

# GGP (Global Geodynamics Project): an international network of superconducting gravimeters to study time-variable gravity

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## Abstract

The Global Geodynamics Project (GGP) is an international network of superconducting gravimeters (SG) first established in 1997 and further extended in 2003. It was decided during the last IUGG assembly in 2007 to move to a permanent network hosted by IAG and become part of GGOS. Several new locations are being planned to extend the network to about 30 stations in 2008/2009. One of the present tasks within GGP is to prepare raw GGP data (at sampling times of 1-5 s) for inclusion into the IRIS data set for the seismologists to include in normal mode studies of the Earth. Of continuing interest within GGP is the issue of combining measurements from absolute gravimeters and permanent GPS at the SG stations for a variety of long-term studies of the gravity field such as tectonic uplift, subduction zone slip, post-glacial rebound and present-day ice melting. One of the most interesting new ideas within GGOS is the determination of the geocenter using a combination of satellite and ground-based gravimetry. The GGP network can provide a unique contribution in this respect through continuous data at the stations where absolute gravimeters (AG) will be deployed. The continuous monitoring of time-variable gravity is a tool to investigate many aspects of global Earth dynamics and to contribute to other sciences such as seismology, oceanography, earth rotation, hydrology, volcanology, and tectonics. Another promising application is the use of SG sub-networks in Europe and Asia to validate time-varying satellite gravity observations (GRACE, GOCE) due to continental hydrology and large-scale seismic deformation.

**Keywords.** Superconducting, gravimetry, GGP, GRACE, IRIS

## 1 GGP Stations

This paper is in part a review of the GGP superconducting gravimeter (SG) network, for the benefit of those who may not be familiar with ground-based time-variable gravity observations. Later, we emphasize the connection between GGP and some of the goals of the GGOS program. We begin, as usual, with a map of stations (Fig. 1) that shows the

distribution of the 25 or so currently recording SG stations, together with the locations of some older stations and others planned for the near future. Note that the original designation Dehradun (India) has been changed to the actual site, Ghuttu.

The SG is a complex instrument requiring specific site properties, and, in common with other comparable technologies, there is a cluster of sites in Europe and Asia, and elsewhere the distribution is more widely scattered. It is noteworthy that scientists in Germany and Japan have made efforts to locate instruments in some of the more remote sites. For example Syowa (Antarctic), Ny-Alesund (Norway), Canberra (Australia), and Bandung (Indonesia) were established by the Japanese, and Sutherland (S. Africa), Concepcion (Chile), and Manaus (Brazil) by the Germans. The French are planning stations in Djougou (Benin Republic) and Tahiti, the latter being the new location for ICET (International Center of Earth Tides). ICET is hosted at the University of French Polynesia, under its new director J.-P. Barriot, and ICET (in partnership with GFZ Potsdam) runs the GGP database. Recently new installations have been realized in S. Korea, Taiwan, Czech Republic, and India, funded by the countries themselves. The paucity of sites in N. America is perhaps unusual as the instrument is manufactured in San Diego (GWR Instruments); but Boulder will be refurbished, and a

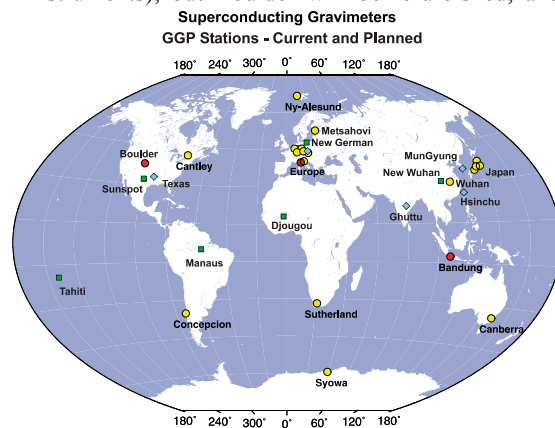


Figure 1. Distribution of SG stations: light circles are operational, dark circles are stopped, diamonds are new installations, and squares are planned.

new site is being established in Texas. The use of gravity observations for geodetic purposes in the US and Canada has languished behind that in Europe (compared for example to the equal use of GPS), not just due to the cost difference for an SG.

