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ORIGINAL ARTICLE

IGS08: the IGS realization of ITRF2008

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Abstract On April 17, 2011, the International GNSS Service (IGS) stopped using the IGS05 reference frame and adopted a new one, called IGS08, as the basis of its products. The latter was derived from the latest release of the International Terrestrial Reference Frame (ITRF2008). However, the simultaneous adoption of a new set of antenna phase center calibrations by the IGS required slight adaptations of ITRF2008 positions for 65 of the 232 IGS08 stations. The impact of the switch from IGS05 to IGS08 on GNSS station coordinates was twofold: in addition to a global transformation due to the frame change from ITRF2005 to ITRF2008, many station coordinates underwent small shifts due to antenna calibration updates, which need to be accounted for in any comparison or alignment of an IGS05-consistent solution to IGS08. Because the heterogeneous distribution of the IGS08 network makes it sub-optimal for the alignment of global frames, a smaller well-distributed sub-network was additionally designed and designated as the IGS08 core network. Only 2 months after their implementation, both the full IGS08 network and the IGS08 core network already strongly suffer from the loss of many reference stations. To avoid a future crisis situation, updates of IGS08 will certainly have to be considered before the next ITRF release.

Keywords IGS · GNSS · ITRF · Terrestrial reference frame · Tracking network · Phase center calibration

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Introduction

In 2008, eleven analysis centers (ACs) of the International GNSS Service (IGS; Dow et al. 2009) reanalyzed the full history of GPS data collected by the IGS global tracking network back to 1994, using the latest models and methodology available at that time. The main objective of this reprocessing campaign was to generate a new consistent set of IGS products (see http://www.acc.igs.org/reprocess.html). Numerous improvements brought to the analysis of GPS data since 1994 and several reference frame changes had made the previous operational IGS products inconsistent over time. Major quality improvements from the operational to the reprocessed products were noted by, e.g., Griffiths et al. (2009) and Collilieux et al. (2011a). This collective effort of the IGS mirrors similar reprocessing activities by individual groups (Steigenberger et al. 2006; Wöppelmann et al. 2007), some of which contribute to the IGS reprocessed products too. The main advantage of the IGS campaign was the intrinsic inter-comparison of AC solutions and the opportunity to form a weighted combined product set that can potentially maximize the benefits from the AC solutions while minimizing their weaknesses.

The reprocessed products delivered by the ACs included weekly SINEX (Software Independent Exchange format) solutions with station positions and daily earth rotation parameters (ERPs). Combinations of the AC reprocessed solutions were performed at Natural Resources Canada (Ferland and Piraszewski 2009; Ferland 2010). The resulting weekly combined solutions constituted the IGS contribution to the latest realization of the International Terrestrial Reference System (ITRS), namely ITRF2008 (Altamimi et al. 2011).

Since 2000, the IGS has used its own realizations of the successive ITRF releases as reference frames for its products (see http://www.acc.igs.org/igs-frames.html). In November 2006, a reference frame based on ITRF2005, called IGS05 (IGS Mail 5447), was adopted by the IGS, simultaneously with the switch from relative to absolute antenna phase center calibrations (Schmid et al. 2007). Because of growing velocity propagation errors and of jumps having affected the positions of many reference stations, IGS05 has become obsolete. So, a new reference frame based on ITRF2008, called IGS08, was designed and officially adopted by the IGS starting with GPS week 1632 (April 17, 2011).

We start by describing how IGS08 was derived from ITRF2008. The IGS08 core network, a well-distributed subset of IGS08 stations, more suitable for global applications than the whole IGS08 network, is then presented. The transformation from IGS05 to IGS08 and its practical implementation are then addressed. Finally, the issue of the rapid decay of IGS08 reference stations is raised, and plans for updates of IGS08 before the next ITRF release are outlined.

How was IGS08 obtained?

From 2000 to 2006, the successive IGS reference frames (IGS97, IGS00 and IGb00; IGS Mails 2899, 4666; Ferland 2004) have been obtained by aligning internal IGS cumulative solutions to the successive ITRF releases through 14-parameter similarities. This practice has been preferred to a direct use of the ITRF realizations for the sake of internal consistency (Kouba et al. 1998; Ray et al. 2004). Another strategy was adopted for the definition of the next IGS reference frame: IGS05 was derived from an extraction of stable GNSS station coordinates from ITRF2005. But while ITRF2005 was based on relative antenna calibrations (igs_01.pcv; Rothacher and Mader 1996), IGS05 had to be consistent with the simultaneously adopted set of absolute calibrations (igs05.atx; Schmid et al. 2007). To account for the antenna phase center calibration changes, position corrections for the IGS05 stations were derived from parallel processing and applied to their ITRF2005 positions to form IGS05 (IGS Mail 5447).

The elaboration of IGS08 followed the same strategy: it is derived from an extraction of stable GNSS station coordinates from ITRF2008, some of which were slightly modified. Indeed, together with IGS08, an updated set of absolute antenna calibrations (igs08.atx) was adopted by the IGS. Compared to igs05.atx, besides the satellite antenna corrections, also most of the receiver antenna calibrations were slightly changed (IGS Mail 6355). While the IGS reprocessing campaign and thus ITRF2008 were based on the igs05.atx calibrations, IGS08 had to be consistent with the latest igs08.atx calibrations. The impact of the receiver antenna calibration update on the IGS08 station positions was thus assessed and turned out to be non-negligible in several cases. So, IGS08 was in the end defined as an extraction from ITRF2008 to which position corrections were applied to account for the receiver antenna calibration update.

Station selection

The first step of the elaboration of IGS08 was the selection of well-behaved, stable stations from the IGS stations contained in ITRF2008. Indeed, the most important feature expected from a reference station is that its actual position over time remains as close as possible to its reference position given by the ITRF piecewise linear (position + velocity) model. For most stations, this selection was made based on the ITRF2008 results and according to the criteria listed in Table 1.

