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ORIGINAL ARTICLE

An assessment of Bernese GPS software precise point positioning using IGS final products for global site velocities

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Abstract We assess the use of precise point positioning (PPP) within the Bernese GPS software (BSW) Version 5.0 over the period from 2000 to 2005. In our strategy, we compute a set of daily PPP solutions for international GNSS service (IGS) reference frame (IGb00) sites by fixing IGS final satellite orbits and clock products, followed by a Helmert transformation of these solutions into ITRF2000, forming a set of continuous position time series over the entire time span. We assess BSW PPP by comparing our set of transformation parameters with those produced by the IGS analysis centre coordinator (ACC) and our position time series with those of the Jet Propulsion Laboratory (JPL) and the Scripps Orbit and Permanent Array Centre at the Scripps Institute of Oceanography (SIO). The distributions of the north (N), east (E) and up (U) daily position differences are characterized by means and SD of +2.2 ± 4.8, –0.6 ± 7.9 and +4.8 ± 17.3 mm with respect to JPL, and of +0.1 ± 4.4, –0.1 ± 7.4 and –0.1 ± 11.8 mm with respect to SIO. Similarly, we find sub-millimetre mean velocity differences and SD for the N, E and U components of 0.9, 1.5 and 2.2 mm/year with JPL, and of 1.2, 1.6 and 2.3 mm/year with SIO. A noise analysis using maximum likelihood estimation (MLE) shows that when estimating global site velocities from our position time series, the series need to be on average up to 1.3 times longer than those of JPL and SIO, before an uncertainty of less than 0.5 mm/year is obtained.

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Introduction

In recent years, precise point positioning (PPP) (Zumberge et al. 1997), using undifferenced GPS observables, has become a valuable tool for investigating many geophysical processes at the millimetre level (e.g. Larson et al. 2004; Smith et al. 2004; Kouba 2005; Hreinsdóttir et al. 2006).

To date, PPP has been associated mainly with the GIPSYOASISII (GOA) software developed at the Jet Propulsion Laboratory (JPL). However, other scientific GPS software packages, such as the Bernese GPS software (BSW) Version5.0 (Hugentobler et al. 2006), developed at the Astronomical Institute at the University of Berne (AIUB), are also capable of analysing undifferenced GPS measurements. Although BSW is used by most analysis centres (AC) processing GPS data of the European Reference Frame (EUREF) Permanent Network (EPN) (Bruyninx et al. 2004) and by the Centre for Orbit Determination in Europe (CODE) at the AIUB for the provision of its GPS products, there are few published results based on BSW PPP and these include only evaluations of the GPS products of the International GNSS Service (IGS) over several days or weeks (Kouba and Springer 2001; Kouba 2003). In this paper, we define GPS products to be satellite orbits and clocks (we do not discuss earth orientation parameters) from an individual IGS AC and IGS products to those from the combination of the IGS AC products carried out by the IGS. In both cases, the final products are the most accurate and are generally recommended for precise geodetic applications. Additionally, the IGS products are believed to have the advantage, through the combination process, of being somewhat more robust and to a degree, AC independent, but at the cost that, strictly speaking, no GPS software is fully consistent with the combined IGS products. In this paper, we present results from the IGS reference frame (IGb00) sites (http://igscb.jpl.nasa.gov/igscb/station/IGb00stns) over a time span of 5 years (2000–2005) obtained using BSW, PPP with IGS final products.

By processing the GPS data on a site-by-site basis, the large normal equation systems of double difference (DD) network analyses can be avoided and the computational burden reduced dramatically (Zumberge et al. 1997). Furthermore, PPP provides a means to obtain site positions directly in the reference frame of the applied GPS products and can thus be used to monitor both products and site stability (Kouba and Héroux 2001; Ferland et al. 2004; Ray et al. 2004). Hence, the IGS analysis centre coordinator (ACC) at the Geo Forschungs Zentrum (GFZ) in Potsdam, Germany, uses PPP to assess the quality of all GPS and IGS products and the stability of the IGb00 sites (http://www.gfz-potsdam.de/pb1/igsacc/index_igsacc_ppp.html). Since 25 May 2003, the IGS ACC also produces a daily set of global transformation parameters between PPP solutions for the IGb00 sites and the IGS weekly combined solution.

Although PPP provides position solutions in the reference frame of the GPS products (see Ferland et al. 2004), Kouba and Springer (2001) already stated that for the IGS final products, which are based on the loosely constrained IGS AC solutions, the PPP position estimates contain centimetre-level motions of the geocentre. They suggested correcting this by using weekly IGS geocentre estimates or by computing a global Helmert transformation. Using the latter approach, the PPP solutions are also transformed into a reference frame more appropriate for geophysical interpretations, e.g. global site velocities in ITRF2000 (Altamimi et al. 2002).

