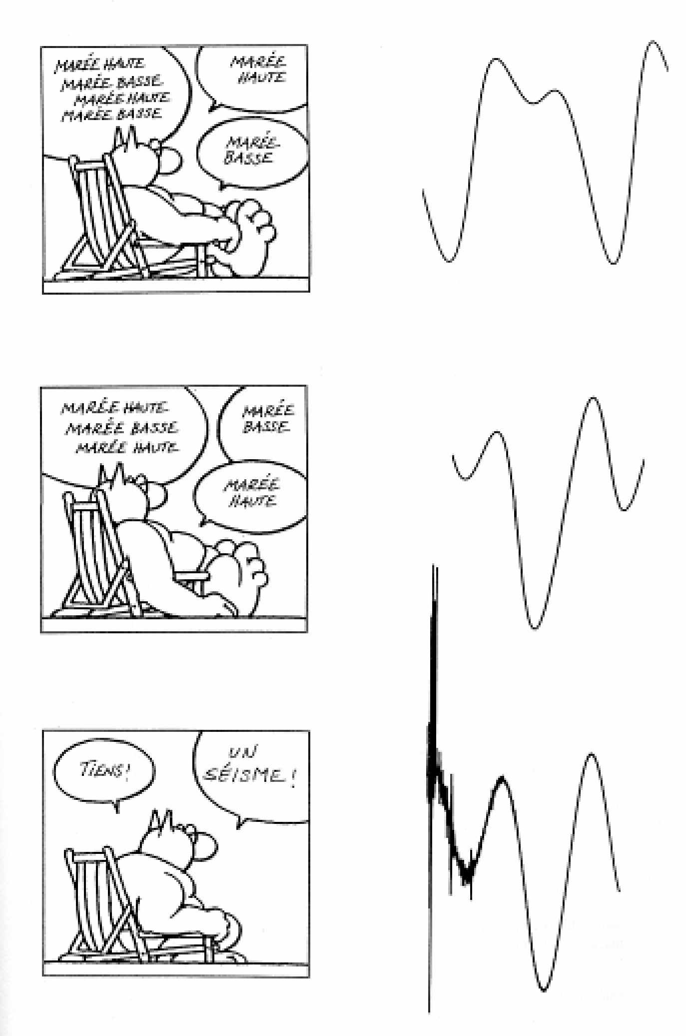
An SG (or accelerometer) has two responses to an earthquake:

(1) normal modes

- for Mw > 6.0 can be seen globally

(2) static displacement

- can be seen only close to source



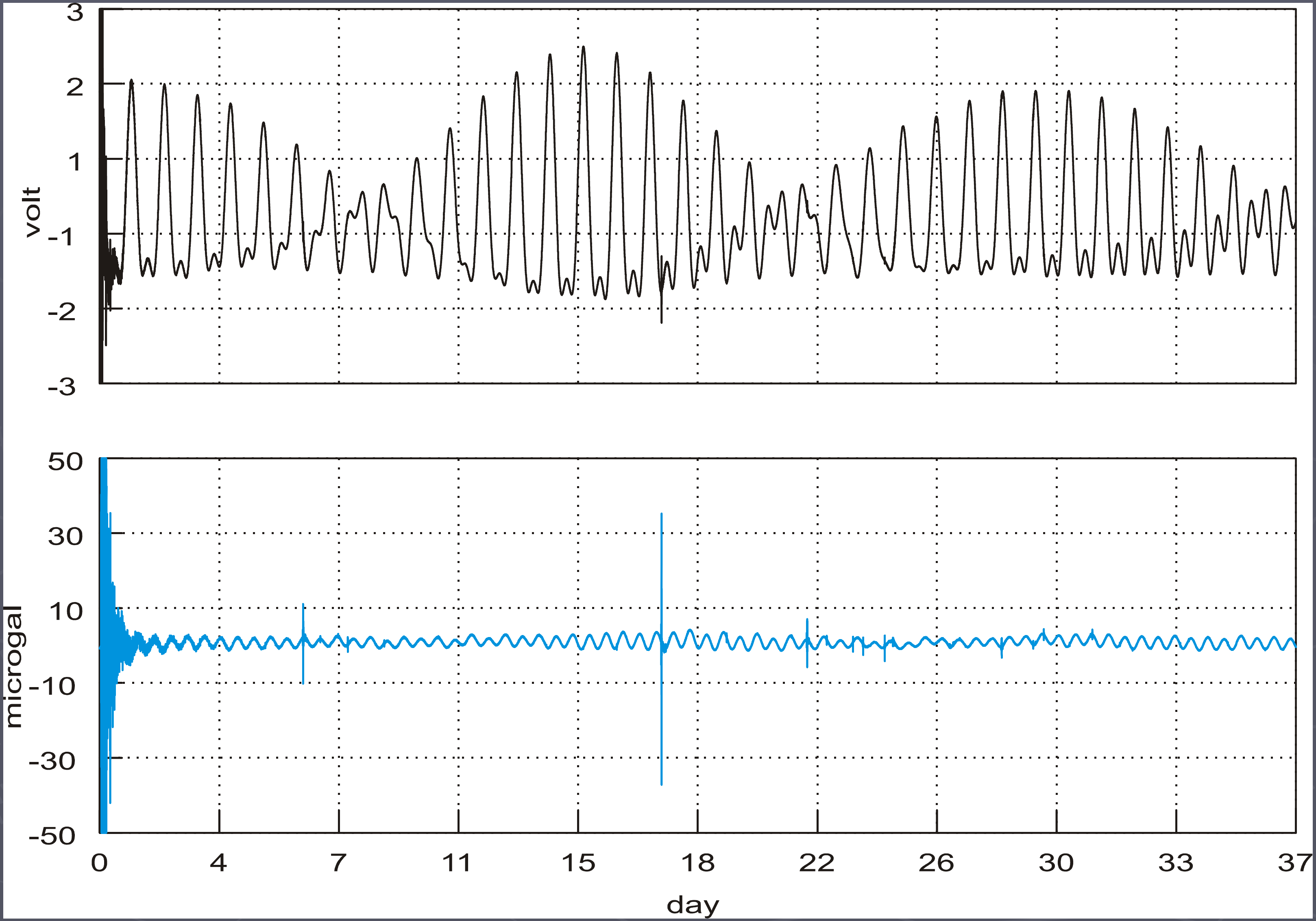
PhD thesis M. Van Camp

Bad Homburg – lower sphere

36 days following Sumatra (12/26/04)