Because of the heterogeneous density of the IGS network, the thresholds given in Table 1 were not uniformly applied. A stricter selection was possible in Europe. But in order to ensure an optimal coverage of the IGS08 network, fifteen stations were selected even though they did not fulfill all criteria (Fig. 1d). Eleven of them, mostly located in seismic areas, had one or more velocity discontinuities; WES2 (Westford, USA) had 6 position discontinuities due to frequent equipment changes until 2002; the RMS of the

Table 1 Criteria used to select IGS08 stations from the IGS stations of ITRF2008

Criterion	Threshold
Data span	>5 years
Maximum time span between two discontinuities	>3 years
Number of discontinuities	<5
Number of velocity discontinuities	=0
3D formal error of latest velocity estimate	<0.3 mm/year
Residual time series	3D RMS <10 mm; visual inspection

All criteria refer to the ITRF2008 results

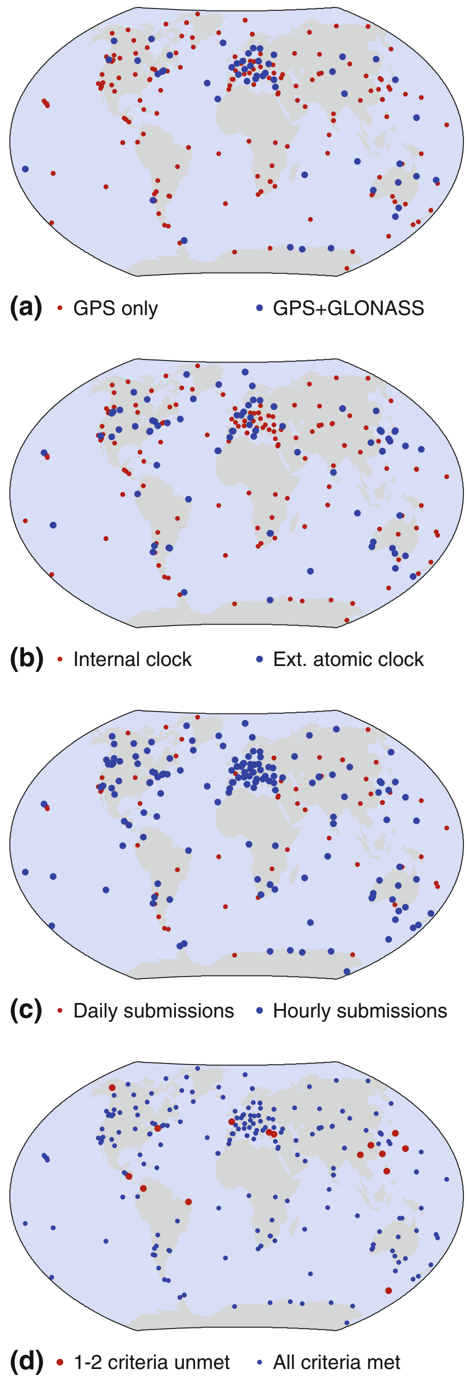

Fig. 1 Distribution of IGS08 network stations **a** GLONASS-capable stations, **b** stations driven by external atomic clocks, **c** stations delivering hourly data, and **d** stations not fulfilling all criteria listed in Table 1

residual time series reached 12 mm for BOGT (Bogota, Colombia) and CCJM (Chichijima, Japan); BRFT (Fortaleza, Brazil) only had 4 years of data.

In regions where multiple candidate stations were available, additional selection criteria were taken into consideration with the following qualities favored:

- stations with GLONASS-capable equipment in view of multi-GNSS applications,
- stations driven by external atomic clocks in view of timing applications,
- stations co-located with instruments of other space geodetic techniques, and
- stations equipped with antennas for which robot calibrations are available.

For near–real-time applications, a good coverage of stations delivering hourly data was also necessary. But even without having taken this aspect into account in the selection process, it turned out that the vast majority of the selected stations actually send hourly data (Fig. 1c).

This selection process resulted in a globally distributed network of 232 stations. The distribution of GLONASS-capable stations, stations driven by external atomic clocks, and stations delivering hourly data is shown in Fig. 1.

Since their installation, most of the IGS08 stations have been subjected to position jumps due to equipment changes, earthquakes, or other unknown causes. In the ITRF2008 combination, these jumps were accounted for by a piecewise linear model: one position + velocity set was estimated for each time period between two successive jumps; the successive velocities were usually constrained to be equal except when this was unreasonable (such as following earthquakes). IGS08, as an extraction of ITRF2008, follows the same model. It can contain several position + velocity sets per station, each set being valid over a specific time period given in ftp://igs-rf.ign.fr/pub/IGS08/soln_IGS08.snx.

Several IGS08 stations have been subjected to discontinuities since the latest IGS inputs into ITRF2008 (epoch 2009.5). New discontinuities at IGS08 stations are indeed occasionally detected in the course of the weekly IGS SINEX combinations and are immediately reported in the file mentioned above. The affected IGS08 stations consequently become unusable as reference stations for the period after new discontinuities, and the geometry of the IGS08 network deteriorates little by little. This issue is discussed in Sect. 5.

Assessing the impact of receiver antenna calibration updates

Once the set of reference stations was selected, the next step in the elaboration of IGS08 was to assess the impact of the update of the receiver antenna calibrations—i.e., due to switching from igs05.atx to igs08.atx. If this impact had been negligible in most cases compared with the uncertainties of the ITRF2008 positions, then those could have been left unchanged for most IGS08 stations, while a few stations would have been excluded from IGS08. But it turned out that the calibration updates significantly affected many IGS08 stations so that position corrections were necessary. Note that according to IGS standards, the position shifts mentioned throughout the paper are consistent with the ionosphere-free linear combination LC.

In order to assess the impact of the calibration updates, two precise point positioning (PPP) solutions were set up, one using the igs05.atx calibration set, the other using igs08.atx. All other input models were the same in both solutions, hereafter referred to as IGN PPP tests. For each IGS08 station equipped or having been equipped with an antenna subjected to a calibration change, computations were made on the first day of each month during the whole period the antenna was in place. A modified version of the Bernese GPS Software 5.0 (Dach et al. 2007) was used. Each computation covered 24 h of observations; other processing options are summarized in Table 2.

