Report of GGP Activities to Commission 3, Completing 10 years for the Worldwide Network of Superconducting Gravimeters.

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Abstract. The Global Geodynamics Project was renewed for the foreseeable future at the IUGG in Perugia. The second cycle (called GGP2) of operations started in 2003, and followed the initial years of GGP1 (1997-2003). Thus GGP has now completed 10 years of collecting data from all the currently operating superconducting gravimeters (SGs). During the last cycle, GGP operations have gone smoothly for most stations, but with the inevitable instrumental problems. We have lost (at least temporarily) stations Boulder and Bandung, but gained an instrument in MunGyung (S. Korea) and two instruments in Hsinchu (Taiwan). New installations were recently done in Pecny (Czech Republic) and Dehradun (India), and several other locations in the US and Asia are being contemplated in the next cycle of GGP (2007-2011). Over the past two years, we have worked to prepare raw GGP data (at sampling times of 1-5 s) for inclusion into the IRIS data set for the seismologists to use in normal mode studies of the Earth. A successful GGP Workshop was held in Jena, Germany in March 2006, and the first official Asian SG Workshop took place in March 2007 in Taiwan, hosted by our colleagues in Hsinchu. Of continuing interest within GGP is the issue of combining measurements from absolute gravimeters at the SG stations for a variety of long-term studies of the gravity field such as tectonic uplift, subduction zone slip, and determination of the Earth's centre of mass with respect to the terrestrial reference field. GGP has now become involved with the development of GGOS, a project that intends to coordinate the use of many different geodetic data sets for future ease of access.

Keywords. Superconducting, gravimeter, GGP, gravity field, time-variable gravity.

1 Introduction and Station Review

We show in the Figure 1 the location of most of the stations in the GGP network for the decade 1997-2007. The cluster of stations in Europe and N.E. Asia are shown separately in Figures 2 and 3 respectively.

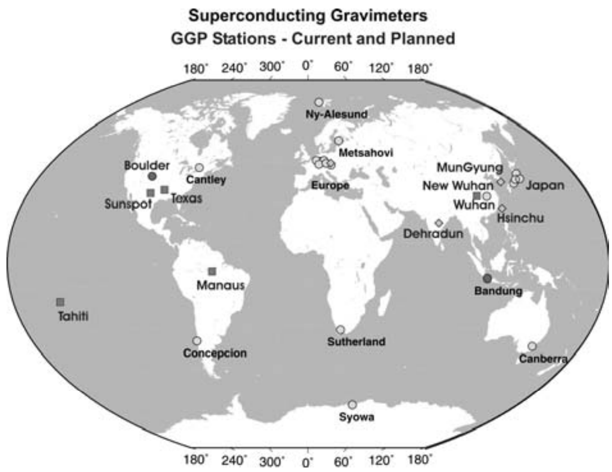

Figure 1. Distribution of SG stations: light circles are operating, dark circles are stopped, diamonds are new installations, and squares are stations projected for the next 2-3 years.

Two stations in the network stopped recording during the current reporting period (2003-2007). These were Bandung, Indonesia, and Boulder, Colorado. The situation in Bandung was instrument failure due to a severe storm that flooded the facility and lifted the instrument off its supporting pillar. The internal components in the dewar were OK, but the damage was too severe to be easily or quickly repaired. There has been talk of reconstituting a station in Indonesia, but in another location. The station and instrument are run by Kyoto University, Japan. The situation in Boulder is different. Due to the retirement of key personnel in Boulder, repair of a data acquisition failure in May 2004 was not done, and no further data has been available to GGP, although some data has been recorded. NOAA has ownership of the instrument, and it is still functioning; for the moment we are informed it will stay at TMGO (Table Mountain Gravity Observatory) until further decisions are made. Suggestions about transferring it to Alaska, or to