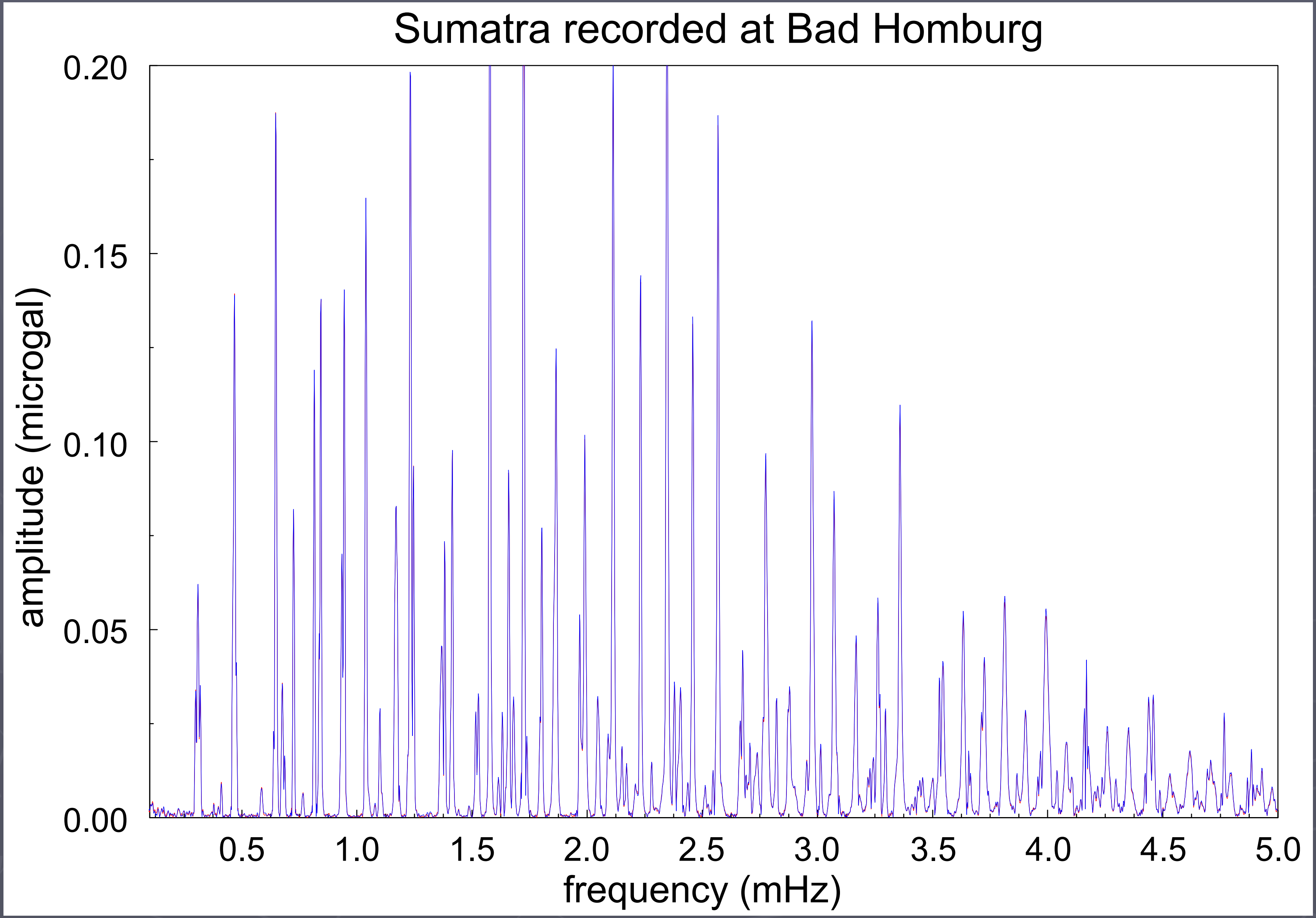
tides

nominal tides removed

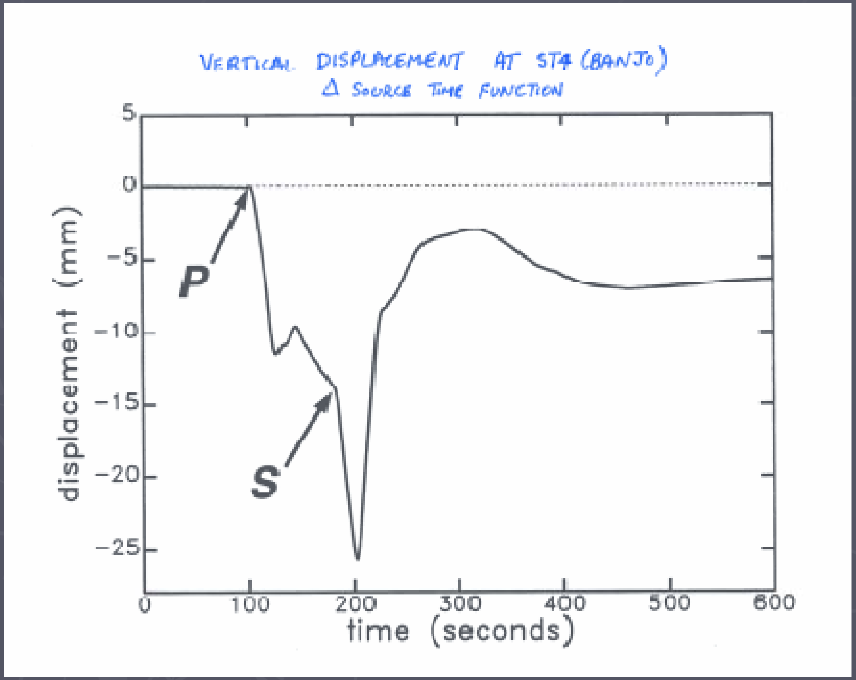


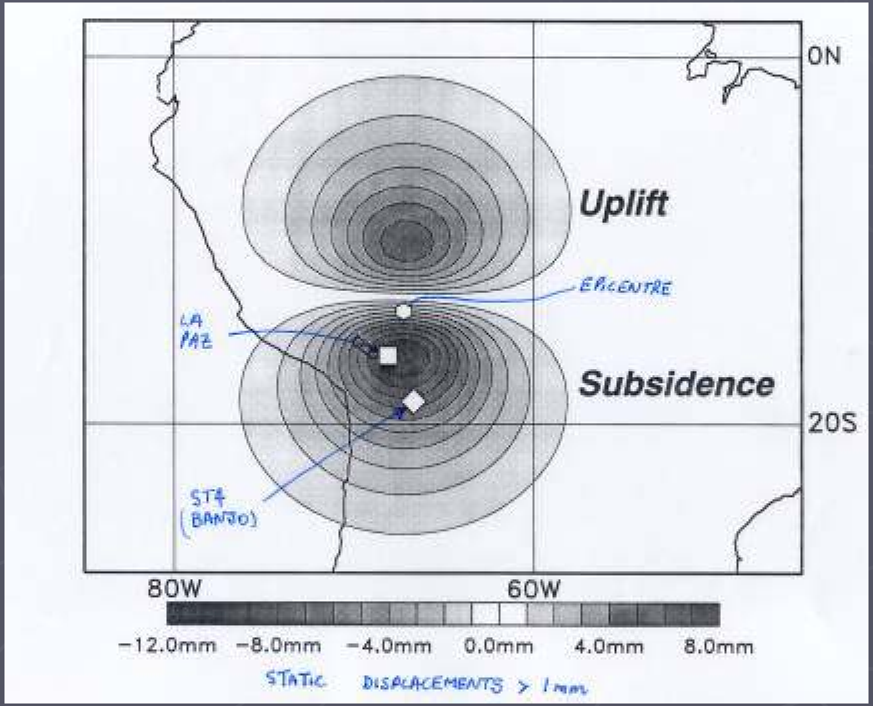
spectrum of 36 days

note upper and lower spheres are almost identical



static displacements, Bolivia 1994, Mw=8.4, very localized





Static earthquake displacements from satellites - Alaska 1964

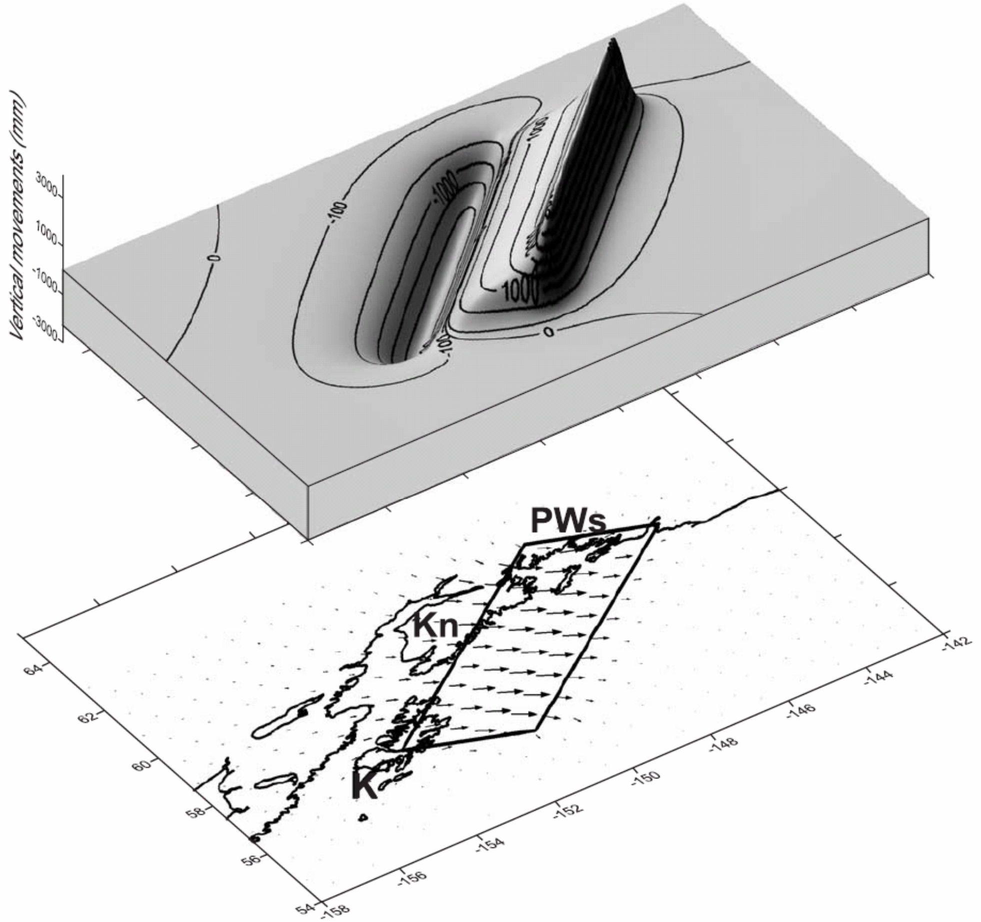
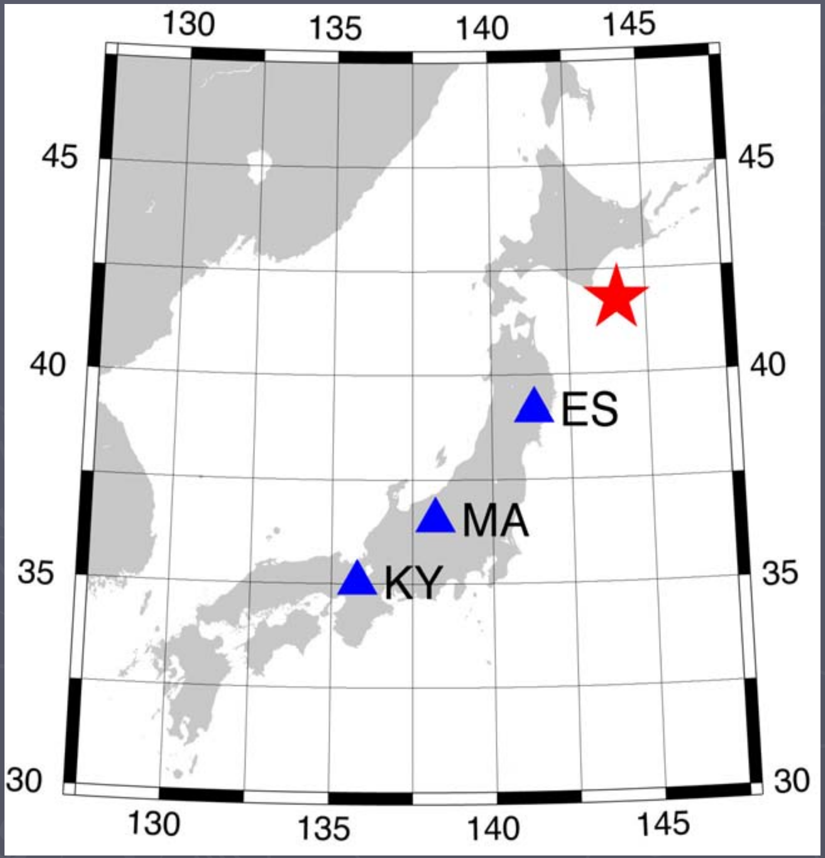
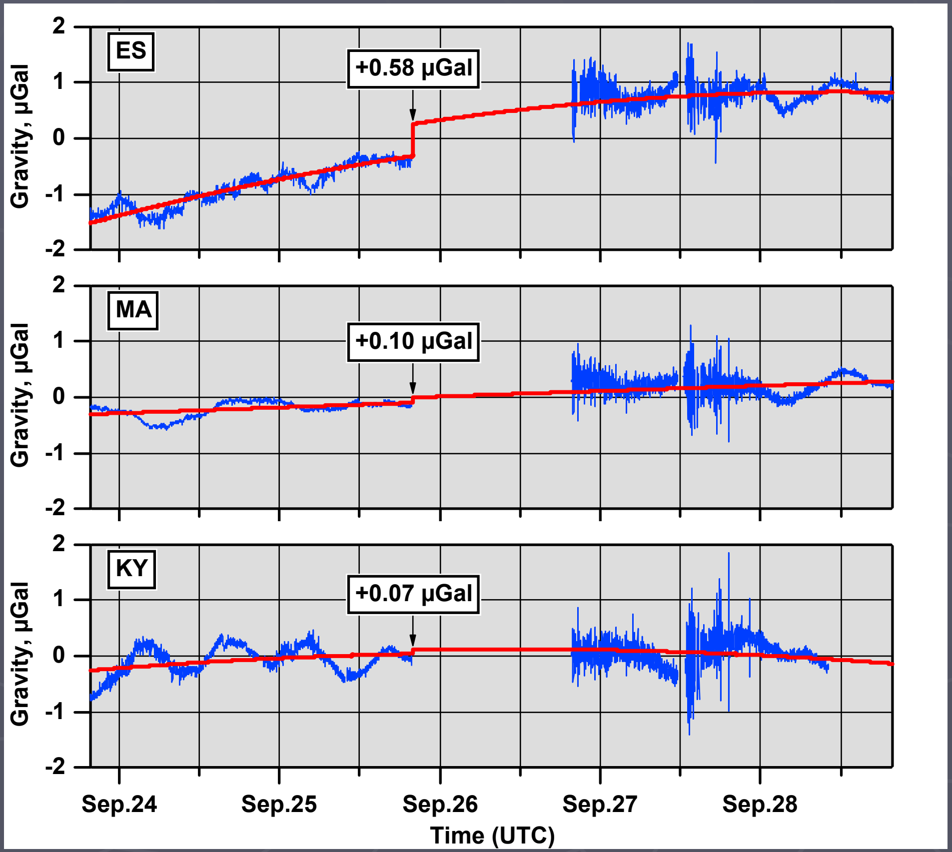


Fig. 3. Vertical displacement of the Earth surface in result of the Alaska-1964 earthquake (meters). Rectangular shows surface projection of the fault plane, corresponding to model 3 of [12]. Arrows show horizontal displacement. Maximal arrow corresponds to 6 m displacement. K—Kodiak island; Kn—Kenai peninsula, PW—Prince William Sound.

- Mikhailov et al., 2004. Can tectonic processes be recovered from new satellite gravity data? *EPSL*, **228**, 281-297.

… but if you are careful (and lucky) in Japan





Mw 8.0 Tokachi-oki earthquake on Sept. 2003 off the coast of Japan

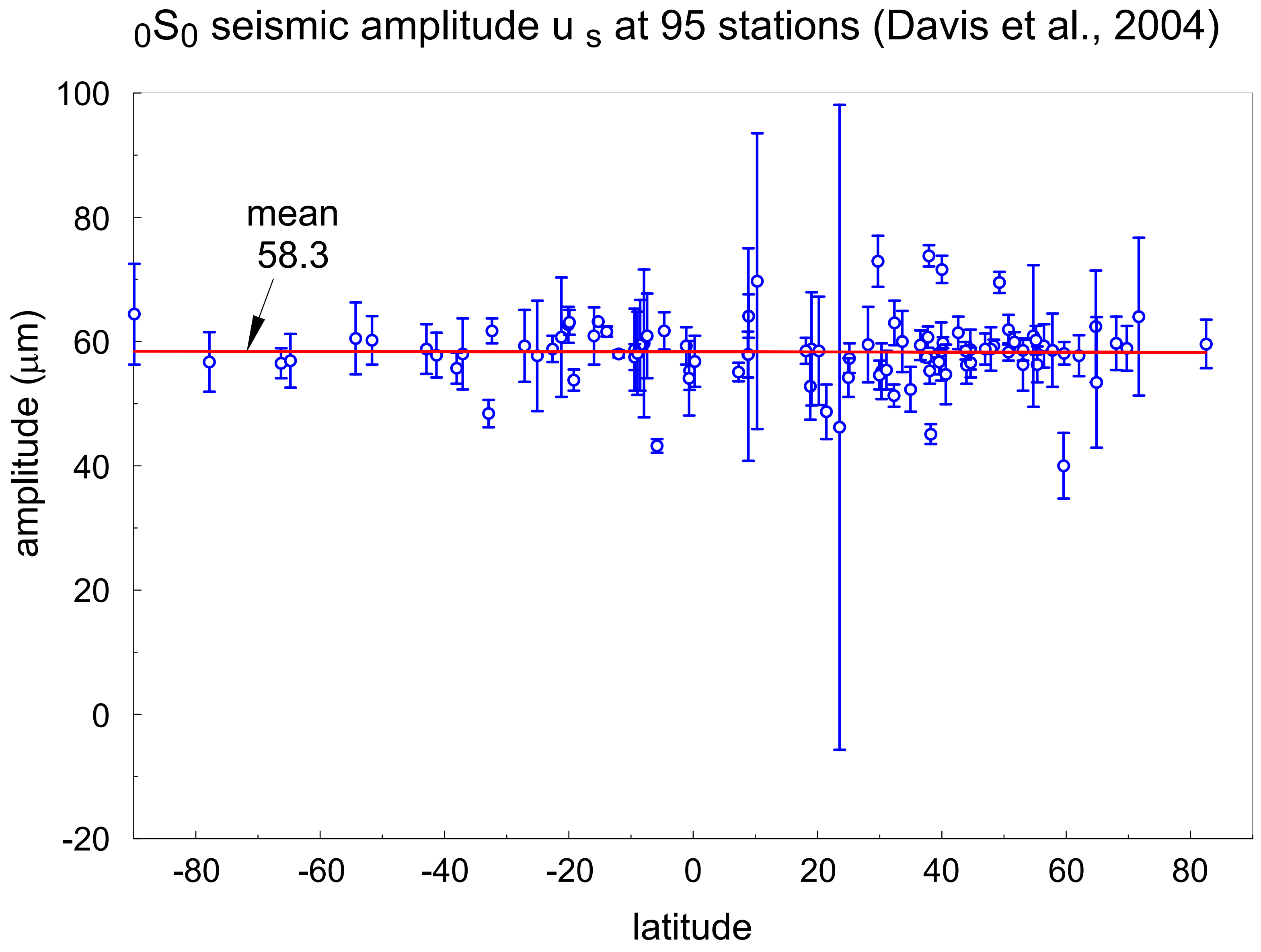
Using $_0S_0$ for GSN calibration

- Davis, Ishii, and Masters (2004)* used 95 stations from the global seismic network (GSN) to measure amplitude of $_0S_0$
- they assumed we know f=0.8146 mHz, Q=5400 → measure initial amplitude A_0 excited by earthquake
- they used two techniques and found a range of values for the initial amplitude, depending on instrument, and commented that

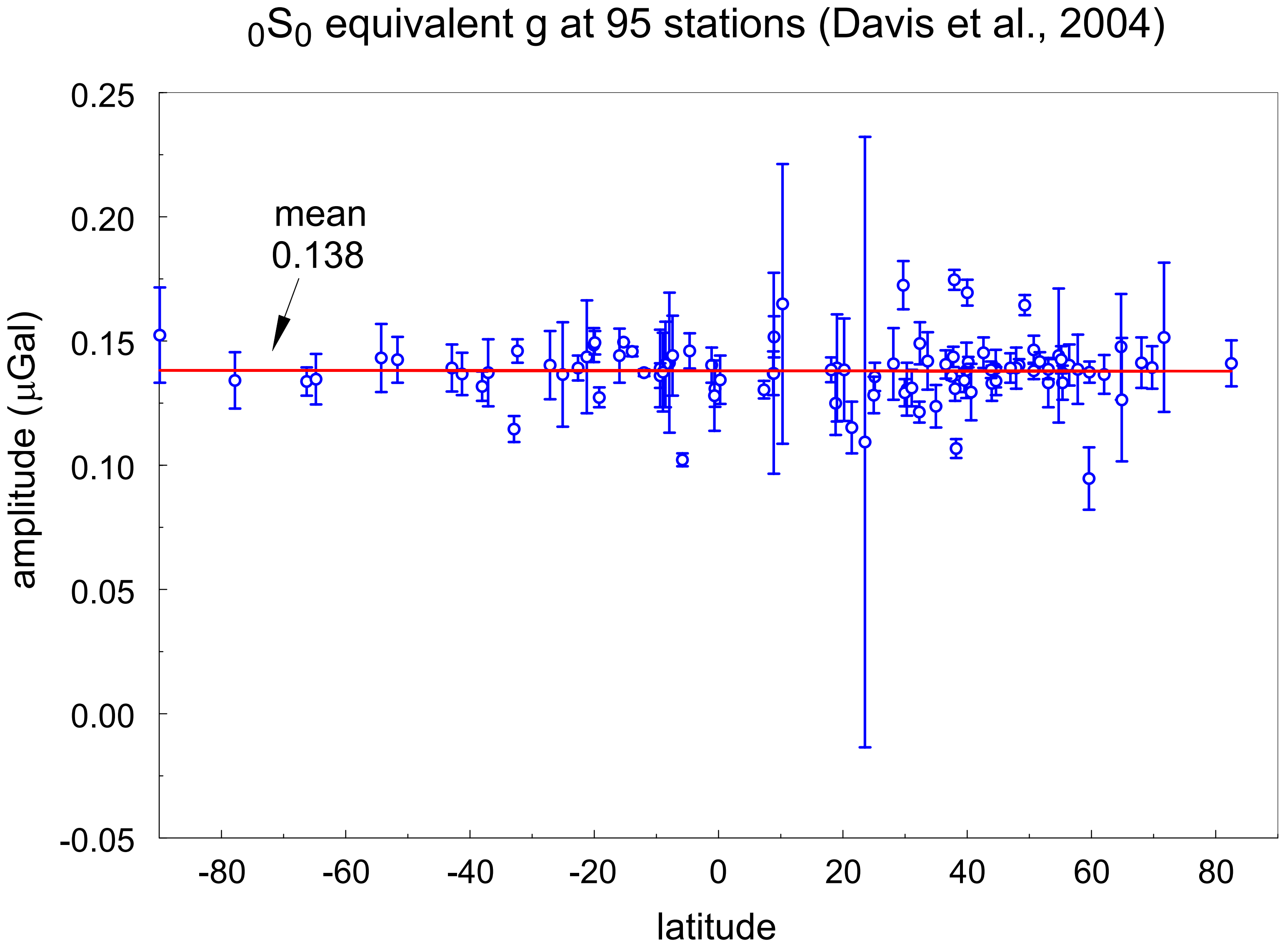
"Superconducting gravimeters also recorded $_0S_0$ very well … A sampling of these data indicate the GSN mean is about 4% larger than measurements at several superconducting gravimeters thought to be calibrated to better than 0.5% (Widmer-Schnidrig, personal communication). Resolving these and other inconsistencies poses an interesting challenge to the GSN station operators …"

*An assessment of the accuracy of GSN sensor response information, Seis. Res. Lett, 76, 678-683