Both sets of positions obtained were then differenced for each station, so as to get time series of position shifts caused by the calibration updates. These time series showed very good repeatabilities: less than 0.5, 0.5, and 1 mm in the East, North, and Up components, respectively, in 97% of the cases. Note that all but one of the other cases concern TRM29659.00 antennas.

Two independent PPP test campaigns were performed at the European Space Operations Centre (ESOC) with the Napeos software (Springer 2009). Both covered 1 day per month during the years 2008/09 for 44 IGS08 stations.

Table 2 Main processing options used for the IGN PPP tests

Modeling aspect	Model/setting/data used
Orbits, clocks, earth rotation parameters	IGS reprocessed products until 2007
	IGS final products since 2008
Sampling rate	5 min
Cutoff angle	10°
Elevation-dependent weighting function	$\sin^2(e)$ with elevation e
Dry part of the troposphere	Global Pressure/Temperature (GPT) model (Boehm et al. 2007)
	Zenith delay from Saastamoinen (1973) model
	Dry Global Mapping Function (GMF; Boehm et al. 2006)
Wet part of the troposphere	One zenith delay estimated per epoch (every 5 min)
	Relative constraints of 5 mm between successive zenith delays
	Wet Global Mapping Function (GMF; Boehm et al. 2006)
Horizontal troposphere gradients	N/S & E/W gradients varying linearly over 24 h
Phase cycle ambiguities	Not fixed (estimated as float numbers)

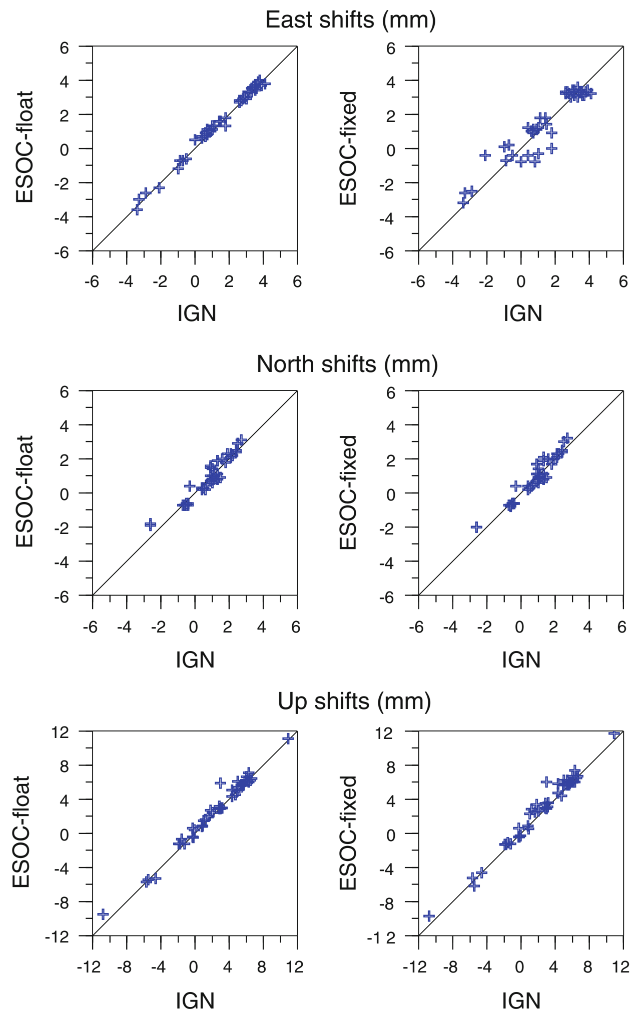

Fig. 2 Comparison of the mean position shifts derived from the IGN and ESOC PPP tests

Ambiguities were estimated as float numbers in the first campaign (ESOC-float), while fixed in a network mode in the second one (ESOC-fixed). Mean shifts derived from the IGN and ESOC time series are compared in Fig. 2. The IGN and ESOC-float results agree at or below the mm level. The agreement between the IGN and ESOC-fixed mean shifts is of comparable quality in the North and Up components. However, in the East component, the ESOC-fixed mean shifts show larger differences, mainly for TPSCR3_GGD antennas (up to 2 mm). This suggests that fixing ambiguities can have a significant impact on the East component of the estimated shifts, depending on the antenna type.

As an additional verification, eight IGS ACs provided global test solutions obtained with igs08.atx in parallel to their routine products for GPS weeks 1596–1599. Each of these test solutions was aligned to the corresponding routine solution, based on igs05.atx, by a 7-parameter similarity transformation ignoring the stations affected by calibration changes. Position differences between the aligned parallel solutions and the routine solutions were formed and averaged for each AC, so as to obtain other independent estimates for the position shifts.

Shifts derived from the parallel AC solutions were generally in good agreement with each other and also with those derived from the PPP tests. For each of the 34 affected IGS08 stations present in at least one parallel AC solution, a figure showing all available results can be found at ftp://igs-rf.ign.fr/pub/IGS08/new_calib/comp_plots. The fact that fixing ambiguities had a noticeable impact for TPSCR3_GGD antennas also seemed to be confirmed.

Making IGS08 consistent with the igs08.atx receiver antenna calibrations

While the formal errors of the ITRF2008 positions are below 1.5 mm for 92% of the IGS08 stations, 137 of the 3D position shifts derived from the IGN PPP tests were larger than 2 mm. The only alternative to make IGS08 consistent with igs08.atx without altering the geometry of the IGS08 network was thus to correct the ITRF2008 positions of the affected IGS08 stations.

For these corrections, it was decided to use the mean shifts derived from the IGN PPP tests because they included all IGS08 stations equipped or having been previously equipped with affected antennas. This approach had the advantage of using a unique, homogeneous source of information. However, some of the shifts derived from the IGN PPP tests might be biased by up to 2 mm due to not fixing phase ambiguities.

