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EXPRESS LETTER

Time-variable gravity fields derived from GPS tracking of Swarm

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SUMMARY

Since 2002 Gravity Recovery and Climate Experiment (GRACE) provides monthly gravity fields from K-band ranging (KBR) between two GRACE satellites. These KBR gravity monthlies have enabled the global observation of time-varying Earth mass signal at a regional scale (about 400 km resolution). Apart from KBR, monthly gravity solutions can be computed from onboard GPS data. The newly reprocessed GPS monthlies from 13 yr of GRACE data are shown to yield correct time-variable gravity signal (seasonality, trends, interannual variations) at a spatial resolution of 1300 km (harmonic degree 15). We show that GPS fields from new Swarm mission are of similar quality as GRACE GPS monthlies. Thus, Swarm GPS monthlies represent new and independent source of information on time-variable gravity, and, although with lower resolution and accuracy, they can be used for its monitoring, particularly if GRACE KBR/GPS data become unavailable before GRACE Follow-On is launched (2017 August).

Key words: Satellite geodesy; Time variable gravity; Global change from geodesy.

1 INTRODUCTION

The intersatellite distance observations using a microwave link between the two Gravity Recovery and Climate Experiment (GRACE) satellites (in orbit since 2002) brought a new era in geodesy, it is now possible to observe time variations of Earth's gravity field from space on a regional scale with a resolution of a few hundred kilometres (Tapley *et al.* 2004). Gravity variations observed by GRACE are mostly connected to changes in the distribution of fluid mass on and below the Earth's surface; monitoring the time-varying gravity by GRACE has been successfully applied in many areas of geoscience, among them continental water cycle and related climate variability, water mass redistribution in the oceans, mass balance of polar ice sheets, sea level rise, postglacial rebound, groundwater storage changes, etc. (for a review, see e.g. Cazenave & Chen 2010; Wouters *et al.* 2014).

Standard products of the GRACE mission, monthly gravity field solutions, are based mainly on intersatellite K-band ranging (KBR), and are provided as sets of spherical harmonic coefficients. The spatial resolution achievable by using directly these KBR monthly gravity fields is at the level of 400–500 km, corresponding to a half-wavelength of the degree 40–50 spherical harmonic. Over the years, sophisticated processing methods have been developed to enhance this limit down to say 300 km, for example, so-called de-striping (Swenson & Wahr 2006), but in this paper they are not needed and will not be discussed. The original design lifetime of the GRACE mission was 5 yr, the US/German GRACE team is making all their efforts to keep GRACE working until its continuation mission, GRACE Follow-On, is launched (planned for 2017) (Watkins *et al.* 2015). The by now more than 13 yr long time-series of GRACE monthly fields has proved to be a valuable and extremely useful information for many geoscience communities, hence there is a strong scientific interest that these observations of time-varying gravity continue uninterrupted.

Apart from the KBR instrument, each of the two GRACE satellites is equipped with a GPS receiver providing the time-series of satellite positions, which can be inverted to estimate the gravity field acting on the satellite. The problem with time-variable gravity signal is that it is rather weak, it amounts to only a few millimetres in the geoid height, corresponding to a few tens of centimetres in equivalent water height (Wahr 2007). The first mission, whose GPS tracking data were supposed to yield time-variable gravity, was CHAMP (in orbit 2000–2010) (Reigber *et al.* 2002). But early attempts to extract time-varying gravity signal from the CHAMP GPS data were unsuccessful (Weigelt *et al.* 2009). With longer time-series and better processing of GPS positions, several studies showed that an average seasonal signal can be obtained for the lowest harmonic degrees (up to degree 10 corresponding to a spatial resolution of 2000 km) (e.g. Prange *et al.* 2010; Bezděk *et al.* 2014). On using a special Kalman filter, Weigelt *et al.* (2013) showed that at this spatial resolution GPS data may yield correct interannual changes and trend estimates in selected regions. Until recently, apart from CHAMP and GRACE, only the gravity field mission GOCE of the European Space Agency (ESA; Rummel *et al.* 2011) was equipped with a geodetic-quality GPS receiver allowing the tiny time-varying gravity effects to be sensed. Due to a relatively short time span of the GOCE mission (2009–2013), GOCE GPS monthlies provided only an average seasonal signal in the lowest degrees (e.g. Visser *et al.* 2014; Jäggi *et al.* 2015a). In November 2013, ESA launched the Swarm mission, a constellation of three satellites, whose main objective is to observe the Earth's magnetic field (Friis-Christensen *et al.* 2008). Gravity field study should be enabled by use of a geodetic-quality GPS receiver on each Swarm satellite (van den IJssel *et al.* 2015).