At this stage, it should be mentioned that although the use of PPP has many advantages over DD network analyses, the latter is still indispensable for the computation of the highly accurate GPS products required by PPP. Furthermore, the fixing of the carrier-phase ambiguities to integers is not possible for PPP, with the approach used within GOA considering pairs of sites during this process.

For the assessment of BSW PPP, we compare our set of Helmert transformation parameters with those of the IGS ACC, and our daily position estimates for sites in the IGb00 network with those from JPL (http://www.sideshow.jpl.nasa.gov/mbh/series.html), computed using GOA, and the Scripps Institution of Oceanography (SIO) (http://www.sopac.ucsd.edu/), computed using GAMIT/GLOBK (GTGK) (Herring 2005; King and Bock 2005). We must mention that both these IGS ACs use their own GPS products in their processing, ensuring full consistency between the products and the subsequent estimation of the site positions. For BSW PPP, this would only be achieved by using the GPS products from CODE. We therefore briefly discuss the effect of using CODE's GPS products rather than IGS products for BSW PPP.

We analyse our position time series (denoted as UNT for University of Nottingham), the JPL and the SIO time series for the IGb00 sites using maximum likelihood estimation (MLE) (e.g. Zhang et al. 1997; Williams 2003; Williams et al. 2004) and compare their noise properties, the site velocity estimates and uncertainties.

We would like to emphasise the importance of our findings in highlighting the PPP capabilities of BSW, considering the current IGS effort to re-analyse the global GPS network in a homogeneous and consistent manner to create a set of revised GPS products useful for precise PPP applications for the period from 1994 to the present (Gendt and Fang 2005).

Methodology

The BSW PPP strategy presented here is in principle similar to the strategy applied in GOA, in terms of fixing predetermined GPS products from a previous analysis when computing site-by-site PPP solutions. When using JPL's GPS products in GOA, it is then possible to transform the *raw* PPP solutions into, e.g. ITRF2000 (Altamimi et al. 2002), using a Helmert transformation computed daily by JPL based on a global set of GPS sites. Similar to the IGS final products, this transformation is necessary due to the loose constraints applied during the product computations at JPL (Zumberge et al. 1997).

As there are no such transformation parameters available for BSW PPP for the complete time span used in this analysis, we computed our own between our daily PPP solutions for the IGb00 sites and their official ITRF2000 site positions and velocities. Although, the IGS ACC has produced a similar set of transformation parameters since 2003, we did not use them in our BSW PPP strategy. We wanted to produce homogeneous position time series in ITRF2000 over a longer time span, avoiding any changes in our BSW PPP strategy and the mixing of different GPS processing sofwares (Gendt et al. 1999).

In this manner, our BSW PPP strategy can be divided into four stages: preparation of data and products, pre-processing of observations, computation of site-by-site PPP solutions and finally the transformation into a specific reference frame. The first three stages are essentially provided by the AIUB (Hugentobler et al. 2006) in the form of the BSW PPP process control file and were used by us with no, or minor, modifications. We then added the fourth stage in order to align the daily PPP solutions to ITRF2000.

In order to produce position time series for the period 2000–2005, we used the IGS final products in their original reference frames, i.e. IGS97 (up to 2 December 2001), IGS00 (up to 11 January 2004) and later IGb00, in combination with a priori site positions in the same frames as the products, i.e. we did not transform the IGS final products into ITRF2000 prior to the BSW PPP processing using the products transformation software by Kouba (2002). Firstly, tests by us confirmed the findings of Kierulf and Plag (2004), who showed that this transformation did not prevent a discontinuity in the PPP derived GPS position time series at the change between IGS97 and IGS00, and secondly, any discontinuities due to this reference frame change would be compensated for by our global Helmert transformation.

The use of the IGS final products also means that for the period before 4 November 2000, only the 15 min satellite clock values from the orbits were available, as IGS final clocks, containing 5 min satellite clock estimates, only became available after this day (Fig. 1). The effect of this is that for data prior to 4 November 2000, only 96 epochs, compared to 288, were processed per day, which resulted in larger standard errors for the earlier position estimates.