Not all of the estimated shifts were applied; only those exceeding certain thresholds were deemed necessary. Thus, the ITRF2008 positions of the IGS08 stations were only corrected by the mean shifts derived from the IGN PPP tests when those exceeded either 1.2 mm in the East or North component or 3 mm in the Up component. The application of the shifts was also conditioned to the presence of position discontinuities in ITRF2008: at the installation date of the affected antenna and also at its removal date if the antenna was replaced in the meantime. This condition was fortunately satisfied in most cases, but 9 previously selected stations had to be eliminated from IGS08 and 7 were removed for certain time periods. Position corrections eventually concerned 87 time periods (solution numbers) of 65 IGS08 stations. The ITRF2008 positions of the 167 remaining IGS08 stations were kept unchanged. A table of the applied corrections can be found at ftp://igs.org/pub/station/coord/ITRF2008_to_IGS08.txt.

In 2006, when the IGS switched from relative (igs_01.pcv) to absolute antenna calibrations (igs05.atx), similar corrections had been estimated and applied to ITRF2005 positions to define the IGS05 reference frame (IGS Mail 5447). All 132 IGS05 stations received corrections, whose means and standard deviations were -1.2 ± 1.6 mm in North, 0.1 ± 1.4 mm in East, and 11.5 ± 10.6 mm in Up. The switch from igs05.atx to igs08.atx has an overall much smaller impact on station positions, but it still cannot be ignored: -1.3 ± 2.8 mm in North, 0.1 ± 1.1 mm in East and 2.2 ± 3.3 mm in Up for the 65 affected stations (out of 232 IGS08 stations). A similar situation is likely to recur with the next calibration update, depending on whether and how well the receiver antenna calibration measurements used by the IGS will eventually converge to stable values.

After IGS05 had been corrected for the relative to absolute calibration changes, it was realigned to ITRF2005 by means of a 14-parameter similarity transformation (IGS Mail 5447). *Such a realignment of IGS08 to ITRF2008 was not performed*. However, this does not mean that IGS08 and ITRF2008 are realizations of different reference systems. IGS08 is just consistent with the igs08.atx antenna calibrations, while ITRF2008 is consistent with igs05.atx, but both frames share the same underlying origin, scale, and orientation. We thus consider that estimating similarity parameters between IGS08 and ITRF2008 would be misleading. The difference between IGS08 and ITRF2008 only consists of station-specific corrections due to the antenna calibration updates.

This also means that, unless corrected for the same antenna calibration updates, a solution obtained with igs05.atx should not be compared or aligned to IGS08. Reciprocally, a solution obtained with igs08.atx should not be compared or aligned to ITRF2008. Such inconsistent comparisons or alignments would indeed be polluted by the effects of the antenna calibration updates and artificially depend on the exact set of stations/antennas used. Advice to users who would like to make results obtained with IGS05/igs05.atx consistent with IGS08/igs08.atx is given in Sect. 4.

Making the igs08.atx satellite antenna *z*-offsets consistent with IGS08

From igs05.atx to igs08.atx, not only the receiver antenna calibrations were updated, but also the radial components of the satellite antenna phase center offsets (z-PCOs). This was necessary because of the significant scale difference between ITRF2008/IGS08 and ITRF2005/IGS05 (about -1 ppb). Indeed, the terrestrial frame scale and the satellite z-PCOs are highly correlated (Zhu et al. 2003). New z-PCOs consistent with the scale of IGS08 were thus derived for the GPS and GLONASS satellites. New phase center variations (PCVs) were also determined for the GLONASS satellites and included in igs08.atx (IGS Mail 6355).

Note that it has been proposed that the scale of future ITRF realizations be fixed conventionally to the ITRF2008 scale due to inaccuracies in the contributing techniques—satellite laser ranging and very long baseline interferometry—of about 1 ppb (Ray et al. 2011). That would simplify the future IGS maintenance of satellite antenna offsets.

The IGS08 core network

Comparisons or alignments of quasi-instantaneous frames to a secular reference frame are usually done by means of a 7-parameter similarity transformation, with the secular frame propagated to the epoch of the quasi-instantaneous realization. These parameters are supposed to model biases between two different reference systems or frames. But in fact, they also absorb part of the non-linear motions of stations (e.g., loading deformations). This aliasing, first addressed by Blewitt and Lavallée (2002), is often referred to as the "network effect" (Collilieux et al. 2007) since it depends highly on the precise selection of stations used to estimate the similarity parameters. It is especially important for unevenly distributed networks as loading deformations are spatially correlated.

As visible in Fig. 1, the IGS08 stations are quite irregularly distributed: many reference stations were selected in regions with dense GNSS coverage to accommodate regional users. So, if the full IGS08 network was used, for example, for the global alignment of weekly solutions, a significant network effect could be expected. Collilieux et al. (2011b) showed that one way to reduce the network effect consists in using a well-distributed network of reference stations. The IGS08 core network was defined for this specific purpose. It consists of a well-distributed sub-network of IGS08 stations and is recommended for the comparison or alignment of any global solution consistent with igs08.atx to IGS08. Since the adoption of IGS08 by the IGS in GPS week 1632, the IGS08 core network is in particular used for the alignment of the weekly IGS SINEX solutions. We thus expect the IGS station position time series to become more geophysically interpretable, provided that the core network itself remains viable (see Sect. 5).