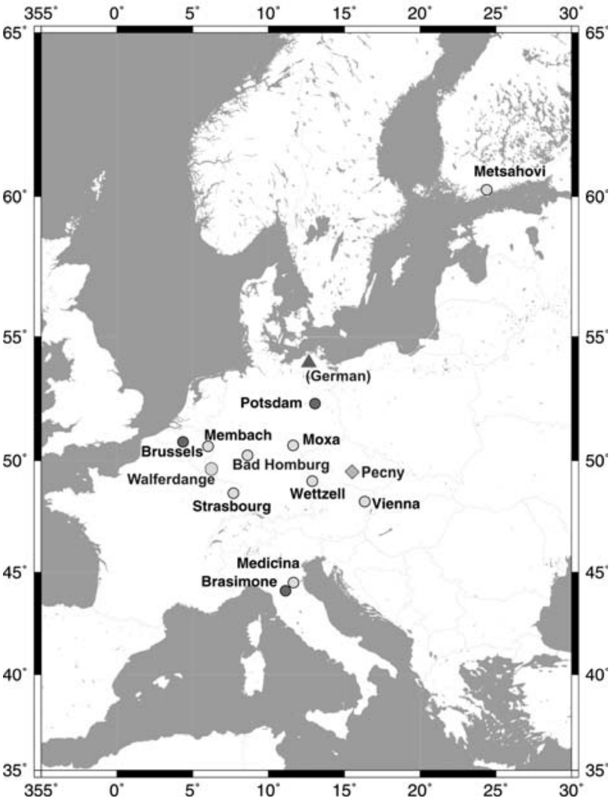

Figure 2. GGP stations in Europe, excepting Ny Alesund (Fig.1). The north German station on the Baltic Sea is in the planning stage.

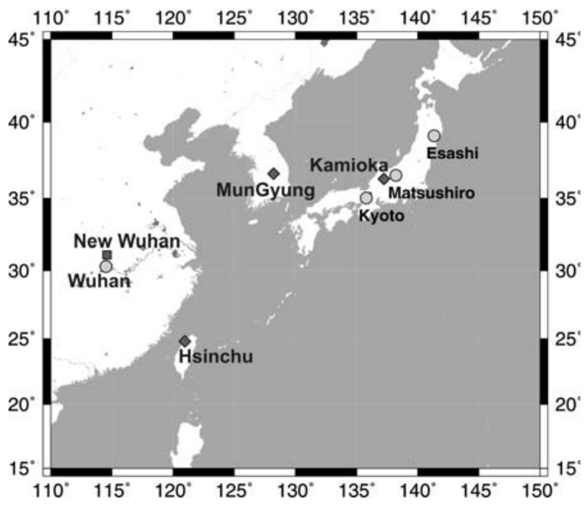

Figure 3. As previous figures, but for N.E. Asia. There are two instruments at Hsinchu

another site in the US have been discussed within GGP and passed on to NOAA.

Two other stations had troubles that have resulted in data interruptions. One is the instrument in Kyoto that has had tilt problems for a long time that has been difficult to fix (Iwano and Fukuda, 2004). Also the instrument in Syowa, Antarctica has had drift problems since 2006, and we have not seen data for some time.

Thankfully all other stations in the network are functioning well and sending data to the GGP database at ICET. Most of these stations have now brought themselves up to date at least into early 2007. Only one station so far has not sent data to GGP. New data is now available from the instrument in Kamioka (Japan), at an underground installation in Mozumi Mine that is more famous for the location of the neutrino detection facility (Super-Kamiokande). Several strainmeters are also installed in the tunnels.

Two new stations have been recording since 2005: MunGyung in S. Korea, and Kamioka in Japan. The former is run by J.-W. Kim of Sejong University, Korea, also associated with the geodesy group at Ohio State University. We are still awaiting data from MunGyung. Two new instruments were installed in Hsinchu, Taiwan, in 2006 by C. Hwang and colleagues of the National Chiao Tung University. One had to be returned to GWR for repairs but is expected back imminently. The other is recording well in an underground facility in Hsinchu and we have seen preliminary data.