A requirement for PPP is that the GPS observation files have the correct time tag for both phase and code measurements. Using the program ClockPrep (Freymueller 2003) on all GPS observation files, it is ensured that any millisecond receiver clock jumps in the code measurements, corrected by some receivers, are also corrected for in the phase measurements. In order for code observations to be consistent with the IGS clock products, it is important to correct the code observations for the satellite-dependent differential code biases (DCB) (Kouba and Héroux 2001). For GPS data after 2 April 2000, this can be achieved either by using cc2noncc (Ray 2003) or directly in BSW. For data prior to 2 April 2000, no such corrections are currently available. However, through the IGS re-processing effort, these will be provided for the complete period since 1994 (Schaer et al. 2006).

Error models applied in PPP have, in general, been described in detail by, e.g. Kouba and Héroux (2001). Due to the *undifferenced* nature of PPP and especially the use of the satellite clock information, it is inherently important that the modelling of systematic biases at the analysis stage is consistent with that during the GPS product computation. Mixing different conventions and error models in the analysis will ultimately lead to biases in the PPP solutions, which are generally assumed to be removed by the DD technique.

In our BSW PPP strategy, we followed the current IGS standards for satellite antenna offsets, relative receiver antenna phase centre variations modelling and an elevation angle cutoff of 10°. Furthermore, we used satellite elevation dependent weighting and applied corrections for solid earth tides, ocean tide loading and sub daily pole and nutation motions according to the IERS conventions (McCarthy and Petit 2004). During the site-by-site PPP computations, we used the ionosphere-free observable and did not fix the carrier-phase ambiguities to integers. We modelled the hydrostatic component of the zenith tropospheric delay and estimated the wet component at 2 h intervals as a step-wise constant function, applying the Niell mapping functions (Niell 1996) and accounting for the azimuthal asymmetry of the local troposphere at each site by inclusion of four horizontal troposphere gradient parameters for each 24 h session.

Results

In this section, we present the results obtained using BSW PPP with IGS final products for IGb00 sites for the period 2000–2005. We discuss the global Helmert transformation and compare our parameter estimates with those of the IGS ACC. Using an example, we present our UNT position time series and compare estimates of the daily positions, site velocities and noise amplitudes for all IGb00 sites with estimates obtained by us for the official JPL and SIO position time series.

Helmert transformation

The parameters for this seven-parameter Helmert transformation were based on all IGb00 sites for which we were able to obtain data and for which the residuals after the transformation satisfied a threshold of 15 mm in the horizontal and 30 mm in the vertical component.

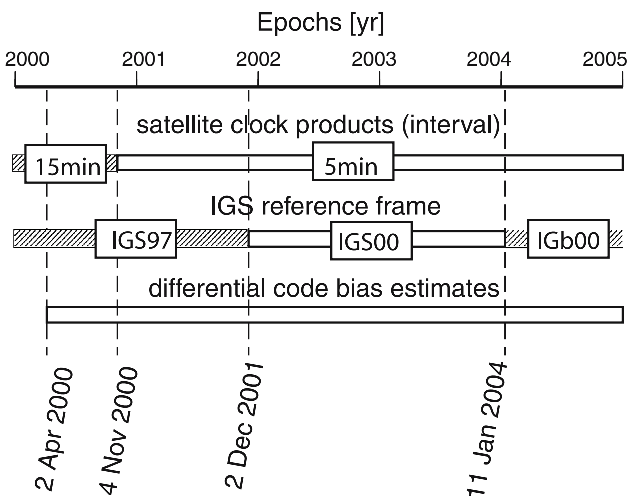

Fig. 1 Evolution of GPS products used in our analysis during 2000-2005. Reference frames of the IGS final products changed from IGS97 to IGS00 on 2 December 2001 and from IGS00 to IGb00 on 11 January 2004; satellite clock estimates from the orbit product at 15 min intervals up to 4 November 2000 and at 5 min intervals from the new clock product thereafter; satellite-dependent differential code bias estimates were available from 2 April 2000 onwards

As outlined above, for the period from 25 May 2003 onwards, it is possible to compare the time series of our transformation parameters with those produced by the IGS ACC.

Figure 2 shows the time series of the estimated transformation parameters from our BSW PPP processing and those from the IGS ACC. Considering only the time series of transformation parameters from BSW PPP, then the most dominant feature is the discontinuity at the change of the reference frame of the IGS products on 2 December 2001. There is evidence of a reduction in the day-to-day scatter of the transformation parameters over the period from 2000 to 2005 and of a significant change in the scale factor, which has been estimated to be 0.54 ppb/year. As Ge et al. (2005) and Schmid et al. (2005) pointed out, this effect is largely due to the incorrect modelling of both satellite and receiver antenna phase centres in a changing GPS satellite constellation. In comparison, both translation and rotation parameter estimates are fairly stable over this period.