Definition

The selection of the IGS08 core stations from the IGS08 network was made empirically. After several regular meshes of the earth's surface had been unsuccessfully tried as basis for this selection, another method was finally employed. Starting with the full IGS08 network, stations were gradually eliminated in denser areas so as to get closer to an ideal distribution. The distribution of the three following quantities was used as an indicator for the uniformity of the station distribution over the earth's surface:

$$\begin{cases} \left(\phi_i^X\right)_{1\le i\le n} = \left(\operatorname{atan}\left(X_i \Big/ \sqrt{Y_i^2+Z_i^2}\right)\right)_{1\le i\le n} \\ \left(\phi_i^Y\right)_{1\le i\le n} = \left(\operatorname{atan}\left(Y_i \Big/ \sqrt{X_i^2+Z_i^2}\right)\right)_{1\le i\le n} \\ \left(\phi_i^Z\right)_{1\le i\le n} = \left(\operatorname{atan}\left(Z_i \Big/ \sqrt{X_i^2+Y_i^2}\right)\right)_{1\le i\le n} \end{cases} \quad (1)$$

If random points (X_i, Y_i, Z_i) are uniformly distributed on a sphere, the three angles $\left(\phi_i^X, \phi_i^Y, \phi_i^Z\right)$ indeed follow cosine distributions.

An optimal distribution was reached after 141 of the 232 IGS08 stations had been eliminated. The 91 remaining stations were designated as the "primary stations" of the IGS08 core network. Although objective criteria were used for this selection, it inevitably included some subjectivity. To make the definition of the next IGS core network more objective, one solution could be to use genetic algorithms that were successfully employed by Coulot et al. (2010) for the selection of core stations among the satellite laser ranging network.

The distribution of the 91 primary stations of the IGS08 core network is shown in Fig. 3, together with histograms of the corresponding $\left(\phi_i^X, \phi_i^Y, \phi_i^Z\right)$ angles. The uniformity of the distribution is good, though some improvements would be possible if the IGS network was strengthened mainly in the equatorial band. However, these 91 stations do not form a changeless network; each of them was installed on a specific date, some are now decommissioned, some have data gaps, etc. A basic solution to mitigate the mutability of the IGS08 core network was the designation, when possible, of one or more nearby substitute stations for each primary station. In case one primary station is unavailable, one of its substitute stations should thus be used instead, so as to reduce the alteration of the network geometry.

The IGS08 core network thus eventually consists of 91 local clusters of stations from each of which one station at a time should be used. These clusters of stations are defined in ftp://igs.org/pub/station/coord/IGS08_core.txt. With such a definition, the IGS08 core network is finally a compromise between a purely "static" network and a dynamically evolving network such as obtained by Coulot et al. (2010). While a static core network would be easier to implement, a dynamically evolving network is likely to provide a more stable referencing.

Evaluation

Simulations were carried out in order to quantify the advantage of using the IGS08 core network as reference rather than the full IGS08 network. From the IGS

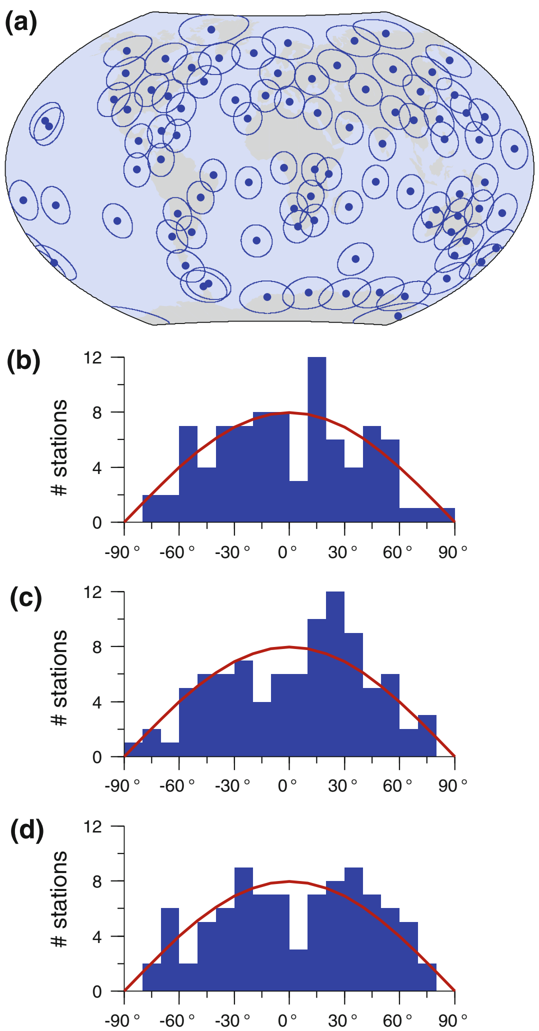

Fig. 3 **a** Distribution of the 91 primary stations of the IGS08 core network. Each station is surrounded by a circle with a radius of 1,000 km. **b**, **c**, **d** Histograms of the corresponding $(\phi_i^X, \phi_i^Y, \phi_i^Z)$ angles, respectively. The *red curves* represent the ideal cosine distributions of these angles

reprocessed SINEX solutions (Ferland 2010), synthetic weekly solutions were first obtained by replacing the actual combined station positions with "known" positions,

$$X_i(t) = X_i^{\mathrm{ITRF2008}} + (t - 2005.0)\dot{X}_i^{\mathrm{ITRF2008}} + \mathrm{d}X_i^{\mathrm{loading}}(t) + \varepsilon_i(t) \quad (2)$$

where X_i^{ITRF2008} designates the ITRF2008 position of station i at epoch 2005.0, $\dot{X}_i^{\mathrm{ITRF2008}}$ its ITRF2008 velocity, and $\mathrm{d}X_i^{\mathrm{loading}}(t)$ is the displacement of station i at epoch t with respect to the center of figure, given by a model of crustal deformations induced by loading effects. We used a loading deformation model provided by T. van Dam (University of Luxembourg), which accounts for atmospheric, non-tidal oceanic, and continental hydrological loading (Collilieux et al. 2009). The symbol $\varepsilon_i(t)$ denotes a spatially correlated noise term derived from the SINEX covariance matrix (Altamimi and Collilieux 2009).

Two sets of similarity parameters, including the scale term, were then estimated between each synthetic weekly solution and ITRF2008: one using the full IGS08 network, the other using the IGS08 core network. In absence of any network effect, these parameters would contain noise only, while the residuals of the comparisons would mainly reflect the introduced loading displacements. The time series of the translations and the scale factor estimated in both cases are shown in Fig. 4. In Table 3, the annual signals of the introduced loading displacements are compared with those present in both sets of residuals.