Our study has several goals. First, we show that our newly reprocessed monthlies from 13 yr of GRACE GPS data are able to produce the average time-variable gravity signal at a spatial resolution of about 1300 km (harmonic degree 15). This includes the global maps of seasonality and of trends. Second, the individual GRACE GPS monthlies are shown to produce correct interannual changes in amplitude and phase in the Amazon basin, and the same rate of decrease in the mass signal in Greenland as the GRACE KBR monthlies. Then, the 1.5-yr overlap shows convincingly that Swarm GPS data provide gravity variations of similar quality as that from GRACE. We conclude that Swarm GPS monthlies can be successfully used for time-variable gravity in the same way as GRACE GPS monthlies. Our GPS-based monthly solutions are available for download at http://www.asu.cas.cz/~bezdek/vyzkum/geopotencial/.

2 DATA AND METHODS

Over the last few years, we have developed a method for the inversion of the GPS positions into a global gravity field model (Bezděk *et al.* 2014), its principal computational features were first used for calibration of space accelerometers (Bezděk 2010). Our inversion method falls under the so-called *acceleration approach*, the starting point of which is Newton's second law relating the actual motion of the satellite to the forces acting on it. The observations are represented by accelerations obtained through numerical second derivative of the GPS-based satellite positions. The applied forces other than those due to Earth's gravity are either measured or modelled (lunisolar perturbations, tides, nongravitational forces). The gravitational force can be conveniently expressed by means of a spherical harmonic series, then the sought geopotential harmonic coefficients enter linearly each observation equation, which is derived from Newton's second law at each point of the satellite orbit. For a given period of time, the linear system of observation equations is solved using standard methods of linear regression. Although the principle of the acceleration approach is simple and straightforward, there are issues that need to be addressed carefully, for example, noise amplification incurred by numerical derivative, or an autocorrelation of the observed GPS positions. For details of our inversion method we refer the reader to Bezděk *et al.* (2014).

The main input into the gravity field inversion procedure are so-called kinematic orbits, a special type of satellite orbits computed from GPS observations in a purely geometric way. This means that no force models are used in the estimation of satellite positions. As the acceleration approach is linear in the geopotential coefficients, GPS-based gravity fields are estimated from scratch only using the GPS-derived positions with no a priori gravity field model involved. The kinematic orbits used in this study were computed at the Institute of Geodesy, Graz University of Technology, Austria (Zehentner & Mayer-Gürr 2014, 2015a). We use 13 yr of kinematic orbits of both GRACE A/B satellites from 2002 April to 2015 April (154 months) and almost 1.5 yr of kinematic orbits of three Swarm satellites from 2013 December through 2015 April (17 months). As for nongravitational forces, we used the measured signal from GRACE onboard accelerometers, currently Swarm accelerometer data sets cannot be used in the gravity field retrievals, so we used their models (*cf.* section 2.5 of Bezděk *et al.* 2014).