## 2 A Typical GGP Site

A typical GGP site needs additional instrumentation to record environmental variables that are so intimately associated with the time variation of gravity. Fig. 2 shows a collection of such instruments for station J9 in Strasbourg (except for 2(b) that is at St. Croix-aux-Mines in the Vosges). Not shown is a vertical well for

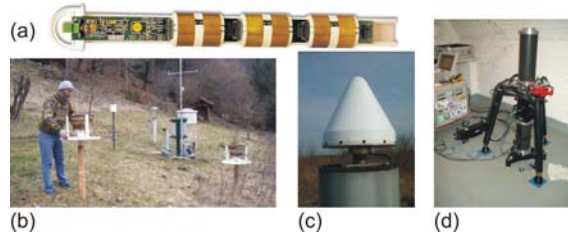


Figure 2. Auxiliary instruments for an SG site (a) Sentek soil moisture meter (b) a met station (barometer, temperature, wind, humidity) with several pluviometers, (c) continuous GPS, and (d) FG5 absolute gravimeter.



Figure 3. Strasbourg SG, model CO26 in a bunker below the soil moisture level.

monitoring groundwater level. The instrument (SG) itself is located in an underground bunker beneath the soil moisture layer, but above groundwater level (Fig. 3).

In the case of J9, as with other well-instrumented sites such as Bad Homburg, Moxa, Wettzell, Membach and Medicina, the monitoring of the local soil conditions has been extended to measurements such as a penetrometer (to measure lithology), soil compaction, electrical DC resistivity, and detailed topography. Standard at all sites is accurate timekeeping and continuous GPS. In the early days of SG recording, the two primary concerns were the gravity signal itself and the barometric pressure, with an accurate clock for sampling. The additional instruments cited above are invaluable in assessing the role played by local environmental conditions (driven primarily by rainfall), in the time domain gravity residual over times between hours and years.

## 3 Performance of the SG

It is somewhat remarkable that the SG, in operation for about 40 years, has maintained a more or less constant precision and accuracy level over that whole time span. The first ‘commercial’ operating machines were installed in Bad Homburg,, Brussels, Strasbourg, and Wuhan in the mid 1980’s. Of great interest was Richter’s (1987) first comparison between two slightly different models (TT40 and TT60), in which the gravity residual signal (after subtraction of tides and atmospheric pressure) showed agreement in variations at about  $0.1 \mu\text{Gal}$  ( $1 \mu\text{Gal} = 10^{-8} \text{ m s}^{-2}$ ). This type of comparison has been repeated several times since (e.g. Kroner et al., 2005), with similar conclusions, thus reinforcing the frequent claim that ground deformation can be reliably measured to at least  $0.1 \mu\text{Gal}$  by the SG.

As discussed frequently (e.g. Hinderer et al., 2007), the specifications of the SG are: sampling =1-5 sec (higher rates have been achieved for specialized purposes), precision (least significant bit) =  $0.1 \text{ nGal}$  ( $1 \text{ nGal} = 10^{-11} \text{ m s}^{-2}$ ), frequency domain accuracy (observation of small non-linear tidal waves) =  $0.1 \text{ nGal}$ , time domain accuracy  $0.1 \mu\text{Gal}$  (as above).

Two important characteristics of SGs are their calibration stability, which is probably better than 0.01% (Amalvict and Hinderer, 2007), and their small drift rate ( $0\text{-}5 \mu\text{Gal yr}^{-1}$ ). Stability is ensured by the superconducting currents that support the 2.54 cm niobium sphere. Early SG models had a noticeably exponential instrument drift that decayed over periods of several years after initial installation. It is still the case that the drift of a particular instrument is a difficult variable to predict, but a significant reduction in drift has followed improving technology and manufacturing. Most recent instruments, such as the SG currently in Hsinchu (Taiwan, Fig. 4), typically have very low initial drift and eventual drift rates that sometimes barely exceed that of the absolute gravimeters (AGs) that are used to calibrate the SGs. AGs have a typical precision of  $1 \mu\text{Gal}$  and an accuracy of  $1\text{-}3 \mu\text{Gal}$ .



Figure 4. GWR model SGT48 operating in Hsinchu, Taiwan. The dewar sits on the ground, and can maintain liquid helium indefinitely. Shown with a standard electronics and data acquisition package, and also an AG.