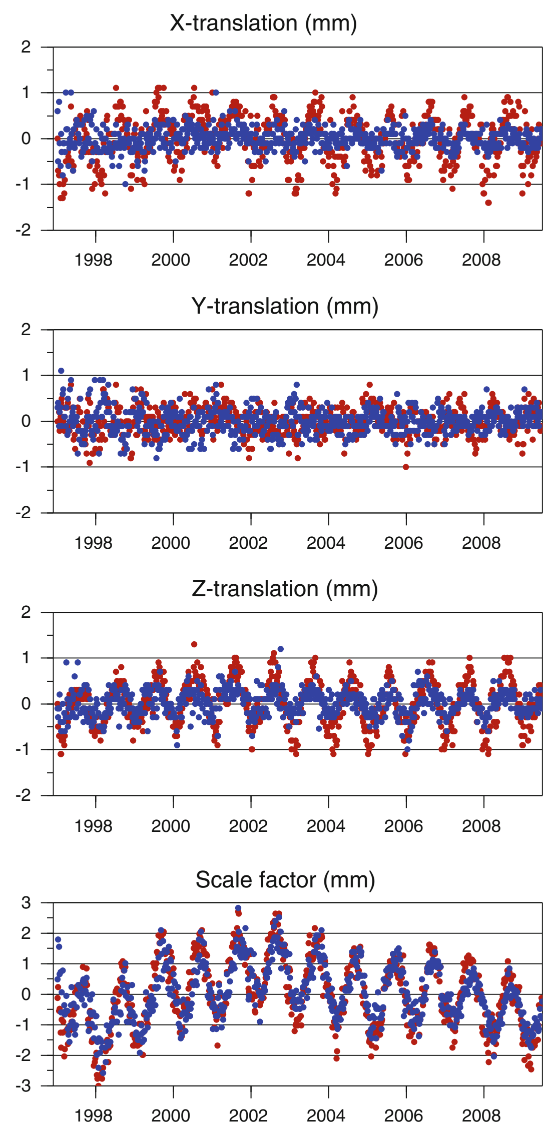

Fig. 4 Translations and the change in scale estimated between the weekly synthetic solutions and ITRF2008. Parameters estimated with the full IGS08 network are shown by red dots, and those estimated with the IGS08 core network by *blue dots*

Table 3 Mean differences (mm) between the annual signals of the introduced loading displacements and those of the residual time series

Reference network	Differences in East		Differences in North		Differences in Up	
	in-phase	out-of-ph.	in-phase	out-of-ph.	in-phase	out-of-ph.
Full IGS08	0.3	0.3	0.4	0.2	1.0	1.3
IGS08 core	0.1	0.1	0.2	0.1	0.6	1.1

Means are computed over all considered stations for the in-phase (cosine) and out-of-phase (sine) amplitudes of their East, North, and Up displacements

These simulations show that using the IGS08 core network instead of the full IGS08 network can reduce the aliasing of horizontal loading signals into similarity parameters by a factor of 2. The aliasing of the vertical loading deformations, even if reduced, is still significant when using the IGS08 core network. One of the strategies proposed by Collilieux et al. (2011b) should be used to effectively dampen it, such as not estimating scale parameters. In summary, the IGS08 core network is preferable to the full IGS08 network for the alignment of global solutions but does not provide by itself a perfect remedy to the network effect related to loading displacements.

Transforming results to the IGS08 framework

Since 2006, many GNSS users have accumulated results in the (IGS05; igs05.atx) framework. The most direct method to obtain results consistent with the new (IGS08; igs08.atx) system is to reprocess all data in this new framework. That is what the IGS will do in the next few years with its second reprocessing campaign. But many users may not find this option to be timely or cost-efficient for the near term. So, an alternative method to make old station coordinate results consistent with the new framework without data reprocessing is outlined in this section.

Method

From the definition of IGS08 (Sect. 2), it follows that the total transformation from IGS05 to IGS08 can be considered as the sum of a global transformation due to the frame change from ITRF2005 to ITRF2008 and of station-specific effects due to the antenna calibration updates from igs05.atx to igs08.atx. Consequently, a direct alignment of an IGS05-consistent solution to IGS08 is not appropriate. A two-step transformation is recommended:

1. Application of station-specific corrections to account for the antenna calibration updates from igs05.atx to igs08.atx:

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{\text{IGS05}} + \begin{pmatrix} \delta x \\ \delta y \\ \delta z \end{pmatrix}_{\text{igs05.atx}\rightarrow\text{igs08.atx}} \quad (3)$$

2. Alignment to IGS08 by means of a 14-parameter similarity transformation:

$$\begin{cases} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{\text{IGS08}} = \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} + T + \lambda \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} + R \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} \\ \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{\text{IGS08}} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{\text{IGS05}} + \dot{T} + \dot{\lambda} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} + \dot{R} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} \end{cases} \quad (4)$$

$T = (t_x, t_y, t_z)^T$ denotes the translation vector, λ the scale factor and R the matrix containing the rotation angles given by

$$R = \begin{pmatrix} 0 & -r_z & r_y \\ r_z & 0 & -r_x \\ -r_y & r_x & 0 \end{pmatrix}$$

The symbols $\dot{T}$, $\dot{\lambda}$, $\dot{R}$ are their respective time derivatives.

