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ORIGINAL ARTICLE

Quality assessment of GPS reprocessed terrestrial reference frame

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Abstract The International GNSS Service (IGS) contributes to the construction of the International Terrestrial Reference Frame (ITRF) by submitting time series of station positions and Earth Rotation Parameters (ERP). For the first time, its submission to the ITRF2008 construction is based on a combination of entirely reprocessed GPS solutions delivered by 11 Analysis Centers (ACs). We analyze the IGS submission and four of the individual AC contributions in terms of the GNSS frame origin and scale, station position repeatability and time series seasonal variations. We show here that the GPS Terrestrial Reference Frame (TRF) origin is consistent with Satellite laser Ranging (SLR) at the centimeter level with a drift lower than 1 mm/year. Although the scale drift compared to Very Long baseline Interferometry (VLBI) and SLR mean scale is smaller than 0.4 mm/year, we think that it would be premature to use that information in the ITRF scale definition due to its strong dependence on the GPS satellite and ground antenna phase center variations. The new position time series also show a better repeatability compared to past IGS combined products and their annual variations are shown to be more consistent with loading models. The comparison of GPS station positions and velocities to those of VLBI via local ties in co-located sites demonstrates that the IGS reprocessed solution submitted to the ITRF2008 is more reliable and precise than any of the past submissions. However, we show that some of the remaining inconsistencies between GPS and VLBI positioning may be caused by uncalibrated GNSS radomes.

Keywords GNSS · Terrestrial reference frames · Loading · Geocenter motion · Systematic errors

Introduction

The study of the solid earth and its surface deformations requires an accurate and stable Terrestrial Reference Frame (TRF). Its properties are specified by the definition of the Terrestrial Reference System (TRS) for which the TRF is a numerical materialization. The TRS that is recommended for earth science applications is the International Terrestrial Reference System (ITRS). Its corresponding frames, named International Terrestrial Reference Frames (ITRFs) are supplied and updated regularly by the International Earth Rotation and Reference Systems Service (IERS). The next available realization will be the ITRF2008, which will supersede the previous ITRF2005 (Altamimi et al. 2007). Indeed, ITRFs are updated regularly to account for new stations and include more data and improved modeling and processing schemes. The ITRF regularized coordinates are treated as piece-wise linear functions of time, which mostly account for tectonic motions but also for rapid events, such as earthquakes, using discrete discontinuities. In order to be

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able to study environmental mass redistributions it is essential that the ITRF conserves its definition over time. This means, for instance, that over decades, the ITRF2008 axes originate from the time-averaged center of mass of the earth (CM). This property is essential to accurately estimate, for instance, the sea level rise and its regional and global variability (Morel and Willis 2005; Beckley et al. 2007).

ITRF solutions are constructed using results from GNSS techniques, Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Doppler Orbitography Integrated by Satellite (DORIS). The International GNSS Service (IGS) is responsible for supplying GPS input data for the ITRF processing (Ferland and Piraszewski 2008; Dow et al. 2009). Up to ITRF2005, the IGS processed GPS data routinely as soon as the data were available using the best available modeling of the time. This procedure delivered products that were not homogenous over time, making the interpretation of trends quite difficult. For the first time, IGS has conducted a campaign to reprocess all the GPS data from 1994 on (though only results from 1997 are used here), involving the contribution of 10 independent groups (see http://acc.igs.org/reprocess.html). Updated standards have been used, including an advanced modeling of the tropospheric delay using the GMF/GPT model (Boehm et al. 2006, 2007), the adoption of a homogenous reference frame and the use of absolute antenna phase center offsets (APCO) and variations (APCV) (Schmid et al. 2007).

Several studies have demonstrated the benefit of homogeneously reprocessing GPS data for the TRF accuracy. Steigenberger et al. (2006) reprocessed 11 years of GPS data and showed a reduction of the position repeatability and subsequent improvement of the TRF in terms of origin and scale. Rülke et al. (2008) have specifically studied the temporal evolution of the origin and scale of the GPS TRF and concluded that GPS was now mature enough to constrain ITRF origin and scale (scale drift only). However, their analysis was based on the results obtained with one software package only. Concerning position time series, two recent papers highlighted their improvement by demonstrating an improved agreement between GPS and VLBI annual variations (Tesmer et al. 2009) and a reduction in the noise power of the time series (Wöppelmann et al. 2009).

We assess the GPS TRF contribution to ITRF2008. The ability of the GPS technique to sense the TRF origin and scale will also be revisited here and the spectral content of position time series and scale will be analyzed in more details. The first Section describes the data that we have analyzed, which include GPS solutions and a loading model. We have then evaluated the GPS frame origin and scale performance by investigating the net translation and the scale factor of the weekly station positions with respect to ITRF2008 preliminary combination. Reprocessed GPS position time series contain strong periodic signatures, which have already been reported in the past and that will be thoroughly detailed in the following section, including an assessment of the annual frequency. Finally, the accuracy of GPS long term station positions and velocities will be assessed using the VLBI contribution to ITRF2008 supplied by the International VLBI Service (IVS; Böckmann et al. 2009; Schlüter and Behrend 2007).

Analyzed data

The network of GPS permanent stations is the largest among the four techniques contributing to the ITRF. Each AC involved in the IGS reprocessing campaign processes raw GPS observations of some core stations selected for their data collection history, their location and data quality. However, each contributor is free to include the GPS stations he is interested in so that each AC processes a different network. By convention, station positions and ERPs are estimated daily by the ACs, together with other parameters not considered here. The daily solutions are then properly averaged to form weekly positions and daily ERPs as well as their full variance–covariance matrices, each AC supplying such data sets for its own network.

Eleven ACs have contributed to the reprocessing of GPS data since 1994, but only submitted data for ITRF2008 since 1997. Their products have been combined by the IGS reference frame coordinator. The coordinator supplies a unique position per station per week in a GPS-only frame, which is consistent with ITRF2005 and is named IGS05. During this combination process, the estimated station positions are carefully checked for errors, i.e. discontinuities are detected and spurious data are eliminated, so that the estimated combined position set is more reliable than any of the individual submission (Ferland and Piraszewski 2008). The solution obtained is named IG1 (Table 1). Up to 561 stations are included for more than 12 years of data. Table 1 also describes the GPS solution that was supplied for the ITRF2005 processing, which will be compared to the newly reprocessed solution.

