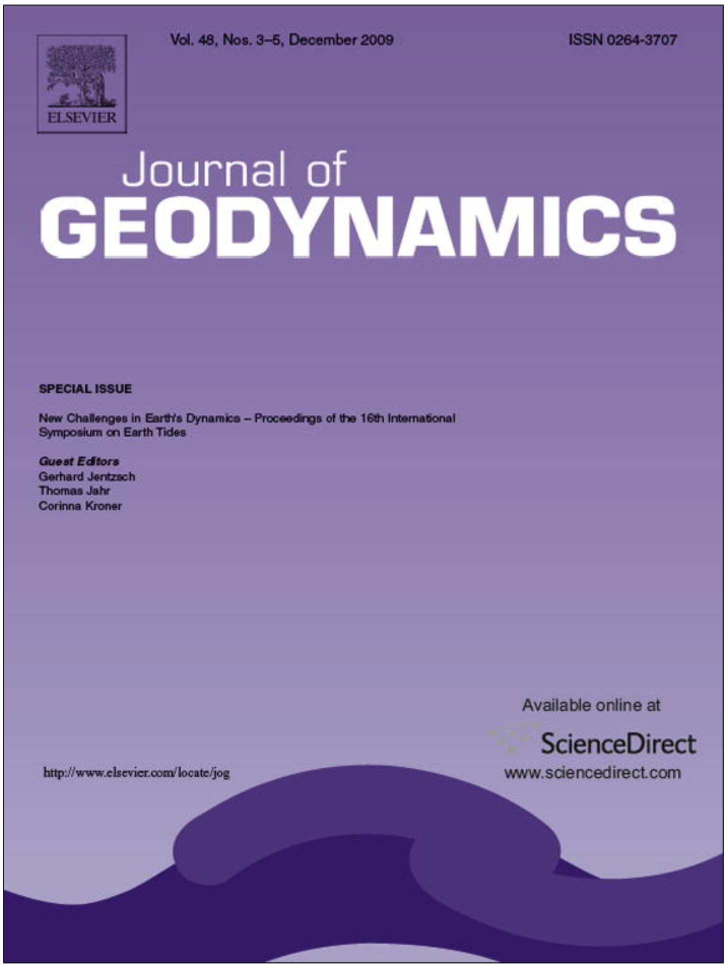
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A review of the GGP network and scientific challenges

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ABSTRACT

The Global Geodynamics Project (GGP) started on July 1, 1997 and is now in its 11th year of operation. It has a relatively small number of stations (24), compared to seismic (GSN) or geodetic (GPS) networks, but it is the only database that is accumulating relative gravity measurements worldwide. As any scientific organization matures, there is a change in the culture of the project and the people involved. To remain viable, it is necessary not only to maintain the original goals, but also to incorporate new ideas and applications on the science involved. The main challenges within GGP are to ensure: (a) that the instruments are properly calibrated, (b) that data is being recorded with the highest accuracy, and with appropriate hydrological instrumentation, and (c) that the flow of data from all recording stations to the ICET database continues as agreed in within the GGP framework. These practical matters are the basis for providing high quality recordings that will extend the usefulness of the network into the future to meet new challenges in geosciences. Several new stations have been brought into operation in the past few years, but the data availability from some of these stations still leaves room for improvement. Nevertheless, the core group of stations established more than 10 years ago has been able to maintain the high standards of the original concept, and much research has been published using network data in areas as diverse as hydrology, polar motion, and Earth's normal modes. GGP will also participate in some of the scientific tasks of the Global Geodetic Observing System program, at least initially by providing relative gravity measurements for collocation with other high precision geodetic measurements.

1. Introduction

GGP has been reviewed several times recently (Crossley and Hinderer, in press, 2007, 2008; Crossley et al., 2006; Hinderer et al., 2006), thus only a brief introduction is required. Fig. 1 shows the current distribution of stations, and their status is summarized in Table 1.