Table 4 contains values for the 14 parameters needed for step (2). They were estimated using 118 stations common to IGS05 and IGS08. For the reasons given in Sect. 2.3, a provisional version of IGS08 was used in which the antenna calibration updates had not been accounted for by position corrections. These parameters are as expected close to those from ITRF2005 to ITRF2008 (see Altamimi et al. 2011). The most significant values are the −1-ppb scale reduction and the 6-mm Z-translation. Users switching from IGS05 to IGS08 should thus see a mean decrease in station heights by about 6 mm, attenuated by the Z-translation in the northern hemisphere, but accentuated in the southern hemisphere. The Z-translation also

Table 4 Similarity parameters describing the frame part (2) of the transformation from IGS05 to IGS08. The most significant are shown in italic

Similarity parameter at epoch 2005.0		Rate of similarity parameter	
t_x (mm)	1.5 ± 0.2	dt_x/dt (mm/year)	−0.1 ± 0.2
t_y (mm)	−0.0 ± 0.2	dt_y/dt (mm/year)	−0.0 ± 0.2
t_z (mm)	*5.8* ± 0.2	dt_z/dt (mm/year)	−0.1 ± 0.2
λ (ppb)	*−1.04* ± 0.04	$d\lambda/dt$ (ppb/year)	0.01 ± 0.04
r_x (mas)	−0.012 ± 0.009	dr_x/dt (mas/year)	−0.002 ± 0.009
r_y (mas)	0.014 ± 0.009	dr_y/dt (mas/year)	−0.003 ± 0.009
r_z (mas)	0.014 ± 0.010	dr_z/dt (mas/year)	0.001 ± 0.010

affects the North component of station positions, especially at low latitudes.

Position corrections needed for step (1) should ideally be determined for each station, as was done for the IGS08 stations (Sect. 2.2). For non-IGS08 stations, one possible approach consists of setting up two PPP solutions, one using igs05.atx and the other igs08.atx. The impact of the antenna calibration update can then be estimated by averaging the positions for each solution and then differencing those averages. However, this method requires an extra effort of processing data and may not be easy to set up.

For user convenience, simple models for the position shifts were derived and made available. The models consist of three latitude-dependent functions for each receiver antenna type contained in both igs05.atx and igs08.atx, which provide the East, North and, Up station-specific corrections needed for step (1). The models have zero coefficients for antenna types with unchanged calibrations. Perl scripts for computing and applying these corrections to SINEX solutions have been provided (IGS Mail 6356). A description of these models is given in the following section.

Latitude-dependent models

The update of a receiver antenna calibration from igs05.atx to igs08.atx can be represented as the sum of a phase center offset (PCO) difference, conceivable as a vector, and of phase center variation (PCV) differences conceivable as an azimuth/elevation-dependent correction map. While the impact of the PCO difference on station positions is independent from the station's location, the impact of the PCV differences depends on their convolution with a station skyplot. As the main feature in a GNSS station skyplot is a substantial hole with a latitude-dependent position, the impact of receiver antenna calibration updates on station positions mainly depends on station latitude. Therefore, latitude-dependent models are proposed here.

These models were determined as follows. For each antenna type with an updated calibration, two sets of positions were estimated for the same selection of 82 well-distributed stations using the PPP strategy described in Sect. 2.2 and 24 h of observations: one set using the igs05.atx calibration of the antenna, the other using igs08.atx. It was systematically assumed that all 82 stations were equipped with the antenna of interest, which is of course not true. However, both sets of positions were then differenced, minimizing common errors. Latitude-dependent functions were finally fitted to the sets of East, North, and Up position differences.

The following generic latitude-dependent function was used:

$$dx = a + b\phi + c_2 \cos(2\phi) + s_2 \sin(2\phi) + c_4 \cos(4\phi) + s_4 \sin(4\phi) \quad (5)$$

where dx denotes either an East, North, or Up position difference and φ is the latitude. In several cases, not all terms of this model were relevant so that simple linear or even constant models could be fitted. Coefficients of the models and RMS values of the fits are given in a table available at ftp://igs.org/pub/station/coord/new_calib/lat_models.txt. Maps and plots of the position difference sets obtained for each antenna type can additionally be found at ftp://igs-rf.ign.fr/pub/IGS08/new_calib/simul.

A partial validation of the latitude-dependent models is discussed in IGS Mail 6356. It consisted of a comparison of corrections obtained with the latitude-dependent models and the PPP shifts individually derived for the IGS08 stations (Sects. 2.2 and 2.3). Differences between the model-derived and individually derived corrections are smaller than 0.5 mm in East and North and smaller than 1 mm in Up in most (76) cases. The average differences are, respectively, −0.0, −0.0 and −0.1 mm in East, North, and Up, with standard deviations of 0.2, 0.1, and 0.7 mm. There is thus an overall good agreement between the latitude-dependent models and the particular set of individual IGS08 corrections.

In summary, the proposed latitude-dependent models can be used to assess and correct the impact of the antenna calibration updates from igs05.atx to igs08.atx on the positions of specific stations. The models however have variable precisions: for some antenna types, the 3D RMS of the fit is as low as 0.1 mm, but it can go up to 6.4 mm for the LEIAT202-GP antenna, for example.

The IGS08 decay issue

Since the latest IGS data inputs into ITRF2008 (epoch 2009.5), many IGS08 stations have been affected by position discontinuities. Because IGS08 does not contain up-to-date coordinates for these stations anymore, they have become unusable as reference stations. The geometry of the IGS08 network is thus gradually degrading. In this section, we first present the current situation of the IGS08 network, which suggests that updates of IGS08 will probably be necessary before the next ITRF release in order to avoid a crisis situation for the IGS products. A strategy for such updates is then proposed.

Current situation of IGS08

From July 2009 to June 2011, 58 discontinuities have affected 48 different IGS08 stations including 31 discontinuities of seismic or post-seismic origin, 23 due to equipment changes and 4 with unknown causes. If we add 37 decommissioned or inactive stations, we end up with a total of 85 unusable IGS08 stations at present. This leaves 147 potentially usable IGS08 stations for current operational applications. But the number of usable reference stations in the latest IGS weekly solutions has rather oscillated around 143.

As an example, Fig. 5a shows the distribution of the 143 usable IGS08 stations in the IGS combined solution of GPS week 1638 (29 May–4 June 2011). One can clearly see the impacts of the large earthquakes of February 2010 in Chile and March 2011 in Japan, which left two large holes in the IGS08 network. Figure 5b shows the distribution of the 59 usable IGS08 core stations present in the same solution. The geometry degradation is clear in comparison with the complete IGS08 core network shown in Fig. 3.

