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Measuring Postglacial Rebound with GPS and Absolute Gravity

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Abstract. We compare vertical rates of deformation derived from continuous Global Positioning System (GPS) observations and episodic measurements of absolute gravity. We concentrate on 4 sites in a region of North America experiencing postglacial rebound. The rates of uplift from gravity and GPS agree within one standard deviation for all sites. The GPS vertical deformation rates are significantly more precise than the gravity rates, primarily because of the denser temporal spacing provided by continuous GPS tracking. We conclude that continuous GPS observations are more cost efficient and provide more precise estimates of vertical deformation rates than campaign style gravity observations where systematic errors are difficult to quantify.

Introduction

Present-day crustal deformation associated with postglacial rebound (PGR) depends upon both the viscosity profile of the Earth and the ice loading history of the region. However, deformation rates can differ significantly depending on how one parameterizes the Earth's viscosity structure. Hence by measuring rates of crustal deformation in a region experiencing PGR, one can constrain the Earth's viscosity structure.

Absolute gravity has been put forward as an effective technique for measuring vertical deformation associated with PGR [*Lambert et al.*, 1989]. Assuming annual measurements with a measurement accuracy of 2.0 μgal, one could measure a gravity rate of change in 5 years with an accuracy of 0.5μgal/yr [*NASA*, 1979] (1 μgal = $10^{-8}\mathrm{m}\cdot\mathrm{s}^{-2}$). This roughly corresponds to a vertical rate uncertainty of 1.5 mm/yr assuming that there are no mass variations during the measurement period. With completion of the GPS constellation and improvements in orbit modelling, vertical precisions have improved to the point that GPS has also been proposed as an effective technique for PGR studies [*BIFROST*, 1996].

In this paper we compare continuous GPS observations with available absolute gravity results from colocated sites. We look critically at both the GPS and absolute gravity systems. Based on data collected at sites in North America, we evaluate which geodetic technique is better suited to study PGR.

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Geodetic Data Analysis

We consider four sites in North America for this study: Churchill, Canada (CHUR), North Liberty, Iowa (NLIB), Flin Flon, Canada (FLIN), and Table Mountain in Boulder, Colorado (TMGO) (Figure 1). Figure 1 These GPS sites are all parts of the International GPS Service (IGS) tracking network [*Beutler et al.*, 1994] and thus are continuously operating. The data are freely available from IGS archives via the internet. These sites were chosen because they had at least three years of continuous GPS observations and there were at least two measurements of absolute gravity.

GPS

The GPS observations were analyzed using the GIPSY software developed at the Jet Propulsion Laboratory (JPL). We used the JPL precise point positioning technique and non-fiducial data products [*Zumberge et al.*, 1997]. For each day that GPS data are available we estimate station coordinates, tropospheric refraction, and the receiver clock behavior. After this initial processing, we transformed all station coordinates into ITRF97 [*Boucher et al.*, 1999] and computed a weekly average of position. The RMS about the best fit straight line is 7-8 mm for the vertical component depending on the site.

In Figure 2 we show the GPS data, superimposed with 1) the best-fit line and 2) the best-fit line plus a seasonal signal. The phase and amplitude of the seasonal signature in the time series could be related to a common source, e.g. orbits, or it might relate to a site specific error such as environmental loading. CHUR and TMGO have the most prominent seasonal signals, with an amplitudes of 6.8 and 4.1 mm, at each site respectively. Figure 2 At these sites, the RMS with respect to the model is improved by 25% by adding the seasonal terms. This demonstrates one benefit of a continuously operating geodetic measurement system - one has a fuller appreciation of the error spectrum.

We have made one correction to the time series shown in Figure 2. In late 1999, the raydome covering the GPS antenna at FLIN was changed. This had a significant impact on the vertical estimates (12 mm), and a bias was removed by fitting data collected one month before and after the change. We also noted a degradation in the data from FLIN in late 1996. Logs kept by the local operators indicate that the receiver began to fail at this time. A new receiver was installed in January 1997.

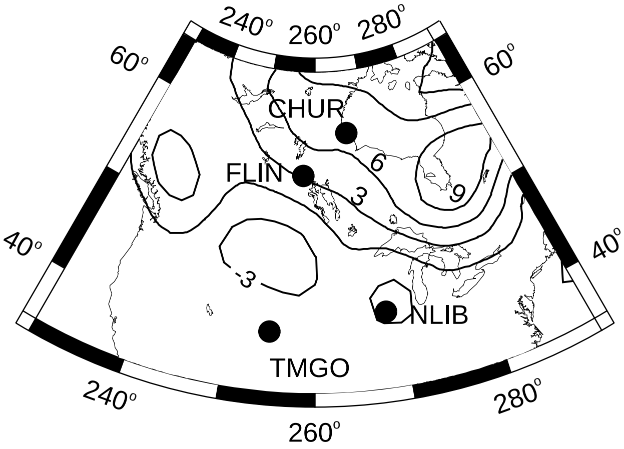

Figure 1. Geodetic sites used in this study. Also shown are contours of predicted postglacial rebound, in mm/yr, using ICE-3G [*Tushingham and Peltier*, 1991], a lithospheric thickness of 120 km, an upper mantle viscosity of 10^{21} Pa s, and a lower mantle viscosity of $2 \cdot 10^{21}$ Pa s.