When considering the transformation parameter time series from BSW PPP and the IGS ACC together, then Fig. 2 clearly demonstrates the similarities found in these for the overlap in 2003 and 2004. Many features in one time series can easily be identified in the other, and especially the translation and rotation parameters of the X and Y components and the scale follow each other very closely. Both translation and rotation of the Z component are slightly more varied. Interestingly, the rate of change of the scale parameter of the IGS ACC confirms the change observed for the scale parameter from BSW PPP.

Besides the different softwares used to compute the PPP solutions for the IGb00 sites and the following Helmert transformation, the small differences in the transformation parameters shown in Fig. 2 are most likely due to different outlier criteria during the computation of the Helmert parameters, resulting in different sets of IGb00 sites used by us and the IGS ACC, and position differences in the epochal ITRF2000 and the IGS weekly combined solution for the IGb00 sites.

Position time series

We obtained our UNT position time series from the daily BSW PPP solutions after their transformation into ITRF2000. Figure 3 shows the position time series for WTZR, as an example.

The figure demonstrates the millimetre level precision in daily position estimates achievable with BSW PPP. Considering the UNT time series for all IGb00 sites, we computed median RMS statistics for the north (N), east (E) and up (U) components to be 3.0, 4.9 and 7.7 mm, which are fairly comparable to those of the time series of JPL (2.7, 3.7 and 8.0 mm) and SIO (2.3, 3.2 and 6.7 mm).

In the horizontal components of our UNT time series, we observed signals with dominantly annual and semi-annual periods, with similar magnitudes in both these frequencies and the effect being more pronounced for the E than for the N component (as visible in Fig. 3). Although different geophysical loading processes and residual signals from mis-modelling of systematic biases have been shown to manifest themselves as periodic variations at these frequencies in GPS position time series (Penna and Stewart 2003; Stewart et al. 2005), these generally dominate in the U component and have smaller amplitudes for the semi-annual than for the annual signals. Furthermore, as PPP heavily relies on the accuracy and homogeneity of the GPS products, we argue that a large portion of the observed periodic variations in the horizontal components of our UNT time series is a consequence of using the current IGS final products. This can be demonstrated using Fig. 4, which shows the effect of using either the IGS final or the CODE final products on the daily BSW PPP solutions before the Helmert transformation is applied.

Clearly visible in the N and E component time series is the effect of the change of the reference frame of the CODE final clock products on 5 September 2002. Since

