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Absolute gravity calibration of GPS velocities and glacial isostatic adjustment in mid-continent North America

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[1] We examine absolute gravity (AG) and vertical Global Positioning System (GPS) time series between 1995 and 2010 at eight collocated sites in mid-continent North America. The comparison of AG and GPS rates aligned to ITRF2005 yields a gravity/uplift ratio of $-0.17 \pm 0.01 \mu\text{Gal mm}^{-1}$ ($1 \mu\text{Gal} = 10 \text{ nm s}^{-2}$) and an intercept of $-0.1 \pm 0.5 \text{ mm yr}^{-1}$. In contrast, aligning the GPS velocities to ITRF2000 results in a gravity/uplift intercept of $-1.3 \pm 0.5 \text{ mm yr}^{-1}$. The near-zero gravity/uplift offset for the ITRF2005 (or ITRF2008) results shows a good alignment of the GPS vertical velocities to Earth's center of mass, and confirms that GPS velocities in this reference frame can be compared to predictions of geodynamic processes such as glacial isostatic adjustment (GIA) or sea-level rise. The observed gravity/uplift ratio is consistent with GIA model predictions. The ratio remains constant in regions of fast and slow uplift, indicating that GIA is the primary driving process and that additional processes such as local hydrology have a limited impact on a decadal time-scale. Combining AG and GPS measurements can provide significant constraints for geodetic, geodynamic, and hydrological studies. **Citation:** Mazzotti, S., A. Lambert, J. Henton, T. S. James, and N. Courtier (2011), Absolute gravity calibration of GPS velocities and glacial isostatic adjustment in mid-continent North America, *Geophys. Res. Lett.*, *38*, L24311, doi:10.1029/2011GL049846.

1. Introduction

[2] In the last two decades, Global Positioning System (GPS) data have increasingly been used to constrain a variety of large-scale geodynamic processes, from glacial isostatic adjustment (GIA) [e.g., *Argus and Peltier*, 2010; *Wu et al.*, 2010] to global sea-level rise [e.g., *Collilieux and Wöppelmann*, 2011]. However, GPS limitations, in particular its poor resolution of Earth's center of mass (CM) variations, can result in uncertainties of up to 1–2 mm/yr in 'absolute' rates, i.e., relative to the reference frame origin [e.g., *Altamimi et al.*, 2007; *Argus*, 2007], with significant impact on geodynamic inferences.

[3] In contrast, absolute gravity (AG) measurements are intrinsically aligned to Earth's CM and could, in theory, be

used to provide an absolute reference for vertical land motion and relative sea level derived from other geodetic techniques. However, due to limitations in both AG and GPS measurements (e.g., data length vs. inter-annual signals), past studies attempting to compare AG and GPS vertical rates have reported either an agreement with large uncertainties [e.g., *Larson and van Dam*, 2000] or a gravity/uplift offset of up to $\sim 2 \text{ mm yr}^{-1}$ that could be attributed to GPS velocity biases [*Teferle et al.*, 2006; *Mazzotti et al.*, 2007].

[4] In this study, we combine decadal time series from GPS and AG data in the mid-continent region of North America to illustrate how AG data can provide useful constraints to absolute GPS vertical velocities, reference frame alignment, and GIA models.

2. Absolute Gravity Data

[5] Absolute gravity measurements, i.e., measurements of the acceleration of a test mass falling in a vacuum, have been carried out annually starting between 1987 and 2002 at eight sites in mid-North America from Churchill, Manitoba to Iowa City, Iowa (Figure 1 and Table 1) [*Lambert et al.*, 2001]. Details of data acquisition and instruments are given in Text S1 in the auxiliary material.¹ Drop data are analyzed using the Micro-g LaCoste software with corrections for tidal, atmospheric, and polar motion effects. Gravity rates are calculated by fitting a linear trend by weighted least square, taking into account the offsets between different AG instruments (cf. Text S1 for data analysis and rate calculations, and Text S2 for AG time series).

[6] We estimate the gravity rate errors by fitting a colored ($1/f^K$) plus white noise model to the frequency spectra of the detrended gravity data from each site (cf. Text S1). The colored component of the noise can be fitted by a relatively low index $K = 0.5$. This is consistent with noise in AG-calibrated superconducting gravity data, which tends toward white noise below a frequency of 1 cpy [*Van Camp et al.*, 2005]. The parameters of these fits are used to estimate errors on the gravity rates using the method described by *Williams* [2003].