## 4 How GGP functions

GGP began as a project of the IUGG interdisciplinary group SEDI (Study of the Earth's Deep Interior), in 1985, largely through the efforts of several Canadian geophysicists (Crossley et al., 1999). The idea was to set up a global network of SGs to detect possible core modes, or internal gravity waves in the Earth's liquid core, a project spurred by initial optimism that such waves would be detectable in the gravity spectrum at periods between 6 hr and 24 hr. The goals of the project rapidly expanded to observing the complete spectrum of gravity variations, from seconds to years. Coherent global signals obviously exist at a number of frequencies (e.g. seismic normal modes, tides, atmospheric pressure waves, and polar motion), and for such signals the stacking of records from the global GGP data set is necessary. On the other hand, many gravity signals are generated by more local effects such as earthquake displacement fields, hydrological variations, weather systems, and secular tectonics. Thus GGP became a widely-based project that puts the full range of the SG to use for both geophysical and geodetic purposes.

GGP began recording collectively on 1 July 1997 and ICET was the organization for archiving the data because of the strong historical connection between tidal gravity variations, SGs, and ICET. From the beginning, GGP data quickly overwhelmed in volume the traditional tidal data from a variety of spring gravimeters, tiltmeters and strainmeters, and ICET devoted additional manpower to processing and checking the data. The database servers were not at ICET, but through mutual agreement accessed through the International System and Data Center (ISDC) at GFZ Potsdam. The new interface for GGP data is <http://isdc.gfz-potsdam.de/>

All GGP groups use the data format originating with Wenzel (1996), known as PRETERNA, in which every value (predominantly gravity and pressure), are time tagged in the original units (volt). The only processing is a decimation filter from the original samples to 1-minute values, but no other corrections are done. The full signal is saved with a precision of 7.5+ digits, ensuring that the tides are adequately recorded as well as the smallest tidal waves (see above). Users should realize that gaps, spikes and offsets still have to be treated if a clean continuous time series is required, or otherwise avoided if the series is processed as non-contiguous blocks. ICET provides corrected minute data on their website, but this treatment is designed for tidal analysis and may not be suitable for all purposes, especially long period studies. A full discussion of data treatment is given in Hinderer et al. (2007).

GGP groups upload one month files to ICET within 6 months of data collection. They are then available to other groups who have provided data for a 'restricted circulation' of a further 6 months. After 1 year of collection, the GGP data is freely available. With some exceptions, (mainly due to instrument or data

acquisition problems), most groups follow this timetable voluntarily, which is one of the key points of the success of GGP. The other feature of GGP is a strict adherence to the quality of site, data acquisition parameters, and data formatting.

GGP was incorporated into the IAG as Inter-Commission Project #3.1 in 2003; it is a joint project between Commission 3 (Earth Rotation and Geodynamics) and Commission 2 (The Gravity Field). GGP has a Chair and Secretary elected every 4 years at the IUGG meeting, and has a mailing list of 120 members. Reviews are given by Crossley et al. (1999) and Crossley (2004); further details can be found at <http://www.eas.slu.edu/GGP/ggphome.html>

## 5 GGP and GGOS

We now turn to the main issue in this paper, which is the relationship between GGP and GGOS (Global Geodetic Observing System). As outlined in this session by H.-P. Plag, GGOS is the primary program of the IAG to coordinate the recording and dissemination of all geodetic data for Earth monitoring, designed to be a fully functioning system by 2010. GGP plays a small but important role in GGOS, namely the recording of the gravity field and especially its time variations. A recent review of this topic was given by Crossley and Hinderer (2008), so we avoid unnecessary duplication of material here.

### 5.1 AG and SG observations

We begin by going back to a paper by Larson and van Dam (2000) on the measurement of PGR (or GIA) using absolute gravity measurements. Fig. 5 shows 5 measurements at CHUR, 2 each at FLIN and NLIB, and a cluster of measurements at TMGO (Table Mountain Gravity Observatory). The AG error bars show a typical formal standard deviation of about 2  $\mu\text{Gal}$ . CHUR shows a clear positive trend that is much weaker at the other sites. Many more recent studies have since provided better data on PGR at Canadian sites, but we are using this earlier paper to