The network is spatially heterogeneous, for historical reasons—although the development of the instrument was in the USA, most of the innovative applications came from institutions in Europe and Japan. The largest group of stations remains in Europe and there is a smaller group in the Japan–S. Korea–China–Taiwan region. Outside these areas, SG stations are sparsely distributed and dedicated to more or less independent projects at each site. At all sites there are barometric pressure measurements, a weather station for rainfall, temperature and humidity and also GPS for timing and positioning. Almost all stations are visited periodically by absolute gravimeters (AGs) to check the SG calibration and monitor the secular changes in gravity. At an increasing number of stations, there are hydrological sensors to measure soil moisture, groundwater levels, and perhaps related properties of the near-surface soils (e.g. Longuevergne, 2008, esp. Ch. 7). Some groups have made efforts to characterize the local geology and the overburden properties using applied geophysics techniques (e.g. Klügel et al., 2006).

Inevitably, a number of stations have stopped recording for a variety of reasons. The SG in Bandung (BA, Indonesia) was damaged during a severe storm in 2003, and the instrument in Brussels (at the Royal Observatory of Belgium) was retired in 2000 after 19 years of continuous operation. Brasimone (BR, in Italy) was retired in 2000, and Boulder (BO, Colorado) had data acquisition problems in 2003 and has not released further data, but it is scheduled to restart in 2009. Kyoto (KY, Japan) has had a history of tilt problems (Iwano and Fukuda, 2004). Potsdam (PO, Germany) was shut down when the instrument was moved to SU (Sutherland), and the SG in Vienna (VI, Austria) was moved to a new site at the Conrad Observatory (CO) in Austria. Syowa (SY) in the Antarctic (Ikeda et al., 2005) has had a large drift problem since 2006, but is still operating although the data has not yet been released.

2. Active GGP stations

The number of active GGP stations is about 24 (23 without the S. Korean instrument, but there is a second instrument in Wuhan, and

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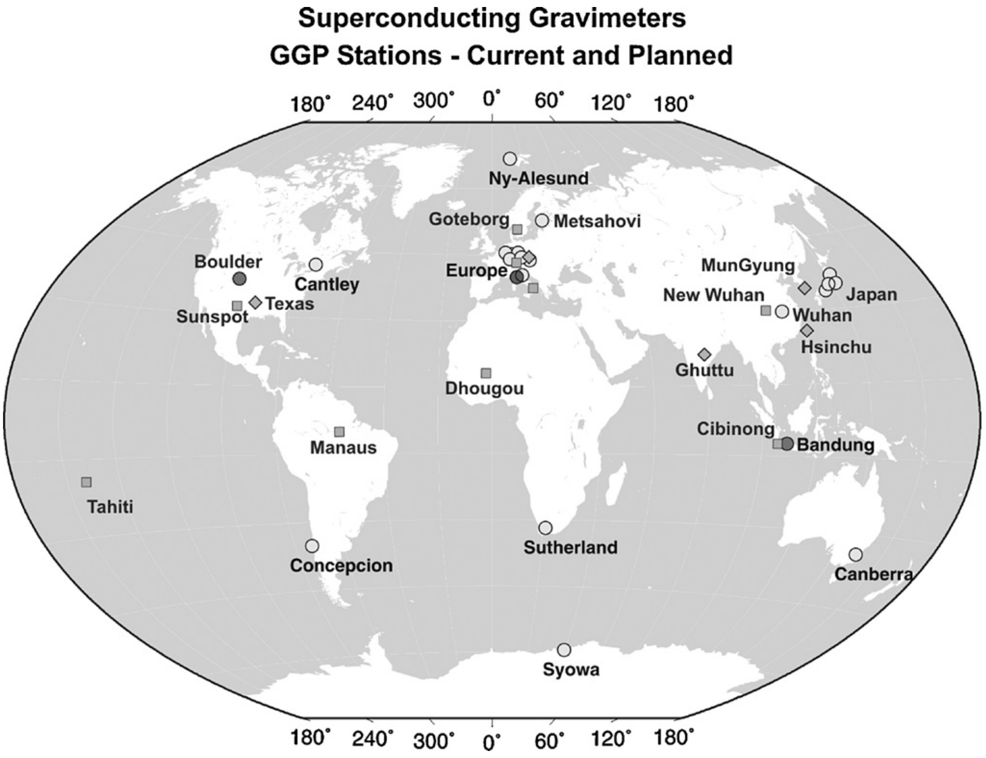

Fig. 1. Distribution of past, present and planned SG stations of the GGP network. Light circles indicate operating stations, dark circles are stopped stations, diamonds are new installations, and squares are planned installations.