3. GPS Data

[7] We define the vertical velocity field in mid-North America using 27 continuous GPS stations from Hudson Bay to central U.S.A. and from the Rockies to the Great Lakes (Figure 1). This subset comprises all existing continuous GPS stations in Canada and a selection of north-central U.S.A. stations based on time span, monument, and data quality. The time period considered for analysis is January

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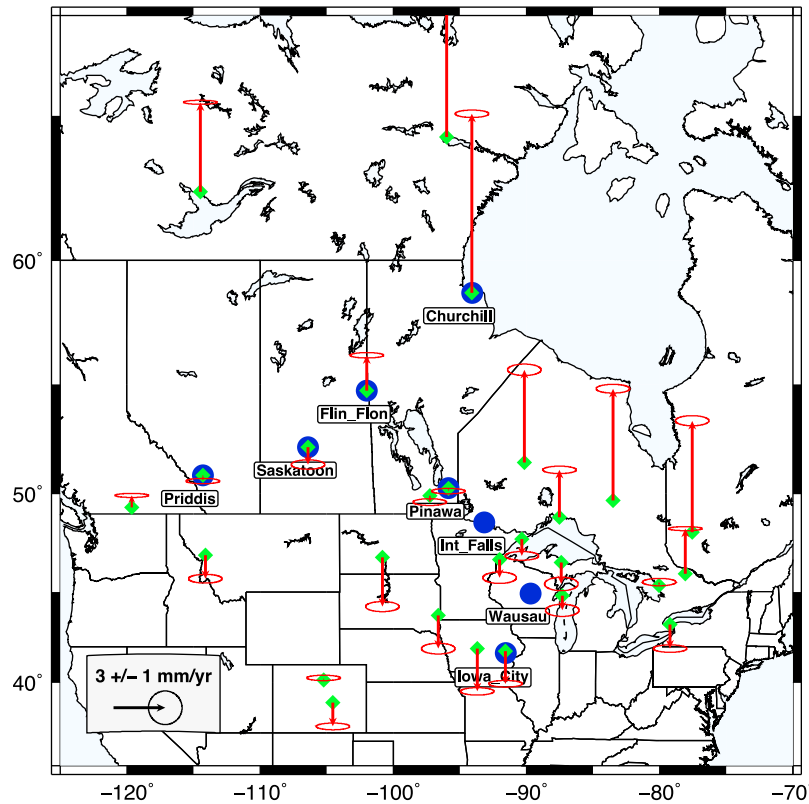


Figure 1. North America mid-continent absolute gravity and GPS stations. Blue circles and green diamonds show absolute gravity and GPS stations, respectively. Red arrow show vertical velocities (up positive) and their 95% confidence interval, aligned to ITRF2005.

1996 to December 2010, with an average time series length of 10.6 yr. GPS data are processed with the NRCan Precise Point Positioning software using absolute antenna phase tables and a VMF1 troposphere model. Velocities are aligned to the ITRF2000 and ITRF2005 realizations of the International Terrestrial Reference Frame [Altamimi *et al.*, 2002, 2007]. Details of processing, time-series analysis, and alignments are given in Text S1; vertical time series are shown in Text S2.

[8] Standard errors on the velocities are calculated using the general formula for uncertainties for a colored noise source of Williams [2003]. For each time series, we estimate the spectral index K of the residual power spectrum (cf. Text S1). The average spectral index is 0.64, which yields standard errors $\sim 60\%$ larger than white noise uncertainties. This is roughly consistent with recent noise studies that find slightly larger

spectral indices (0.7–0.8) for times series longer than 10 years [e.g., Santamaría-Gómez *et al.*, 2011].

4. Gravity/GPS Comparison and Absolute GPS Rates

[9] Absolute gravity rates and vertical velocities at our eight collocated or nearby sites are given in Table 1. The International Falls, MN, and Wausau, WI, gravity sites are not collocated with a continuous GPS station. We estimate the vertical velocity at these sites by interpolating the velocities of nearby GPS stations using a 2-D adaptive Gaussian interpolation function, with a half-width defined as the distance to the nearest GPS station (respectively 107 km and 226 km).