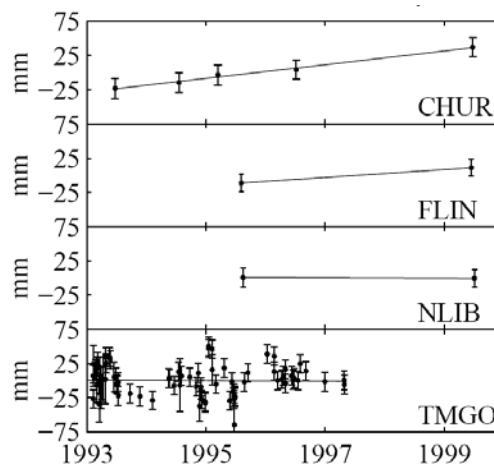


Figure 5. Equivalent vertical motion at several sites in N. America, showing PGR over a 6-year time period. AG gravity measurements are scaled by the factor  $-6.5 \text{ mm}/\mu\text{Gal}$ .

make an important point about AG and hydrology.

When frequent AG measurements are available, they often show a scatter such as for TMGO, as noted by Larson and van Dam. In this case, what is the cause? We show in Fig. 6 a comparison of the SG and AG time series for two years beginning in April 1995. Both data sets confirm a gravity decrease between days 50-150 of the record. The SG recording was without noticeable problems over the whole time span, so we are fairly sure there are no hidden offsets in the data. Tides, atmospheric pressure and polar motion are subtracted, and for the SG an exponential drift was removed (but this was not fitted to the AG data). Fig. 6 thus confirms the inference in Fig. 5 that there is no AG gravity trend between 1993 and 1999 at TMGO. But Fig. 6 shows while some of the AG scatter is confirmed by the more detailed SG residuals, other values may be biased by instrumental effects.

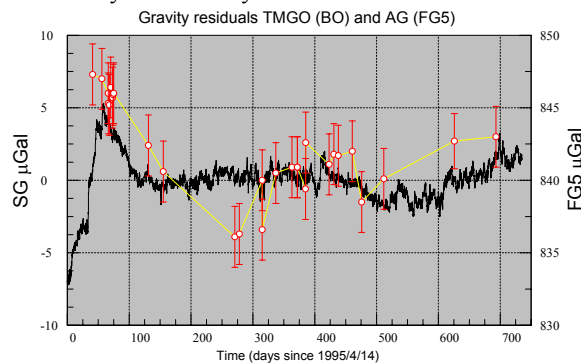


Figure 6. A comparison of SG and AG measurements at TMGO from April 1995 (Crossley et al., 1998).

The conclusion from this one example is that where there is the possibility of combining AG and SG observations, it will be much easier to assess the quality of the AG data, even when long time periods are of interest. The only caveat in using SG series as a reference is that offsets must be removed with care, and instrumental drift be appropriately modeled. The most detailed comparison of SG and AG data to date is the work of Wziontek et al. (2006). They show that AG steps can be estimated, and corrected if desired, using SG observations.

It goes without saying that any intercomparison of AG instruments should actively use a collocated SG to monitor the short term temporal variations of gravity, probably with a significant reduction in bias between AG determinations.

## 5.2 SG Drift

There are a very large number of studies where SG and AG measurements have been compared and combined to assess the drift rate of the SG and its calibration. It is sometimes argued that the SG is unsuitable for long-term gravity variations because it does have a drift, but in practice this is not a critical limitation. Almost all SG studies have concluded that the SG instrument drift is a simple mathematical function due to leakage of trapped magnetic flux when

the instrument is initialized (i.e. the sphere is levitated). This leakage can be expressed either as a decaying exponential, or a linear, function of time; the two are indistinguishable after the instrument has been operating for some time. It is virtually impossible to separate SG drift from actual secular gravity changes except by comparison with AG data, save for the initial installation of the SG when a clear exponential behavior may be seen.

Thus we conclude that at any important geodetic site where gravity is to be monitored, the combined use of AG and SG data is highly recommended. The complementary and independent nature of the technologies ensures that data from one of the instruments will in all cases significantly benefit the interpretation of data from the other. Such reasoning applies to the plan to use AG and GPS measurements to determine the offset of the Earth's center of mass from the origin of the Terrestrial Reference System (Plag et al., 2007).

## 5.3 Hydrology Effects on Gravity

Returning to the data from TMGO, Crossley et al. (1998) modeled for the effect of hydrology by converting the observed rainfall to variations in the thickness of the groundwater layer below the instrument, and fitting a 2-time-constant model to the observed gravity (Fig. 7). This was done because groundwater was not measured on site. The water layer was treated as a Bouguer slab attraction, but no loading was included. A good agreement was found for a recharge time constant of 4 hr (time for rainfall to enter the water layer) and a discharge time constant of 91 day (time for groundwater to drain). Similar values were obtained using this model at Bad Homburg by Harnisch et al. (2006).