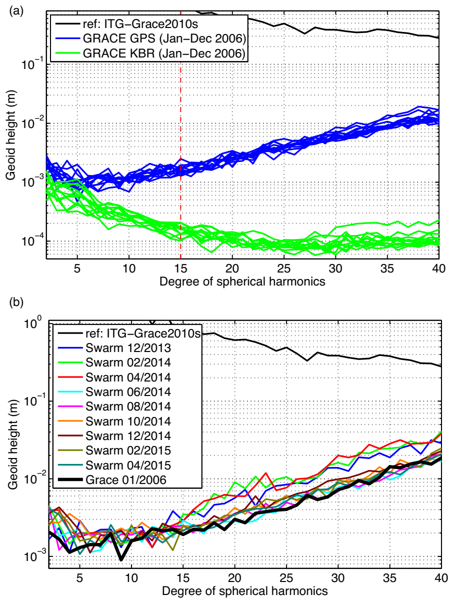

Figure 1. Degree difference amplitudes of GRACE and Swarm monthly solutions in terms of geoid height. (a) GRACE GPS monthlies (blue) over 2006 are compared with corresponding GRACE KBR monthtlies (green) computed by CSR. At harmonic degree 15 (dashed red line), KBR monthlies are 10 times more accurate than GPS monthlies. (b) Swarm monthly fields over 2013–2015 are shown together with the GRACE GPS field from 2006 January for comparison. Note the millimetre precision of GPS monthlies in the lowest degrees with respect to the reference model ITG-Grace2010s. (Only every second Swarm GPS solution is displayed in order not to overload the figure.)

The data used for producing Swarm's kinematic orbits are made available by the Swarm team as a L1B product (Olsen *et al.* 2013). Each Swarm satellite is equipped with two eight-channel GPS receivers, which have undergone numerous modifications to improve the quality of the gathered data (van den IJssel *et al.* 2015). Since 2014 July, the original data rate of 0.1 Hz has been increased to 1 Hz. Since 2014 October, the field of view of GPS receivers was increased from 80° to 83°, then in 2015 January to 88°.

Due to higher noise in the gravity fields derived from GPS compared to those from KBR, we limited the monthly solutions to a maximum degree 40. To reduce aliasing from higher degrees of the real gravity field we subtracted the signal from harmonic degrees 41–120 by using a suitable static gravity field model. Here, we used the ITG-Grace2010s model (Mayer-Gürr *et al.* 2010), but other static KBR gravity field models produced virtually the same results.

As GRACE standard monthly gravity fields (we will call these 'KBR monthlies' as opposed to 'GPS monthlies', which are derived from GPS tracking), we use RL05 monthly gravity solutions computed by two GRACE data processing centres, Center for Space Research (CSR) at the University of Texas, USA and the Geoforschungszentrum (GFZ) in Potsdam, Germany. These KBR solutions are obtained by a conventional, dynamic orbit and gravity adjustment process using least squares (e.g. Tapley *et al.* 2004).

Fig. 1 shows degree difference amplitudes of GPS monthly solutions with respect to a reference static field ITG-Grace2010s (*cf.* Bezděk *et al.* 2014, section 3.4). Fig. 1(a) compares the accuracy