Table 1. AG and GPS Station Locations, Rates, and Standard Errors^a

Site	Latitude (deg)	Longitude (deg)	g ($\mu\text{Gal yr}^{-1}$)	σ_g ($\mu\text{Gal yr}^{-1}$)	T $_g$ (yr)	GPS	Vu05 (mm yr^{-1})	σ_u (mm yr^{-1})	Vu00 (mm yr^{-1})	TGPS (yr)
Churchill, MB	58.762	-94.086	-1.75	0.09	21.7	CHUR	10.38	0.11	10.79	15.0
Flin Flon, MB	54.725	-101.978	-0.25	0.28	14.4	FLIN	2.05	0.08	1.69	14.6
Pinawa, MB	50.259	-95.865	-0.07	0.18	15.2	DUBO	-0.17	0.08	-1.12	14.5
International Falls, MN	48.585	-93.162	-0.10	0.13	20.9	**	-0.12	0.12	-1.19	-
Wausau, WI	44.920	-89.680	0.14	0.21	15.2	**	-0.99	0.13	-2.33	-
Iowa City, IA	41.658	-91.543	0.51	0.18	14.0	NLIB *	-1.90	0.10	-3.92	13.7
Saskatoon, SK	52.195	-106.399	0.94	0.40	8.0	SASK	-1.01	0.14	-1.80	7.6
Priddis, AB	50.871	-114.293	-0.20	0.51	7.0	PRDS	-0.33	0.08	-1.27	13.3

^a g and σ_g : Absolute gravity rate and colored-noise standard error. T $_g$: length of absolute gravity time series. GPS: Collocated GPS station code. Vu05 and σ_u : Vertical velocity and colored-noise standard error in ITRF2005. Vu00: Vertical velocity in ITRF2000. TGPS: length of GPS time series. **: No collocated GPS station; uplift rates derived from interpolation of nearby GPS stations (cf. text). *: NLIB GPS station located 13 km north of absolute gravity station.