The GPS satellite positioning technique is theoretically capable of estimating station coordinates with respect to the CM. It is possible to verify that fact by investigating the net translation of the network with respect to an external reference frame, which is assumed to have its origin at CM. However, the IG1 combined solution has been explicitly transformed to ITRF2005 which means that the inherent origin information of the TRF has been modified. As discussed by Ferland and Piraszewski (2008), translations and scale parameters are available as outputs of the combination but they rely on IGS05 that has not been updated since 2006.0. As a consequence, we chose to re-estimate them rigorously based on an updated TRF. We investigate four

Table 1 Solutions that are analyzed in this study

AC	Id	Epoch	No of stations	Data	Strategy
IGS	ITRF2005	1996.0–2006.0	303	GPS	Combined
IGS	IG1	1997.0–2009.5	561	GPS/GLONASS	Combined
GFZ	GF1	1998.0–2008.0	248	GPS	Undifferenced
ESA	ES1	1997.0–2009.0	358	GPS/GLONASS	Undifferenced
COD	CO1	1997.0–2009.0	224	GPS	Double differenced
MIT	MI1	1998.0–2008.0	748	GPS	Double differenced
IVS	IVS	1980.0–2009.0	24 co-located	VLBI	Combined

of the individual solutions that were used to form the combined IG1. The solutions CO1, ES1, GF1 and MI1 have been adopted and are described in Table 1.

Two non-GPS products have been used to supply comparative information on the data quality. Since GPS stations monitor the ground deformations due to the redistribution of masses in the earth's fluid envelopes, the GPS coordinate variations will be compared to a loading model first. This model is similar to the one of Collilieux et al. (2009) in that it accounts for the atmosphere, hydrological and non-tidal ocean loading effects and consists of displacement time series at GPS station locations, but differs by the hydrology contribution. The weekly water storage estimates are interpolated monthly Global Land Data Assimilation System model output (Rodell et al. 2004). Other mass data have been supplied by NCEP and ECCO models, at a sampling rate of 6 and 12 h, respectively. These surface masses have been convolved with Green's functions derived for an elastic earth model. The 6-h atmospheric loading results and the 12-h ocean bottom pressure results are then averaged to form weekly displacement time series. Although displacements can reach up to 1 cm at the seasonal time-scale, the secular displacements related to loading effects are rather small. We considered here loading model displacements in the Center of Figure (CF) frame since they do not contain any net-translation component. We adopt, as a second independent data set, VLBI position time series supplied by the IVS. About 24 stations are co-located with GPS stations so that GPS reference positions and velocities can be controlled for those sites. Like GPS, the VLBI contribution is also the result of a combination and has been built using the most updated standards (Böckmann et al. 2009).

In the next section the GPS origin and scale information will be investigated, and the possibility of using GPS to constrain contributions to the origin and scale of the ITRF will be discussed.

GPS terrestrial reference frame origin and scale

A common way to evaluate origin and scale information of a TRF is to compute the coordinate differences of some stations with respect to an external coordinate dataset, such as an ITRF solution. This operation is usually realized sequentially by computing translation, rotation and scale parameters between the set of weekly station positions and the ITRF coordinates of the epoch. This approach is reliable except when the considered epoch exceeds the time span of geodetic data used to compute the chosen ITRF. In this case, the number of available stations for the comparison also decreases due to network changes resulting from decommissioning of stations and due to the large number of new offsets that are detected in station position time series but not modeled in the ITRF. In order to overcome these issues, a practical alternative consists of estimating a new set of reference positions and velocities for all stations in a well-defined TRF for the whole period. We applied that method to compute GPS station positions and velocities in an ITRF2008 preliminary solution, hereafter referred to as ITRF2008P, by estimating simultaneously a set of translation, rotation and scale parameters for each week. The details of this strategy are described in Altamimi et al. (2007). Translation and scale time series are investigated in the next two sections.

GPS origin

Due to the design of the SLR geodetic satellites and the precision of the laser range measurements, a TRF estimated with SLR data can be accurately tied to the earth CM. For that reason, the ITRF2008P origin has been defined using this technique as it was done for ITRF2000 and ITRF2005 (Altamimi et al. 2002, 2007). In the combination strategy of the latest ITRFs, only SLR origin information was conserved so that GPS, DORIS, and VLBI station coordinates in these realizations also refer to the SLR CM. As a consequence, the net-translations of GPS frames with respect to ITRF2008P can be considered as the motion of the GPS CM estimation with respect to the SLR time-averaged CM.

An independent secular reference frame rigorously expressed in the ITRF2008P has been estimated for each of the four individual AC GPS reprocessed solutions presented in Table 1. The constraint used to define the frame has to be applied on a subset of station coordinates since the adopted core network has an impact on the origin and scale of the realized frame. This core network is composed of stations having long data history, few discontinuities and high position repeatability in order to increase the robustness. It was not possible to find the same core network for all four ACs with those criteria so that an optimal core network has been designed for each AC. Figure 1 shows the translation and scale time series of CO1, ES1, GF1 and MI1 weekly frames with respect to ITRF2008P along the X, Y and Z directions. The four AC translation time series presented in Fig. 1 are similar in shape although minor differences can be observed. Generally, similar biases are observed with respect to SLR. Table 2 reports the offsets and trends of the four solutions computed at the epoch 2000.0. Differences of up to 13 mm compared to SLR can be observed in the offsets depending on the AC. Clear biases of about −4 mm in Y and −11 mm in Z are detected at the epoch 2000.0 for all the ACs. Although some of them show almost no trend in the X and Y components, all ACs supply a different trend in the Z component, from 0.3 to 0.7 mm/year. Some part of the observed differences among ACs may be related to the adoption of different core networks but we could not find a subset of stations that could improve the fit. A sensitivity of about 0.1–0.2 mm/year has been noticed when changing the core network. The different GPS data analysis strategies may explain most of the differences since the origin component is especially sensitive to any satellite orbit modeling deficiencies. Here, it seems that clear systematic differences in offsets and drifts can be observed with respect to SLR, especially in the Y and Z component.