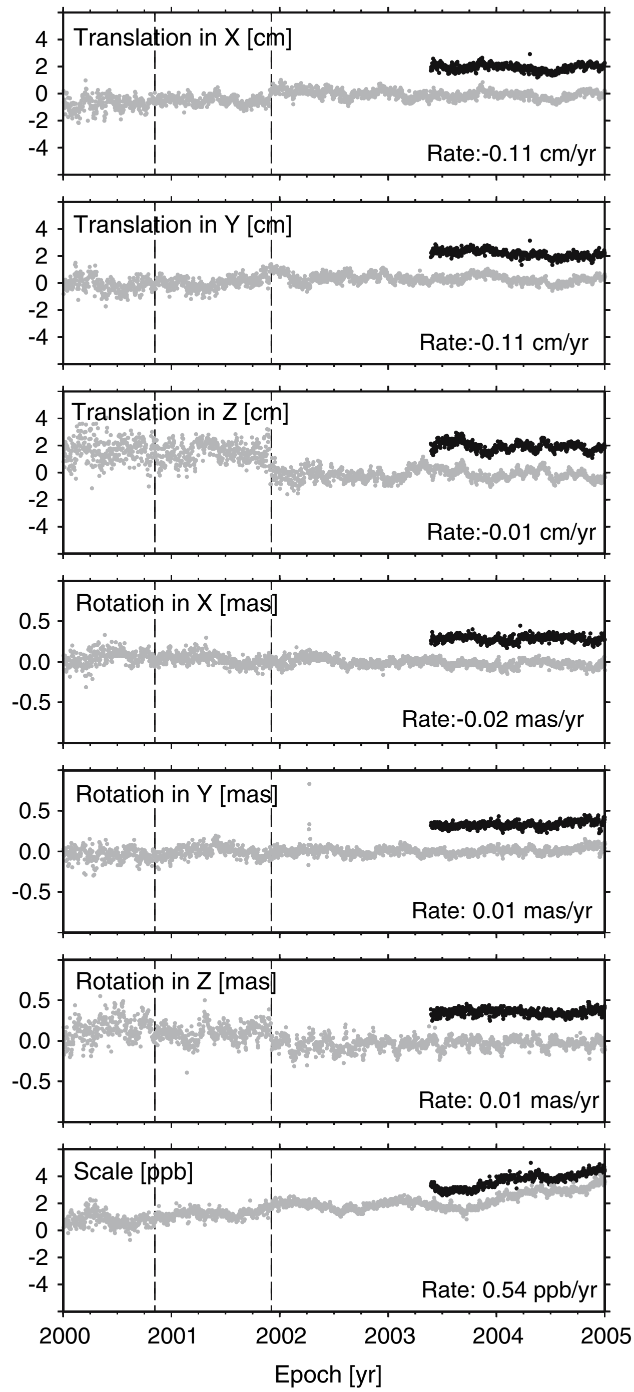

Fig. 2 Time series of Helmert transformation parameters from this analysis (*grey*) for the period of 1 January 2000 to 31 December 2004 compared with those of the IGS analysis centre coordinator (*black*) for the period of 25 May 2003 to 31 December 2004. The latter have been offset for clarity. The *vertical lines* indicate the introduction of the clock products on 4 November 2000 and the change in the reference frame of the IGS final products on 2 December 2001

then, the CODE final clock product is consistent with the International Terrestrial Reference Frame (ITRF), i.e. using the CODE final clock product gives PPP

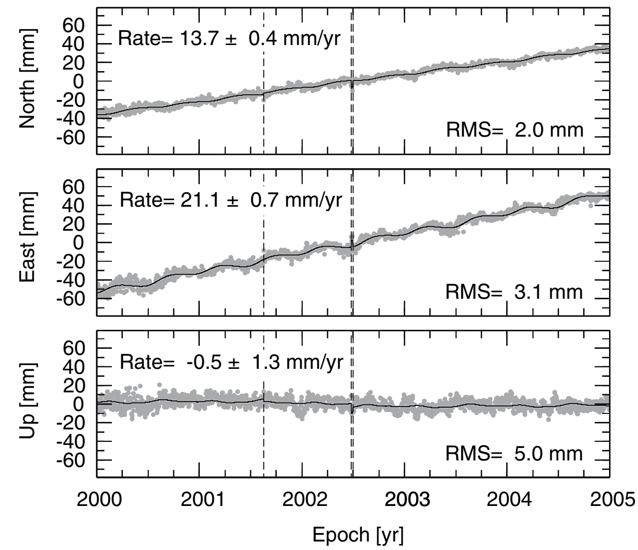

Fig. 3 Position time series for WTZR obtained from BSW PPP using IGS final products and a Helmert transformation into ITRF2000. Also shown are the root-mean-square (RMS) statistic and the site velocity (*rate*) with the associated uncertainty accounting for white and coloured noise. The *vertical lines* indicate epochs of reported receiver and/or antenna changes

solutions in ITRF. Prior to this date, the CODE final clock product followed a geocentric reference frame, which is also the case for the early IGS final clock product. Also visible are the variations and discontinuities in the time series based on the IGS final products, which are believed to be largely a result of inhomogeneities in the IGS final clock product. Currently, this clock product is a combination of IGS AC clock products of which the majority are consistent with ITRF; however, the products from two ACs are still in a geocentric reference frame (see Gendt and Kouba 2006).

Nevertheless, although this inconsistency within the IGS final products is not satisfactory, we will show that their effect on determining global site velocities is manageable, assuming a sufficient time span and in the context of using BSW PPP for this purpose.

Daily position comparison

In order to obtain information on the accuracy of our BSW PPP derived UNT time series, we compared these with the official JPL and SIO time series. The JPL time series are also based on transformed daily PPP solutions, whereas the SIO time series are based on daily, global DD network solutions (Prawirodirdjo and Bock 2004). Taking their reference cartesian positions and their daily N, E and U component time series for the 5 years' time span, we re-constructed

