International Earth Rotation and Reference Systems Service (IERS)
Service International de la Rotation Terrestre et des Systèmes de Référence

IERS Technical Note No. 37

Analysis and results of ITRF2008

Z. Altamimi, X. Collilieux, L. Métivier

Verlag des Bundesamts für Kartographie und Geodäsie
Frankfurt am Main 2012

Analysis and results of ITRF2008

Z. Altamimi, X. Collilieux, L. Métivier

(IERS Technical Note ; No. 37)

International Earth Rotation and Reference Systems Service
Central Bureau
Bundesamt für Kartographie und Geodäsie
Richard-Strauss-Allee 11
60598 Frankfurt am Main
Germany
phone: ++49-69-6333-273/261/250
fax: ++49-69-6333-425
e-mail: central_bureau@iers.org
URL: www.iers.org

ISSN: 1019-4568 (print version)
ISBN: 978-3-86482-046-5 (print version)

An online version of this document is available at:
http://www.iers.org/TN37

Druckerei: Bonifatius GmbH, Paderborn

©Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, 2012

Contents

Summary **2**

I. ITRF2008 input data **3**
I.1. Space geodesy solutions 3
I.2. Local ties in co-location sites 4

II. ITRF2008 data analysis **5**
II.1. Combination model 5
II.2. ITRF2008 frame definition 6

III. ITRF2008 Results **7**
III.1. ITRF2008 origin and scale 7
III.2. ITRF2008 adjusted parameters 7
III.3. Transformation Parameters Between ITRF2008 and ITRF2005 8
III.4. Consistency between local ties and space geodesy estimates 9

IV. Access to the ITRF2008 files **11**

References **11**

Appendix **13**
A1. ITRF2008 tie and space geodesy discrepancies 14
A2. ITRF2008 Article 17
A3. Description of Technique Center solutions 37

Summary

The ITRF2008 is an improved realization of the International Terrestrial Reference System (ITRS) and is demonstrated to be of higher quality than the past ITRF versions. It is achieved in two-step procedure: (1) stacking the time series of station positions and Earth Orientation Parameters (EOPs) provided by the four IERS Technique Centers (TC); (2) combining the long-term solutions as obtained in step 1, together with local ties in co-location sites. The two-step procedure makes use of full variance-covariance information provided in SINEX format. The TC solutions incorporated in the ITRF2008 combination are free from any external constraints, thus preserving the actual space geodesy estimates of station positions, velocities and EOPs. The ITRF2008 origin is defined in such a way that it has zero translations and translation rates with respect to the mean Earth center of mass, averaged by the SLR station positions time series. Its scale is defined by nullifying the scale factor and its rate with respect to the mean of VLBI and SLR long-term solutions as obtained by stacking their respective time series. The ITRF2008 orientation (at epoch 2005.0) and its rate are aligned to the ITRF2005 using 179 stations of high geodetic quality.

The ITRF2008 includes the positions and velocities of 934 stations located at 580 sites. Figure 1 shows the coverage of these sites, underlying the co-located space geodesy techniques.