Fig. 7 demonstrates that gravity residuals up to 5  $\mu\text{Gal}$  or more can be dominated by hydrological effects at a station. Where there is rainfall (and there are no SGs yet located in desert regions), the effects can occur within minutes of rainfall and last several months. It is unlikely that the effects of the atmosphere and hydrology can be fully separated due to the limitations of modeling in the local area around a gravimeter. Moreover, the regional and global loading that occurs for both the atmosphere and hydrosphere is data intensive and requires considerable numerical computations, particularly at a time sampling of 1 minute.

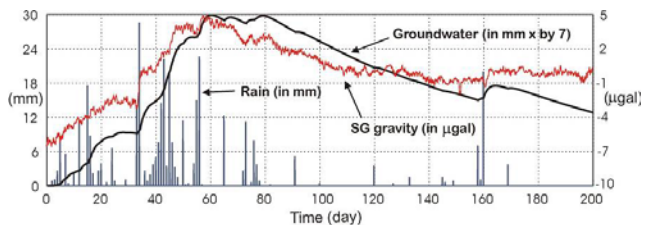


Figure 7. Rainfall converted to groundwater level and compared to SG residuals at TMGO.

Nevertheless progress in modeling the gravity effects of hydrology has been considerable in the past 10 years, due primarily to availability of high quality data from SGs, and the increasing use of hydrological instrumentation at a station (as described in section 2). Of the many SG sites where hydrology has been observed and modeled, we select a few to show the range of current results.

The above-ground SG station Medicina, on the Po Plain in northern Italy, is close to Bologna. Zerbini and colleagues (Zerbini et al., 2007) have made an effort to model all possible effects on gravity by including soil moisture and compaction, non-tidal ocean flow, 3-D mass effects in the atmosphere, and the vertical deformation observed by GPS, and of course AG data (Fig. 8). Overall the model is a good fit to the SG and AG data, and a clear seasonal signal is seen in most variables at about the  $\pm 2 \mu\text{Gal}$  level. Unlike TMGO, the AG values within their error bars coincide with the SG series. Note also the hydrology follows gravity because the SG is on the surface.

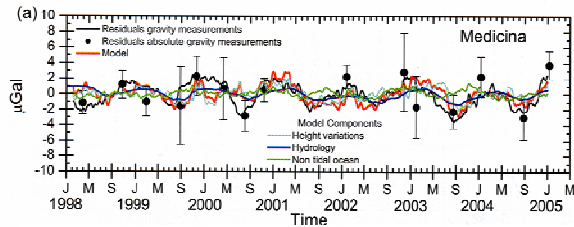


Figure 8. Integrated model (red) for gravity effects from height variations, hydrology and ocean effects, compared to observed SG (dark blue) and AG measurements.

Next we show the much more complex hydrological situation at Moxa, Germany (Kroner and Jahr, 2006). At this site the SG is located underground, beneath a layer of soil and vegetation that is above the instrument. In the surrounding area there is a small valley floor with a creek and steep sides with dense forest. Figure 9 shows two samples (at different time periods) of precipitation and groundwater level and the observed SG residuals. Note the expected relation between precipitation and groundwater recharge and discharge (cf. Fig. 7); the gravity response in the upper example is quite complex, but simpler in the lower series. In both cases gravity decreases due to increased soil moisture above the instrument. Much additional work has been done at Moxa, especially on experiments to inject water at various locations and measure the gravity effect. Recently all the vegetation immediately above the SG was removed to simplify the gravity response. The site has also been surveyed repeatedly with portable gravimeters to assess the spatial gravity variations (Naujoks et al., 2007).