Table 1
Details of the current and planned GGP stations, 2009/3/7.

	Code	Location	Country	Started	Latitude	Longitude	Responsible	Institute	Other[a]
1	BH	Bad Homburg	Germany	February-2001	50.2285	8.6113	H. Wilmes	BKG Frankfurt	
2	CA	Cantley	Canada	November-1989	45.5850	284.1929	J. Liard	GSC Ottawa	SP
3	CB	Canberra	Australia	January-1997	−35.3206	149.0077	Y. Tamura	NAO Mizusawa	S, D
4	CO	Conrad	Austria	November-2007	47.9288	15.8609	B. Meurers	U. Vienna	
5	ES	Esashi	Japan	February-1988	39.1511	141.3318	Y. Tamura	NAO Mizusawa	tilt
6	HS	Hsinchu	Taiwan	April-2006	24.7890	120.9710	C. Hwang	Nat. Chiao Tung U.	
7	KA	Kamioka	Japan	October-2004	36.4250	137.3100	Y. Tamura	NAO Mizusawa	
8	MA	Matsushiro	Japan	December-1995	36.5439	138.2032	Y. Imanishi	U. Tokyo	–
9	MB	Membach	Belgium	August-1995	50.6093	6.0066	M. van Camp	ROB Brussels	
10	MC	Medicina	Italy	July-1996	44.5219	11.6450	H. Wilmes	BKG Frankfurt	V, S
11	ME	Metsahovi	Finland	January-1997	60.2172	24.3958	H. Virtanen	FGI Masala	V, S, D
12	MG	MunGyung	S. Korea	March-2005	36.6402	128.2147	J.-W. Kim	Sejong U.	
13	MO	Moxa	Germany	December-1999	50.6447	11.6156	G. Jentzsch	FSU Jena	
14	NY	Ny-Alesund	Norway	September-1999	78.9306	11.8672	Y. Tamura	NAO Mizusawa	V, D
15	PE	Pecny	Czech Rep.	April-2007	49.9138	14.7856	V. Palinkas,	VUGTK Pecny	
16	ST	Strasbourg	France	July-1996	48.6217	7.6838	J. Hinderer	EOST Strasbourg	
17	SU	Sutherland	S. Africa	February-2000	−32.3814	20.8109	C. Kroner	GFZ Potsdam	G
18	SY	Syowa	Antarctica	March-1993	−69.0067	39.5857	K. Shibuya	NIPR Tokyo	V
19	TC	Concepcion	Chile	November-2002	−36.8437	286.9745	H. Wilmes	BKG Frankfurt	V, S
20	TX	Texas	USA	June-05	30.2900	−97.7400	C. Wilson	U. Austin	
21	WA	Walferdange	Luxembourg	January-2004	49.6650	6.1530	O. Francis	U. Luxembourg	
22	WE	Wettzell	Germany	June-1996	49.1440	12.8780	H. Wilmes	BKG Frankfurt	V, S, L, D
23	WG	Ghuttu	India	April-2007	30.3170	78.0660	B. Arora	WIHG Dehradun	
24	WU	Wuhan	China	December-1997	30.5159	114.4898	H.-P. Sun	IGG Wuhan	S
New and planned stations									
25		Cibinong	Indonesia	November-2008	−6.2300	106.7300	Y. Fukuda	U. Kyoto	
26		Sunspot	USA	February-09	32.7660	−105.8200	T. Murphy	UCSD California	L, D
27		Goteborg	Sweden	March-2009	57.3958	11.9267	H. Scherneck	Onsala Space O.	V, G
28		Manaus	Brazil	May-2009	−3.0100	−60.0000	C. Kroner	GFZ Potsdam	
29		Schiltach	Germany	July-2009	48.3306	8.3294	W. Zurn	U. Karlsruhe	
30		Djougou	Benin	September-2009	9.3500	2.6200	J. Hinderer	EOST Strasbourg	
31		Yebes	Spain	May-2010	40.517	−3.083	J. Gomez	IGN, Madrid	V, G
32		Matera	Italy	NA	40.6486	16.7046	G. Bianco	ASI Matera	V, S, P
33		Tahiti	France	NA	−17.5769	−149.6063	J.-P. Barriot	U. Fr. Polynesia	V, D

[a] V: VLBI, S: SLR, D: Doris, L: LLR, P: PRARE, G: GGOS, SP: SPOT satellite.