The nonlinear variations of GPS translations are also a valuable source of information. Indeed, the CM is expected to move with respect to the earth's crust due to the redistribution of masses in the earth. The entire earth's crust is commonly symbolized by its geometrical center, CF, so that the CM relative to CF motion is called geocenter motion (GMO). A geodetic network samples the earth surface at a small number of locations, but if the network is

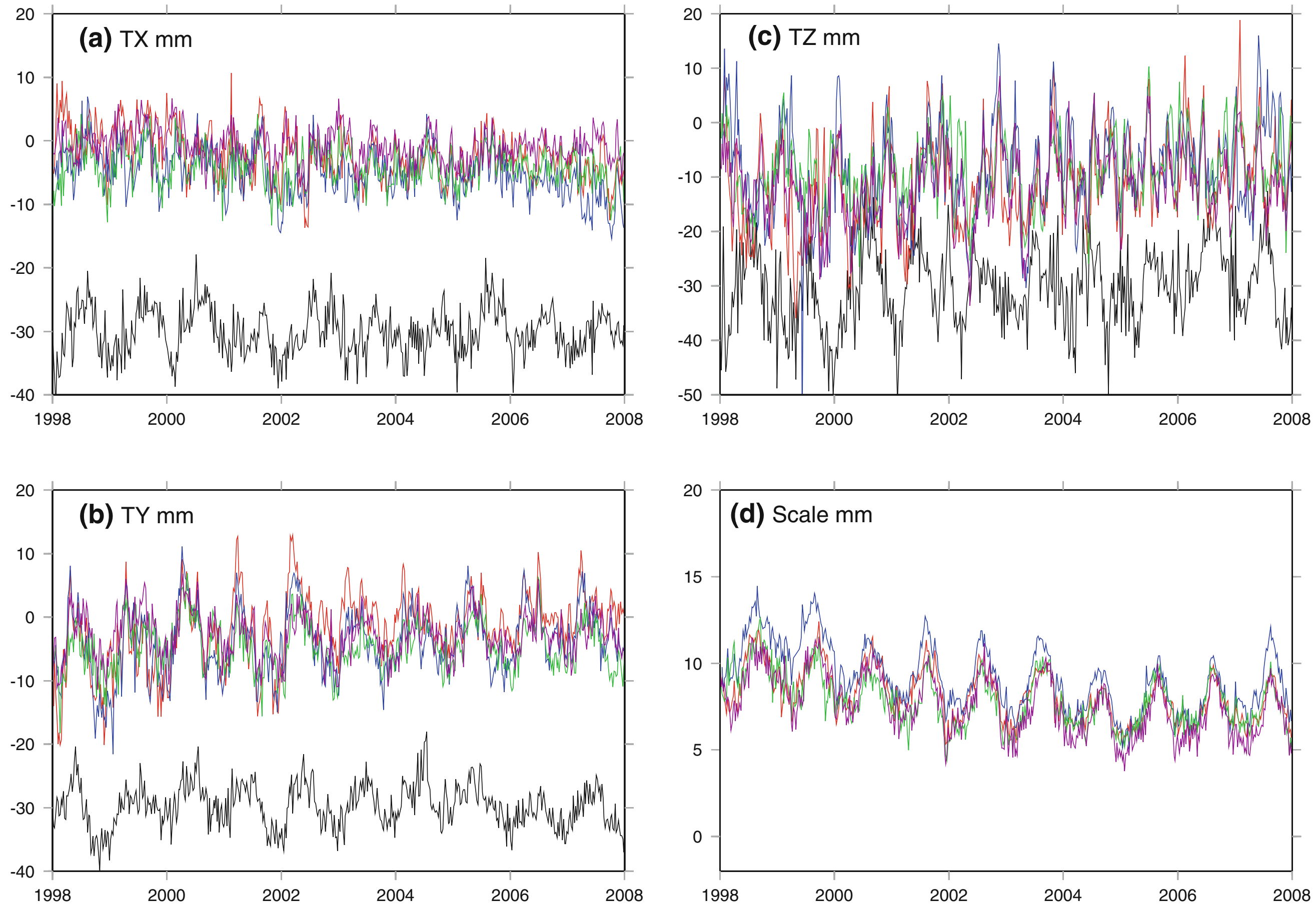

Fig. 1 **a–c** GPS AC translation (TX, TY, TZ along X, Y, Z, respectively) and scale parameters with respect to ITRF2008P: MI1 (*red*), GF1 (*blue*), CO1 (*green*), ES1 (*purple*). **d** Scale factors are supplied in millimeters according to a conversion factor of 6.4 mm for 1 ppb. SLR translations variations (ILRS solution submitted for ITRF2008) have been superimposed in *black* and shifted by −30 mm for clarity

Table 2 Offsets (at epoch 2000.0) and drifts of GPS AC translations and scale factors with respect to ITRF2008P

	AC	TX	TY	TZ	Scale
Offset (mm)	GF1	−3.4 ± 0.2	−5.3 ± 0.2	−10.3 ± 0.5	10.2 ± 0.1
	ES1	−0.2 ± 0.2	−2.8 ± 0.2	−12.8 ± 0.4	8.5 ± 0.1
	CO1	−3.7 ± 0.2	−4.8 ± 0.2	−10.1 ± 0.4	8.6 ± 0.1
	MI1	−0.4 ± 0.2	−4.6 ± 0.3	−13.5 ± 0.5	9.0 ± 0.1
Drift (mm/year)	GF1	−0.5 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	−0.4 ± 0.1
	ES1	−0.2 ± 0.1	−0.0 ± 0.1	0.5 ± 0.1	−0.3 ± 0.1
	CO1	−0.1 ± 0.1	−0.1 ± 0.1	0.3 ± 0.1	−0.2 ± 0.1
	MI1	−0.6 ± 0.1	0.9 ± 0.1	0.7 ± 0.1	−0.3 ± 0.1

Table 3 Annual signal in GPS translations

	AC	TX	TY	TZ
Amplitude (mm)	GF1	1.8 ± 0.2	5.4 ± 0.2	3.6 ± 0.5
	ES1	0.1 ± 0.2	3.2 ± 0.2	1.8 ± 0.4
	CO1	1.1 ± 0.2	3.3 ± 0.2	3.1 ± 0.4
	MI1	0.3 ± 0.2	4.1 ± 0.3	3.5 ± 0.5
	Loading	2.1 ± 0.1	2.1 ± 0.1	2.7 ± 0.1
	SLR + GPS	2.5 ± 0.4	3.2 ± 0.3	3.4 ± 0.5
Phase (degree)	GF1	214 ± 6	120 ± 2	329 ± 8
	ES1	262 ± 77	154 ± 3	337 ± 12
	CO1	178 ± 9	141 ± 3	351 ± 7
	MI1	263 ± 41	125 ± 4	307 ± 8
	Loading	208 ± 2	158 ± 2	228 ± 2
	SLR + GPS	199 ± 8	147 ± 6	197 ± 8