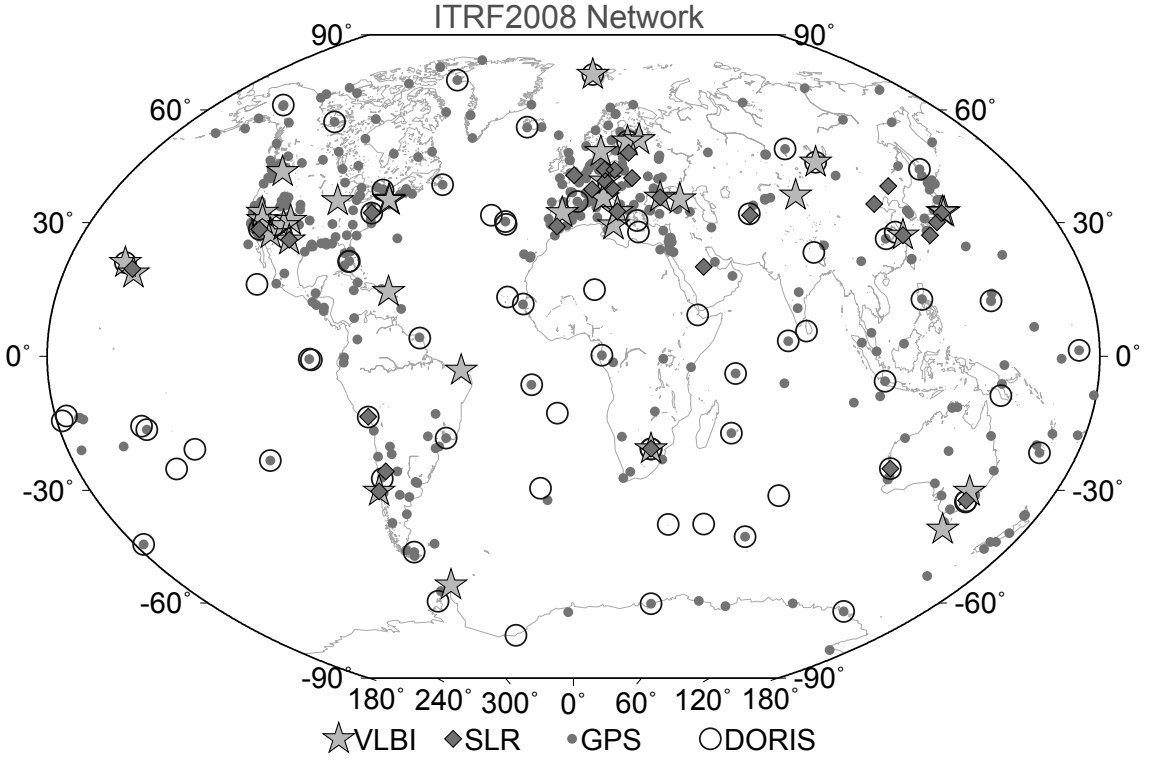


Figure 1. ITRF2008 Network

This technical note contains the main ITRF2008 products: station positions and velocities, the post fit residuals of the least squares adjustment as well as the transformation parameters between ITRF2008 and ITRF2005. The main technical procedure used to generate the ITRF2008, a thorough discussion of its quality as well as most important geodetic and geophysical results were published in (Altamimi et al, 2011), appended to this Technical Note.

I.ITRF2008 input data

As for any ITRF solution, the ITRF2008 relies not only on space geodesy solutions (stations positions time series and EOPs), but also on local ties at co-location sites. In the following two sub-sections we describe the two sets of data used in the ITRF2008 construction.

I.1. Space geodesy solutions

We recall that the ITRF input time series solutions are provided on a weekly basis by the International Association of Geodesy (IAG) International Services of satellite techniques: International GNSS Service (IGS), International Laser Ranging Service (ILRS), and International DORIS Service (IDS) and on a daily (VLBI session-wise) basis by the International VLBI Service (IVS). Each per-technique time series is already a combination of the individual Analysis Center (AC) solutions of that technique. A typical solution includes notably the positions of a network of stations, EOPs as well as the associated variance-covariance matrix. Table 1 summarizes the submitted solutions by the IAG services, specifying the time span, solution type and the constraints applied by the TCs as well as the estimated Earth Orientation Parameters (EOPs). The submitted VLBI solution involves more than 4000 session-wise SINEX[1] files spanning the entire VLBI observation history. The SLR solution covers also its full observation history, and comprises fortnightly SINEX files, with polar motion and Length of Day (LOD) estimated every three days between 1983.0 and 1993.0 and weekly SINEX files with daily polar motion and LOD estimates afterwards. The GPS submitted solution represents a large part of the first reprocessed solution by the IGS and covers the time period 1997.0 - 2009.5. Note that a very small portion of GLONASS observations were used by some IGS ACs that contributed to the reprocessing effort. For the first time the DORIS contribution is a combined time series involving seven ACs and covers its full observation history, using data from all available satellites with onboard DORIS receiver, except Jason-2. More detailed descriptions of the submitted solutions are available in the appendix of this technical note.