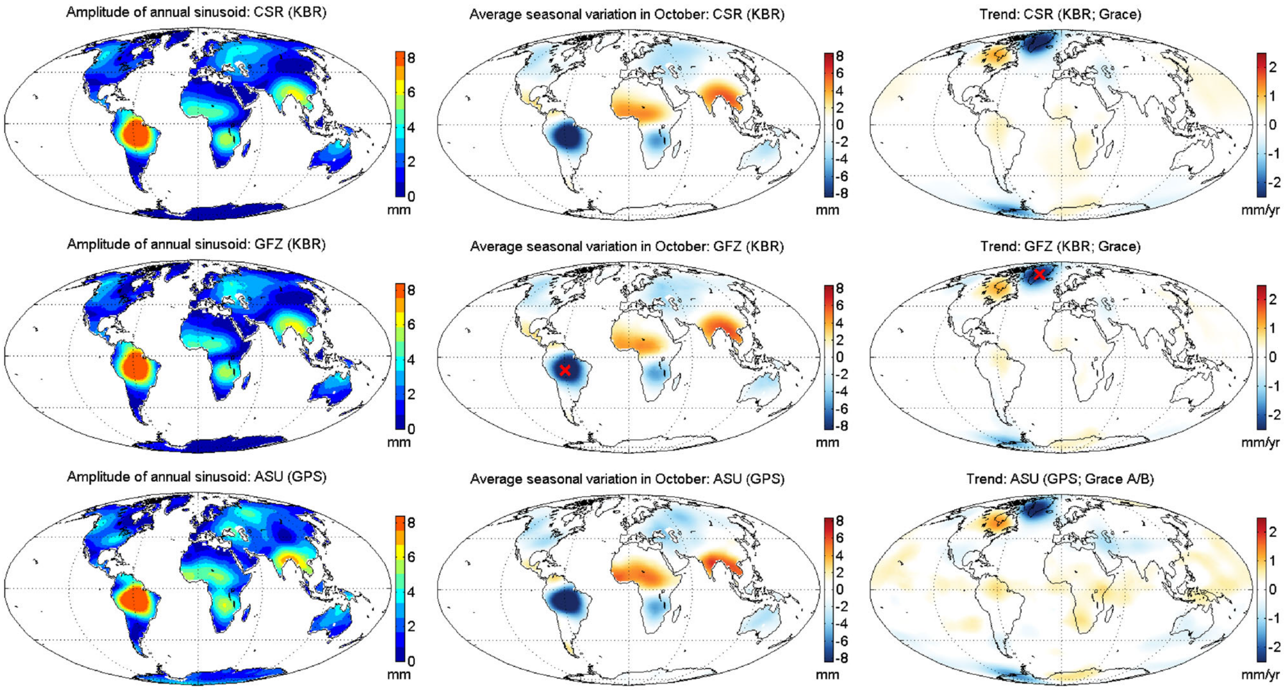

Figure 2. Average seasonality and trends in terms of geoid height derived from GRACE KBR monthly gravity fields produced by CSR (first row) and by GFZ (second row) compared to the same quantities computed from GPS monthlies (third row, labelled ASU). Non-zero amplitude of the fitted annual sinusoid (first column) highlights the areas with pronounced seasonal variation. Average seasonal variation in October (second column) reflects the annual phase, as the global seasonal pattern peaks in April/October. Non-zero values of the trend (third column) identify areas with important secular mass change. The maps are based on KBR/GPS monthly gravity solutions covering the 13-yr period (2002–2015), limited to maximum spherical harmonic degree 15 (spatial resolution of about 1300 km). The quantities in the first and second columns are displayed only over land. (The red crosses in two figures of the second row indicate the places, where the time-series of Fig. 3 are located.)

of GRACE GPS monthlies and GRACE KBR monthlies over 2006 in relation to the more precise static KBR model. At the spherical harmonic degree 15 (spatial features of ∼1300 km), the relative accuracy of GPS monthlies is *10 times worse* relative to that of KBR monthlies. Similar plots were obtained for all years 2002–2015, therefore this is general information that should be kept in mind when looking at comparisons of GPS versus KBR monthly fields later in Figs 2 and 3. Fig. 1(b) displays the improvement in the quality of Swarm GPS monthlies (starting with 2014 June), which reflects the changes made to the Swarm GPS receiver settings and data processing over the year 2014. For comparison we added the GRACE GPS solution from 2006 January, when the GRACE satellites had approximately the same altitude (see Section 1 in the Supporting Information for a more detailed explanation of this choice).

3 RESULTS

3.1 Average seasonal and secular variations from GPS monthly solutions of GRACE

Fig. 2 shows the maps of average seasonal pattern and trends derived from 13 yr of GRACE KBR and GPS data expressed in terms of the geoid height. The plots in the first row were computed from GRACE CSR monthlies, to which a time-series model consisting of the mean, trend and seasonal components was fitted (see Section 2 in the Supporting Information for more details). From the left, the first plot shows the amplitude of the fitted annual sinusoid identifying the places with strongest seasonal variation. In the middle plot, the annual amplitudes are combined with phases, the mean October variation (close to the seasonal sine component) points out differences in seasonal variation mainly as function of latitude. Here, the seasonal signal highlights important continental hydrology areas in the tropics together with the north temperate zone. Finally, the upper right plot shows the global distribution of GRACE trends, pinpointing especially the well-known and discussed regions of ice mass loss in Greenland and Antarctica (e.g. Wouters *et al.* 2014).

In the second row of Fig. 2, there are plots computed from GFZ KBR monthlies. At this scale, compared to the CSR plots barely any difference is visible for the seasonal maps (second column), there are some small differences in the map of the trends (third column). Both CSR and GFZ solutions are based on the same GRACE KBR data, here we added these two KBR-derived time-variable gravity signals to show that there are some differences between them (this will be seen more clearly in the following Fig. 3).