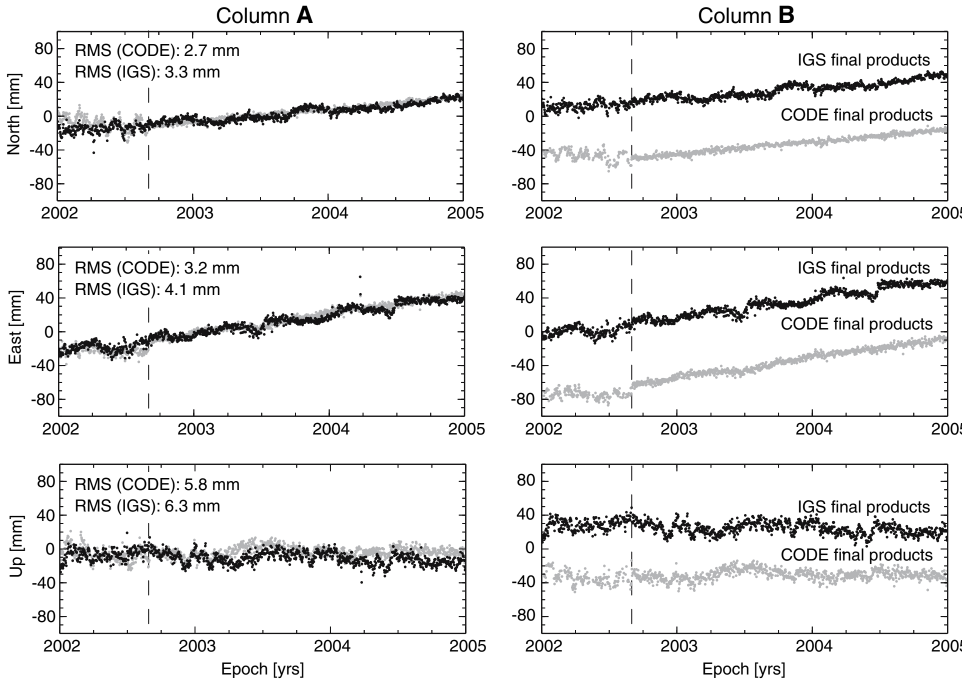

Fig. 4 Effect of GPS products on daily PPP solutions (no Helmert transformation) for WTZR (example) using the BSW PPP strategy. The figure includes the north, east and up time series based on IGS final (*black*) and CODE final (*grey*) products for the period 2002–2005 and states the associated RMS statistics. *Column A* gives an indication of the overall level of agreement in the absolute position solutions and temporal evolution of these, whereas in *Column B* the position time series have been arbitrarily offset from each other for a better appreciation of the different characteristics of the series. The *dashed vertical lines* indicate the change of the reference frame of the CODE final clock products on 5 September 2002

their daily cartesian positions, computed the cartesian position differences by subtracting the daily estimates for UNT from JPL and SIO, and for SIO from JPL, and then converted these cartesian position differences back into topocentric components. Figure 5 shows the distribution of more than 100,000 daily position differences for the N, E and U components for all IGb00 sites. Considering the issues related to the inhomogeneities in the GPS products from which the BSW PPP solutions suffer, the agreements in the daily position estimates among JPL, SIO and UNT are impressive. Only the N and U components in the comparison between JPL and UNT show mean values larger than 1 mm, indicating that the UNT time series contain slightly lower N and U components than the JPL time series. All mean position differences between the SIO and UNT time series are negligible at the tenth of a millimetre level. In all comparisons, the SD are smallest for the N component and increase for the E and U components.

Site velocity and noise comparison

Investigations into geophysical processes, such as plate tectonics and post-glacial rebound, require accurate long-term estimates of station motions, i.e. site velocities, with realistic error bounds. These velocity estimates are commonly obtained by fitting a more or less elaborate model in a least-squares sense to position time series. In our analysis, we composed the model of an initial position, a constant velocity, offset magnitudes for epochs with known/unknown discontinuities, and the parameters for an annual, a semi-annual and a 13.66-day (Penna and Stewart 2003) periodic signal. In order to obtain the realistic uncertainties associated with these parameter estimates, we carried out an MLE, assuming a combination of white and coloured (flicker) noise (e.g. Zhang et al. 1997; Williams 2003; Williams et al. 2004) for all JPL, SIO and UNT time series, as Williams et al. (2004) already showed that this model is most appropriate for the global JPL and SIO time series.

We used our velocity estimates from the MLE for the IGb00 sites for the JPL, SIO and UNT time series to compute the velocity differences by subtracting those for UNT from JPL and SIO, and those for SIO from JPL. Figure 6 shows the distribution of these velocity differences, clearly indicating the overall equivalence of the site velocities and demonstrating the ability to obtain these on a global