Seismic amplitude vs latitude



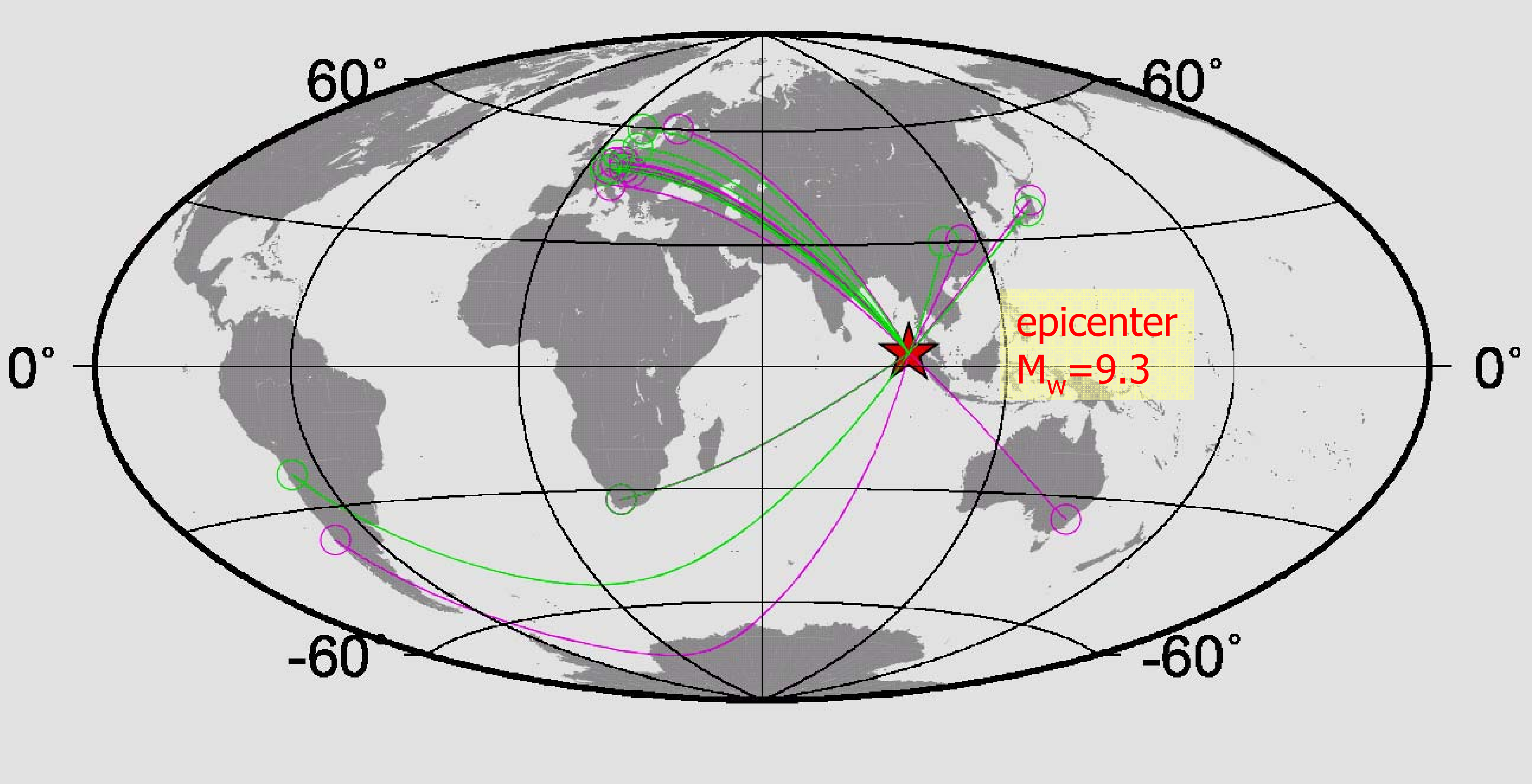
Gravity vs latitude



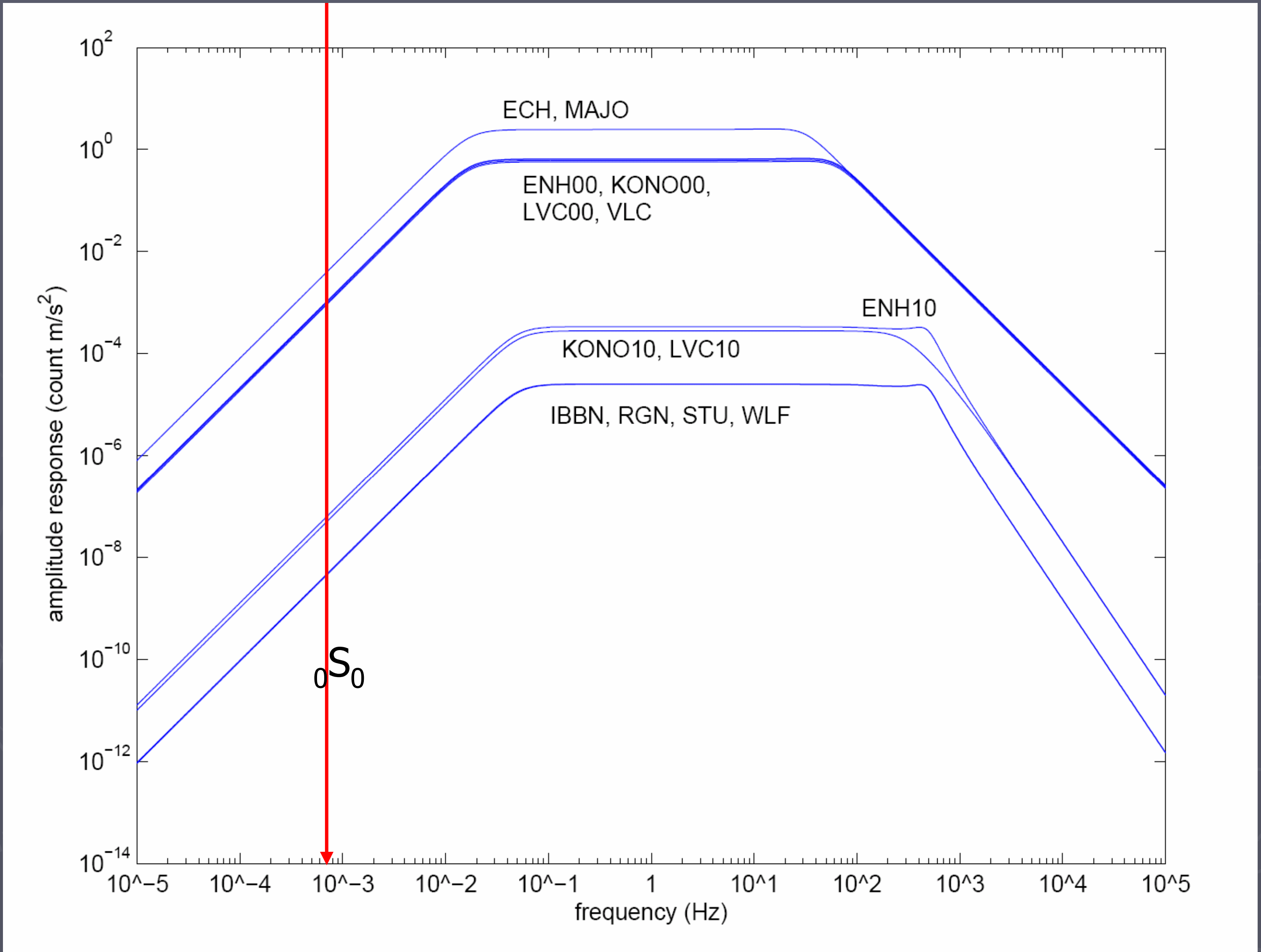
$_0S_0$ from Sumatra-Andamen 2004

red circles = 13 SG stations
green circles = 13 GSN stations

done with student Yan Xu



Seismometer amplitude response



Method

assume a damped cosine with amplitude

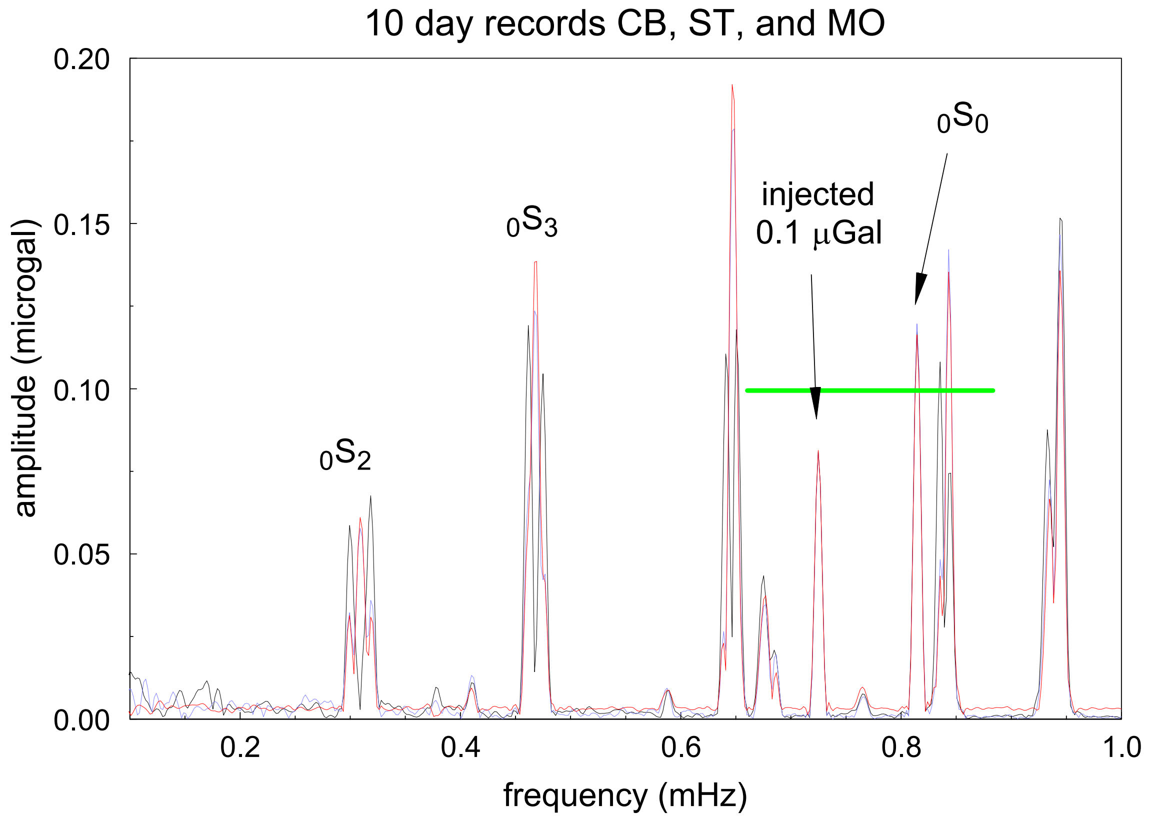
$$A(t) = A_{max}exp\left[\frac{-(t-t_0)\pi}{QT}\right]$$

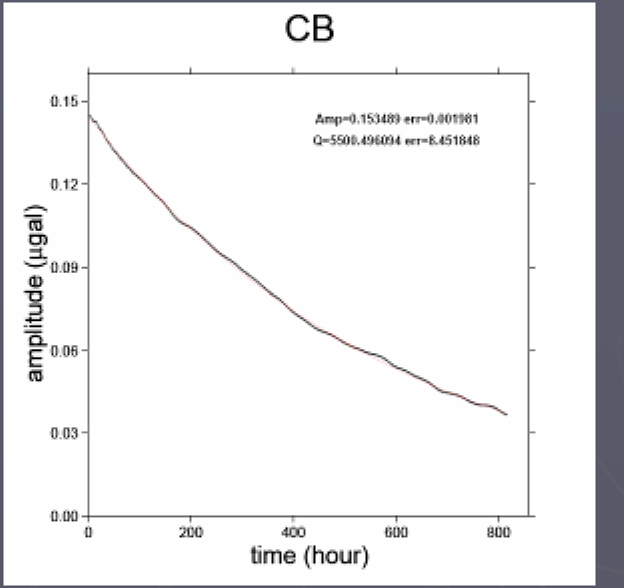
Following Nowroozi (1968), the amplitude of the spectral peak from a data set between times t_1 and t_2 can be expressed as:

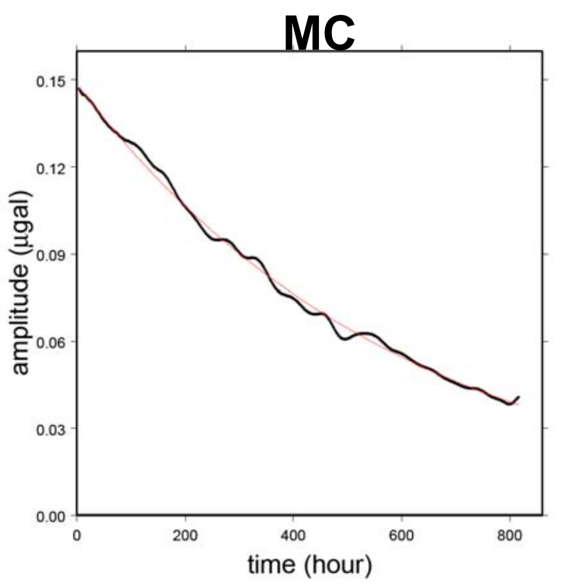
$$A_{1,2} = \frac{\int_{t_1}^{t_2} A(t)dt}{t_2 - t_1} = -\frac{A_{max}exp(\frac{\pi t_0}{QT})}{t_2 - t_1} \cdot \frac{QT}{\pi}\left[exp(-\frac{t_2\pi}{QT}) - exp(-\frac{t_1\pi}{QT})\right]$$

we estimate A_{12} for each 72 hr window starting 2 hr after earthquake and displaced 1 hr until last window reaches end of day 36 (31 January 2005)

Examples of amplitudes and Q from SGs

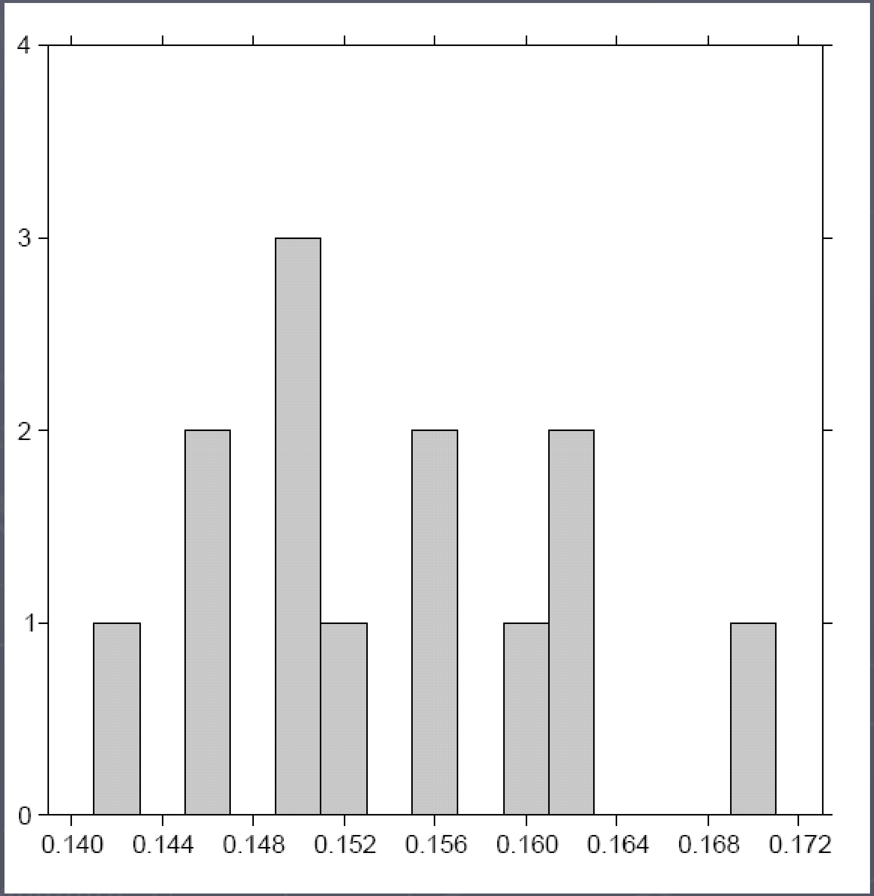




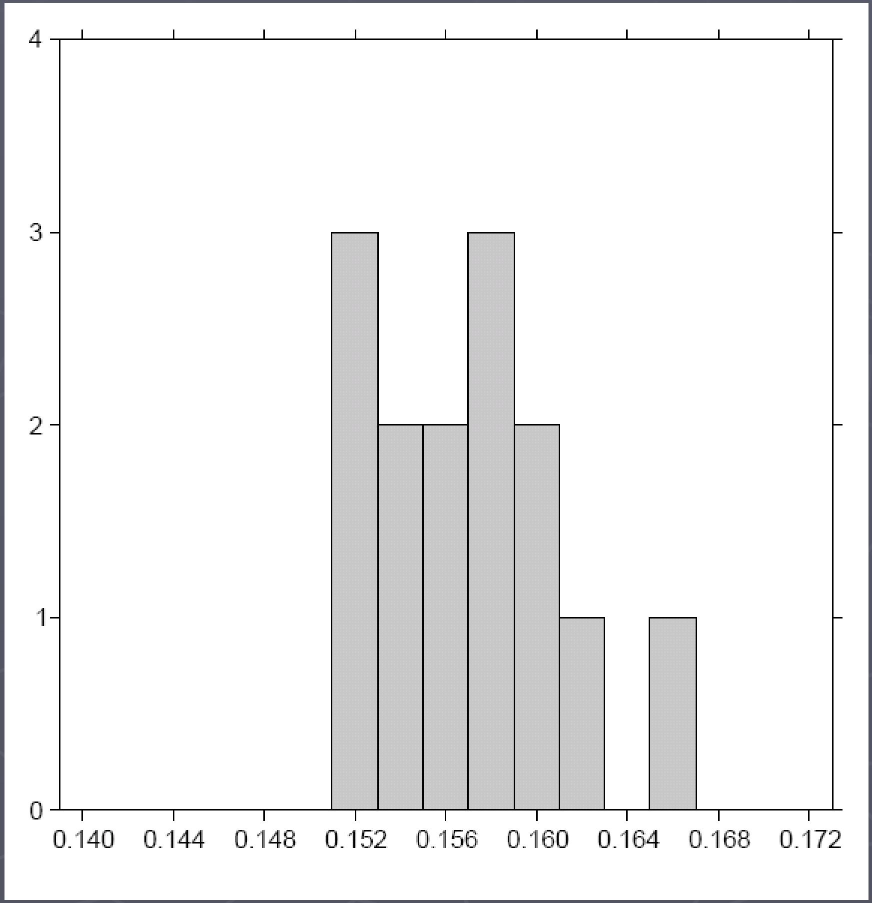


preliminary result of comparison of 13 SG data sets with 13 STS1 and STS2 data sets

→ SG amplitude is more consistent (less scatter), but about 10% higher than Davis et al.