Loading and SLR + GPS values are taken from Collilieux et al. (2009)

well distributed and sufficiently extended, the geometric center of the network, called Center of Network (CN), can approximate the CF. The detrended translations, as detailed above, undergo the same nonlinear variations as the CN relative to CM. The theoretical difference between CN-CM and CF-CM variations has been demonstrated to be smaller than 0.2 mm in X and Y and 0.3 mm in Z RMS for a global GPS network (Collilieux 2008, 2009). Thus, as GPS is theoretically sensitive to CM, GPS translation variations should mostly reflect GMO. Table 3 shows the annual signals that have been estimated in the four GPS solutions. For comparison, two GMO estimations taken from Collilieux et al. (2009) are also included. The first is derived from a loading model that differs from the one used in this paper by the hydrology contribution and the second from a combination of GPS station displacements and SLR frames. It is worth recalling that GPS is only used in this combination to mitigate aliasing effects related to the SLR network distribution. The two external estimates show agreement to better than 1 month in phase and to one millimeter in amplitude, which demonstrates that SLR estimation of GMO is reliable. Larger discrepancies with the GPS ACs are visible, especially for the X component amplitude and the Z component phase. Overall CO1 equatorial component seems to agree best with SLR and the loading model at the annual frequency. All the techniques show similar amplitude within 1 mm, and phase within 1 month in the Y component, except the GF1 amplitude, which shows that the Y component is the best determined and the most consistent with SLR. The largest discrepancies are visible for the Z component phase, where a shift of more than 3 months is seen in all the GPS estimates.

The analysis of the four reprocessed GPS solutions allows us to conclude that the annual variations in the GPS frame origin are not yet as reliable as SLR although the orders of magnitude of the amplitudes of the annual signals are correct. At longer time-scale, we demonstrated that GPS reprocessed frame origins are significantly different from SLR, especially in the Y (offset) and Z components (offset and drift). The reason for this is not yet clear. It has been shown that not applying higher order ionospheric corrections affects GPS origin time evolution in the Z component (Petrie et al. 2010) depending on the time window of the GPS data used. However, as we observe differences between the AC translations, satellite orbit modeling deficiencies (Urschl et al. 2007) could also be a candidate to explain our results.

As a consequence, it would be premature to use GPS to contribute to the ITRF origin definition, especially if significant discrepancies are visible between different GPS observation strategies. Complementary analyses need to be conducted, especially to understand the nonlinear behavior of the GPS translations.

GPS scale

The GPS technique is theoretically sensitive to the frame scale since the phase measurements can be converted to distances. However, the satellite APCO and APCV are not strictly known so that the distance measurements do not refer to well known points in space. Progress was made to calibrate receiver antennas on the ground (Schmid et al. 2007) but the calibration of satellite APCOs is still dependent on the adopted ITRF scale (Zhu et al. 2003). Indeed, it is necessary to fix the TRF scale to properly estimate the APCOs. The satellite calibrations used to process the GPS solutions analyzed here are consistent with the ITRF2000 scale at the epoch 2000.0 (Schmid et al. 2007). The ITRF2008P scale that is used as a reference in this section has been defined as the weighted averaged scale supplied by VLBI and SLR techniques. It differs from the ITRF2005 scale by 1.1 ± 0.1 ppb at the epoch 2000.0. Firstly, this scale offset between the two ITRF solutions is explained by a different handling of the mean pole tide correction in the two submitted VLBI solutions (ITRF2005 and ITRF2008) which led to a scale difference of 0.5 ppb (Böckmann et al. 2009). Secondly, the SLR and VLBI submitted solutions agree within 1 ppb so that the remaining scale difference is within the uncertainty of the current absolute scale determination.

The GPS scale offsets for each AC solution are reported in Table 2 with respect to ITRF2008P. We notice a large scale offset at the epoch 2000.0 between 1.3 and 1.6 ppb. This figure could be rather well explained by the ITRF2008P and ITRF2000 scale difference which is 1.5 ppb. Figure 1 shows the scale factor time series in millimeters, i.e. the ppb value is scaled by 6.4. The scale trends fluctuate between −0.2 and −0.4 mm/year depending on the AC. Although the trend is significant, the scale long-term behavior is not strictly linear since the scale factors seem to stabilize from 2002 onward. As this pattern is visible for all four AC solutions, the network distribution is probably not responsible for this behavior. Ge et al. (2005) have already reported such scale changes related to the satellite constellation changes. It might be possible that the IGS calibrated APCOs are not yet optimal but this needs to be demonstrated. Moreover, assuring stability of GPS scale is challenging since any new GNSS satellites need APCOs that are calibrated so that both scale offset and drift rely on the knowledge of an a priori reference frame scale.

The clear seasonal pattern observed in the GPS scale parameter is still unexplained although some authors suspected that crustal motion signals could alias into the scale parameter (Blewitt and Lavallée 2000, Lavallée et al. 2006). Indeed, the deformations of the network polyhedron caused by loading cannot be related to the secular reference frame by a simple similarity transformation since the adjusted secular frame does not model such nonlinear variations. We have used the same strategy introduced by Collilieux et al. (2009) to compute a model of the contribution of loading displacements to GPS scale. In order to have comparable scale models between the various ACs, we have restricted the GPS network of each AC to the available IGS05 core stations (Ferland 2006). Figure 2a) shows the scale model in black and the GPS scale factors in color. They are clearly correlated and the modeled annual pattern is in phase with the observations. Correcting the GPS scales with the model leads to a Weighted Root Mean Scatter (WRMS) reduction of the scales between 35 and 42% depending on the ACs. Figure 2b shows the time series of the differences with the model. It can be noticed that the residuals still show periodic signals, mostly annual and semiannual. There are several possible explanations for this and the most likely explanation is a combination of three main effects. The first could be a deficiency of the loading model that does not include the ice sheet dynamics at high latitudes (Rodell et al. 2004). The power spectrum of the scale parameters, not shown here, also presents a spurious spectral line at a period of 87 days especially for mi1 and gf1 solutions. This period is the 4th harmonic of the GPS "draconitic" year, which is about 351 days (Schmid et al. 2007), the period during which the GPS satellite orbital planes come back to their initial positions with respect to the sun. These harmonics are also visible in the translation parameters but different overtones are detected depending on the AC. For example, the Z translation discussed above shows the 3rd harmonics for all ACs but the 4th for mi1 and gf1. More generally, the draconitic period and its harmonics have been found in SLR residuals of GPS orbits (Urschl et al. 2005; Griffiths et al. 2009), in station positions (Ray et al. 2008) and in polar motion estimates (Gross 2009). As a consequence, it is not surprising to detect such periods in the scale factors. This suggests that the draconitic year could pollute the annual signal determination. It is also plausible that bedrock thermal expansion might affect the GPS height annual signal determination. Indeed, Yan et al. (2009) showed that using a model of this effect improves the agreement between GPS results and loading models.