Finally, two very recent installations were completed early this year (2007). One is at the historic Geodetic Observatory in Pecny, Czech Republic. Another was installed at the Wadia Institute of Himalayan Geology in Dehradun, India to study earthquake precursory signals in conjunction with other geophysical methods. Both installations were successful and we look forward to receiving their data. A preliminary look at data from Dehradun is encouraging.

As for future stations, we are anticipating the installation of an SG in Manaus, Amazon Basin, as part of the effort of GFZ (Potsdam) to characterize the very large annual hydrology signal over the basin seen by the GRACE satellites. The anticipated date is Fall 2007. We also know of several other planned locations identified on the maps. There will be an SG in Texas to monitor hydrology (C. Wilson, U. Texas, Austin), and a second instrument in Wuhan to be installed by the Chinese Bureau of Seismology. The installation of an SG in Tahiti is in the works, with an instrument being considered in the southern US at Sunspot in New Mexico, the site of the lunar laser ranging facility. The German group is planning to locate an SG station on the Baltic Sea coast (Figure 2). Overall the list of stations will soon reach 30, of which at least 25 should be functioning within the next year or two.

2. GGOS

Along with many other IAG organizations, GGP will contribute data to the Global Geodetic Observing System (GGOS) as part of the extensive range of goals identified in the GGOS Reference Document (GGOS-2020). The combined use of SGs and AGs to monitor the long term changes in the surface gravity field has now become commonplace and we look forward to the opportunity to see SGs installed at more of the fiducial (or core) stations of the proposed GGOS ground-based network. One of the projects involving ground-based SG and AG data will be to constrain the position of the Earth's Center of Mass as a fundamental variable in the determination of the gravity field for space and satellite missions.

Of the current GGP stations, only a few are installed at space-geodetic stations (e.g. Wettzell, Tigo-Concepcion, Ny-Alesund, Sutherland). The majority were installed for specific tasks such as hydrology or tectonics - based research, but even though SGs might be installed for one purpose, the data cam be used in a wide variety of projects. A fuller report on the relationship between GGP and GGOS can be found in Crossley and Hinderer (2007).

3 ICET

The future location and organization of the International Center for Earth Tides was discussed at the IUGG in Perugia, 2007. At a meeting of the ICET Directing Board, a recommendation was made by in favor of the proposal by University of French Polynesia (UFP), Tahiti, under the directorship of Jean-Pierre Barriot. This rather exotic physical location was favored over a competing proposal from central Europe primarily on the basis of the infrastructure available for the task at UFP. Also, the Directing Board hoped they would be invited to frequent meetings at UFP. In particular, UFP has a strong computing effort, and there will be a major overhaul of the ICET Website and new arrangements to be made with GFZ concerning the operation of the GGP database. In other respects, ICET has played a strong supporting role, under the Directorship of Bernard Ducarme, e.g. for the processing and analysis of GGP data. For these and other services related to GGP, we have been assured that the necessary effort will be forthcoming from UFP.

4 IRIS

We have had a project now for almost 2 years, to get GGP raw data (recorded at 1, 2, or 5 sec sampling) into the global seismic database IRIS (Incorporated Research Institutions for Seismology). There have been some difficulties in specifying the complete SG instrument response in the very precise format required by seismology. To a geodesist, the issue is very simple: what is the calibration (or scale) factor? It is the DC response of the instrument to convert volt to acceleration, a topic with a long history in gravimetry, and it is known that SGs can be calibrated to better than 0.1% in amplitude (approaching 0 .02% in some experiments). Such a specification is incomplete for seismology, because we also need an accurate phase calibration; we note this is also important for ocean tide loading (e.g. Bos and Baker, 2005). The phase response at high frequencies can only be accurately measured using special equipment not normally available at SG stations. Information on the technique is available at http://www.eas.slu.edu/GGP/phasecal.html. We have struggled somewhat with the issue and this has delayed the project.