seismometer amplitude histogram



SG amplitude histogram

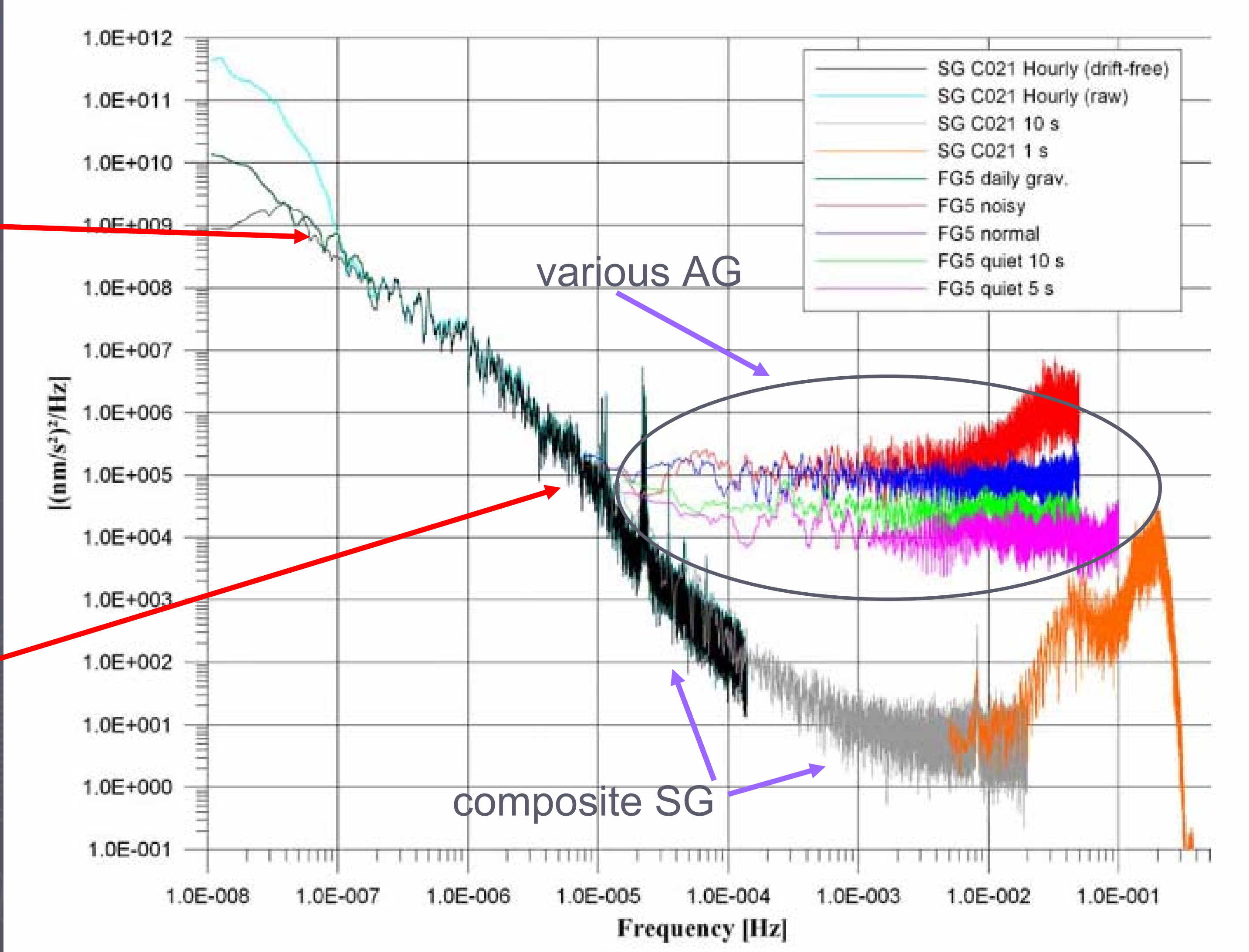
Comparison SG and AG

SG
Medicina

Fig. 7 Parallel measurements with FG5-220 (IfE) and FG5-221 (FGI) at station Metsähovi in Finland.

AG vs AG
Metsahovi

Spectral comparison AG-SG



differences at > 6 mo depending on SG drift

various AG

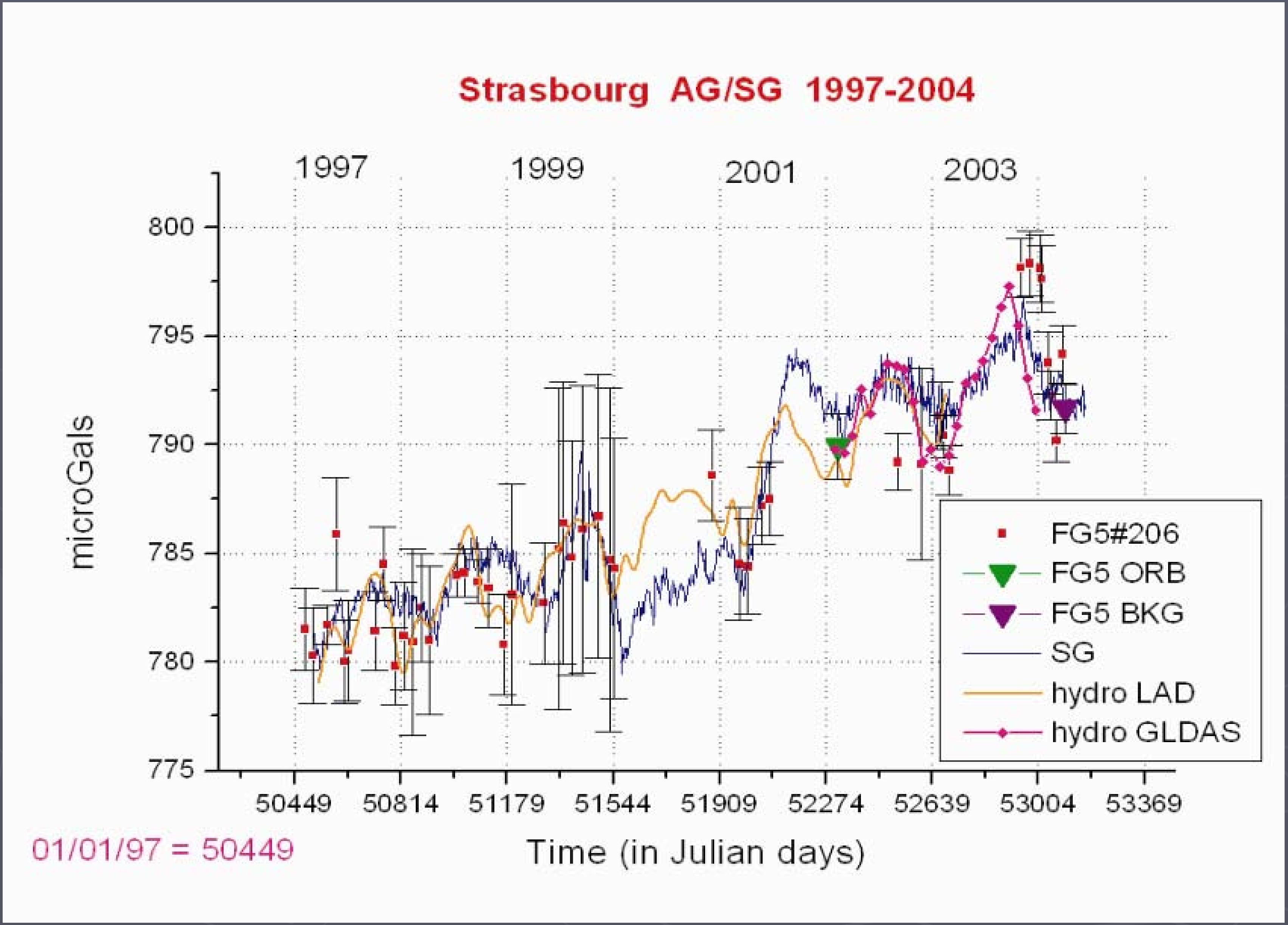
spectra meet at

~ 3 day

composite SG

Van Camp et al. (JGR, 2005)

Instructive comparison of AG, SG, and hydrology over 8 years



SG amplitude calibration by AG and Frankfurt platform

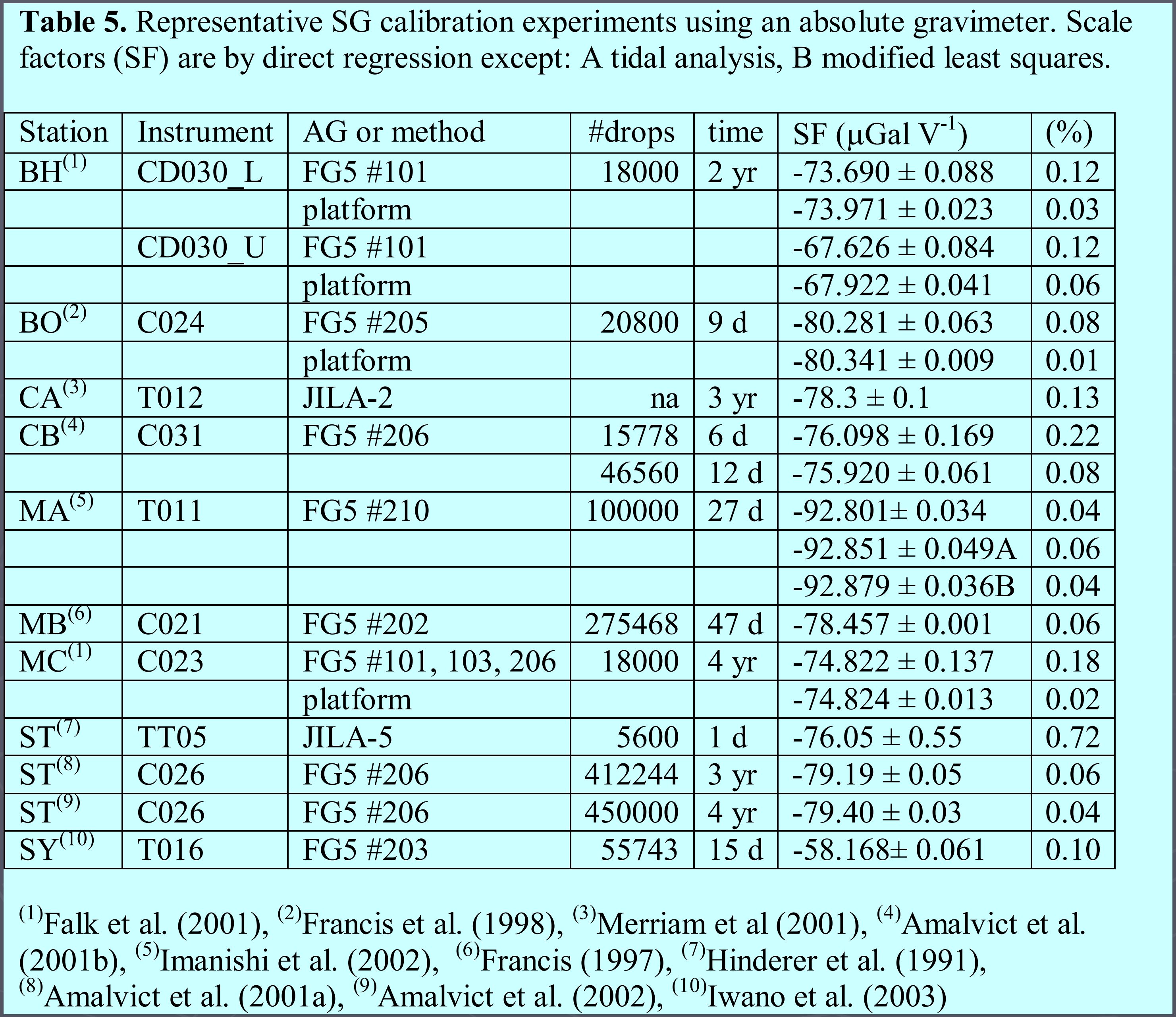


Table 5. Representative SG calibration experiments using an absolute gravimeter. Scale factors (SF) are by direct regression except: A tidal analysis, B modified least squares.

Station	Instrument	AG or method	#drops	time	SF (μGal V^{-1})	(%)
BH(1)	CD030_L	FG5 #101	18000	2 yr	-73.690 ± 0.088	0.12
		platform			-73.971 ± 0.023	0.03
	CD030_U	FG5 #101			-67.626 ± 0.084	0.12
		platform			-67.922 ± 0.041	0.06
BO(2)	C024	FG5 #205	20800	9 d	-80.281 ± 0.063	0.08
		platform			-80.341 ± 0.009	0.01
CA(3)	T012	JILA-2	na	3 yr	-78.3 ± 0.1	0.13
CB(4)	C031	FG5 #206	15778	6 d	-76.098 ± 0.169	0.22
			46560	12 d	-75.920 ± 0.061	0.08
MA(5)	T011	FG5 #210	100000	27 d	-92.801± 0.034	0.04
					-92.851 ± 0.049A	0.06
					-92.879 ± 0.036B	0.04
MB(6)	C021	FG5 #202	275468	47 d	-78.457 ± 0.001	0.06
MC(1)	C023	FG5 #101, 103, 206	18000	4 yr	-74.822 ± 0.137	0.18
		platform			-74.824 ± 0.013	0.02
ST(7)	TT05	JILA-5	5600	1 d	-76.05 ± 0.55	0.72
ST(8)	C026	FG5 #206	412244	3 yr	-79.19 ± 0.05	0.06
ST(9)	C026	FG5 #206	450000	4 yr	-79.40 ± 0.03	0.04
SY(10)	T016	FG5 #203	55743	15 d	-58.168± 0.061	0.10

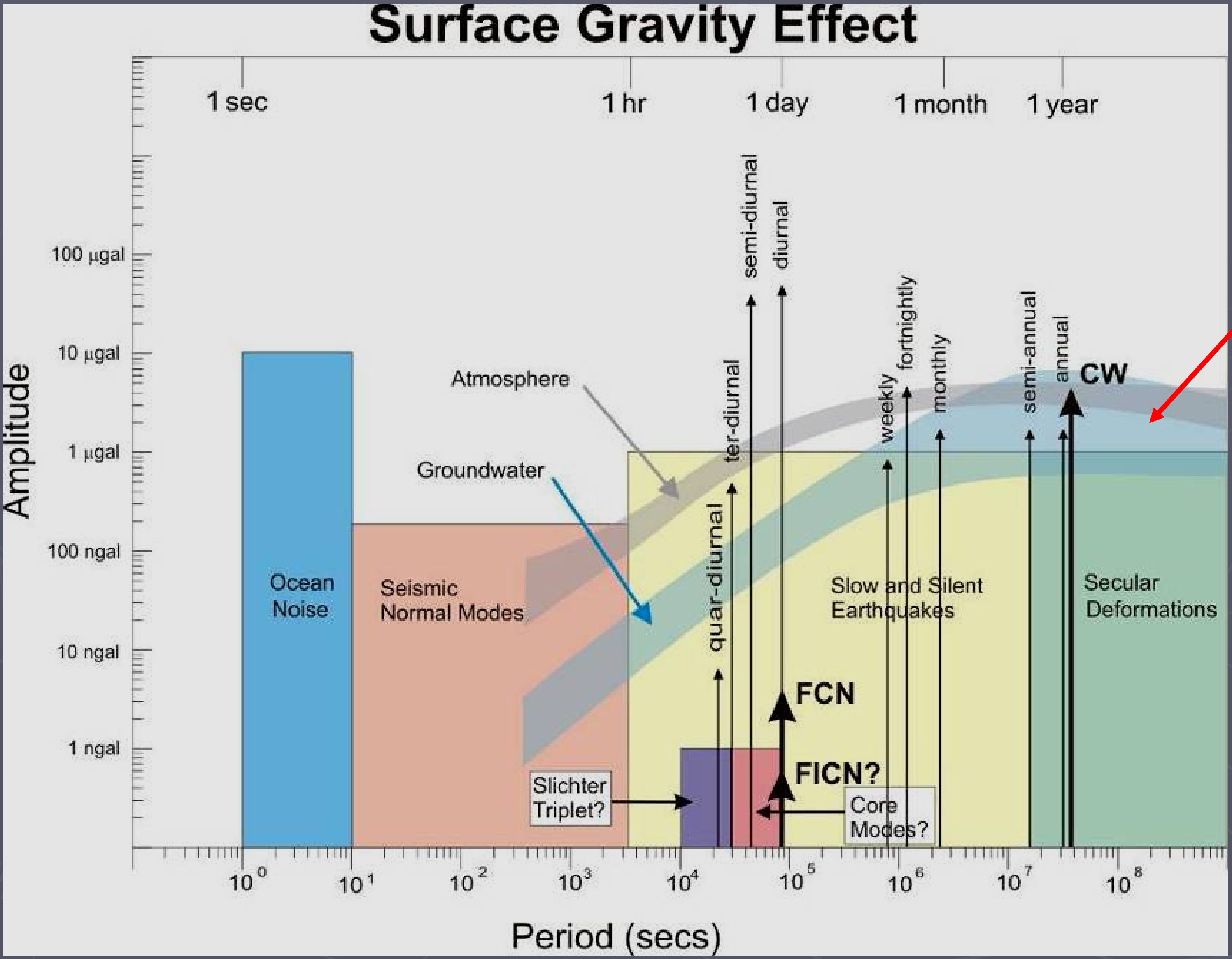
(1)Falk et al. (2001), (2)Francis et al. (1998), (3)Merriam et al (2001), (4)Amalvict et al. (2001b), (5)Imanishi et al. (2002), (6)Francis (1997), (7)Hinderer et al. (1991), (8)Amalvict et al. (2001a), (9)Amalvict et al. (2002), (10)Iwano et al. (2003)