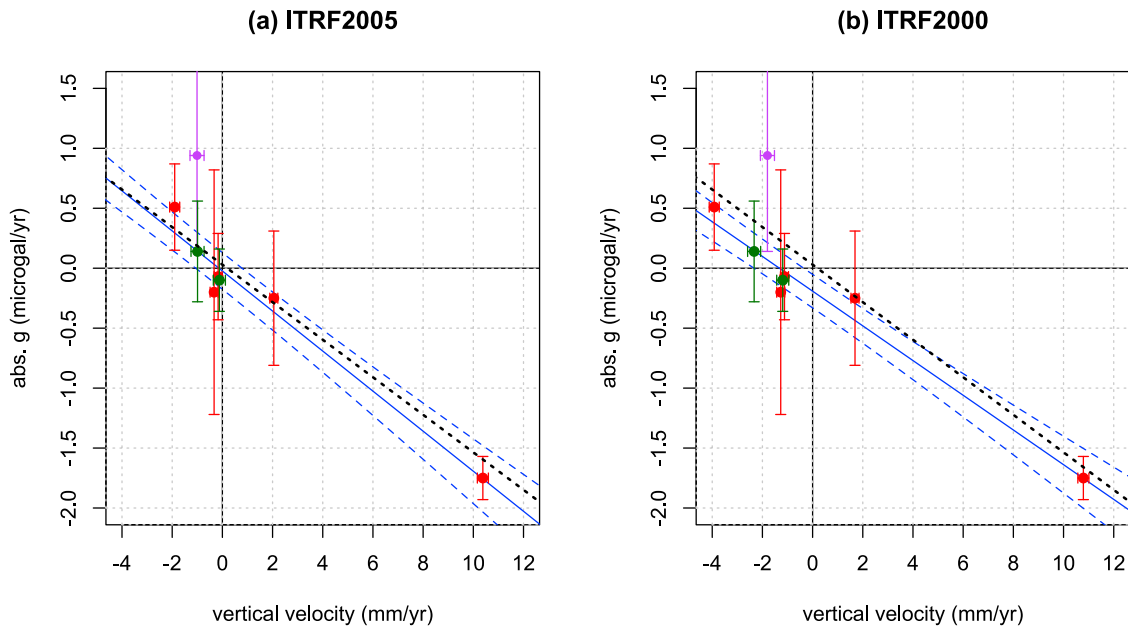


Figure 2. Absolute gravity vs. GPS uplift rates. GPS vertical velocities aligned to (a) ITRF2005 and (b) ITRF2000. Red and green symbols show absolute gravity and GPS uplift rates with 95% confidence intervals at collocated and interpolated sites, respectively. From left to right, gravity stations are: Iowa City, Wausau, Saskatoon (purple symbol not used in fit), Priddis, Pinawa, Int. Falls, Flin Flon, Churchill. Blue solid and dashed lines show best-fit linear regression and its 95% confidence interval, respectively. Black dashed line shows model-predicted, center-of-mass aligned, linear relation based on rates predicted by the Multi-Dome-1/VM2 model.

[10] Figure 2a shows the AG rates versus GPS vertical velocities in ITRF2005, as well as the best-fit linear regression between the two variables, taking into account the uncertainties on both axes [York, 1966]. AG data at Saskatoon strongly correlate with groundwater variations measured by regional weighing lysimeters (G. van der Kamp, personal communication, 2010). Because of its relatively short length (~ 8 yr), the trend estimated for the Saskatoon time series is more sensitive to hydrology processes with 1–5 yr period, compared to the other longer datasets (13–15 yr). Thus, the data point for Saskatoon is excluded from the regression analysis. The best-fit model yields a gravity/uplift ratio of $-0.17 \pm 0.01 \mu\text{Gal mm}^{-1}$ and an intercept of $-0.02 \pm 0.08 \mu\text{Gal yr}^{-1}$ (or $-0.1 \pm 0.5 \text{ mm yr}^{-1}$).

[11] The gravity/uplift ratio is strongly constrained by the data point for Churchill, MB (Figure 2a). Removing this site from the analysis yields a more poorly defined ratio of $-0.22 \pm 0.08 \mu\text{Gal mm}^{-1}$, albeit similar to the ratio including Churchill within the standard errors. The ratio including all sites is consistent with the predicted ratio of $-0.157 \mu\text{Gal mm}^{-1}$ for the Multi-Dome-1/VM2 glacial isostatic adjustment model [Lambert *et al.*, 2005, 2006], derived by fitting model-predicted gravity and uplift rates at the observation sites. This model is a modification of ICE-3G [Tushingham and Peltier, 1991] with a thinner ice-sheet in southern Manitoba and immediately west of Hudson Bay relative to ICE-5G [Peltier, 2004], as required by a combination of recent geodetic data [Argus and Peltier, 2010].

[12] The intercept of the best-fit regression on the observed rates is well defined as $-0.1 \pm 0.5 \text{ mm yr}^{-1}$ ($-0.02 \pm 0.08 \mu\text{Gal yr}^{-1}$), consistent with the small intercept of 0.2 mm yr^{-1} for the model-predicted regression

(Figure 2a). In previous studies of gravity and GPS rates in mid-North America, Larson and van Dam [2000] and Lambert *et al.* [2006] found a similar near zero gravity/uplift offset. However, due to the smaller number of sites and length of absolute gravity data, both studies were limited to an accuracy of about $\pm 2.0 \text{ mm yr}^{-1}$. In contrast, non-zero gravity/uplift offsets ($0.5\text{--}2.0 \text{ mm yr}^{-1}$) have been reported for studies in western Canada [Mazzotti *et al.*, 2007] and Britain [Teferle *et al.*, 2006]. Because of uncertainties in the ITRF2000 reference frame definition [e.g., Altamimi *et al.*, 2007; Argus, 2007] and potential biases in antenna phase-center calibrations [Ge *et al.*, 2005], these non-zero offsets may be attributed to GPS velocity biases [Teferle *et al.*, 2006; Mazzotti *et al.*, 2007].

[13] Unlike earlier assessments, our analysis provides a comparison of AG rates with GPS velocities aligned to ITRF2005 using antenna absolute phase-center calibrations, thus minimizing potential GPS biases. The absence of a gravity/uplift offset in Figure 2a indicates that, at least in the North American mid-continent region, vertical velocities aligned to the ITRF2005 are also properly aligned to Earth's center of mass, within 0.9 mm yr^{-1} at the 95% confidence level. This result also applies to ITRF2008, since there is no significant rate difference in origin, scale or orientation that would affect our observations relative to ITRF2005 [Altamimi *et al.*, 2011].