But now we have the means to finalize this issue with the help of seismologists. This will enable us to follow the example of station Membach, where through the efforts of M. Van Camp, data from the MB SG (special seismic output) has been sent to IRIS for more than a year. We are aided in this venture by GFZ Potsdam, and we promise some real results from other GGP stations soon.

5 Workshops and Special Publications

GGP normally meets once a year in connection with a major meeting or as a stand-alone workshop. We here review the various occasions, following the IUGG in Sapporo, 2003. As always, the shorter meetings are for business only, while the specialized workshops (in 2004, 2006) are the major opportunity to exchange scientific information. All events are reported in GGP Newsletters that are distributed to the GGP mailing list, available at http://www.eas.slu.edu/GGP/ggpnews.html. We summarize them by year.

2004

(a) **Earth Tides Symposium, Ottawa, Canada**. Because the ETC overlaps almost completely with the GGP community, the ET meetings are equivalent to stand-alone GGP meetings in terms of scientific importance. The papers from this symposium are available as a special publication of the Journal of Geodynamics (Volume 41 (1-3), 2006) http://www.sciencedirect.com/science/journal/02643707

(b) In October 2004 there was an International Symposium on Remote Sensing, held on Jeju Island, Korea and organized by the Geohazard Information Laboratory at Sejong University. Among the papers presented, several were from GGP (e.g. Kim et al., 2005; Crossley and

Hinderer, 2005; Neumeyer, 2005) perspectives and the conference served to introduce SG technology to Korean geodesists.

(c) A special issue of Journal of Geodynamics (Volume 38, 2004) was published to summarize the achievements of the first 6-year phase of GGP. It can also be accessed from the Science Direct website listed above.

2006

(a) **GGP Workshop, Jena**. A workshop on "Analysis of Data from Superconducting Gravimeters and Deformation Observations regarding Geodynamic Signals and Environmental Influences" was held in Jena in March. This brought together GGP members and those working on the environmental influences on gravity. The proceedings and papers from this workshop are available online through ICET (Bulletin d'Informations des Marees Terrestre) at http://www.astro.oma.be/ICET/bim/141.html

2007

(a) GGP Workshop, Taiwan. The Taiwanese hosted the "First Asia workshop on superconducting gravimetry" in Hsinchu, Taiwan, March 12-15. It had the distinction of being the only workshop (so far) to be held within a tunnel complex only a few meters from the SG room itself (the activities of the conference of course were recorded in the data). The purpose of the workshop was to emphasize the increasing number of SGs in Asia, and to focus attention on scientific problems in this part of the world. Of special interest is the very high uplift rate of Taiwan itself, which is currently to be monitored both by AG and SG measurements. Scientific papers from the workshop can be found under the Scientific Program on the website http://space.cv.nctu.edu.tw/SG/Asia_workshop.html.

(b) Of interest to GGP may be the upcoming series of volumes on the Treatise on Geophysics, Geodesy Volume, edited by T. Herring and G. Schubert. It includes an extensive treatment of SG issues, as well as articles on AGs and other topics of interest to GGP. The volumes will be released at the Fall AGU in San Francisco (Hinderer et al., 2007a).

(c) IUGG, Perugia. A GGP Meeting was held on Thursday 5 July 5:30-7:30 pm, following the business meeting of the Earth Tides Commission (ETC). We are happy to say that Gerhard Jentzsch (U. Jena, Germany) was unanimously approved as the continuing President of the ETC for a further 4-year term. His leadership both in tides and gravity is a valued asset to GGP.