The ITRF2008 network comprises 934 stations located at 580 sites, with 463 sites in the northern hemisphere and 117 in the southern hemisphere. The ITRF2008 combination involves 84 co-location sites where two or more technique instruments were or are currently operating and for which local ties are available. Figure 1 illustrates the full ITRF2008 network where we superimposed the VLBI, SLR and DORIS sites co-located with GPS. In fact all the 84 co-location sites comprise permanent GPS stations, except two sites: Dionysos (Greece) were DORIS and an old mobile SLR were co-located, and Richmond (Virginia, USA) where VLBI, SLR and DORIS systems were co-located.

Table 1. Summary of Submitted Solutions to ITRF2008

TC	Data-Span	Solution Type	Constraints	EOPs
IVS	1980.0 - 2009.0	Normal Equation	None	Polar Motion, rate, UT1-UTC, LOD
ILRS	1983.0 - 2009.0	Variance-Covariance	Loose	Polar Motion, LOD
IGS	1997.0 - 2009.5	Variance-Covariance	Minimum	Polar Motion, rate, LOD
IDS	1993.0 - 2009.0	Variance-Covariance	Minimum	Polar Motion, rate, LOD

[1] http://www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex_cont.html

I.2. Local ties in co-location sites

The local ties used in the ITRF2008 combination are provided in SINEX format with known measurement epochs, and 63% of them are available with full variance-covariance information. Most of the local ties used in the ITRF2005 combination are used here with some updates, e.g. Tahiti (GPS, SLR, DORIS), Tsukuba (GPS, VLBI), Herstmonceux (GPS, SLR), Medicina and Noto (GPS, VLBI), Greenbelt (GPS, VLBI, SLR, DORIS), Maui/ Haleakala (GPS, SLR), San Fernando (GPS, SLR), Onsala (GPS, VLBI). Most of the local tie SINEX files were provided by the national agencies operating co-location sites, and all the DORIS co-location sites were re-adjusted by the IGN survey department in order to generate full SINEX files, using the most recent surveys operated at these sites. All the local tie SINEX files used in the ITRF2008 combination are available at

`http://itrf.ign.fr/local_surveys.php.`

The local ties (mainly old ones) which are not available in SINEX format were converted into a complete set of positions for each site, provided in SINEX format. This has been achieved by solving for the following system of observation equations (I.1):

$$\begin{pmatrix} \Delta x_s^{i,j} \\ \Delta y_s^{i,j} \\ \Delta z_s^{i,j} \end{pmatrix} = \begin{pmatrix} x^j - x^i \\ y^j - y^i \\ z^j - z^i \end{pmatrix} \tag{I.1}$$

Where ($\Delta x_s^{i,j}$, $\Delta y_s^{i,j}$, $\Delta z_s^{i,j}$) are the geocentric components of the tie vector linking two points i and j, of a given data set s. The standard deviations (SD) ($\sigma\Delta x_s^{i,j}$, $\sigma\Delta y_s^{i,j}$, $\sigma\Delta z_s^{i,j}$) for each local tie vector are used to compute a diagonal variance matrix. If these SD are not available, they are computed by :

$$\sigma_{computed} = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{I.2}$$

where,

σ_1 = 3 mm and $\sigma_2 = 10^{-6} \times \sqrt{(\Delta x_s^{i,j})^2 + (\Delta y_s^{i,j})^2 + (\Delta z_s^{i,j})^2}$

The equation system (I.1) needs of course initial coordinates for one point per tie vector set s, which are taken from existing ITRF solutions with 1 meter as standard deviation.

Counting the number of co-locations between VLBI, SLR and DORIS, taken by pairs, we find 8 VLBI-SLR, 10 VLBI-DORIS and 10 SLR-DORIS. These are very poor numbers of co-locations to allow a reliable combination of these three techniques alone. Therefore, the GPS is playing a major role in the ITRF combination, by linking together the three other techniques. We count in total 137 tie vectors between GPS and the three other techniques: 44 for VLBI, 48 for SLR and 45 for DORIS. 15 additional ties were also used between old and current DORIS beacon reference points in DORIS-only sites.