[14] In contrast, aligning our GPS velocities to ITRF2000 (Figure 2b) yields a gravity/uplift ratio of $-0.15 \pm 0.01 \mu\text{Gal mm}^{-1}$ and a gravity/uplift offset of $-1.3 \pm 0.5 \text{ mm yr}^{-1}$ ($-0.19 \pm 0.07 \mu\text{Gal yr}^{-1}$), indicating a bias of the ITRF2000 origin rate significantly different from zero at the 95% confidence level. The difference in the best-fit gravity/uplift intercept between our ITRF2000 and ITRF2005 results

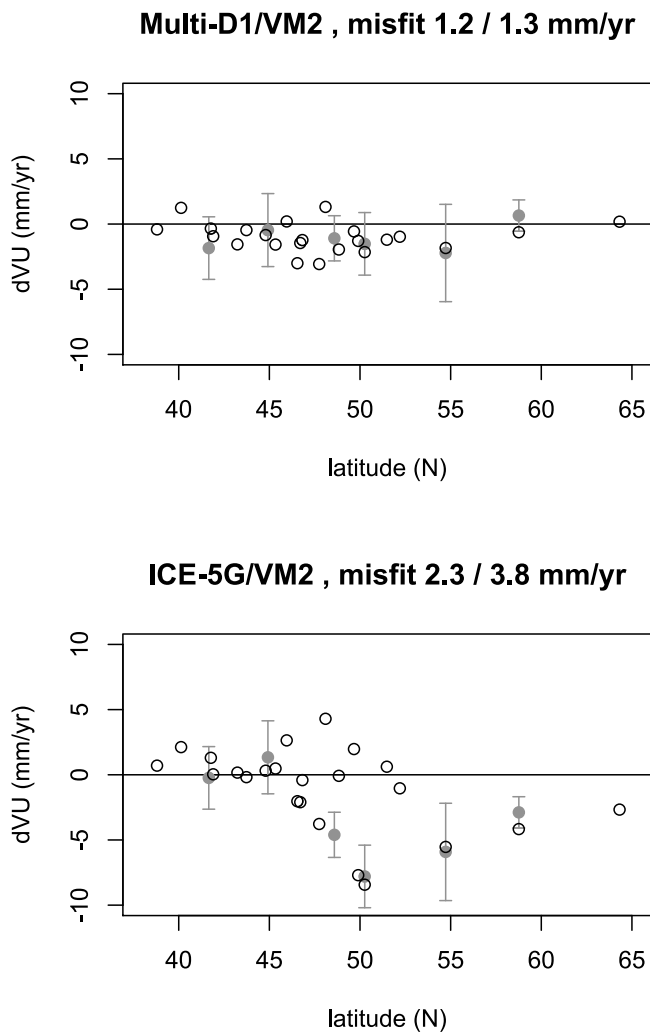


Figure 3. Residual GPS uplift and absolute gravity rates for GIA model predictions. Open and grey circles show residual (observation minus model prediction) GPS vertical velocities, aligned to ITRF2005, and residual absolute gravity rates (converted to velocities), respectively, as a function of site latitude. Error bars are 95% confidence (errors bars for GPS are smaller than symbols). (top) Multi-D1/VM2 and (bottom) ICE-5G/VM2 GIA models. Misfit (mean residual) quoted for GPS/absolute gravity datasets.

(ITRF2000 minus ITRF2005) is $-1.2 \pm 0.7 \text{ mm yr}^{-1}$. This is consistent with the official transformation from ITRF2005 to ITRF2000 (ITRF2000 minus ITRF2005 [Altamimi et al., 2007]), which predicts a difference in vertical velocities in mid North America of about $-0.9 \pm 0.6 \text{ mm yr}^{-1}$, composed of an origin rate component ($-1.4 \pm 0.5 \text{ mm yr}^{-1}$) and a scale rate component ($+0.5 \pm 0.3 \text{ mm yr}^{-1}$) that tend to cancel. Our results suggest that the ITRF2005 (ITRF2008) origin, defined through SLR observations [Altamimi et al., 2007, 2011], is in good agreement with Earth's center of mass as defined by absolute gravity data.