2008

(a) ETC Symposium, 1-5 September, Jena, Germany. The 16th International Symposium on Earth Tides will be held in Jena next year, following the tradition of several GGP meeting being held there in the past (see above). This symposium is distinguished by combining the topic of Earth Tides with Crustal Deformation, Geophysical Fluids, as well as GGP. In this way, the ETC is hoping to broaden its base of interest from tides, and tide-related topics, to a wider coverage of gravimetry-related topics and crustal geodynamics. The meeting involves several sub-commissions of IAG.

6 Some results from the GGP Workshops

We have space for just a few of the many interesting results from the last 4 years, here taken from the ET symposium in Ottawa and the GGP Workshops in Jena and Taiwan. We minimize overlap with the companion paper on GGOS (Crossley and Hinderer, 2007), as there we treat some of the connections between SGs and AGs, hydrology and geodesy.

6.1 Instrumental

Some recent SG installations appear in publications that are helpful references on the operation of the various stations. An example is Tigo-Concepcion in Chile, where the initial operation of GWR R038 – a new type of remotely controlled SG – is introduced by Wilmes et al. (2006). We show one of their plots (Figure 4) that has some interesting aspects. The estimated drift appears very small (0.12 μGal / yr), though this has not been verified with the typical AG measurements. The most intriguing information is a strong annual signal of amplitude about 6 μGal that remains, even after the effect of rainfall and groundwater changes have been removed from the data. The co-located VLBI measurements are also affected by the height variations of about 10 mm, with the anticipated polarity (i.e. height reduction with gravity high), one of the first indications of the usefulness of gravity measurements at fiducial stations (see discussion in Crossley and Hinderer, 2007).

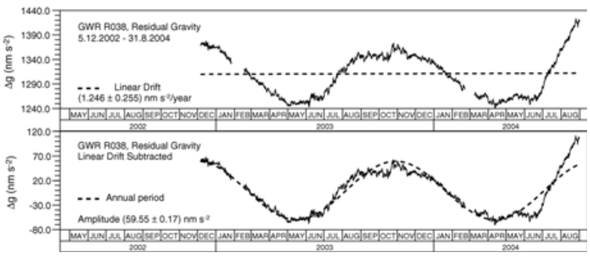

Figure 4. Residual gravity at TC in Chile. Tides, pressure, polar motion, and groundwater-induced gravity variations have been removed (Wilmes et al. 2006).

The MunGyung installation (Kim et al., 2007) shows very promising data and a correlation of groundwater with gravity with a diurnal periodicity. A report on early data from the Hsinchu SGs was given by Kao et al. (2007), highlighting the difference between the instruments SG048, that is working well, and SG049. The latter had a larger-than-expected drift and was sent back to the manufacturer for correction.

SGs have become relatively well known, and much publicized, instruments; it is thus rare to see new uses appear in research. An interesting suggestion was made by Shiomi (2007) on the testing of the universality of the free fall principle using SGs (note the paper title does not imply "testing the free fall of SGs"!). The physics involves detecting the differential motion of the inner core of the Earth as it orbits the Sun, supposing the former can move preferentially with respect to the mantle.

6.2 Tides, ocean loading, and sea level

Tides are still an active research topic using SGs, particularly the aspect of ocean tide loading. Boy et al. (2006a) analyzed gravity at 6 SG stations for the long-period tides, and then corrected the amplitude and phase of each monthly (Mm) and fortnightly (Mf) tidal constituent using an anelastic solid earth model. The residual amplitude and phase is then the observed ocean tide, compared to several models. The results shown in Figure 5 indicate large observed errors that span most of the range of ocean tide models. This is in contrast with similar analyses at diurnal periods where the SG data are able to discriminate some differences in ocean tide loading (Boy et al. 2003, Bos and Baker, 2005). Long period tides are influenced by many factors such as instrument handling, site location, data quality, and hydrology. Shallow water tides detected by SGs was covered in a paper by Boy et al. (2004).