The third row of Fig. 2 presents results based on our new GRACE GPS gravity solutions (ASU, Astronomický ústav). The geographical distribution of the average seasonal signal from GPS monthlies (lower left and middle plots) matches very well the corresponding areas in the KBR-derived maps, both near the equator and in the middle latitudes. Also, in both GPS and KBR maps there is no seasonal gravity signal in the major arid areas (e.g. Sahara and other large deserts). The global pattern of the GPS-derived mass trends (lower right) compares quite well to that from KBR monthlies in that it correctly identifies the regions with strongest rates (Greenland and north-eastern Canada, Antarctica). The GPS trends over the oceans show more noise at a submillimetre-per-year level, but at this level there are differences also among the two KBR-based solution series (CSR/GFZ in upper/middle right plots). A point worth emphasizing is that to obtain the maps of time-variable gravity in

Fig. 2, the time-variable signal from GPS monthlies agrees with that from KBR monthlies not only in the geographical location, but also in the magnitude.

To study the temporal variations, we used the monthly solutions up to degree 15 (the approximate spatial resolution is usually characterized by the half-wavelength of the shortest spherical harmonic, in this case about 1300 km). The choice of this value was found through a visual 'trial-and-error' procedure, by inspecting when the noise in the figures obviously outweighed the signal. More formally, the chosen maximum degree 15 is in accordance with applying the degree correlation analysis (shown explicitly in Section 3 of the Supporting Information). We recall that at the 1300 km resolution the relative accuracy of GPS fields compared to that of KBR fields is worse by a factor of 10 (Fig. 1, upper plot). On the other hand, both plots in Fig. 1 show that our choice of maximum degree 15 confines the degree difference amplitudes of individual monthly solutions to stay within few millimetres, where the time-variable gravity signal starts to appear.

3.2 Individual monthly gravity solutions from GPS tracking of GRACE and Swarm

In the previous section, we compared the *average* time-variable gravity signal derived from 13 yr of GPS and KBR monthlies of GRACE. Now we examine *individual* GPS/KBR monthly solutions from GRACE together with Swarm GPS monthlies in the 1.5-yr overlap. As example areas we selected two places with strong seasonal and secular time-variable gravity signal (shown as red crosses in Fig. 2).

In Fig. 3(a), individual monthly solutions from KBR data (blue and green) show a strong seasonal signal at a location in the Amazon basin. Apart from the dominant annual frequency, one may discern interannual variations in magnitude and phase of the gravity field signal. These features are clearly reproduced by the GRACE GPS monthlies (red), although with somewhat more noise. The Swarm GPS monthlies (black), which are added to the last 1.5-yr period of the plot, agree fairly well with both KBR and GPS monthlies from GRACE.

Fig. 3(b) shows the secular decrease of the mass signal in Greenland. The rate of this trend can be estimated as the slope of the tangent to some suitable curve fitting locally the monthly solutions. At the chosen place in Greenland, a visible variability is already notable between the two KBR data sets (blue and green). As with the Amazon basin, the GRACE GPS monthlies (red) have much the same behaviour as the KBR solutions, but again contain somewhat more noise. A similar statement is applicable to Swarm GPS monthlies (black).

We note that the maps of time-variable gravity in Fig. 2 and especially the interannual changes shown in Fig. 3 are based solely on GPS gravity fields computed independently for each month. No use was made of Kalman filtering or other stabilizing or constraining method (*cf.* Weigelt *et al.* 2013). One of the reasons may be the good quality of the new kinematic orbits used in this study (Section 2). (See Section 4 in the Supporting Information explaining the reasons to present Swarm GPS fields only in Amazonia and Greenland.)