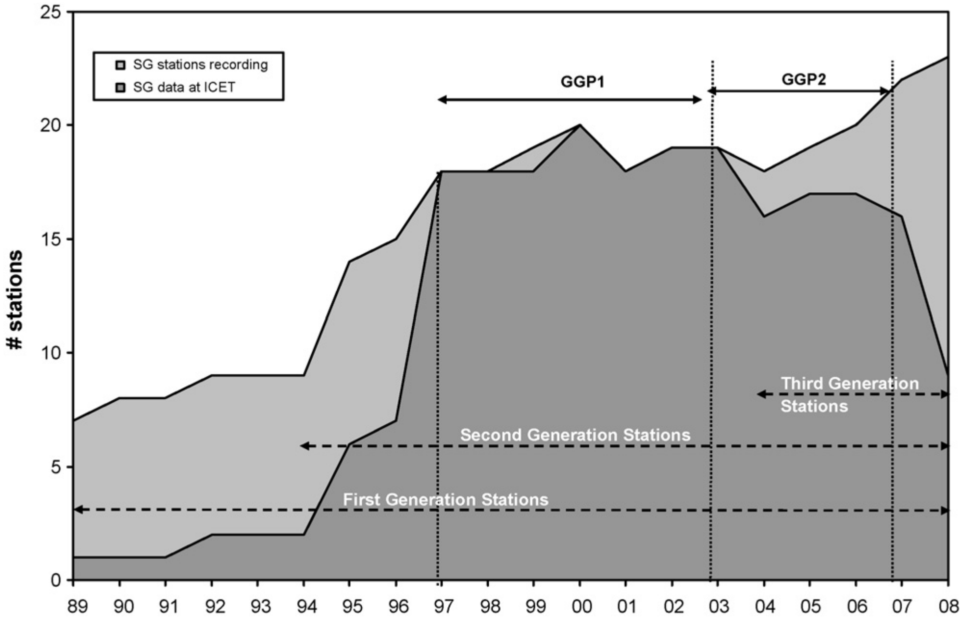

Fig. 2. Operational SG stations and those archiving data at ICET.

a second instrument in India, but little is known yet of these last two) and details are shown in Table 1. We include their location, scientific association, and start dates. We also show whether there is other major geodetic instrumentation at the sites, a particularly important consideration for the realization of the GGOS (Global Geodetic Observing System) program (e.g. Plag, 2006; Crossley and Hinderer, 2008).

A list of geodetic stations can be found at http://indigo.nasa.gov/sgp_locations_full_db_site.html. GGOS will focus on co-located complementary geodetic observations, dominantly positional, but also including gravimetry, for improved accuracy and coverage of global deformation and the gravity field. The deployment of SGs began in the early 1980s, and continues to increase, particularly at the start of the GGP project in 1997. The overall availability of data at ICET is summarized in Fig. 2.

Note we have grouped the stations arbitrarily into 3 categories. First Generation stations are those recording before the start of GGP in 1997; they were all established for the investigation of tidal gravity signals. The early investigators were actively involved in the improvement of the instrument, particularly with respect to reducing the drift, improving the technology and decreasing its size. Second Generation stations refer to those sites that started about the time of GGP and became active in sharing data especially for studies that required stacking the data for global signals such as polar motion. Third Generation stations indicate those installed after about 2004, often by institutions looking for signals for tectonic or other purposes. During the first phase of GGP (1997–2003), almost all SG data was archived at ICET, and this made possible a large number of studies published using the database. During GGP2, which ran from 2003–2007, the number of stations gradually increased, but the amount of archived data began to fall. This trend has continued to the present GGP operation (the phase terminology has been dropped), and the number of stations contributing is currently the same as at the beginning of GGP.