Absolute Gravity

The gravity measurements were made with the FG5 absolute gravimeter [*Bilham and Sasagawa*, 1994]. The gravity measurements have been corrected for solid Earth and ocean tides. Atmospheric pressure loading, deformation and mass effects were removed using a constant of -0.3μgal/mbar. The instrumental precision is approximately 1.5 μgal [*Niebauer et al.*, 1995]. However, in practice the scatter is usually larger (on the order of 2.1 μgal) because of our inability to model the environmental effects perfectly. The absolute gravity data used in this study are shown in Figure 3. Figure 3 Each point on the plot represents the average of 48 to 72 hours of observations.

It is well known that changes in surface gravity result from both vertical crustal motions and mass changes below and above the surface of the Earth. The FG5's sensitivity to small mass changes means that its gravity records contain a signal that is not observed by GPS. For example, a comparison of the absolute gravity time series from TMGO for the spring of 1995 show a significant correlation with anomalously high rainfall there that year [*van Dam and Francis*, 1998]. There is no corresponding signal in the GPS data.

The data from TMGO and CHUR provide strikingly different perspectives on using gravity to measure PGR. The CHUR data fit a linear model much better than expected from the standard deviations. Unfortunately there are only 5 observations and nearly all the measurements were made at the same time of the year, so that errors with seasonal characteristics cannot be seen. The TMGO data, on the other hand, have a much greater scatter than we would expect from the standard deviations. We know that some of the misfit to the linear model at TMGO comes from local hydrological effects. The exact relationship between gravity and surface hydrology is difficult to quantify [*van Dam and Francis*, 1998].

Comparison of GPS and gravity

In regions where mass change is not expected, gravity rates of change can be converted to vertical deformation rates using the the free-air gravity gradient of approximately -0.3μgal/mm. This is the gravitational perturbation due to vertical displacement. Since PGR crustal motion is driven by a redistribution of mass within the Earth, the free-air gravity gradient cannot be used to convert gravity changes to vertical changes. *Wahr et al.* [1995] empirically determined that for a wide range of viscosity profiles a proportionality constant of -6.5 mm/μgal was the approximate relationship between vertical crustal motion and gravity changes associated with PGR (see also [*James and Ivins*, 1998]).

In Figure 4 we compare GPS vertical and absolute gravity rates using the proportionality constant of *Wahr et al.* [1995]. Figure 4 If we compute the formal GPS uncertainty by standard least squares error propagation, the values are less than 1 mm/yr. These formal errors are unreasonable because our errors are not randomly distributed. GPS height estimates are also sensitive to errors in defining the reference frame, particularly the geocenter. We have therefore augmented the uncertainty as $\sigma^2 = \sigma^2_{formal} + \sigma^2_{ref}$, where σ_{ref} = 5 mm/(# yrs) [*Argus and Heflin*, 1995]. The gravity rate uncertainty was determined using standard least squares error propagation. Vertical deformation rates determined by the two techniques agree to within one standard deviation at all sites. The measured deformation rates also agree within 20% with the simple model of PGR shown in Figure 1.

Discussion

Which is the best geodetic system to measure PGR in the shortest amount of time? If the errors are randomly distributed, the choice will be based on the observation standard deviation, how frequently data are collected, and how expensive it is to purchase and operate the instrument.

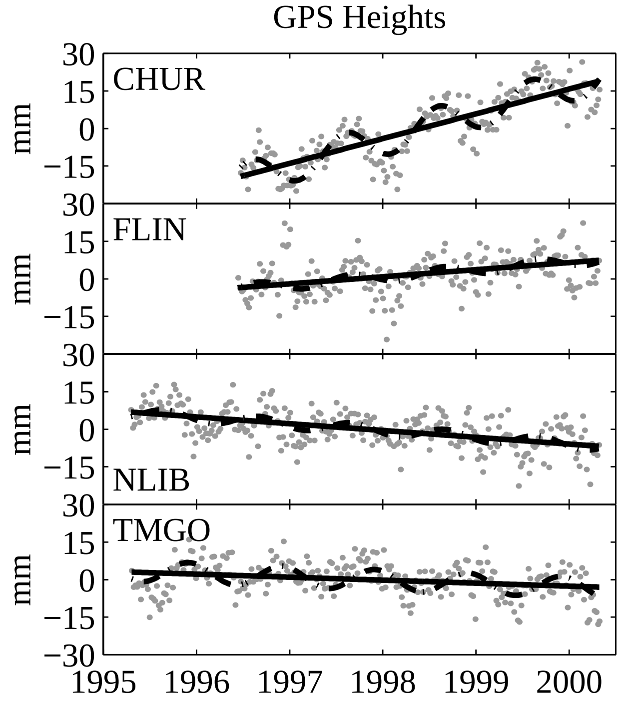

Figure 2. Gray circles are weekly averaged GPS heights. Two fits are shown: linear (solid) and linear + seasonal term (dashed). Error bars have been removed for clarity.