A similar situation occurs at station J9 in Strasbourg where the soil moisture layer (Fig. 3) retains moisture and gravity decreases, despite the addition of groundwater. The time constants for recharge and discharge (this time of the soil layer itself), are a few hr and 1-2 months respectively. The

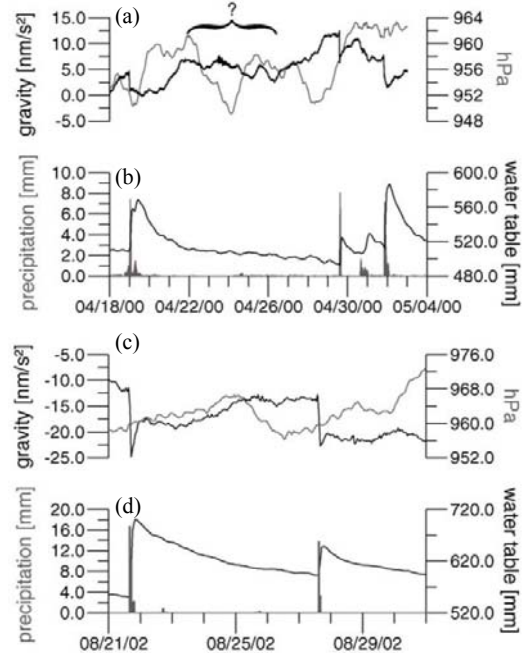


Figure 9. (a) and (c) SG residuals and pressure, with (b) and (d), precipitation and groundwater levels, for two time periods at Moxa (Kroner and Jahr, 2006).

hydrology has been instrumented and analyzed in detail by Longuevergne et al. (2007). Similar work has been reported for stations Matsushiro, Metsahovi, and Membach.

Conceptually the easiest way to model hydrology variations in gravity is the empirical approach, involving rainfall as input to various reservoirs, connected by variable fluxes (e.g. with exponential time dependency). The good agreement in predicting observed flow with such models gives hope that the models can be extended to treat the variation of gravity at an SG installation. Additional hydrological data would help to constrain some of the fluxes and reservoir volumes. This approach is easier than a full physical flow model.

## 5.4 GGP and GRACE

We turn briefly to another topic of considerable relevance to GGOS, which is the satellite gravity field as determined by GRACE. Ground validation of GRACE must inevitably be done with point measurements, and some means must be found to spatially average these over distances of 500-100 km for comparison with GRACE. Our approach is to use the European sub-array, as reported elsewhere, and use the EOF decomposition of a gridded version of the ground field at  $0.25^\circ$  cells. We find (Crossley et al., 2007) that the more recent CNES/GRGS 10-day version of the GRACE fields shows details that for some time intervals is similar to the GGP 10-day filtered field. The first PC for the GRGS solution has higher amplitude than GGP field, but the higher time sampling (compared to the 1-month CSR and GFZ

solutions) reveals short term fluctuations in the middle of 2006 that correlate better with GGP. New stations in Europe (Pecny, Walferdange, and N. Germany) will add significantly to this comparison, and permit other GRACE solutions and to be tested against GGP data.

## 6 Other GGP projects

Many projects within GGP extend to areas other than hydrology. At the short periods of the Earth's normal modes (1-54 min), GGP data has been successfully used to observe the amplitudes of the long period modes, particularly  ${}_0S_0$ , at frequencies less than 1 mHz (Xu et al., 2008; Rosat et al., 2007). SG's compare very favorably to seismometers in this period range. One goal of GGP is to permit SG data to be sent directly to IRIS for inclusion in future normal mode studies. The delay in implementing this has been due to the problem of characterizing the SG instrument response in the form required by seismologists.

The potential of SGs to observe the episodic slip associated with subduction-style slow earthquakes is large. As demonstrated by Lambert et al. (2006) for the Cascadia subduction zone, the gravity signal is a well-defined sawtooth whose onset defines a slip event that can be identified on seismometers. The amplitude rise between slip events is a few  $\mu\text{Gal}$  that can easily be seen on an SG, and should correlate with frequent AG data. It has already been established that SGs can detect the static offset associated with large earthquakes (Imanishi et al., 2004), but the poor global coverage is insufficient to be able to easily observe events from large subduction zones (such as Sumatra).

## Conclusions

1. the GGP network is steadily growing, with a more uniform global coverage as new stations in Asia, Africa and the Southern Hemisphere are installed; at the same time new SGs in Europe are being added that will improve our confidence in GRACE validation and continental hydrology studies. New stations in the USA will be welcome for specific purposes such as aquifer studies and perhaps (in future) subduction zone monitoring,
2. GGP can benefit GGOS if the concept of collocated AG and SG sites is embraced by the AG community, and
3. GGP is working to ensure that AG measurements at its stations are available to the new WGAG database (Wilmes, personal communication); and finally, we will soon be implementing the transfer of high-rate data to IRIS for seismology.

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