One reason for the drop in data is that some reliable stations have stopped operations, as discussed previously. A further contributing factor is that some new scientific groups are relatively new to working with SGs, and there can be a steep learning curve, particularly in the instrument maintenance and processing of data. For example, MunGyung, in S. Korea, which only operated for a few years, stopped due to a lack of institutional resources rather than any problem with the instrument (J.-W. Kim, discussion in Jena ETS2008). Fortunately, a paper on the data has just appeared (Kim et al., 2009). Another trend is that some SGs are being installed for shorter-term operation, rather than as a long-term permanent station, thus reducing the impact of the data for long-term studies. Nonetheless, we include the new station in Texas, which is of the short-term type, in Table 1.

3. New SG stations

Also shown in Table 1 are 8 new stations, 4 of them requiring new gravimeters in 2009, and 6 of which are scheduled to be operational in 2009, according to GWR Instruments. Roughly in order of start-up they are:

(1) Cibinong, Indonesia, is a new installation successfully completed in 2008 by Y. Fukuda and colleagues. It has been operational since November 2008, and seems to be working OK. This is very good news after the problem with the previous SG in Bandung. Indonesia is one of the most tectonically active areas in the world, and this SG site is the only one that would have been within useful distance of the large Sumatra-Andaman event of 2004.

(2) Apache Point (New Mexico, USA) is the site of the high precision Lunar Laser Ranging facility at Apache Point Observatory (labeled Sunspot in Fig. 1). The purpose of installing an SG is to provide precise vertical ground control for the very accurate lunar laser ranging (LLR), currently at the 1–3 cm. With the introduction of an SG in 2009, it is hoped that (together with existing GPS), the precision can be improved to the mm level to enable progress in a number of experiments in fundamental physics (Murphy et al., in press).

(3) Goteborg, Sweden is the site of the Onsala Space Observatory with a VLBI antenna. The instrument has been delivered, and work is being done on construction of the piers and building. The responsible scientist, H.-G. Scherneck, made extensive inquiries within the GGP community about site construction, particularly on coupling the instrument to bedrock. The site is

above ground and will not have the problem encountered by stations located underground, where there is inevitably a soil moisture layer above the instrument's sensor. The SG will be used to provide continuous monitoring of the station with co-located AG measurements and nearby tide gauge observations. This fiducial station serves a number of different scientific goals, including the monitoring of glacial isostatic adjustment (GIA) and sea level changes.

(4) Manaus (Brazil), in the Amazon basin, is to be the site of the dual-sphere instrument previously at Sutherland (S. Africa). This location became well known in the Amazon as a very high rainfall site that became one of the initial targets of the GRACE project (Wahr et al., 1998). We have no details yet of the site, but permanent GPS, water table, soil moisture, and precipitation measurements are planned.

(5) Schiltach (Germany) is a high quality seismic installation at the Black Forest Observatory (BFO). BFO is a very quiet site with excellent seismometers and has one of the best Lacoste spring gravimeters for recording normal modes. The SG is expected to be delivered in the second half of 2009 and will be used by seismologists for several studies, including normal modes of the Earth.

(6) Djougou, Benin is one of the stations of the GHYRAF (gravity and hydrology in Africa) project, where an SG is to be installed at this very high rainfall area that catches the West Africa monsoon (Hinderer et al., 2009). The project will study the gravity and vertical displacements that occur seasonally due to meteorology and hydrology along a N–S transect from the desert environment of Tamanrasset in the Sahara, to Djougou in the south. With ancillary measurements from GPS and AGs (both the FG5 and A10 models), and also a portable Scintrex gravimeter, it should be possible to perform a surface averaging of ground gravity for comparisons with GRACE satellite data. The SG will operate for at least 2 years.

Most of the new installations have the potential to produce high quality data as they will be under the direction of experienced geoscientists. In addition, Table 1 shows two other sites that have been in the planning stages for several years: Matera, in Southern Italy, and Tahiti. At present they are still under consideration.

The installation of these new SGs in interesting geophysical and geological environments continues the tradition of the early SG pioneers. The instruments are being deployed for purposes far removed from the tidal gravity (and normal mode detection) purposes of the past. GGP will continue to tie together the growing SG community and help its scientists realize the best use of the instruments.