The errors in GPS vertical measurements are not randomly distributed, but the availability of continuous data makes it possible to identify and correct some systematic errors, including seasonal errors and equipment biases. At this point in time the largest contribution in the GPS error budget is likely to be the uncertainty in defining the reference frame [*Argus et al.*, 1999]. For common time periods, the difference between the vertical velocities is determined to much better than 1 mm/yr after 5 years. A geodetic quality GPS receiver costs on the order of $15,000 and usually requires little manual intervention after installation. Data are downloaded automatically and remotely (in general at no cost because of prevalent internet accessibility), and the data from one site can be handled within the infrastructure developed to handle typical GPS network operations.

In contrast to GPS, the FG5 gravity meter is truly absolute. However, this absoluteness does not imply that it is free of systematic errors. The gravity data from TMGO do not have randomly distributed measurement errors and hydrologic influences cannot be ignored. These errors can contribute a large offset to the measurements and thus significantly influence the estimate of a long-term trend. The FG5 instrument costs on the order of $300,000. Because of its size, weight and fragility, it is expensive to transport. Further, because the instrument is composed of many precisely machined moving components that wear and must be regularly replaced, the instrument has only been deployed in ”campaign” mode. The requirement of a highly trained operator (i.e. full-time staff member or Ph.D. scientist) to deploy the system also significantly increases operation costs.

If one were limited to campaign style GPS measurements, the GPS rate errors would of course be much larger. However, GPS is still the better choice: it is a much less expensive instrument and it can be easily set up and operated by high school students [*Sauber et al.*, 1998].

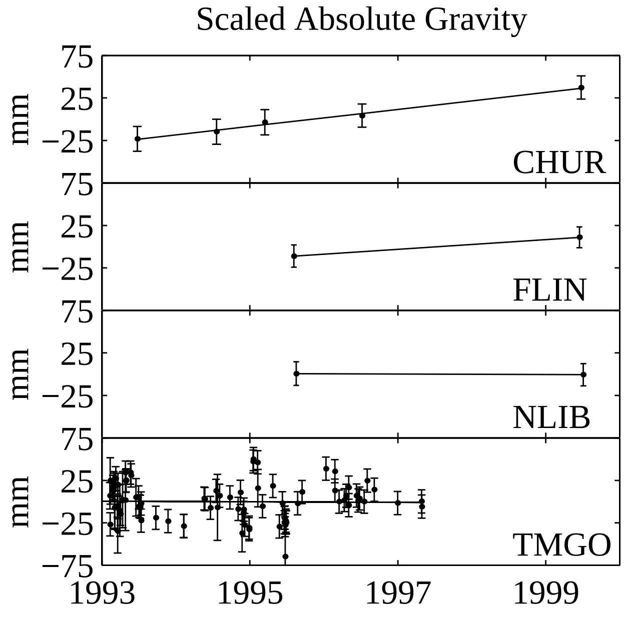

Figure 3. Gravity observations scaled by -6.5 mm/μgal [*Wahr et al.*, 1995]. Error bars are one standard deviation.

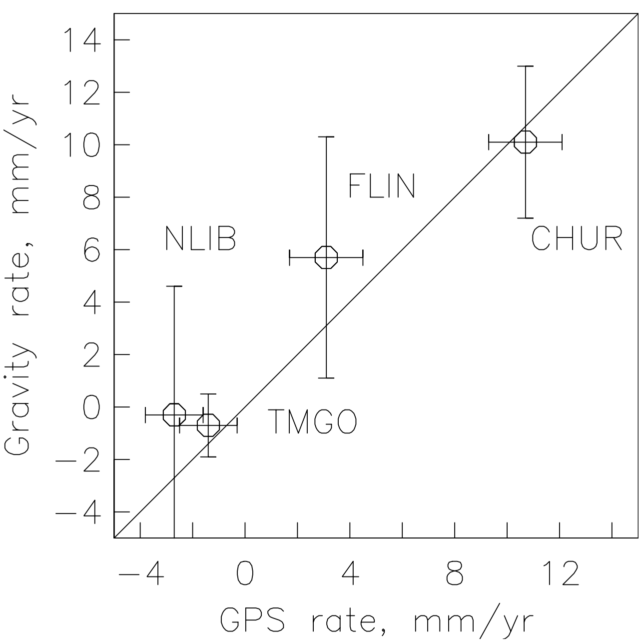

Figure 4. Vertical deformation rates using GPS and gravity. Error bars are one standard deviation.

Conclusions

Because of instrument and deployment costs and the difficulty of eliminating systematic errors from gravity measurements, we find that GPS is the better system for monitoring PGR. This comparison also suggests that absolute gravity is not as effective as GPS for measuring vertical deformation rates in tectonically active regions. There are geophysical problems which do merit use of the absolute gravity technique, specifically anything sensitive to mass changes. Examples include magma transport and constraining temporal variations in thickness of the Greenland ice sheet [*van Dam et al.*, 2000].

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