We evidenced here that the GPS scale is more stable than in the past (Altamimi et al. 2002) and that its seasonal variations are partly understood. However, the rather small slope changes of the scale factor need further investigation. Regarding the conclusions of the analyzes of GPS translations and scale parameters, we assert that the IERS choice of adjusting the GPS frame to match the VLBI and SLR average is still justified in order to supply to GPS frame a reliable scale and origin information.

GPS time series

We investigate the position time series of the GPS stations once secular terms and discontinuities have been removed. About 50% of the stations exhibit discontinuities so that detecting reliably these breaks becomes a crucial problem due to the increase of the number of stations. We formed detrended position residuals by removing discontinuities as well as transformation parameters (translation, rotation and scale) from the original position time series.

Repeatability

It is a common practice to evaluate the quality of position time series by computing their repeatability. This metric should, however, be interpreted with some caution since in some cases the smallest repeatability is not the best. Steigenberger et al. (2009) have illustrated that point by

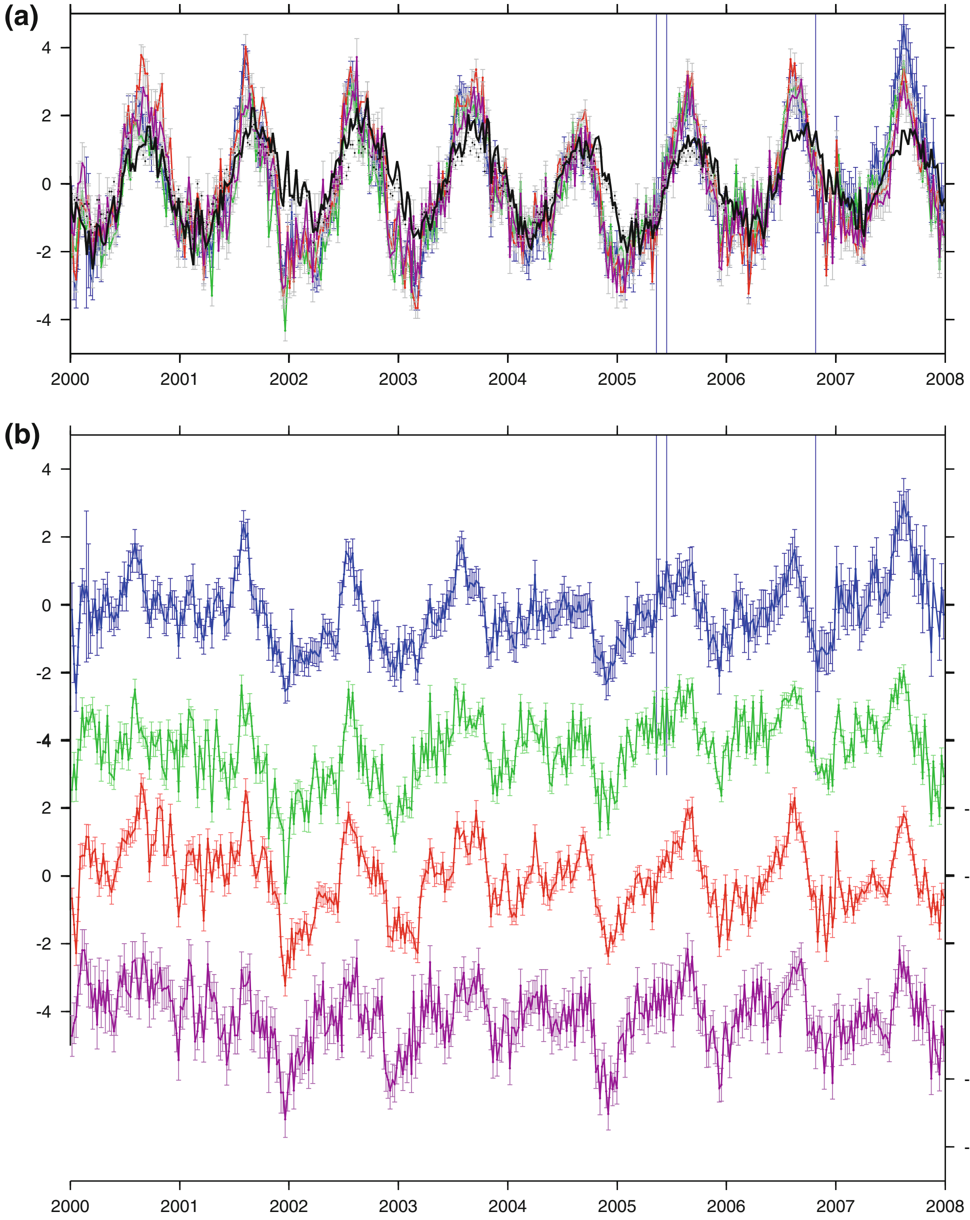

Fig. 2 **a** GPS scale variations for various ACs in color. Predicted scale of the loading model are shown in *black*. **b** Scale differences between GPS ACs and the loading model

showing that GPS position time series computed with a simple a priori tropospheric model have the smallest repeatability compared to more realistic models when atmospheric loading is not modeled in the GPS processing due to correlations among the neglected errors (Tregoning and Herring 2006). The tropospheric model used for the reprocessing performed better than previous estimates and includes a slowly temporally and spatially varying empirical a priori pressure field compared to constant values used in the past so that the repeatability of the new products should not show so clearly this paradox. Moreover, Altamimi and Collilieux (2009) showed that GPS position time series averaged weekly repeatability might reach a minimum of 1 mm in horizontal and 3 mm in vertical due to crustal motion so that current GPS repeatability still contains a contribution due to noise processes. Thus, it is worth investigating the statistics for newly reprocessed time series.