4. Current GGP challenges

4.1. *Auxiliary data, log files and calibration*

One of the early issues with SG data, prior to the start of GGP, was the lack of standardization of data formats and no common database. To use SG data for scientific investigations, researchers had to contact each group and request data for particular periods. This is still true for data other than gravity or pressure. Although ICET is set up to receive stations log files and auxiliary data (such as groundwater, rainfall, or soil moisture), only a few stations have sent this data. With the current interest in using gravity data to assist in hydrology modeling, the lack of auxiliary station data at ICET is unfortunate. We counted only 6 stations sending groundwater data (BH, MC, ME, MO, ST, and WE) and 4 sending rainfall (MC, MO, SU, and TC).

Also frequently missing are the station log files, where the major problems and changes in instrumentation are noted. These are important for identifying problems in the data such as helium refills, power supply problems and other disturbances. In some cases, particularly with some of the German instruments, there are disturbances in the residual gravity when the calibration is done using the Frankfurt calibration experiments (Richter et al., 1995) because the SG is physically displaced during the calibration. This disturbance would look mysterious in the residual gravity signal without the help of a log file. Other disturbances could, for example, be due to tilt problems (e.g. Iwano and Fukuda, 2004) or other factors such as heavy rainfall that sometimes look like geophysical signals or rapid slews. Log files are then helpful when identifying offsets in the processing for long periods.

4.2. *Amplitude calibration of SGs*

Ambiguity exists within the ICET database concerning the correct reporting and application of the calibration constants, i.e. the amplitude calibration (or scale) factor and the phase calibration or time delay. The amplitude calibration has found to be generally stable provided the basic geometry of the gravity sensor (i.e. coil position, current strength, feedback system) is unchanged (e.g. Amalvict et al., 2001; Wziontek et al., 2008; Rosat et al., 2009). Calibrations are almost universally done now by parallel recordings with AGs. As demonstrated by Francis et al. (1998), it is essential to use at least 5 continuous days of recording – when the tidal amplitudes are high – in order to achieve a consistent and reliable result for the calibration. This was emphasized again in the paper by Rosat et al. (2009). When new calibrations are done, there may be an improved accuracy to the existing scale factor, or perhaps a better-determined mean value, and not necessarily an explicit change (or step) in its value. The newer value should then in principle apply to all previous data (within the stipulations above); but is this always the case? No explicit guidance exists in the GGP file headers, suggesting that a systematic review of the calibration changes in the file headers must be done to clarify this point for users of the data, so that it is clear when calibration changes are retroactive. This then becomes a priority challenge that the GGP community through ICET must address immediately. One application where accurate calibration is required is the determination of ocean tide loading (e.g. Bos and Baker, 2005), where an amplitude calibration of better than 0.1% is needed to discriminate between ocean tide loading models.

4.3. *Phase calibration of SGs*

The phase calibration, quoted in GGP headers as the time (or group) delay, is dependent on the systems electronics, in particular the anti-aliasing filter. When changes in this filter are made, a new time delay must be used for all the data after the change; it cannot be used retroactively. All analysis must be done with such time delays embedded in the processing, e.g. for computing the theoretical tide at a station, or for seismic processing. Such details are a normal part of using GGP data, but this is generally apparent only to those people aware of the issues. Users of ICET data outside GGP should have better documentation of such information.

The phase calibration is important when providing raw data (directly from an analogue anti-aliasing filter) to the seismic community via the IRIS data management operation (http://www.iris.edu/hq/). Both the amplitude and phase calibration are used to determine the frequencies and amplitudes of the long-period normal modes, an important application of the SG in its high frequency band (e.g. Xu et al., 2008). Van Camp et al. (2008) have described the use of a Quanterra seismic data logger to retrieve