Absolute calibration by a known mass can be difficult

vertical ring at Brasimone, circa 1995

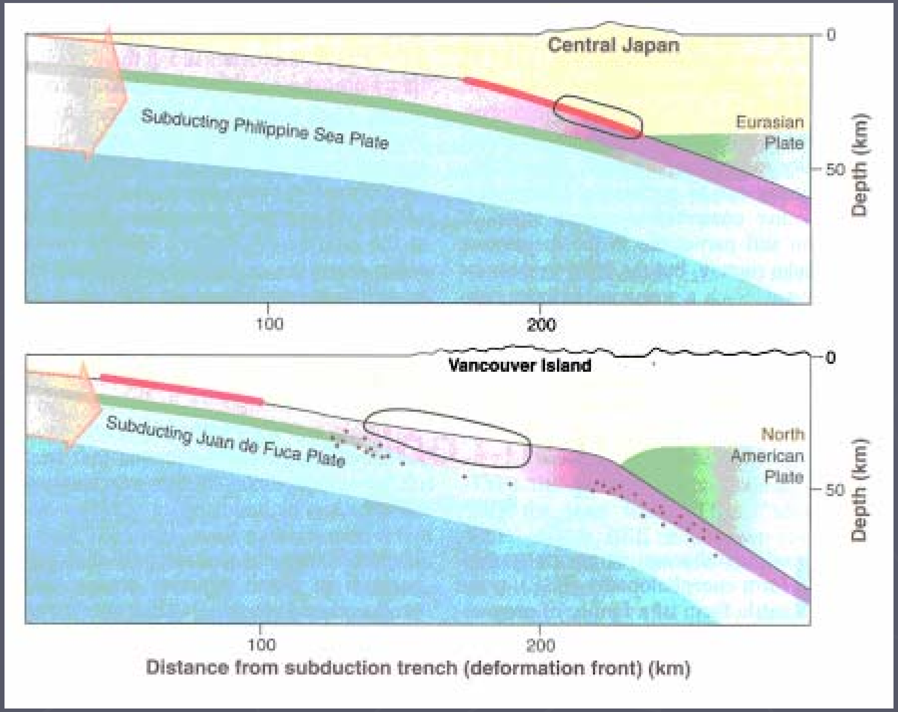
Geodynamic Examples

- episodic slip at subduction zones (GPS, AG)
- postglacial rebound (AG)
- sea level variations (SG, Sato, steric vs. non-steric correction to sea surface height)
- volcano monitoring (AG, LCR, Scintrex)
- geodynamic (earthquake) monitoring by satellite - feasibility study
- hydrology monitoring by satellite (and SGs)

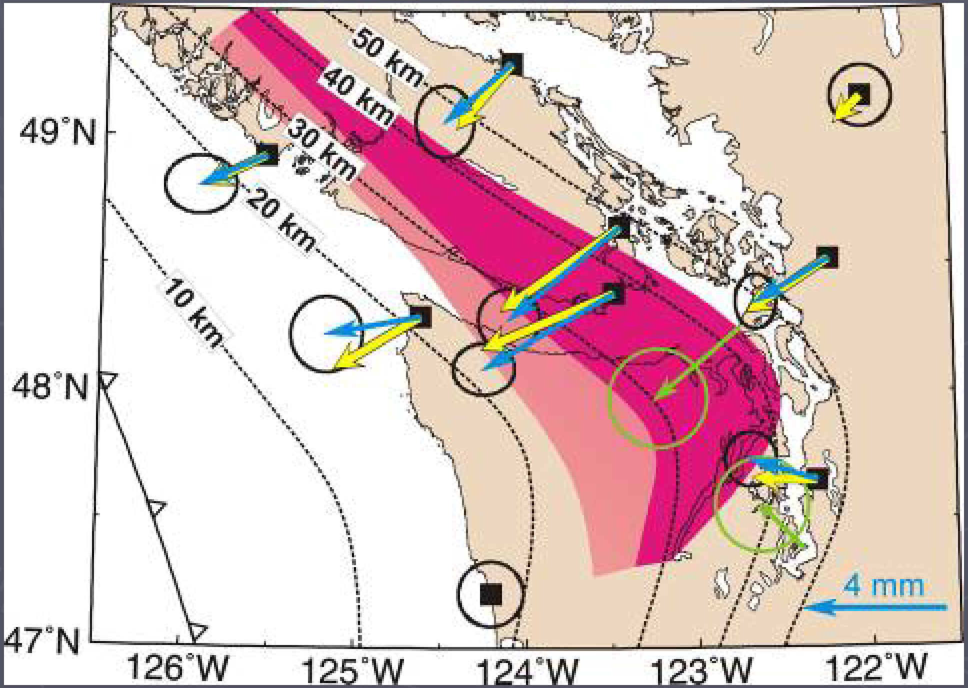


note no periodic components, only secular deformation, hydrology and atmosphere.

Episodic slip at subduction zones



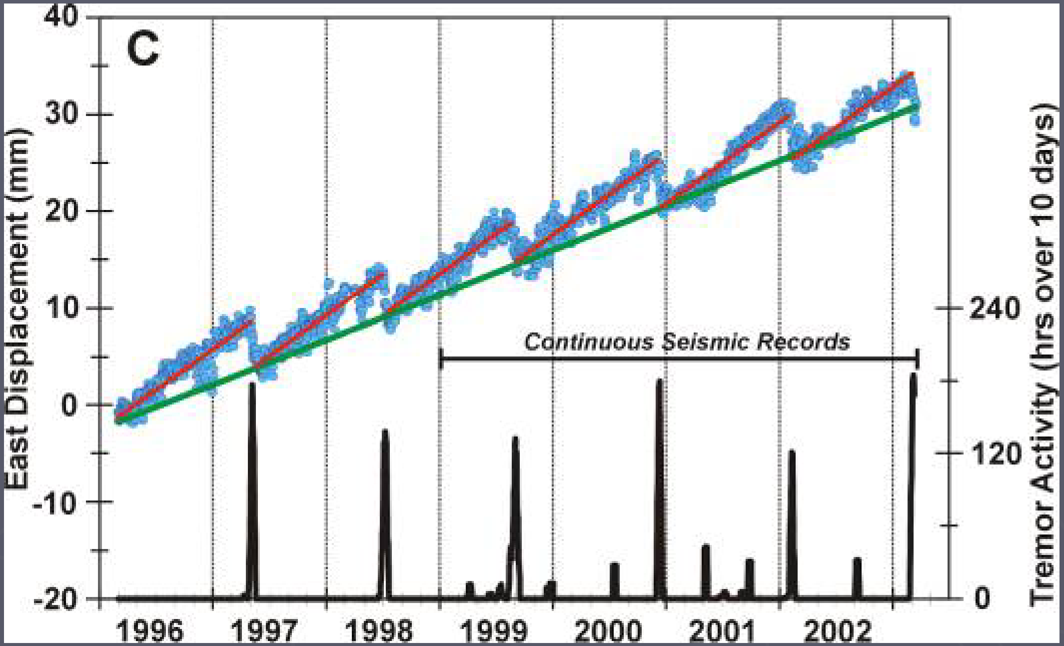
Slip does not occur where there are regular earthquakes



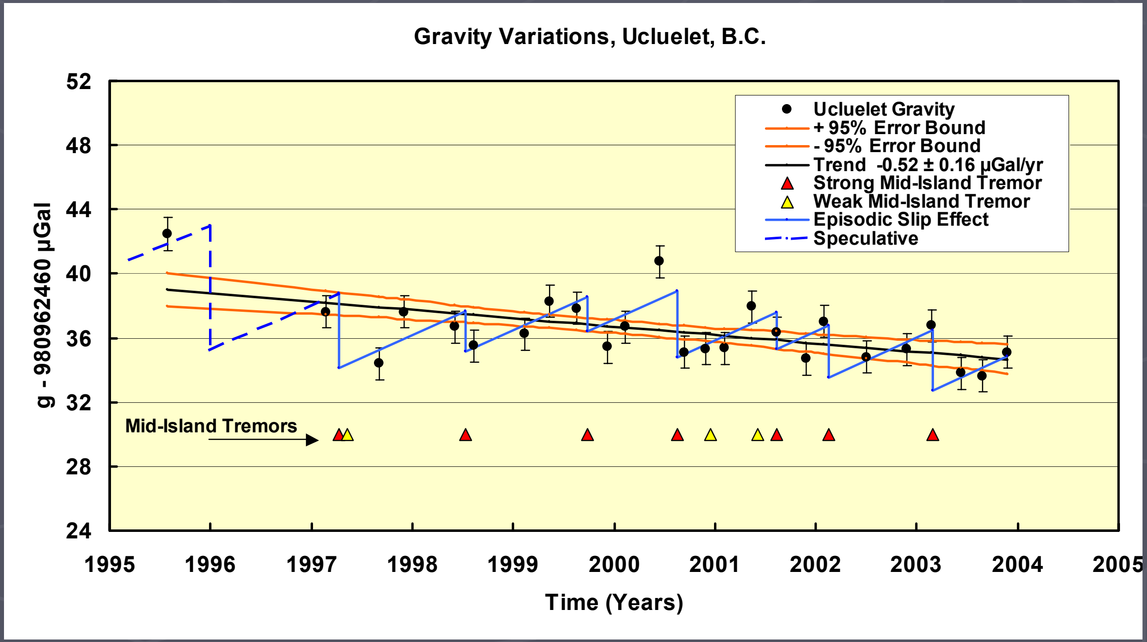
Reverse motion over subduction zone propagates SE to NW

seismometer and GPS detection

Dragert et al. (2001)

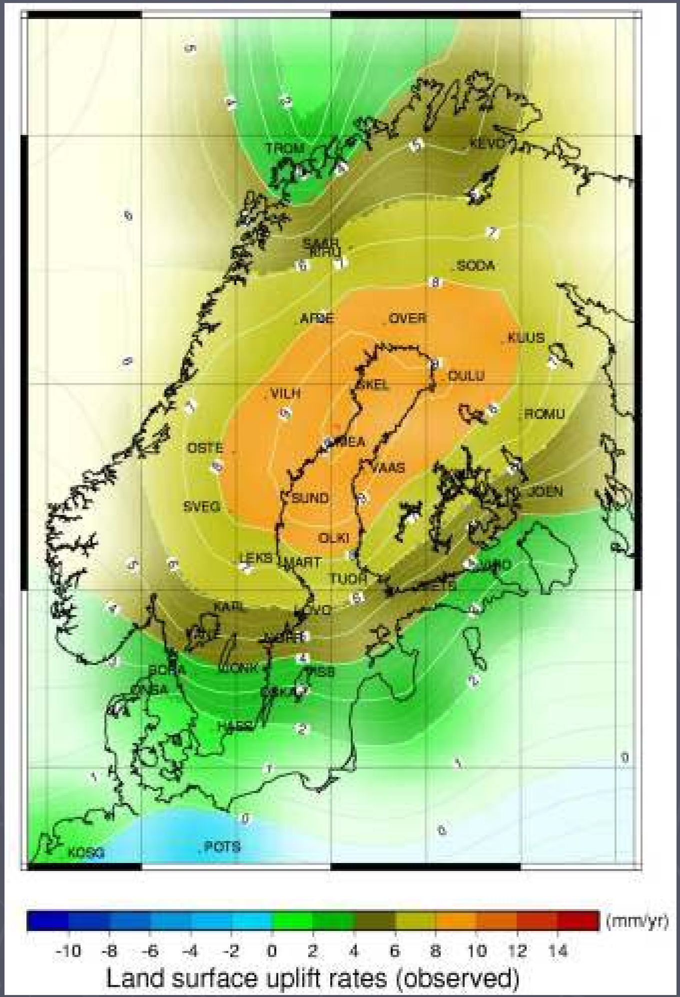


AG detection?



Episodic gravity variations - model and AG observations (Lambert, 2004)

Fennoscandian uplift using AGs - proposal



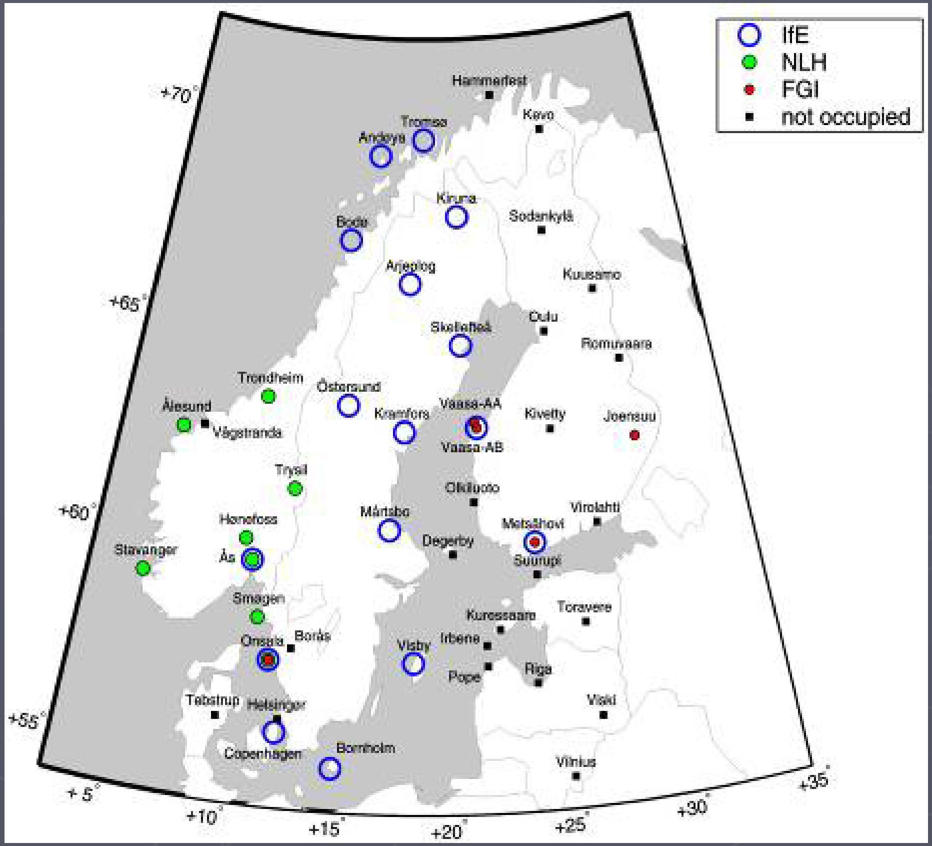


Fig. 4 Observed absolute gravity stations in 2004 occupied by the absolute gravimeters FG5-220 (IfE), FG5-221 (FGI), FG5-226 (UMB).