Figure 3 shows the WRMS of the station position stacking, that could be understood as the network-averaged repeatability for the vertical and horizontal components. The ITRF2005 IGS station position time series is shown in black on the plot. A bump clearly visible in the earliest data before 2000.0, has disappeared in the newly reprocessed position time series that are shown in color. The individual AC contributions behave similarly. It is worth noting that all AC solutions perform better than the ITRF2005 IGS combined solution. Over the period 1997–2009, the

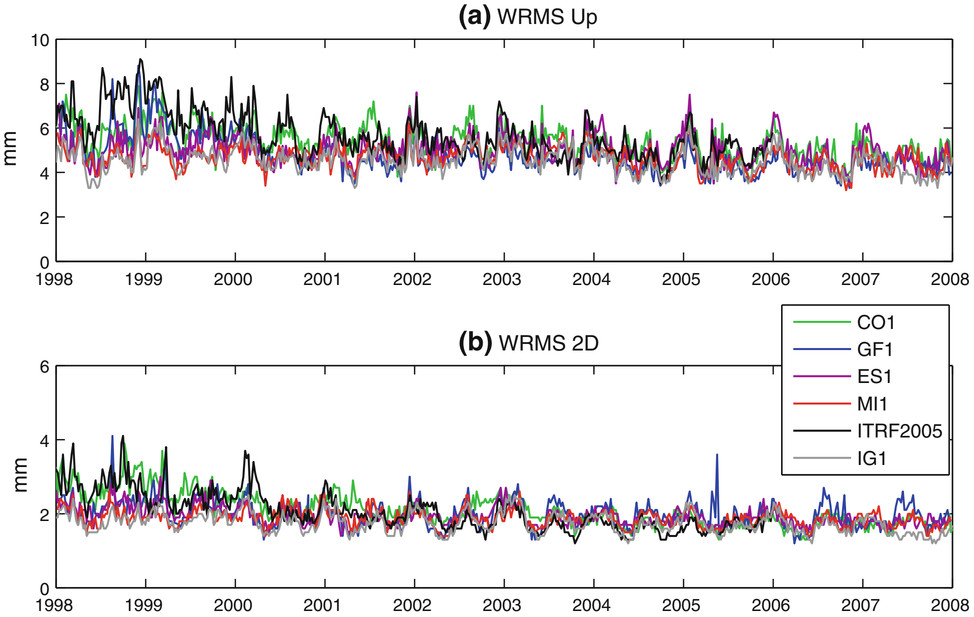

Fig. 3 WRMS of the GPS position time series as an indicator of the mean repeatability. A 7-parameter Helmert transformation as well as discontinuities, have been removed from original position time series

reprocessed IGS combined solution has the smallest repeatability with a median repeatability of 4.7 mm in the vertical and 1.5 mm in horizontal.

Spectral analysis

We used the FAMOUS software to map the spectral content of the position residual time series with detections restricted to spectral lines with a signal to noise ratio (SNR) greater than three (Collilieux et al. 2007; Mignard 2005). We have analyzed the position time series of the four analysis centers and they all show similar results. For this reason, we will concentrate here on the combined IG1 solution. Figure 4 summarizes the detected frequencies above SNR = 3 and gives the proportion of stations where these frequencies are detected.

As previously reported (Collilieux et al. 2007; Ray et al. 2008) using the IGS ITRF2005 solution, the harmonics of the draconitic frequencies are widely detected. They are visible here up to the sixth tone, at least. This confirms what we previously evidenced in the GPS individual scale factors. There is, of course, no reason to expect crustal motion at these frequencies. Tregoning and Watson (2009) and King and Watson (2010) have recently tried to explain these harmonics. Although they succeed in decreasing their amplitude by fixing ambiguities, which is also done in the IGS reprocessed solutions, or modeling atmospheric tides, which is not yet done by the IGS, they did not remove them. There might be a connection between the draconitic signal detected in GPS orbit residuals and the modeling of the solar radiation pressure handling as discussed by Urschl et al. (2007). But the mechanism of how this signal propagates into almost all GPS products is still unclear.

We wanted to verify if the amplitude of these spurious signals in the position time series has decreased in the homogenously reprocessed solutions. We have estimated the amplitude of the 4th harmonic of the draconitic frequency in both ITRF2005 and IG1 dataset for the period 2001–2006 for all common stations. Although we noticed different values among stations, we did not evidence any reduction in average. It is thus possible to conclude that the improvement in the modeling of the tropospheric delay, the adoption of a unique reference frame and the use of APCO and APCV do not influence the anomalous signal power.

Annual signal and loading effects

GPS position time series are now used for a wide set of applications. For example, the GPS technique contributes remarkably to the understanding of mass fluid transports at the earth surface (Blewitt et al. 2001). It especially supplies an independent estimation of mass transport to validate GRACE mission results (Tapley et al. 2004) but also complements it for the GMO estimation (Wu et al. 2006). The principle of these studies relies on the indirect elastic effect of mass redistribution that deforms the earth's crust. Most of the power of these processes occurs at the annual frequency. For this reason, we suggest here investigating the possible improvement of the signal at this frequency. We assumed that the annual signal amplitude in the residual position time series was constant in the following and estimated them in the GPS solutions for the same period.

Annual signals estimated in the different reprocessed AC contributions are generally consistent for sites located at the same place in the three components although

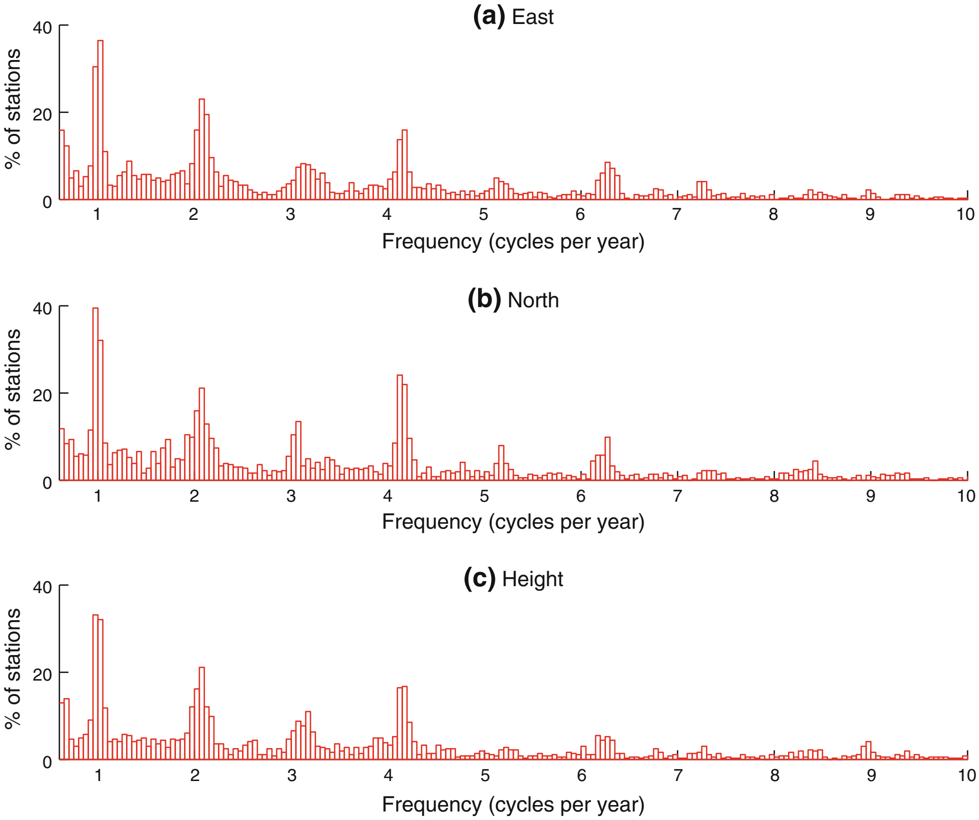

Fig. 4 Histograms of the detected frequencies in the GPS position time series for the period 2004–2008