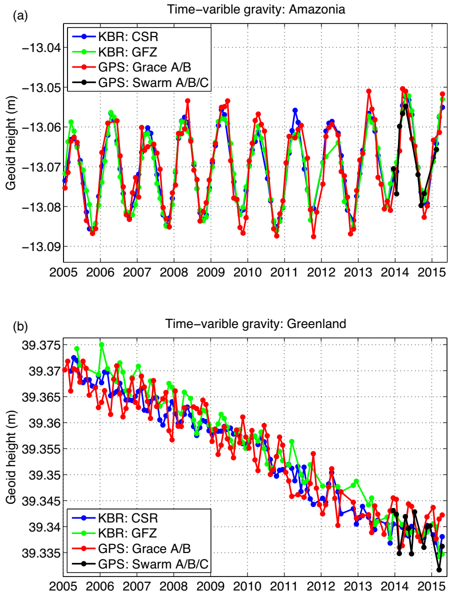

Figure 3. Time-series of monthly gravity field solutions in regions with strong seasonality or trends. (a) In Amazonia, over the 10-yr period the two KBR solutions (blue and green) manifest interannual variations in amplitude and phase; these are clearly reproduced by the GRACE GPS solutions (red), although with some noise. (b) In Greenland, GRACE GPS monthlies follow the same rate of secular decrease (trend) in the gravity signal as the KBR monthlies. The Swarm GPS monthly solutions are available for the last 1.5 yr, where they agree both with the GRACE KBR and GPS solutions.

4 CONCLUSIONS

The by now more than a 13 yr long time-series of GRACE monthly gravity fields of an unprecedented precision and spatial resolution (around 400 km) has proved to be of fundamental benefit to many scientific fields that deal with redistribution of mass within the Earth system, such as the continental water cycle and related climate variability, mass balance of polar ice sheets and mountain glaciers, ocean mass and global sea level change, solid Earth geophysics, etc. Currently, the GRACE satellites have well surpassed their original 5-yr design lifetime and the GRACE mission control team is fully engaged in the efforts to keep the mission operational until the GRACE Follow-On is active, which is planned for 2017 (Watkins *et al.* 2015).

Besides the standard GRACE monthly gravity fields based primarily on intersatellite KBR, one can produce an alternative set of monthly gravity fields derived from satellite GPS positions. Until recently, the sensitivity of these GPS gravity monthlies [or alternatively of gravity fields derived from SLR observations, see Sośnica *et al.* (2015)], was shown to reach only the continental level with the spatial resolution of more than 2000 km (Weigelt *et al.* 2013; Bezděk *et al.* 2014; Jäggi *et al.* 2015a). In this paper, we show that from 13 yr of GRACE GPS data it is possible to obtain seasonality and trends in the time-variable gravity signal at the spatial resolution of 1300 km. The interannual changes in the seasonal time-variable gravity signal over the Amazon basin, which are revealed by the standard GRACE KBR monthlies, are clearly reproduced by our GRACE GPS monthlies. The same applies to the strong negative trend in the mass signal over Greenland. This demonstrates that, albeit at a reduced spatial resolution and with more noise, GRACE GPS fields are capable of reproducing the time-series of standard GRACE KBR monthlies.

Finally, we introduce the new ESA mission Swarm, in orbit since 2013 November, and we show that after the enhancements made to the GPS receiver settings and data over 2014, in the 1.5-yr overlap the Swarm GPS gravity monthlies are of comparable quality to those from GRACE. The fact that Swarm GPS orbits are sensitive enough to be useful for time-variable gravity was recently presented also by several research groups (Bezděk *et al.* 2015; Jäggi *et al.* 2015b; Zehentner & Mayer-Gürr 2015b). Potentially, one may use GPS/GNSS data of as many satellites as possible to improve the estimated gravity fields (Ditmar *et al.* 2009; Gunter *et al.* 2011). Unfortunately, Zehentner & Mayer-Gürr (2015a) showed recently that out of the currently available satellite GPS orbits only those from CHAMP, GRACE and GOCE are of quality sufficient to produce time-variable gravity. As the CHAMP and GOCE satellites have already decayed from orbit, besides GRACE, Swarm is now the only active mission capable of providing good quality GPS gravity monthlies. Moreover, the latest information from the Swarm team says that ESA will support Swarm at least until 2018. Therefore, in case of unavailability of both KBR *and* GPS data from GRACE, GPS monthlies from Swarm are demonstrated to be capable—even though currently at a coarser spatial resolution and with more noise—to continue monitoring the millimetre-level time variations of the global Earth's gravity field.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this paper:

Figure S1: Degree correlation between KBR-based and GPS-based GRACE monthly gravity field solutions (data from the time period 2002–2015).
(http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggw094/-/DC1).