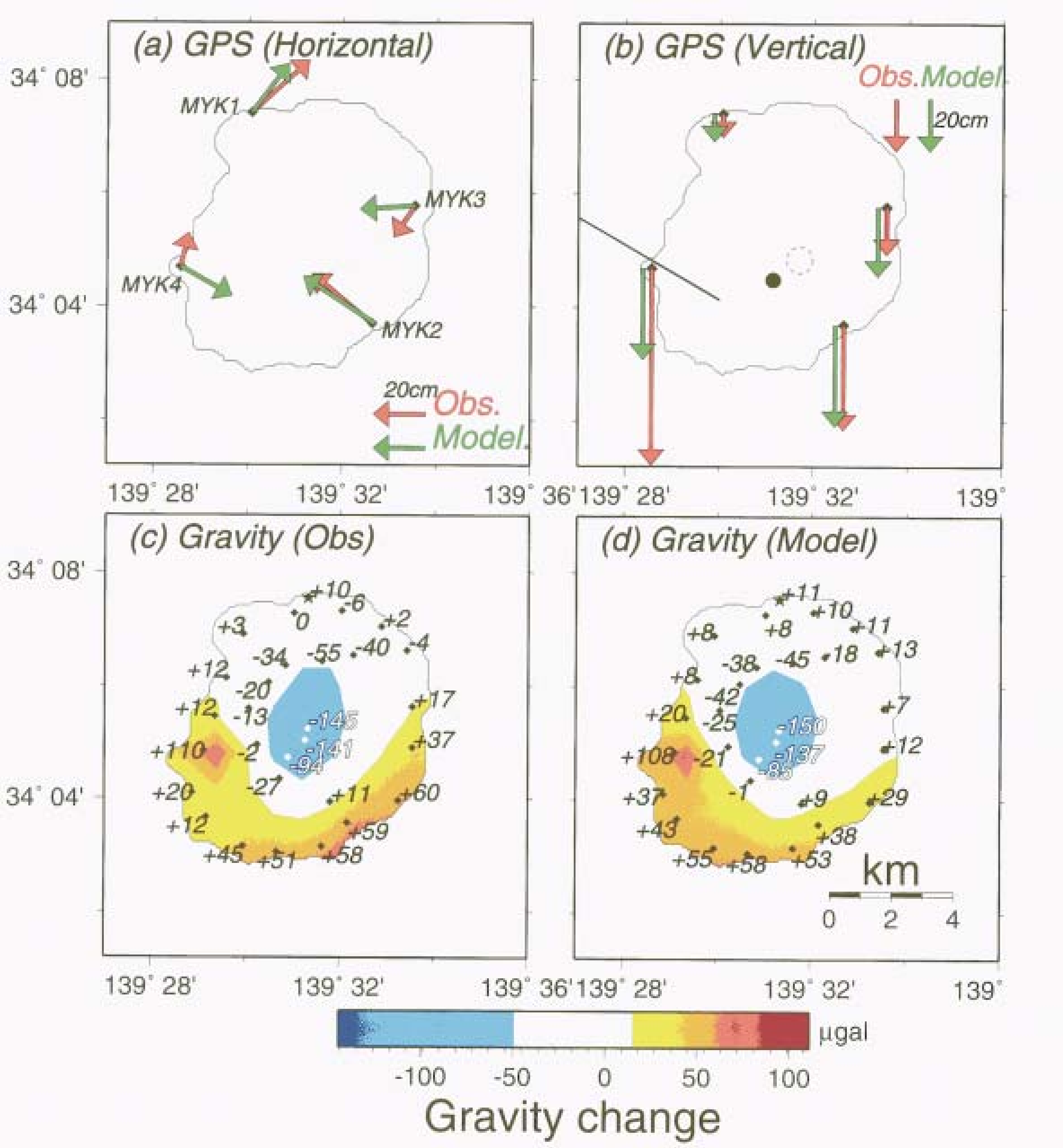
Timmen et al., 2004. Observing Fennoscandian Gravity Change by Absolute Gravimetry

Gravity and deformation on Miyakejima, Japan (AG and LCR)

Measurements of gravity and deformation just before the collapse of the dome of the Miyakejima Volcano, Japan in 2000

(Furuya et al. 2003).

Ideal situation for SG to act as a base station.

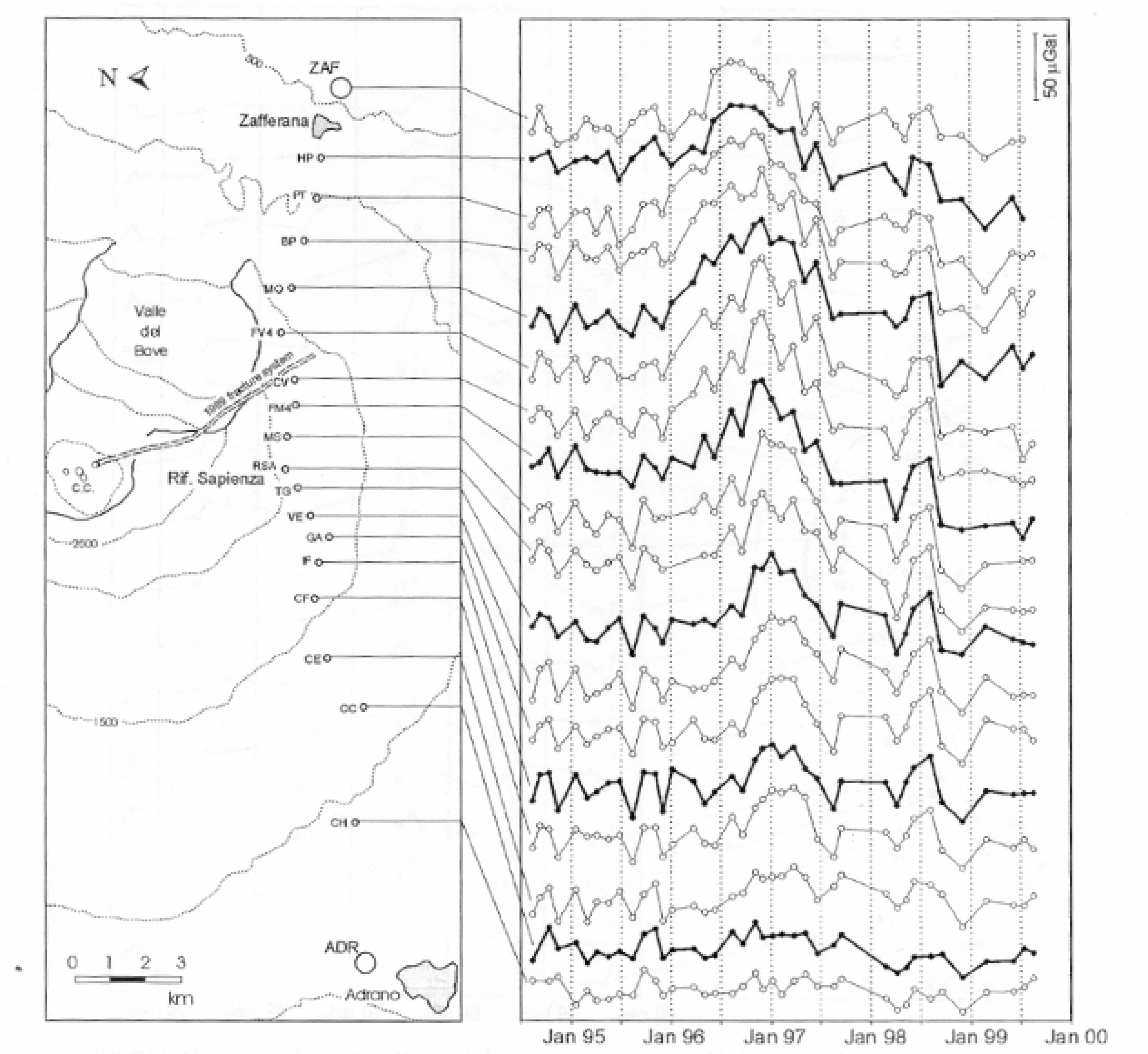


Gravity survey on Mt. Etna (LCRs)

Gravity profile E-W on the south flank of Mt. Etna for August 1994 – August 1999, corrected for water table fluctuations.

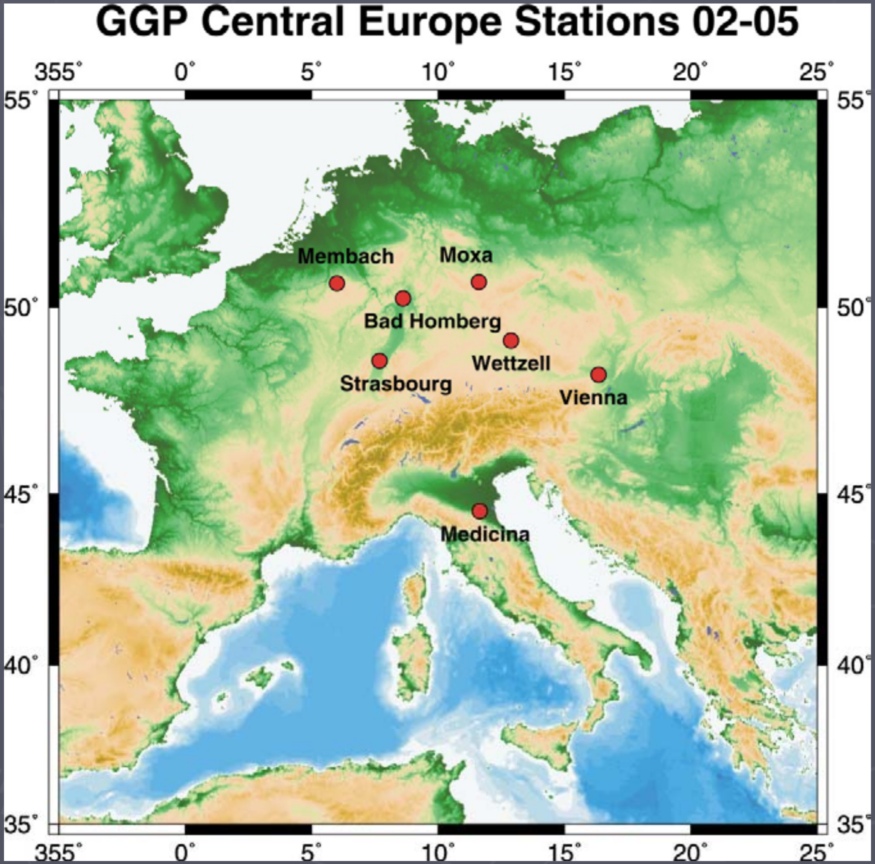
Stations ZAF (Zafferana) and ADR (Adrano) are reference stations.

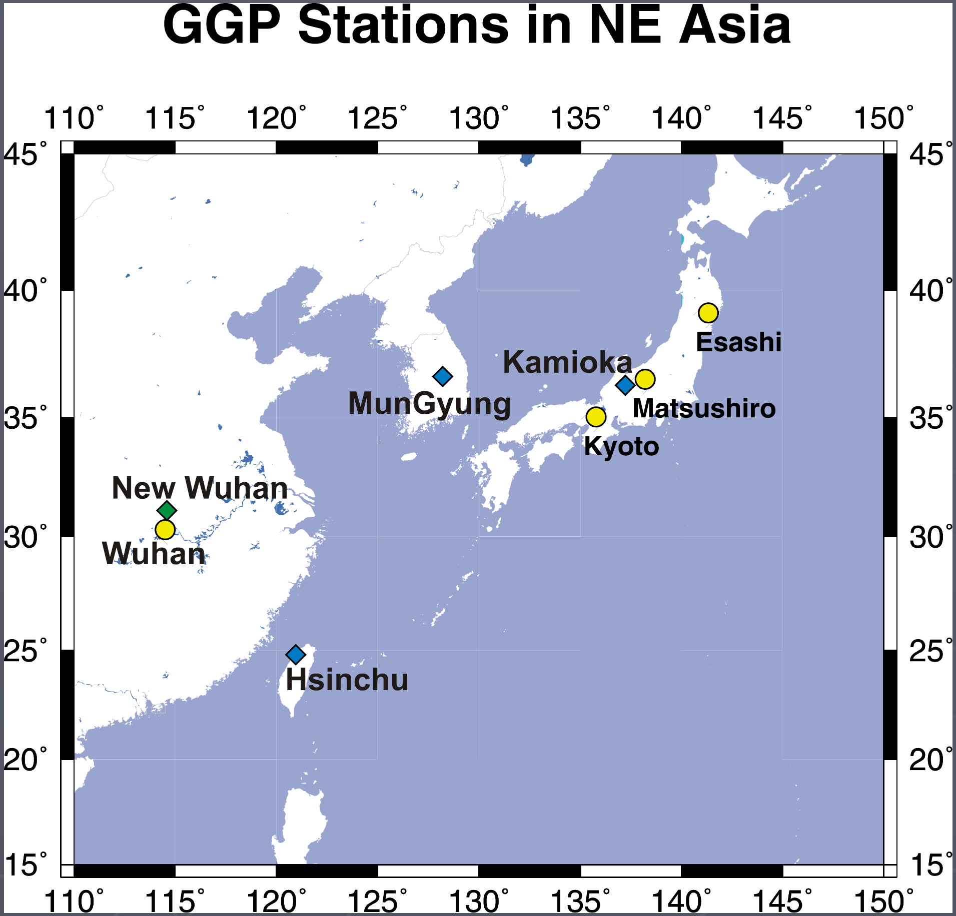
Note the gravity increase of at least 50 μGal during 1996 and the decrease thereafter, from Carbone et al. (2003a).



Hydrology (GGP and GRACE)

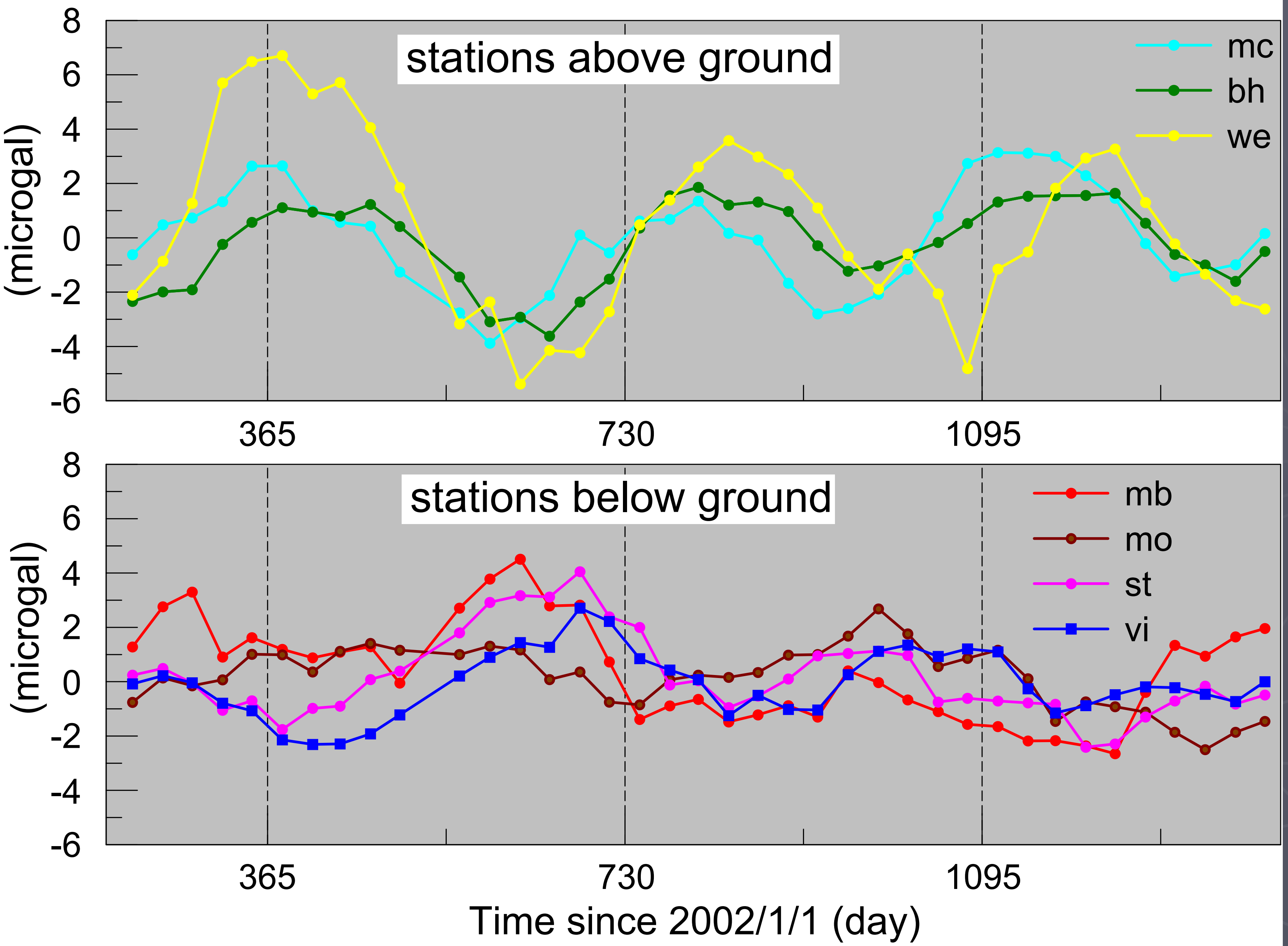
stations that have been
used for comparison
with GRACE