SGs have contributed significantly to tides in two other areas. One is in more precise measurements of the free core nutation (FCN) period by Sato et al. (2004) and Ducarme et al. (2007). These developments have particularly resolved the issue of the Q of the FCN and brought the results more in line with geodetic techniques such as VLBI. At long periods, SG measurements of polar motion have revealed new insights into the long period admittance of the Earth through determination of the gravimetric factors (Ducarme et al., 2006; Harnisch and Harnisch, 2006a).

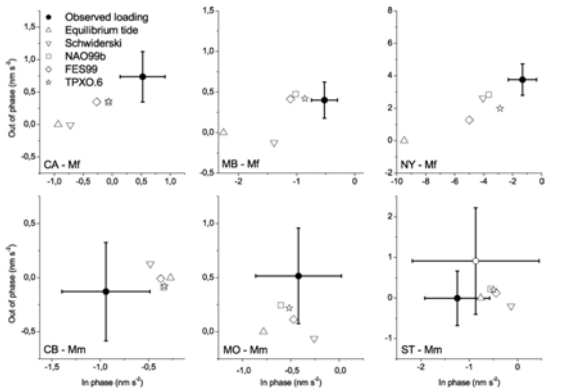

Figure 5. Fortnightly and monthly tides as observed by 6 SGs compared to ocean tide models. Boy et al . (2006a).

SGs have been used successfully to investigate atmospheric tides (Boy et al., 2006b). Sato et al. (2001) used SG records from Esashi, Canberra, and Syowa to demonstrate the importance of the steric correction to sea surface height (SSH) change. The steric part does not involve any additional mass change and hence does not alter gravity by loading; thus inland SG measurements are a unique tool to distinguish between steric and non-steric SSH components.

6.3 Earthquakes and normal modes

Hinderer et al. (2007b) generated a solution to the static deformation of the Earth following the Sumatra 2004 event, using the summation of normal modes with a time - dependent distributed source event. This study did not use GGP data because unfortunately station Bandung was not operational, and there was no other SG close enough to measure

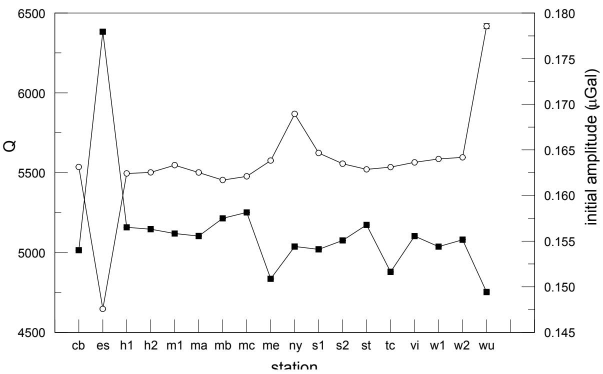

Figure 6. Q (left axis, open circles) and initial amplitude (black squares) for mode ${}_0S_0$ from the Sumatra earthquake at all 18 GGP SG sites.

the static displacement (~100 μGal near the fault). The event was picked up by the GRACE satellites and has been widely reported.

Nevertheless, the normal modes excited from the 2004 Andamen-Sumatra earthquake were very well recorded over the GGP network, and this has generated some publications. Roult et al. (2006) measured the frequencies and Q's of several of the lower frequency modes that are well recorded by SGs and Rosat et al. (2007) analyzed ${}_0S_0$ amplitudes at SG stations and found a geographic pattern that is similar to that expected from the coupling of ${}_0S_0$ to the mode ${}_0S_5$ due to lateral heterogeneity in the upper mantle. A somewhat similar study by Crossley and Xu (2007) showed that the Q and initial amplitude of ${}_0S_0$ was very consistently measured as 5550 and 0.156 μGal respectively across the GGP array (Figure 6). The SG-determined amplitude had significantly less scatter than amplitudes measured from a much larger number of GSN (Global Seismograph Network) seismometers because of the much better calibration of the SGs.