Proposal for IGS08 updates

Among the IGS final products, a long-term cumulative frame is updated weekly. It is obtained by stacking the IGS weekly combined SINEX solutions with the same piece-wise linear model as used in the ITRF combination (IGS Mail 6401). As it contains up-to-date information, the IGS cumulative solution could be a useful tool to repair position breaks that affect IGS08 stations. After such a break, the IGS cumulative solution indeed contains two pre- and post-break position sets at the same reference epoch t_0 for the affected station, whose difference provides an estimate of the break amplitude. This estimate could then be used to add a post-break coordinate set to IGS08:

$$\begin{cases} X^{\text{post}}_{\text{IGS08}}(t_0) = X^{\text{pre}}_{\text{IGS08}}(t_0) + \left(X^{\text{post}}_{\text{cum}}(t_0) - X^{\text{pre}}_{\text{cum}}(t_0)\right) \\ \dot{X}^{\text{post}}_{\text{IGS08}} = \dot{X}^{\text{pre}}_{\text{IGS08}} \end{cases} \quad (6)$$

These equations just give the really basic idea of how updates of IGS08 could be performed. Their practical use, however, will require very special caution. The following conditions should be fulfilled at least:

- The break should not affect the velocity of the station. For example, this method would not be applicable in case of post-seismic deformations.
- It should be ensured that the position shift derived from the IGS cumulative solution is not biased because of periodic station motions. This could be achieved by waiting at least 2.5 years after a discontinuity happened before repairing it. A more practical solution would be to remove an estimate or a model of periodic station motions while estimating the position shift.

A similar method could also be used to transfer the coordinates of a decommissioned IGS08 station in case another co-located station has been installed beforehand. In such a case, a pseudo-local tie between the station pair could be derived from the IGS cumulative solution and then be used to introduce the new co-located station into IGS08. Once again, several conditions would have to be fulfilled. In particular, both stations should have simultaneously operated long enough to ensure that their velocities can be considered as equal.

However, such updates of IGS08 based on empirical offset corrections are not perfect by nature. That is why we urge IGS08 station operators to avoid unnecessary operations on station equipments that could lead to additional position discontinuities.

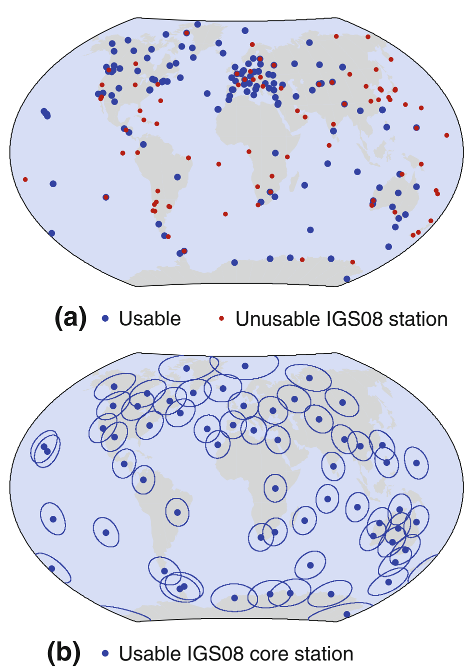

Fig. 5 Distribution **a** of the 143 usable IGS08 reference stations in the IGS combined solution of GPS week 1638 and **b** of the 59 usable IGS08 core stations—including substitute stations—the same solution

Conclusion

Starting with GPS week 1632, the IGS adopted a new reference frame (IGS08) directly derived from the latest ITRS realization (ITRF2008). In order to make IGS08 consistent with the new set of antenna calibrations (igs08.atx) simultaneously adopted by the IGS, corrections were however applied to the ITRF2008 positions of 65 IGS08 stations. These station-specific corrections make the definition and use of IGS08 inextricably linked to igs08.atx, as was also the case previously for IGS05 and igs05.atx. That is why IGS08 should be considered together with igs08.atx as a new framework rather than separately—as just a new reference frame.

We want in particular to warn users against inconsistent comparisons or alignments, which could be made, for example, between solutions derived with igs05.atx and IGS08. The correct way to transform results derived with igs05.atx to the IGS08 framework consists in (1) applying station-specific corrections accounting for the antenna calibration updates from igs05.atx to igs08.atx and (2) aligning the corrected solution to IGS08.

Corrections for step (1) are mainly antenna-type-dependent but also depend on station location (especially latitude) and environment. They can reach several centimeters. For users' convenience, a latitude-dependent model of the calibration change impact on station positions was derived for each antenna type contained in igs08.atx. These models however have variable precisions and should be used with care.

A set of 14 similarity parameters describing the frame part of the transformation from IGS05 to IGS08was computed and can be used for step (2). It is dominated, like the transformation from ITRF2005 to ITRF2008, by a −1-ppb scale reduction and a 6-mm *Z*-translation.

Because of the heterogeneous distribution of the IGS08 stations, a smaller well-distributed network was additionally designed and designated as the IGS08 core network. Its objective is to reduce the aliasing of non-linear station motions into similarity parameters, which occurs when aligning quasi-instantaneous global solutions to a secular reference frame. Simulations showed that using the IGS08 core network rather than the full IGS08 network helps to reduce this network effect. The IGS08 core network is thus recommended for the alignment of global solutions to IGS08. It is in particular used for the alignment of the weekly IGS SINEX solutions.

Both the full IGS08 network and the IGS08 core network have already seriously suffered from recent discontinuities at reference stations, mostly due to earthquakes and equipment changes. The decay of IGS08 will continue in future years and might eventually lead to a critical situation, in particular for the IGS products. That is why updates of IGS08 before the next ITRF release could turn out to be necessary. Those could rely on the operational IGS cumulative SINEX solution, practical details of which remain to be defined.

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