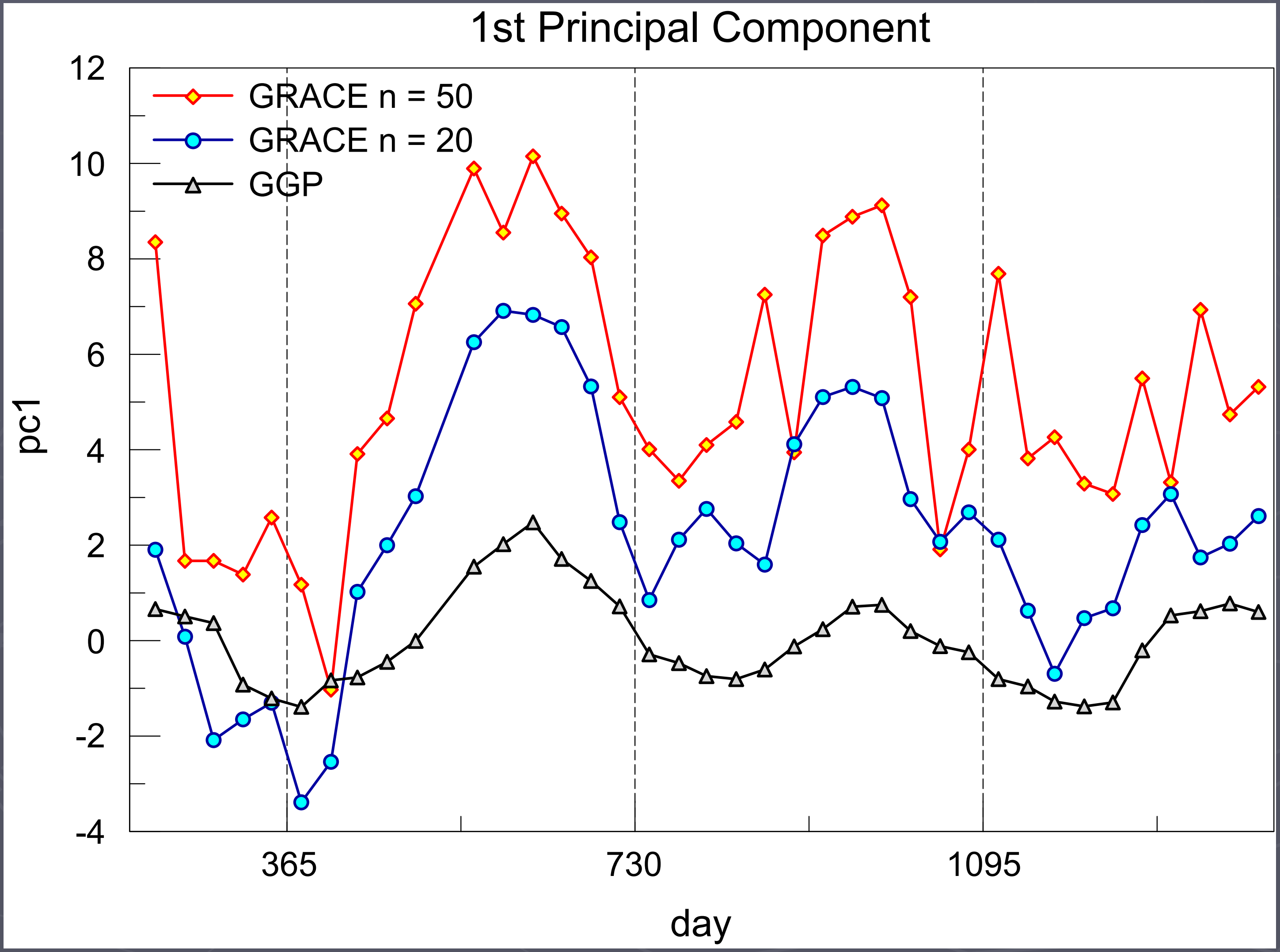
stations that could be
used for comparison
with GRACE

Observed GGP Data at GRACE Epochs

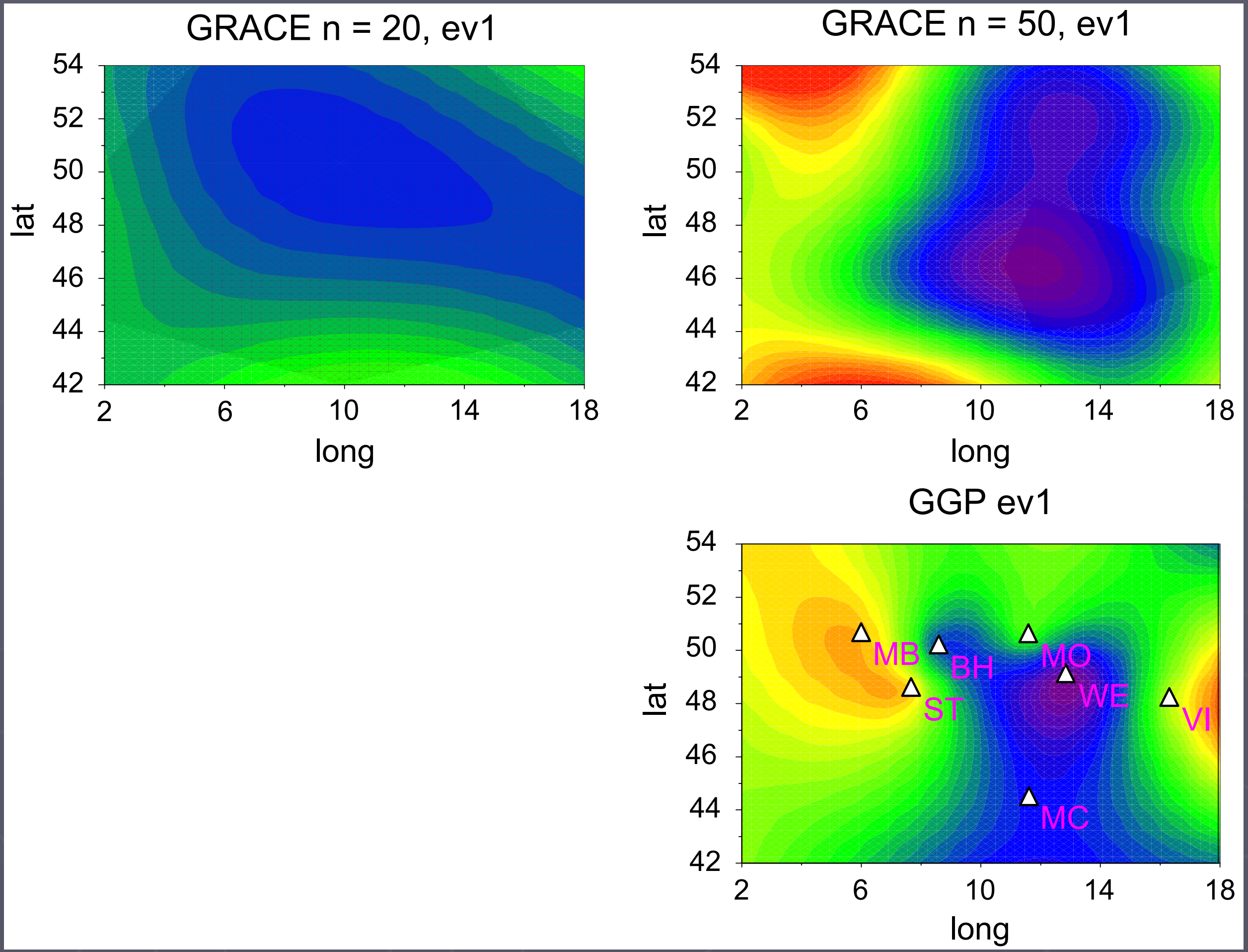


EOF Analysis of GRACE and GGP data 2002-2005

space-time gravity field (1000 km x 4 yr) = spatial pattern (eigenvectors) + temporal variation (principal components)



First Eigenvector



A comparison of the first eigenfunction of the EOF decomposition of the GRACE and GGP fields. The n=20 solution is very smooth, as expected for 1000 km wavelength, but the n=50 pattern has more character. The GGP solution shows inverted phase of stations MB, ST, and VI compared to the others, exactly as expected.

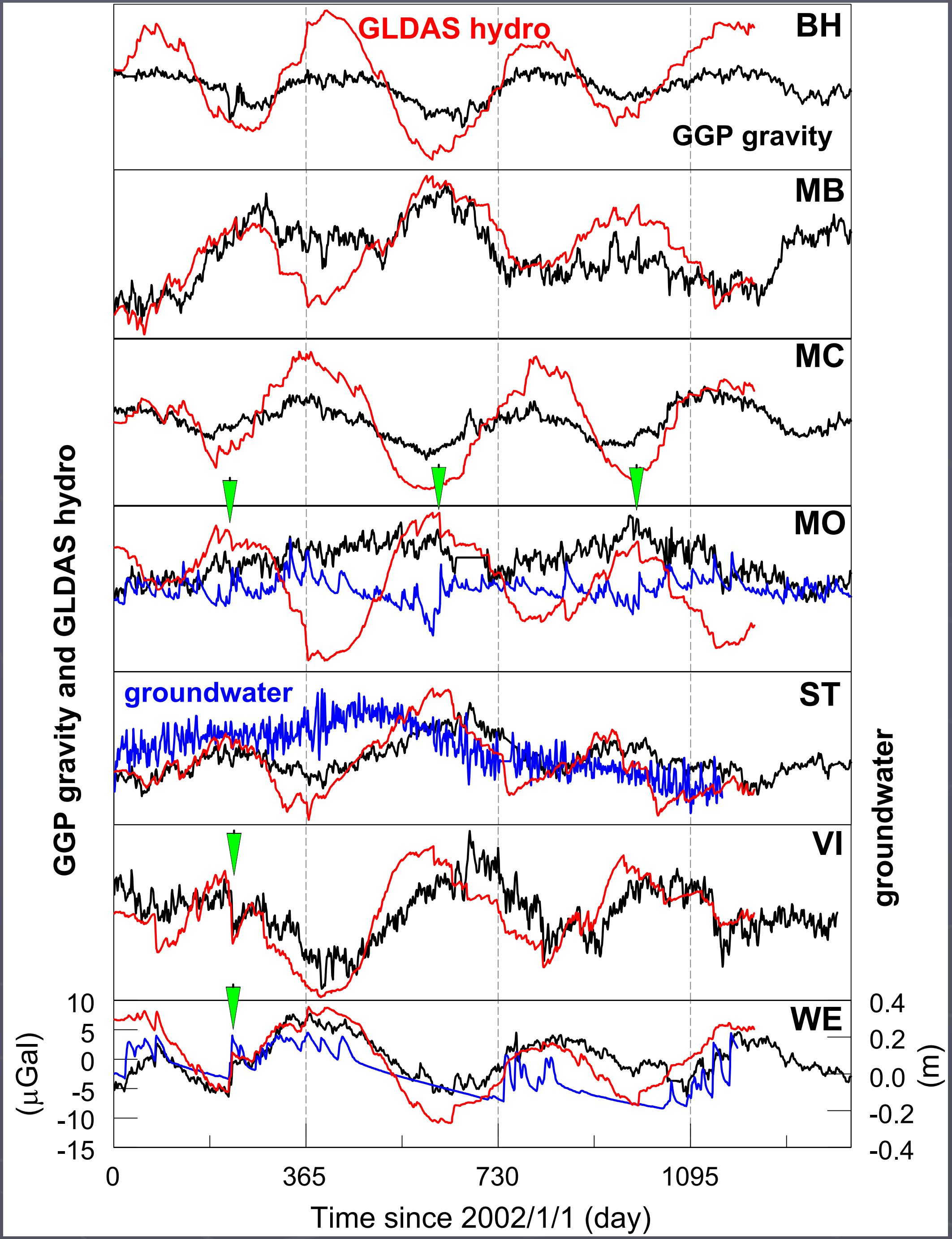
Hydrology comparison

GLDAS hydrology has been adjusted for sign of the local component:

+1 if SG at surface,

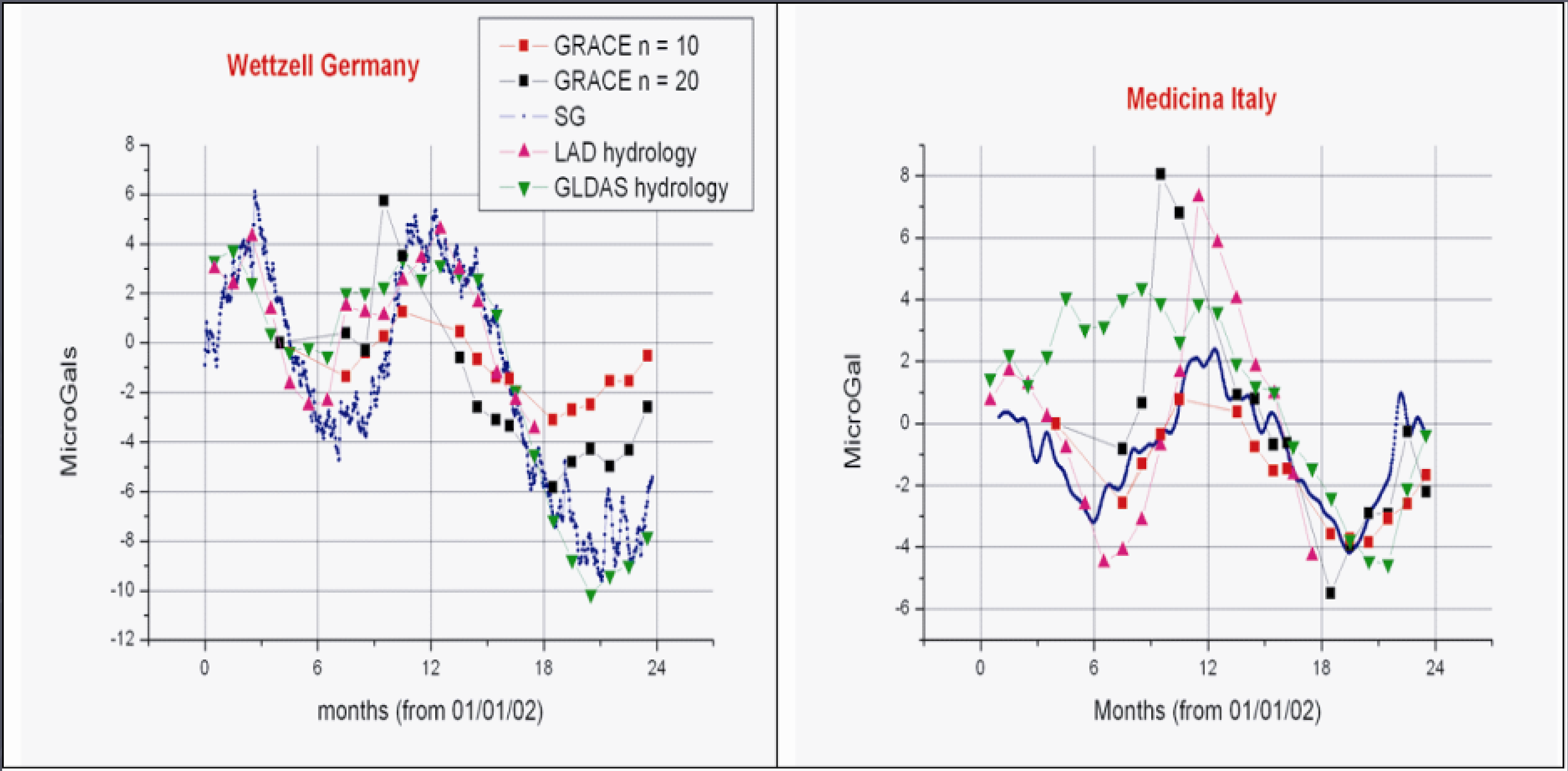
-1 if SG below surface

note the rapid gravity changes at some widely distributed stations due to large-scale precipitation events (green arrows)