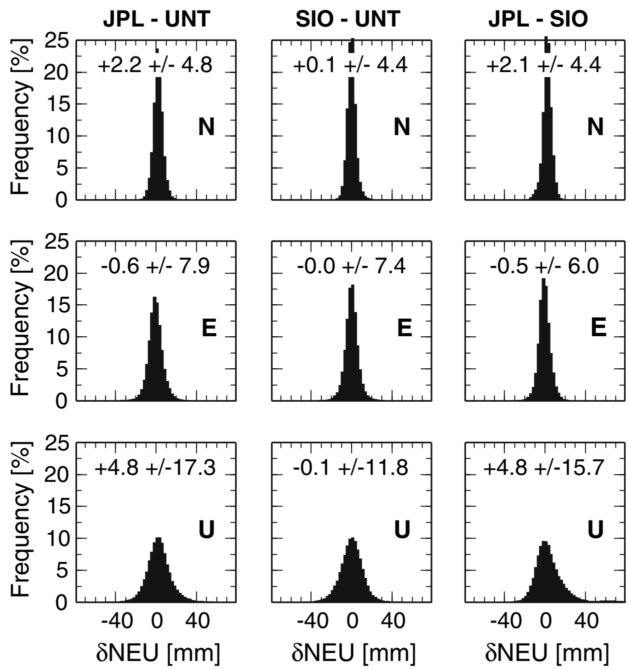

Fig. 5 Distribution of north (*N*), east (*E*) and up (*U*) daily position differences (*δNEU*) for IGb00 sites computed between time series of JPL and UNT, SIO and UNT, and JPL and SIO. The mean position differences and the associated standard deviations are show in mm

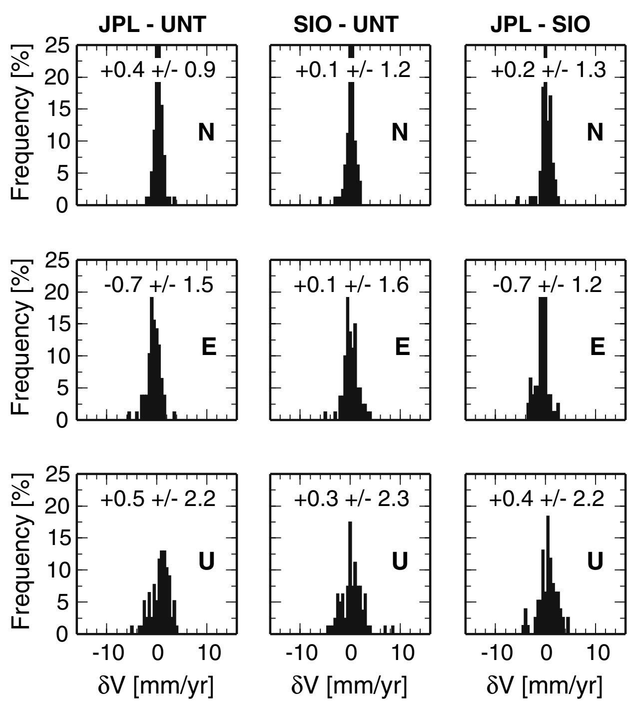

Fig. 6 Distribution of north (*N*), east (*E*) and up (*U*) velocity differences (*δV*) for IGb00 sites computed between the time series of JPL and UNT, SIO and UNT, and JPL and SIO. The mean velocity differences and the associated SD are shown in mm/year

scale using BSW PPP. For all comparisons and components, the mean velocity differences are at the sub-millimetre level and the associated standard deviations for the N, E and U components are 0.9, 1.5 and 2.2 mm/year for comparison with JPL and 1.2, 1.6 and 2.3 mm/year for comparison with SIO.

Considering the different number of sites and the different time span used in our analysis, our median JPL and SIO specific white and flicker noise amplitudes (Table 1) compare well with those in Williams et al. (2004). We therefore have much confidence in the noise estimates obtained for our UNT time series, giving fairly equivalent magnitudes for white and flicker noise in the N and E components as for the JPL and SIO time series, but larger magnitudes in the U component. The importance of these findings lies in the effect of the noise on the velocity uncertainties and thus the time series length needed to obtain site velocity estimates with a required uncertainty. Using our JPL, SIO and UNT noise estimates we compute, applying the theory of Williams (2003), that in order to achieve an uncertainty of less than 0.5 mm/year, the UNT time series need to be, for the N, E and U components, respectively, on average 0.9, 1.3 and 1.3 times longer than JPL, and 1.2, 1.3 and 1.3 times longer than SIO. We also demonstrate this in Fig. 7, showing the evolution of the velocity uncertainty σ_r for the N, E and U components for the JPL, SIO and UNT noise levels over time.