6.4 Hydrology

Hydrology effects have become the prime target for long period studies with SGs because they are so easily measured. An example is Imanishi et. al. (2006) who showed the effectiveness of a simple bucket (or tank) model to explain the gravity changes with rainfall (as done by several previous studies). In Figure 7 it is seen that the gravity decreases sharply within about 1 hour, and then recovers after about 1 month. These time scales are similar to the results of Wilmes et al. (2006) for Tigo-Concepcion and Harnisch and Harnisch (2006b) for Bad Homburg.

Another study of note is that of Virtanen et al. (2006) who clearly separated the effects of local, regional, and global hydrology for station Metsahovi in Finland. This station is above ground, and demonstrates a very high correlation (0.83) between groundwater-and gravity, leading to a well-determined admittance of 2.5 μGal m^{-1}.

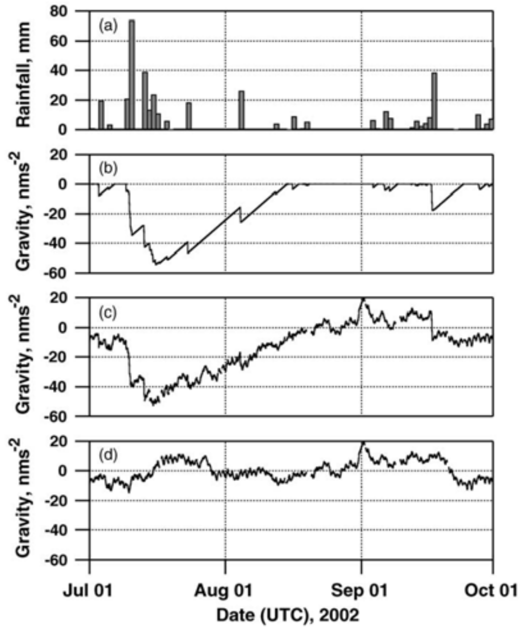

Figure 7. From top to bottom: (a) rainfall, (b) modeled gravity, (c) SG observed, and (d) SG corrected, for station Matsushiro (Imanishi et al., 2006).

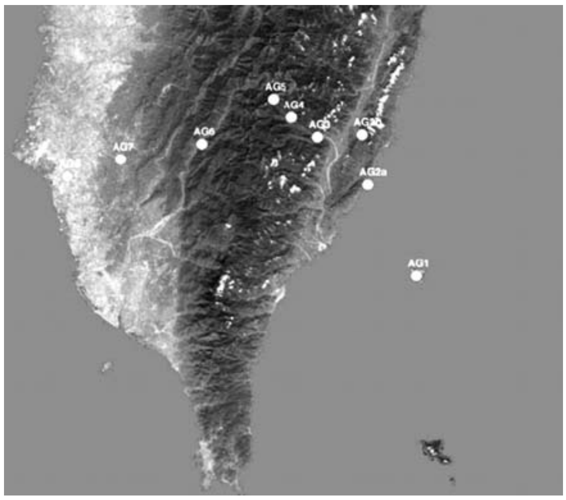

Figure 8. The 9 AG stations across a transect of Taiwan to measure uplift (Masson et al., 2007)

6.5 Tectonics

As mentioned above, one of the Taiwan SGs is being repaired and when it returns, it will probably be situated somewhere along the ATGO (Absolute Gravity of the Taiwanese Orogen) profile (Masson et al., 2007), shown in Figure 8. The easternmost station (AG1) is on an island and the last point (AG9) is on the West coast. Taiwan has one of the highest uplift rates in the world (up to 5 cm / yr). The ATGO project will require frequent AG measurements at the 9 stations shown, together with GPS, and the SG will be at one of the sites. With a gravity / height ratio of -0.2 μGal / mm this should yield a strong signal of > 4 μGal per year (larger than the drift of most SGs). The SG will be able to verify the hydrological part of this signal, together with soil moisture and groundwater observations.