differences can be found on a station by station basis. But this is out of the scope of this paper to study these subtle differences that can easily be investigated using the time series of residuals of the IGS weekly combination. For comparison with previous datasets we have considered combined ITRF2005 GPS and IG1 data. As these position time series were explicitly expressed with respect to ITRF2000 and ITRF2005 frames, respectively, height signals in these data sets were affected by the estimation of the scale parameter in the weekly combination process. We have reapplied transformation parameters estimated with a well distributed sub-network (Collilieux et al. 2007) in order to minimize aliasing of the loading signal into the seven parameters and especially the scale. We have shown using synthetic position sets based on a loading model that such a procedure attenuates aliasing in the scale parameter with a residual signal of 0.6 mm (Collilieux 2008). Thus, newly built height residual time series might still be slightly biased but this bias may be similar between both GPS solution sets since the well-distributed networks use common stations. We estimated annual signals for each coordinate component for each individual station and for the loading displacement model, ITRF2005 IGS and IG1 residual time series of 206 stations for the period 1997.0–2006.0. Figure 5 shows the amplitudes of annual signals in each GPS solution with respect to the amplitudes of annual signals in the loading model. It can be noticed on Fig. 5a that ITRF2005 IGS solution annual signals are correlated with the loading signal. The correlation is −4, 22 and 49% on the East, North and Height component, respectively. These correlations of the three components increase when looking at the reprocessed GPS solution with respectively 9, 28 and 60%. But similar patterns are identified with the two data sets. For most of stations, GPS horizontal annual signals seem to be overestimated compared to the loading model. However, the agreement of amplitudes in the vertical is much better, especially with the reprocessed data set, possibly related to the height signals being larger than in the horizontal. Differences between the GPS and loading model annual variations are smaller with reprocessed solutions as can be noticed on Fig. 5. The best agreement in phase is noticed on the vertical with standard deviation of the phase differences between GPS and model of 53 days with ITRF2005 IGS data and 45 days with IG1 data. Horizontal components agree within 86 days in the East and 70 days in the North with only an improvement in the North component for the newly reprocessed data (by 6 days).

Evaluation of GPS station positions and velocities

It has been clearly demonstrated here that reprocessed GPS annual variations are more precise than those estimated in

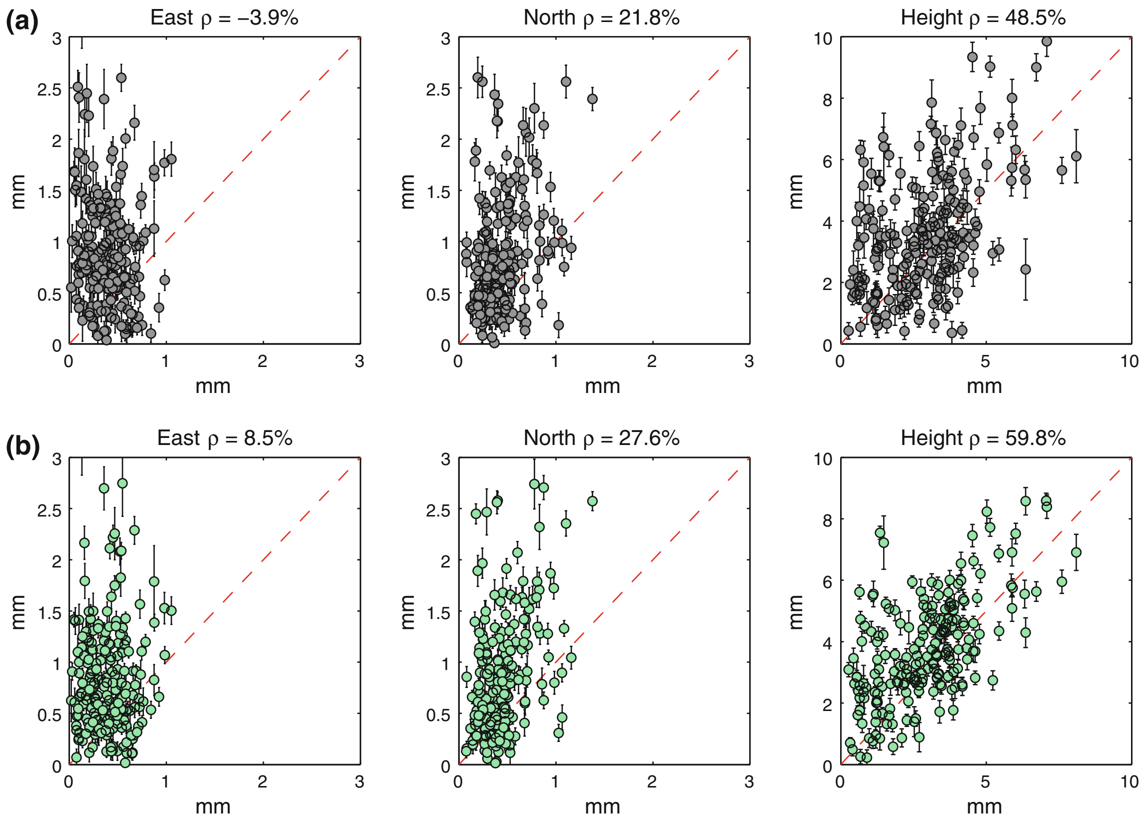

Fig. 5 Amplitude of the GPS annual signal estimated **a** in ITRF2005 IGS residuals and **b** IG1 residuals with respect to loading annual signal

previous datasets which confirms the conclusions of Tesmer et al. (2009). In this section, we evaluate the long term positions and velocities that are inputs to the ITRF multi-technique combination. VLBI session-wise TRF have been stacked to estimate long term positions and velocities for each station. In this process, as previously done for GPS, discontinuities have been detected and modeled by estimating a new position and velocity after each event. As VLBI and GPS frames are different, we had to estimate 14 parameters between the position and velocity data sets. This operation is possible if only local ties are introduced and if velocities are constrained to be equal at co-location sites. Thus, the estimation of these 14 parameters only relies on the 24 co-location sites. In order not to be affected by the weighting strategy, we have fixed the VLBI coordinates in the process in order to evaluate the GPS frame.