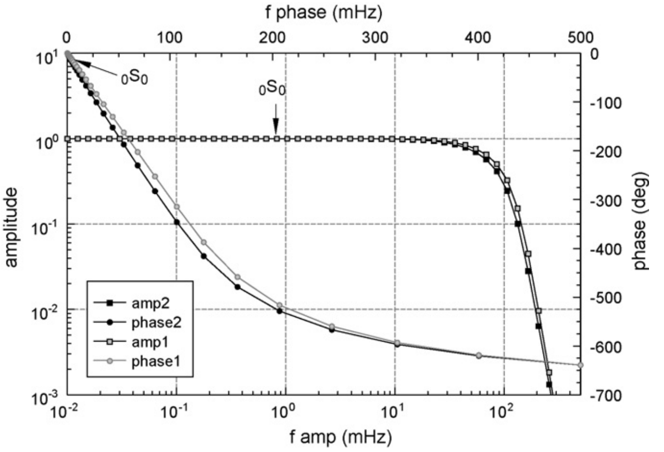

Fig. 3. Amplitude and phase response of the two GGP anti-aliasing filters provided by GWR Instruments. The left and bottom axes are for the amplitude curves, and the upper and right axes are for the phase curves. The location of the ${}_0S_0$ normal mode is identified at the appropriate places on the respective curves.

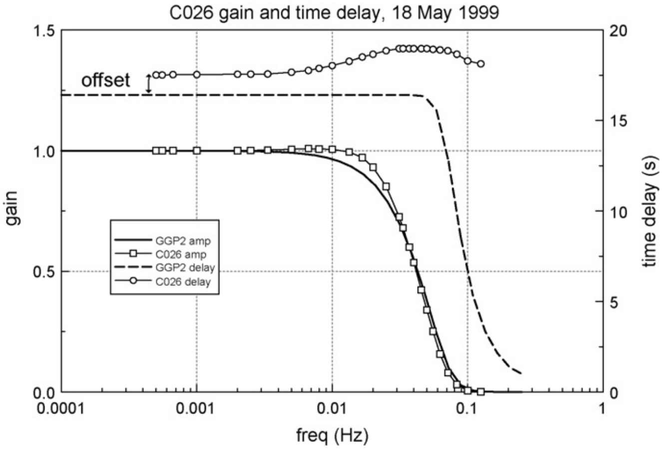

Fig. 4. Observed response of the Strasbourg C026 gravimeter system (periods 8–2000s), compared to the nominal GWR system for 2 s sampling (determined with the help of M. van Camp). The frequency axis is common to all curves, the left axis applies to gain (squares for observed values), and the right axis to time delay (circles for measured values). The time delay is the slope of the phase curve in Fig. 3. Note the offset at the longest period (2000s) between the nominal time delay of 16.41 s for the GGP2 filter alone, and the measured value of 17.18 ± 0.05 s for the complete data acquisition system.

the SG high frequency output, rather than the standard GWR (or other) system that is designed for 1 or 2 s sampling.

The determination of the phase response of SGs must match that of seismometers for the data to be interesting to seismologists. For this reason an electronic calibration that includes the amplitude and phase response of the system electronics (not the same as the scale factor referred to in the previous section) is done with either an artificial step response method (Wenzel, 1995) or sinusoids of different frequencies (Van Camp et al., 2000). It is of some concern to us that the electronic calibration procedure has been used at only a small number of stations (MB, ST, WA), but yet it requires only a day or so of time and laboratory-grade signal generators to be effective. The standard response of the most recent GWR filter boards is shown in Fig. 3, where the design amplitude response is flat to 10 mHz (100 s) and the phase response is linear to 100 mHz (10 s) or better. These characteristics more than fulfill the arguments of Widmer-Schnidrig (2003) that normal modes of frequencies lower than 1 mHz are the ones that add most new knowledge to normal modes studies.

Though the response of an SG data acquisition system is dominated by the anti-aliasing filter, other electronic components have some effect. For the electronic calibration at Strasbourg, done in 1999, the results in Fig. 4 were obtained from one of the data acquisitions systems connected to the filtered output ‘GGP-2’. Departures from the nominal values are seen (e.g. the time delay is 17.3 s compared to the nominal 16.2 s for 2-s sampling, and there is a noticeable peak in both calibrations at about 20 s) that will lead to a modified pole-zero distribution from the nominal 8-pole analogue Bessel filter used by GWR. This can be done by fitting a pole/zero model to the amplitude and phase measurements using a straightforward Matlab script; details will be reported elsewhere. The data acquisition system has now (2008) been changed in Strasbourg, so this electronic calibration has to be repeated for the next epoch in the recording.

The SG data can be converted to the seismic standard as a miniseed file, with the dataless seed being a metadata file that contains the instrument response, as just discussed. Sending as much of the existing and future SG data as possible to IRIS is one of the goals of GGP.