Without reprocessing of the complete IGb00 network using CODE final products in order to compute a new set of parameters for the Helmert transformation of the daily PPP solutions into ITRF2000, it is difficult to assess the impact of using CODE final products on the noise estimates for our UNT time series and to give an estimate of the position time series length required to obtain an uncertainty of less than 0.5 mm/year. However, a noise analysis of the untransformed PPP position time series for WTZR based on CODE final products for the period between 5 September 2002 and 31 December 2005 (Fig. 4) gives similar noise estimates as for the current UNT time series for WTZR. Assuming that the following Helmert transformation using the recomputed parameters would further reduce the amount of noise in the position time series, then this would indicate that the currently higher noise level of these, when compared to JPL and SIO, can be attributed to the use of IGS final products and not BSW PPP. We would then expect to see a reduction in the position time series length required to obtain an uncertainty of less than 0.5 mm/year.

Table 1 Median white and coloured (flicker) noise amplitudes for the north (N), east (E) and up (U) components for IGb00 sites for the JPL, SIO and the UNT time series

Time series	N Component		E Component		U Component	
	A	*b*	*a*	*b*	*a*	*b*
JPL	1.9	2.8	5.5	5.7	7.0	17.0
SIO	1.3	2.0	3.4	5.6	6.8	17.4
UNT	1.4	2.5	4.1	7.6	12.4	22.0

White noise amplitudes *a* are in mm and the flicker noise amplitudes *b* are in mm year$^{-1/4}$

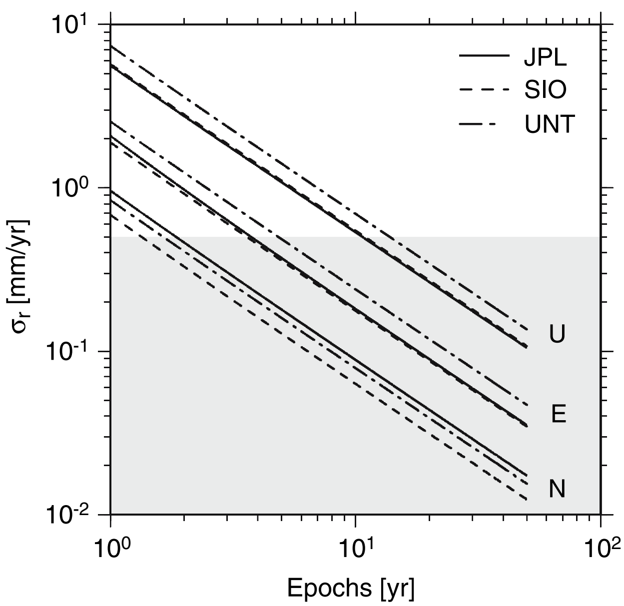

Fig. 7 Log-log plot of the time evolution of the site velocity uncertainty σ_r for the north (*N*), east (*E*) and up (*U*) components of the JPL, SIO and UNT median noise levels (Table 1). *Shading* indicates area with $\sigma_r \leq 0.5$ mm/year

Conclusions

We have assessed BSW PPP using IGS final products for computing global site velocities over a 5-year period (2000–2005). We obtained site positions in ITRF2000 on a site-per-site basis without the need for large GPS network analyses using double differencing, and demonstrated that by transforming the individual daily PPP solutions, using a Helmert transformation for which we have estimated parameters using the IGb00 sites, globally referenced position time series, comparable to those of JPL and SIO, can be formed.

A comparison of our transformation parameters with those from the IGS ACC for a limited period demonstrates their similarities and confirms the potential for BSW PPP to give highly accurate position solutions. We showed millimetre-to-centimetre level agreements in daily position estimates for IGb00 sites between our UNT time series and those from JPL and SIO, and sub-millimetre mean velocity differences for IGb00 sites with standard deviations for the N, E and U components of 0.9, 1.5 and 2.2 mm/year between UNT and JPL and 1.2, 1.6 and 2.3 mm/year between UNT and SIO. A noise analysis of the time series indicates that our UNT N, E and U component time series need to be on average up to 1.3 times longer than those from JPL and SIO in order to obtain velocity uncertainties of less than 0.5 mm/year.

Although these results are very encouraging, they also highlight the limitations in using the current IGS final products for PPP. As satellite and station dependent biases are not canceled by differencing, PPP at the several-millimetre level is strongly dependent on the availability of highly accurate models for systematic biases, the consistency of these models between the GPS software packages and on consistent and homogeneous GPS products, over the short to longer terms. We believe that the PPP technique will benefit from the consistent set of GPS products of the planned re-analysis of the IGS tracking network, as has already been demonstrated by Steigenberger et al. (2006), and see BSW PPP as a valuable tool not only for global site velocities but also for quality monitoring applications within the IGS.

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