We have performed two combinations following the strategy described above. Both used as input the newly reprocessed VLBI positions and velocities as well as the local ties. In the first case, the GPS solution is the ITRF2005 IGS contribution stacked over the period 1997.0–2006.0. In the second case, the GPS solution is that of IG1 stacked over the same period. Few GPS sites have different sets of discontinuities in the two solutions so that we had to choose which reference position to tie to VLBI coordinates. This was done in order to have local ties introduced at the same epoch. Local ties are introduced with realistic standard deviations (about 4 mm on average for each component) and GPS positions and velocities with their covariance matrices such that their uncertainties are about ten times smaller than those of the local ties. We noticed a decrease of residuals for 15 of the 24 local ties when considering the newly reprocessed solution. The decrease of local tie residuals is only detectable in the height component from 5.6 mm WRMS to 4.5 mm WRMS. But these numbers depend on the weighting strategy that we have adopted. The WRMS of the GPS solution with respect to VLBI are listed in Table 4. The agreement in position increased by about 50% with WRMS of about 0.1 and 0.8 mm in horizontal and height positioning, respectively, using the new GPS product. Although

Table 4 WRMS between mean positions and velocities of GPS with respect to newly reprocessed VLBI

	Positions (t = 2000.0)		Velocities	
	2D (mm)	h (mm)	2D (mm/year)	h (mm/year)
ITRF2005	0.3	1.6	0.1	0.5
ITRF2008P	0.1	0.8	0.1	0.4

the improvement is clearly visible, it is worth mentioning that these numbers account for the adjustment of a scale factor and that local ties are introduced with their own uncertainties. As a consequence, they should not be understood as absolute numbers of the GPS and VLBI consistency. Except for the measurement noise, there are still some reasons to expect these WRMS to be non-zero. First, some of the co-located GPS stations still have uncalibrated radomes. This is the case for Kauai station (KOKB) before 2002 at the epoch of the local survey and for Fort Davis (MDO1) and Santiago (SANT) stations (Ralf Schmid, personal communication). They show the largest local tie residuals in the height component. However, other stations with uncalibrated radome do not show large residuals but it is not possible to know a priori how much the bias is. Another source of error that affects GPS position estimation is the multipath and the station environment effects (Dilssner et al. 2008). Secondly, gravitational deformation may affect VLBI heights by up to 1 cm (Sarti et al. 2009) but it is probable that this effect leads to nonzero scale bias so that the WRMS only partly reflect this effect. The improvement in terms of velocities is small, but noticeable, with a consistency of 0.4 mm/year in the height component.

Conclusion

We have made a quantitative assessment of the IGS contribution to ITRF2008. For the first time, GPS data have been homogeneously reprocessed from 1994.0 to 2009.0 by 11 ACs. This reprocessing has led to a major improvement of the GPS weekly TRFs. Station position time series repeatability, analyzed for the period 1997.0–2009.0, is smaller and now reaches 4.7 mm in height and 1.5 mm in horizontal. Moreover, annual signals in the GPS station position time series are closer to those predicted by loading models, especially in the height component. The estimated station positions and velocities, that are the basis of the ITRF component of IGS products, are also more consistent with VLBI data. We succeed in explaining up to 40% of the weekly scale parameter scattering and have demonstrated that most of the annual variations in this parameter are explained by surface height displacements due to loading effects.

However, it is evidenced that there are still systematic errors in GPS products that need to be understood. Although GPS AC frame origins differ from SLR origin by less than 1 mm/year, there are still significant differences between ACs and a commonly observed drift in the Z component between 0.3 and 0.7 mm/year. Moreover, the GPS translation annual variations are still biased compared to SLR and the loading model, especially in the Z component, although the agreement looks better than in the past. The GPS scale drift with respect to SLR and VLBI mean scale is smaller than 0.4 mm/year but the behavior of this parameter is not strictly linear. Attention should be paid to these nonlinear variations in the future. Moreover, it was possible to correlate the highest GPS-VLBI height local tie residual with GPS stations equipped with uncalibrated radomes which shows that GPS scale is still perfectible. Finally, the periodic spurious signals at the harmonics of the draconitic frequency are still detected in the position time series up to the 6th component with similar amplitude than in the nonhomogeneously reprocessed products. Understanding the cause of the mechanisms that generates these signals will be one of the major tasks of the IGS for the next years.

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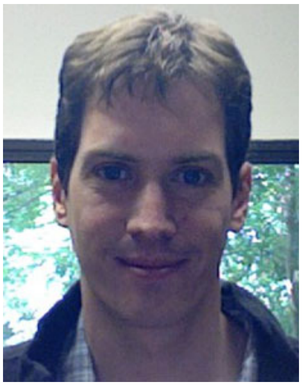

Laurent Métivier received his Ph.D. degree in solid earth geophysics from the Institut de Physique du Globe de Paris in 2004. For his Ph.D. thesis, he investigated solid earth theoretical deformations in response to the application of external forces. In 2005, he joined the French Space Agency (CNES) and the Royal Observatory of Belgium in Brussels, where he began applying his newly developed method to problems in planetary sciences. In 2006, he joined the NASA Goddard Space Flight Center and the University of Maryland Baltimore County, where he investigated tidal and loading deformations for Earth and Mars. In 2007–2008, he worked at the Johns Hopkins University in Baltimore on tidal phenomena and seismicity. Since 2008, he has been working as a researcher in geophysics and geodesy at the Institut Géographique National in France, notably on reference system-related issues.

Zuheir Altamimi is head of the terrestrial reference systems research group at the Laboratoire de Recherche en Géodésie of the Institut Géographique National (IGN), France. He is also a member of the International Earth Rotation and Reference Systems Service (IERS) Directing Board and of the Governing Board of the International Laser Ranging Service (ILRS). He has been currently elected as President of Commission 1 (Reference Frames) of the International Association of Geodesy (IAG), and he is head of the International Terrestrial Reference System (ITRS) Product Center of the IERS. His principal research focus is the theory and realization of terrestrial reference systems. He received his Ph.D. in space geodesy from the Paris Observatory, and his habilitation (2nd doctorate) from Paris University VI.

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