4.4. Absolute gravity data and GGP

In the past two years, there has been significant progress toward the establishment of an AG database that will help researchers interested in the long-term gravity changes at GGP sites. This initiative (AGrav) is a joint effort of BGI (Toulouse) and BKG (Frankfurt) and is described in detail elsewhere (Wilmes et al., 2009). The idea is to provide AG observations, in variety of formats (depending on the data supplier), which can be used either stand-alone or in conjunction with SG data at the GGP stations.

The advantages of combining AG and SG measurements have been widely accepted within GGP both for the SG calibration, and also for the determination of long-term trends at stations (e.g. Crossley and Hinderer, in press; Rosat et al., 2009; Wziontek et al., 2008). The lack of readily available AG data in an online database means (as discussed above for auxiliary GGP data) that researchers have to make a special effort to get AG data, even at GGP stations. Therefore GGP strongly supports the AGrav group in pursuit of an AG database that should be of interest to a wide community of users. AGrav is now openly requesting AG data from the community and will continue to develop its software and online processing capabilities.

4.5. SG contributions to hydrology

Of all the challenges faced collectively by the GGP network, none has received as much attention as the role of SGs in the context of hydrology. In the past decade, it has become clear that most GGP stations need to be equipped not just with a meteorological instruments (as well as GPS), but also well-chosen hydrological sensors. This is because at time periods of minutes to years, the hydrological mass variations are easily captured by either single SGs (e.g. Longuevergne, 2008; Kroner and Jahr, 2006; Virtanen et al., 2006) and also by SGs acting in a network sense (e.g. for the European network—Neumeyer et al., 2006; Crossley et al., 2009). Obviously SGs can integrate the (variable) total amount of water in the neighborhood of a station, but hydrological models using rainfall, soil moisture content, soil properties, and groundwater levels must be added as part of a comprehensive geophysical program to describe the hydrological transfer. This modeling is not necessarily an end in itself, but may be essential to understand before other signals of interest (e.g. seismic precursors, coseismic deformation, or post-glacial rebound) can be adequately recognized in gravity. This is also an area in which experience with SGs may be usefully transferred to AG measurements which are also inevitably contaminated by hydrological signals. The challenge here is to make sure SG sites are properly equipped with the hydrological instrumentation.

5. GGP and the new ICET

ICET has, since 2008/1/1, been established at the University of French Polynesia (UPF) in Tahiti, with the assistance of B. Ducarme. The new ICET Director, J.-P. Barriot, has taken responsibility for providing services of the ICET/GFZ database to GGP and a new ICET interface is being prepared for GGP users. Additionally, ICET will continue to provide corrected minute data for tidal analysis to the GGP database, and to establish a portal for all tidal and gravimetric data collected during the lifetime of ICET in Brussels. The Bulletin d'Information des Marées Terrestres (BIM) will also move to an entirely electronic distribution.

6. Potential for GGP to become an IAG service

Further to the adoption of GGP as an inter-Commission project of IAG in 2003, a suggestion has been made to modify GGP from a project to an IAG service. This will further establish the role of GGP to provide relative gravimeter data for IAG and the international community. The idea was adopted as a resolution of the 2008 Earth Tide Symposium in Jena, and a time window for consideration was given until the IUGG in 2011 in Melbourne.

7. Conclusions

Our conclusions are (a) some types of data, namely station log files and auxiliary hydrological data are in short supply at ICET. These deficiencies need to be addressed, (b) there is a surge in the number of SG stations being installed, indicating the GGP community will continue to expand into new areas of scientific interest, (c) GGP is now actively pursuing collaboration with both IRIS and the AG community to extend the utility of data collected by SGs, and (d) GGP may develop in future as a more formalized data provider within IAG than in the past, particularly in connection with the GGOS program.

Acknowledgments

We acknowledge all the GGP stations operators for continuing to provide their data freely to the ICET database, and sharing it openly with the geoscience community. Special thanks go to B. Ducarme (retired) for his dedicated service as Director of ICET, and also to B. Ritschel who has maintained the involvement of GFZ Potsdam for the GGP data. Our thanks also to two anonymous reviewers for useful comments.

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