5. Discussion

[15] Our ITRF2005 results provide a robust empirical calibration of the gravity/uplift ratio for the glacial isostatic adjustment process: $-0.17 \pm 0.01 \mu\text{Gal mm}^{-1}$, consistent

with model results of $-0.157 \mu\text{Gal mm}^{-1}$ for the same region and with the theoretical ratio of about $-0.15 \mu\text{Gal mm}^{-1}$ [Wahr et al., 1995; James and Ivins, 1998]. Aside from Saskatoon, the gravity/uplift relation at each site is consistent with the theoretical and best-fit ratios, well within the 95% confidence interval of the observations (Figure 2a). This consistency indicates that GIA is the primary driving process for uplift and gravity trends on a decadal time-scale. In other words, the impact of additional processes, such as local hydrology or meteorology, on decadal gravity and uplift trends is smaller than the measurement uncertainties (about $\pm 0.1 - 0.4 \mu\text{Gal yr}^{-1}$ and $\pm 0.1 \text{ mm yr}^{-1}$, respectively). This result is consistent with comparisons of the spectral behavior of superconducting gravity data and hydrological models, which indicate that separating tectonic from hydrological signals at the $0.1 \mu\text{Gal yr}^{-1}$ level requires between 3.5 and 17 years of data [Van Camp et al., 2010]. The only clear case for significant local perturbation to the gravity and uplift trends is for the Saskatoon site (Figure 2), where the large gravity increase and gravity/uplift ratio ($-1.18 \pm 0.41 \mu\text{Gal mm}^{-1}$) reflect the influence of local hydrological changes on trends derived from relatively short GPS and gravity times series ($\sim 8 \text{ yr}$, Table 1).

[16] Our joint analysis of GPS and AG shows that GPS data referenced to ITRF2005 (and ITRF2008) provide vertical velocities relative to Earth's center of mass that can be directly compared to GIA model predictions. Our results provide support for the practice of defining the frame origin and its velocity through SLR observations [Altamimi et al., 2007, 2011] and suggest that AG data could be used to reinforce SLR data and increase the stability of the ITRF origin definition. As an example, Figure 3 shows a comparison between our observed rates (GPS and AG, converted to velocities) and predictions from two GIA models: Multi-Dome-1/VM2 and ICE-5G/VM2. The two models use the same 1-D Earth rheology and only differ by the ice sheet history. Multi-Dome-1 [Lambert et al., 2005, 2006] has been adjusted to previous measurements of AG rates in mid-North America, which require ice thicknesses intermediate between that of ICE-3G and ICE-5G, as suggested by Argus and Peltier [2010]. Both models provide a reasonable fit of observations at low latitudes ($40-45^\circ\text{N}$, Figure 3). As pointed out by Argus and Peltier [2010], ICE-5G/VM2 shows significant misfit west of the Great Lakes ($45-55^\circ\text{N}$, Figure 3), indicating the value of well-calibrated geodetic data for better defining local ice sheet models.

6. Conclusion

[17] Absolute gravity can provide a calibration of GPS vertical rates and GIA models relative to Earth's center of mass. On the basis of absolute gravity comparison, we show that GPS vertical velocities aligned to ITRF2005 and ITRF2008 can be directly compared to GIA model predictions, in contrast with velocities aligned to ITRF2000, which suffer from a bias of $\sim 1.5 \text{ mm yr}^{-1}$. This reference frame accuracy issue is significantly larger than the velocity standard errors obtained for 10–15 year-long time series ($0.1-0.2 \text{ mm yr}^{-1}$), which only reflect the precision of the measurements. In comparison, standard errors on the absolute gravity rates ($0.1-0.5 \mu\text{Gal yr}^{-1}$) are a better representation of accuracy.

[18] Our results indicate that, on decadal time-scales, GIA is the primary process driving vertical crustal movements and mass changes in mid-continent North America. The impact of other processes is limited, except at specific locations where the data time frame is shorter and more sensitive to the influence of rapid regional groundwater changes (e.g., Saskatoon). In contrast with previous studies, which used datasets too limited in time, sampling, and number of stations to yield meaningful constraints, we show that combined absolute gravity and GPS measurements can provide significant constraints to global geodetic, geodynamic, and hydrological studies.

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