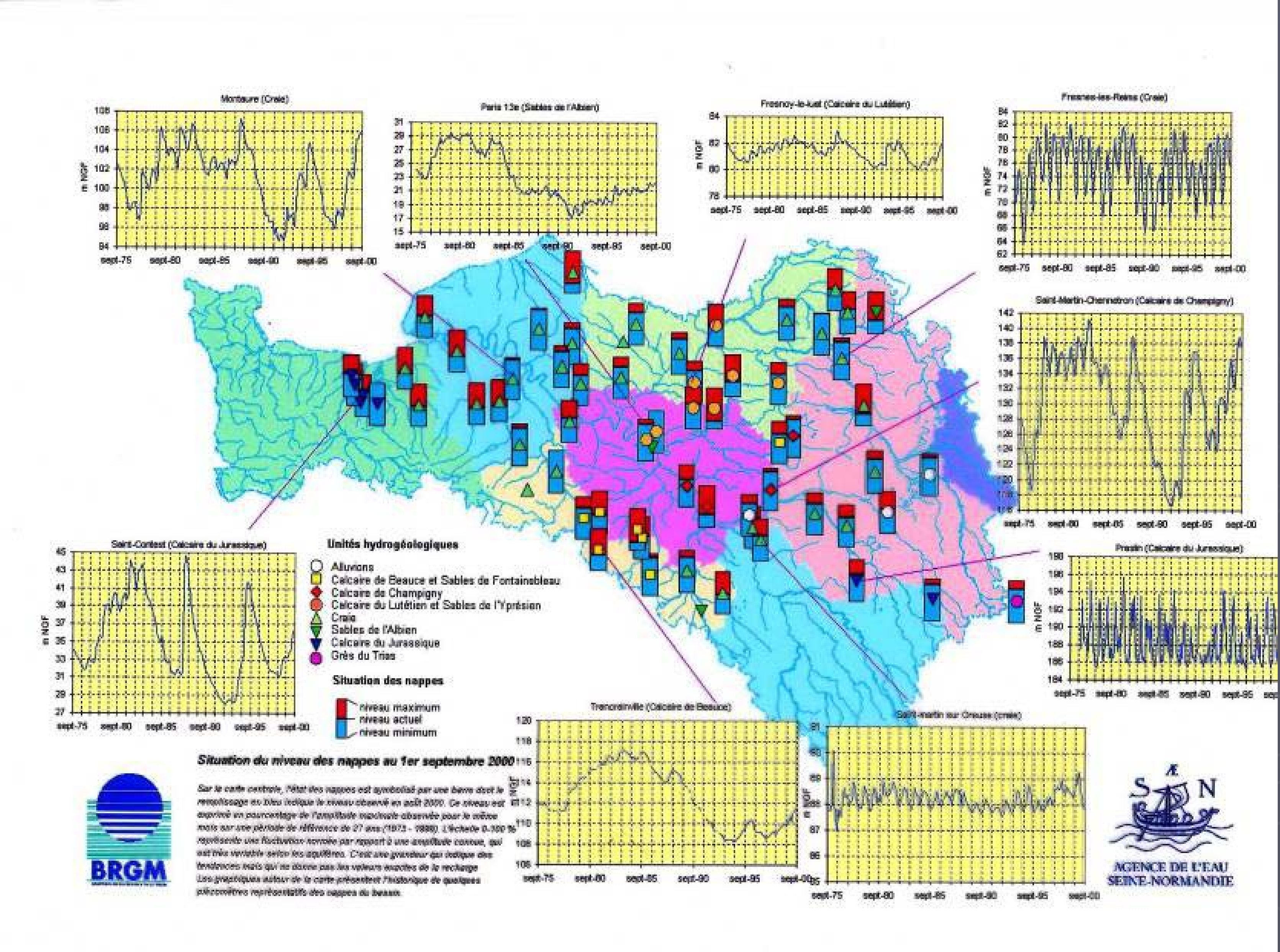
GRACE correlates (sort of) with individual stations

(… but GRACE data cannot be reduced to a local measurement without incurring huge variance that is not shown)



Regional hydrology is variable 1

Paris basin groundwater over 25 yr



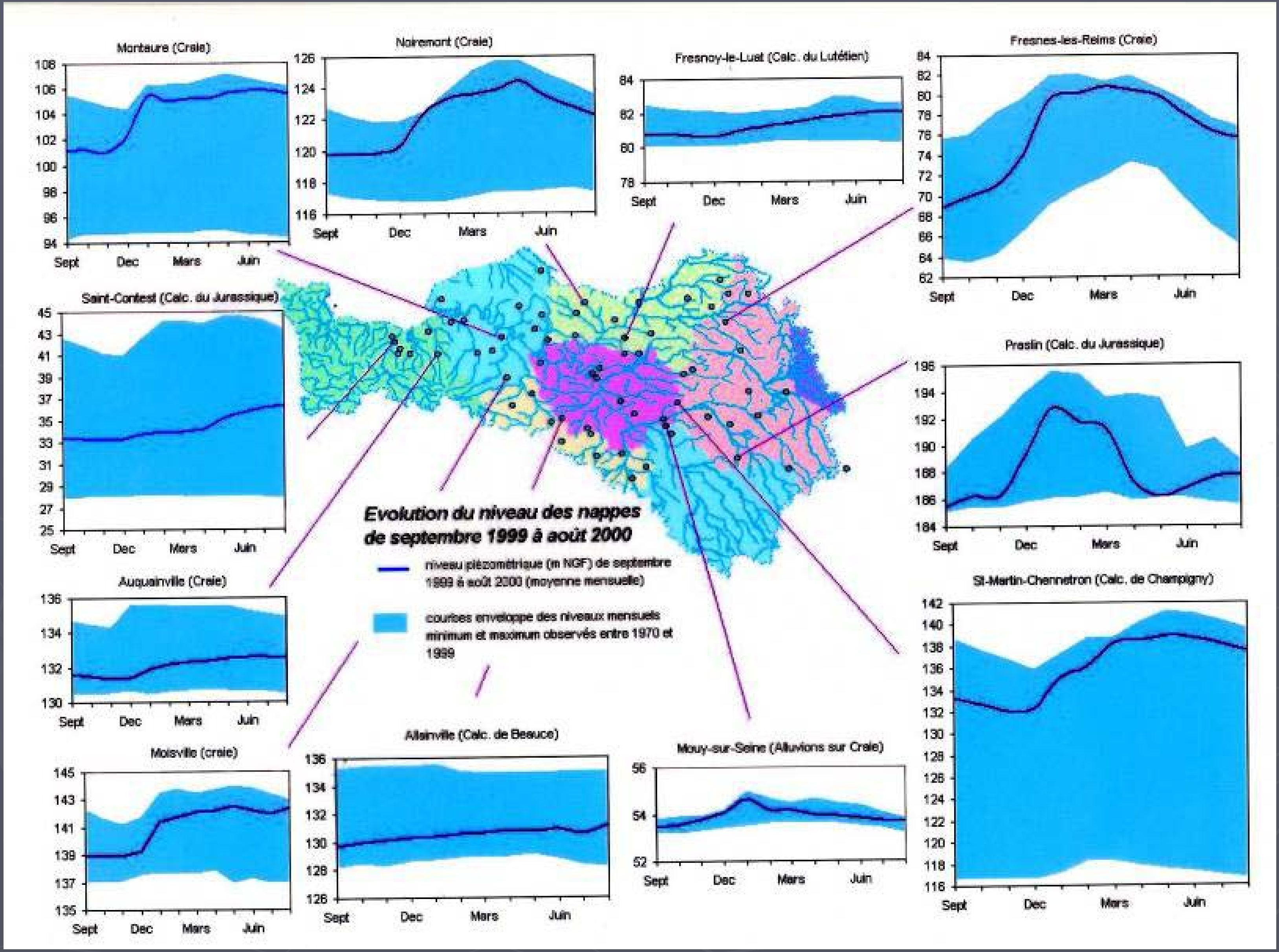
Situation du niveau des nappes au 1er septembre 2000

Sur la carte centrale, l'état des nappes est symbolisé par une barre dont le remplissage en bleu indique le niveau observé en août 2000. Ce niveau est exprimé en pourcentage de l'amplitude maximale observée pour le même mois sur une période de référence de 27 ans (1973 - 1999). L'échelle 0-100 % représente une fluctuation normale par rapport à une amplitude connue, qui est très variable selon les aquifères. C'est une grandeur qui indique des tendances mais qui ne donne pas les valeurs exactes de la recharge. Les graphiques autour de la carte présentent l'historique de quelques piézomètres représentatifs des nappes du bassin.

Regional hydrology is variable 2

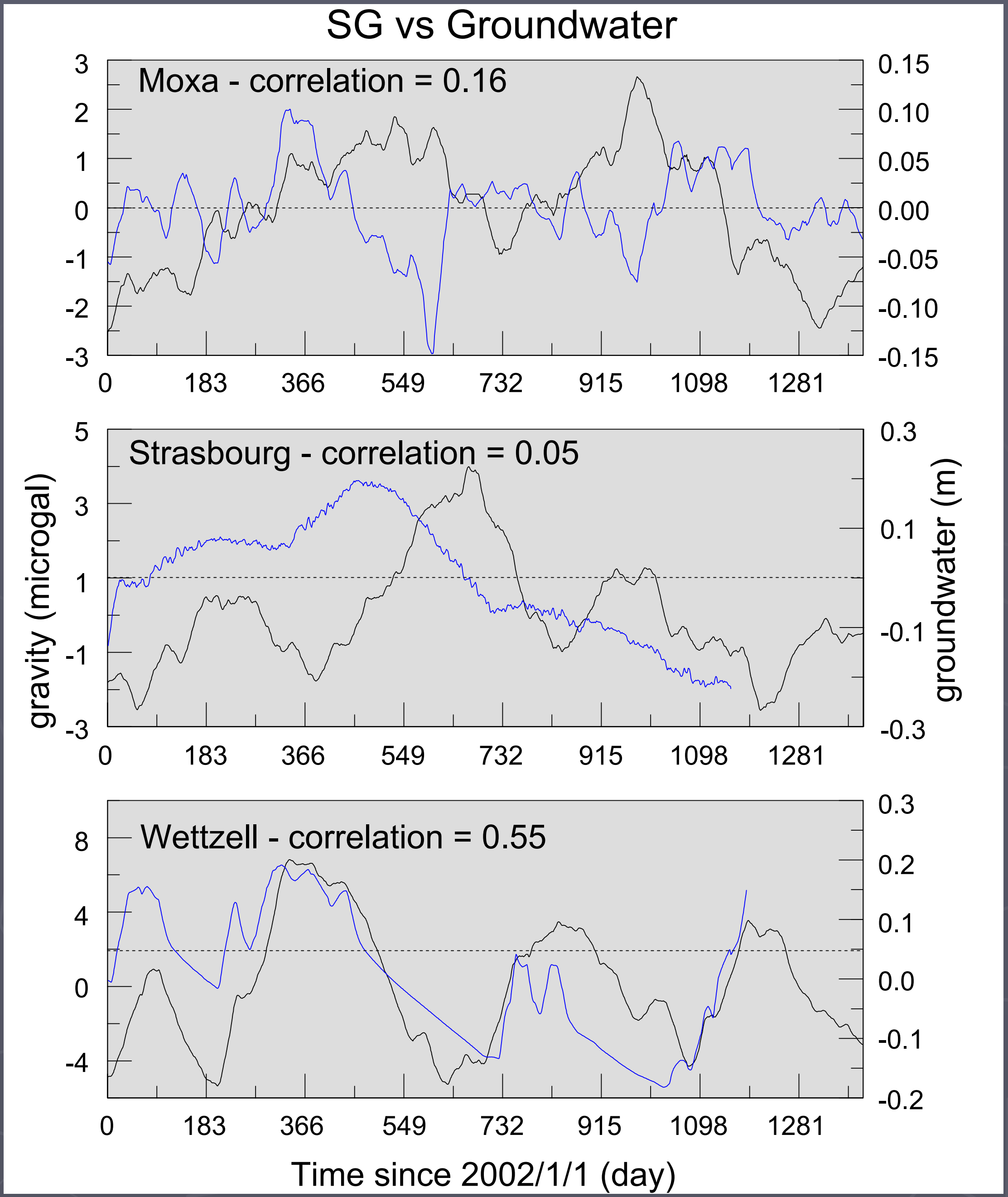
Paris basin groundwater

mean monthly values for 1 year



Groundwater and gravity do not always correlate

indicates we cannot be sure that a groundwater 'correction' is valid for local gravity, (unless two data sets have high correlation)



Geodynamics Networks

Timmen et al., 2004. Observing Fennoscandian Gravity Change by Absolute Gravimetry

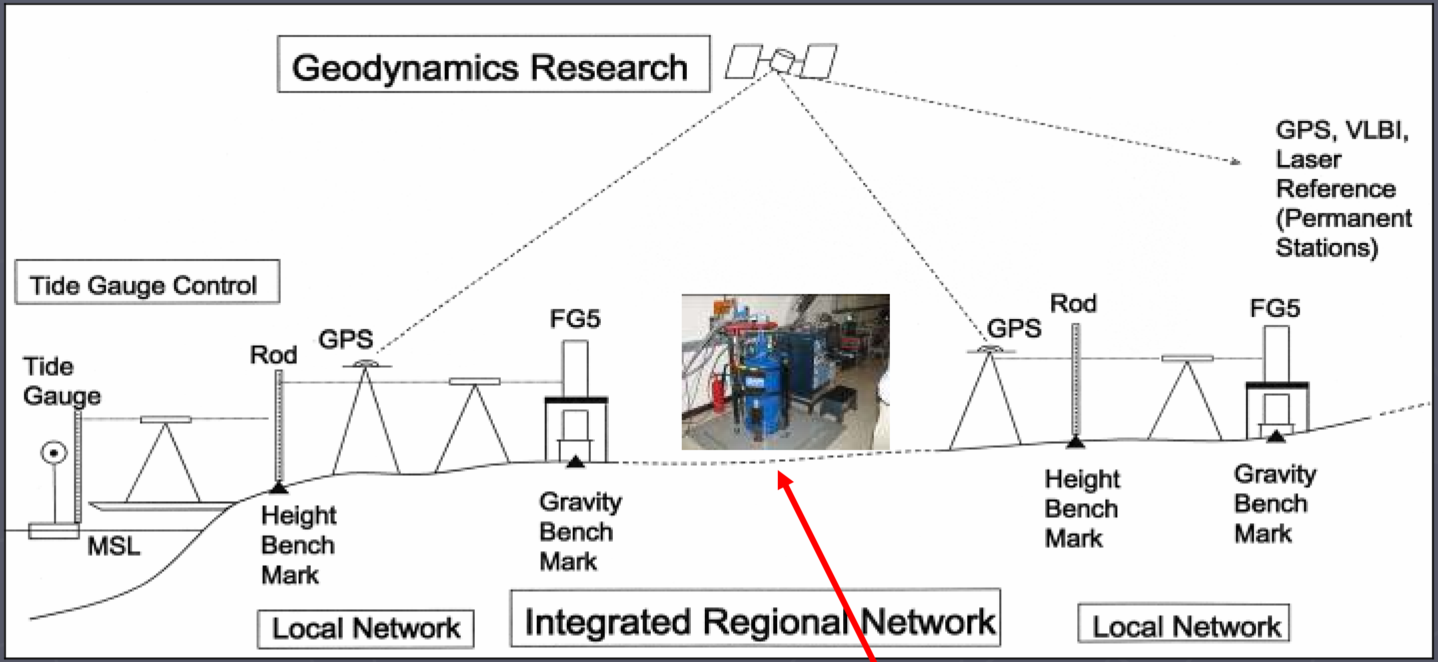
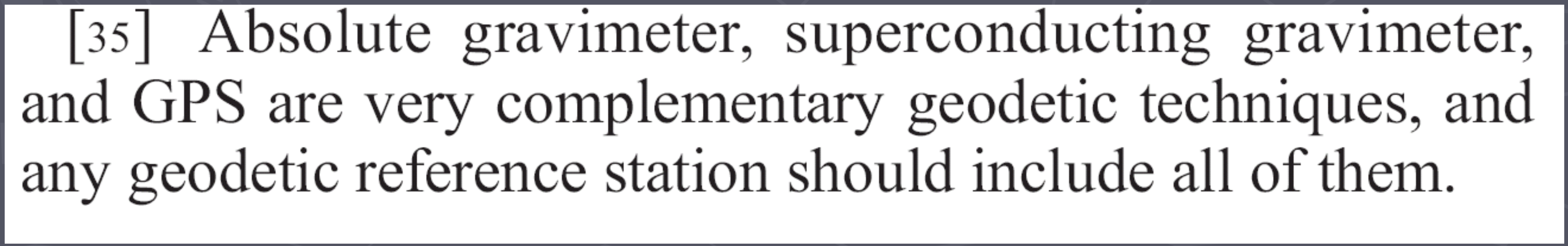


Fig. 3 Integration of different geodetic techniques to survey the temporal gravity and geoid variations of the Fennoscandian land uplift area.

all secular networks require an SG!!

Van Camp et al. (JGR, 2005):

"



[35] Absolute gravimeter, superconducting gravimeter, and GPS are very complementary geodetic techniques, and any geodetic reference station should include all of them.

"

New and planned GGP stations

- Czech Republic – now installed at Pecny (Feb 2007)
- India - will be operating in northern India near Dehradun by Wadia Institute of Himalayan Geology (installation March 2007)
- China – 2 new instruments, one in Wuhan operated by China Earthquake Administration
- Manaus, Amazon Basin, Brazil (GFZ)
- Two in the US - one will operate at Sunspot New Mexico in Lunar Ranging Station; the second for hydrology near Austin, Texas
- Two French proposals – one in Tahiti and an SG-based array in East Africa

Conclusions

- There is a future in high precision gravimetry, and GGP will be there to provide a focus of discussion
- Increasingly, the trend is towards integrating SGs with other equipment for maximum benefit
- Asia is playing a leading role in the new science (China, Japan, S. Korea and Taiwan)

That’s All Folks!