Other tectonically-related SG projects have been discussed in connection with GGOS goals (Crossley and Hinderer, 2007), but essentially many of them remain as future prospects to be undertaken with co-located AG measurements.

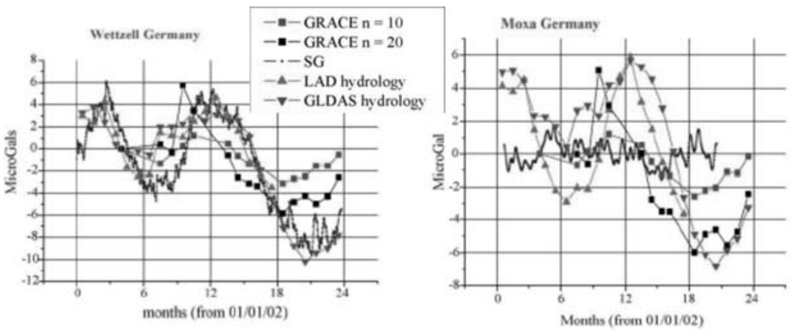

Figure 9. GRACE-GGP comparisons for Wettzell where groundwater correlates with gravity. At Moxa the SG series is uncorrelated with other signals (Boy and Hinderer, 2006).

6.6 GGP and GRACE

The 6-8 SG stations in Europe have been used as potential ground truth for the GRACE mission since 2002. In a recent paper, Boy and Hinderer (2006) summarized the seasonal changes in hydrology as detected by GRACE and at the ground-based GGP stations, compared to the changes predicted by hydrology models. Figure 9 shows comparisons for two stations: Wettzell, above ground, and Moxa, below. Neumeyer et al. (2006) also did this type of comparison with similar results, but also included some precise modeling of the 3-D atmospheric attraction effect and a consideration of the additional vertical displacement effect on the gravimeters that is not seen by GRACE. Despite the apparent ‘success’ of such comparisons, these results are problematic because the satellite data cannot give accurate results over wavelengths < 600-1000 km. A different method using all the SG data together to find a smoothed field has been pursued by Crossley et al. (2005). The ground and satellite fields are compared by analysis of the EOF eigenfunctions and principal components, using all the spatial and temporal data together. This approach gives a more satisfying averaging of the ground fields. Figure 10 shows a recent result for the CNES/GRGS 10-day GRACE solution. Good agreement is evident in the time evolution of the 3 first principal components of the spatial data sets.

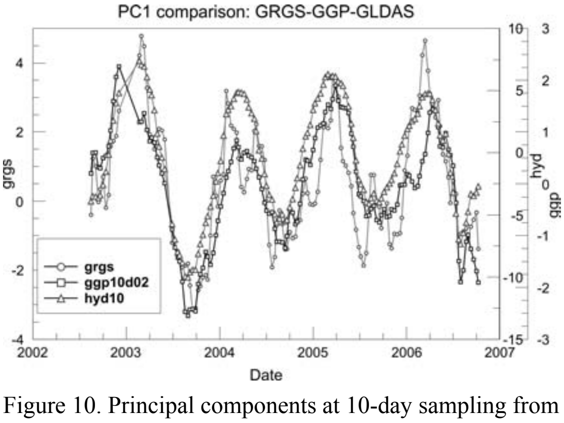

Figure 10. Principal components at 10-day sampling from GRACE CNES/GRGS solution (grgs), 7 European GGP ground stations 10 day (ggp10d02) and GLDAS hydrology (hyd10).

7 Acknowledgements

GGP appreciates the cooperation of the many dedicated individuals who maintain their instruments and willingly share their data. We are indebted to Bernard Ducarme and his assistants at ICET for their unfailing support of GGP. We also acknowledge the retirement of Tadahiro Sato who has pioneered many new ideas and projects in gravimetry, particularly with SGs. We also thought Jurgen Neumeyer had retired, but apparently not; he has been instrumental (no pun intended) in the installation of new SGs.

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