II.ITRF2008 data analysis

II.1. Combination model

The CATREF combination model used for the ITRF combination is extensively described in previous publications and in particular Altamimi et al. (2002), Altamimi et al. (2007). For the ITRF2008 generation, we followed the same analysis strategy used for the ITRF2005 combination, described in Altamimi et al. (2007). We recall here that two steps are currently used for the ITRF construction: (1) stacking the individual time series to estimate a long-term solution per technique comprising station positions at a reference epoch, velocities and daily EOPs; and (2) combining the resulting long-term solutions of the four techniques together with the local ties in co-location sites. The main two equations of the combination model are given below for completeness. They involve a 14-parameter similarity transformation, station positions and velocities and EOPs and are written as:

$$\begin{cases} X_s^i &= X_c^i + (t_s^i - t_0)\dot{X}_c^i \\ &+ T_k + D_k X_c^i + R_k X_c^i \\ &+ (t_s^i - t_k)\left[\dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i\right] \\ \\ \dot{X}_s^i &= \dot{X}_c^i + \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i \end{cases} \tag{II.1}$$

$$\begin{cases} x_s^p &= x_c^p + R2_k \\ y_s^p &= y_c^p + R1_k \\ UT_s &= UT_c - \frac{1}{f} R3_k \\ \dot{x}_s^p &= \dot{x}_c^p \\ \dot{y}_s^p &= \dot{y}_c^p \\ LOD_s &= LOD_c \end{cases} \tag{II.2}$$

where for each point i, X_s^i (at epoch t_s^i) and $\dot{X}_s^i$ are positions and velocities of technique solution s and X_c^i (at epoch t_0) and $\dot{X}_c^i$ are those of the combined solution c. For each individual frame k, as implicitly defined by solution s, D_k is the scale factor, T_k the translation vector and R_k the rotation matrix. The dotted parameters designate their derivatives with respect to time. The translation vector T_k is composed of three origin components, namely T_x, T_y, T_z, and the rotation matrix of three small rotation angles: R_x, R_y, R_z, following the three axes, respectively X, Y, Z. t_k is a conventionally selected epoch of the 7 transformation parameters. In addition to Eq. (II.1) involving station positions (and velocities), the EOPs are added by Eq. (II.2), making use of pole coordinates x_s^p, y_s^p and universal time UT_s as well as their daily rates $\dot{x}_s^p$, $\dot{y}_s^p$ and LOD_s. The link between the combined frame and the EOPs is ensured via the three rotation parameters appearing in the first three lines of Eq. (II.2).

The first line of Eq. (II.1) and the entire equation (II.2) are used to estimate long-term solutions for each technique, by accumulating (rigorously stacking) the individual technique time series of station positions and EOPs. In this process, the second line of equation (II.1) and the rates of the translation, scale and rotation parameters are not included, because station velocities are not available at the weekly (daily) basis. Moreover, a precise definition of the reference frame associated with the resulting long-term solution (comprising station positions at a reference epoch, station velocities and EOPs) has to be clearly specified. As transformation parameters are estimated between each weekly (or session-wise) frame and the long-term frame, it becomes necessary to define the long-term frame origin, scale, orientation and their time evolution, and therefore to complete the rank deficiency of the constructed normal equation. It is essential that the long-term solutions be representative of the mean origin and mean scale information of the space geodesy techniques. The particular type of minimal constraints introduced in Altamimi et al. (2007) have been designed for such purpose and are consequently

used here to preserve the long-term solution origin (for SLR and DORIS) and scale (for VLBI, SLR and DORIS). As the input GPS weekly frames have been explicitly expressed in the IGS05 (derived from ITRF2005, see IGSMail #5447), GPS long-term solution has been expressed with respect to ITRF2005 and was not used for the ITRF2008 origin and scale definition.

II.2. ITRF2008 frame definition

The second step of the ITRF2008 analysis consists in combining the long-term solutions of the four technique solutions together with local ties at co-location sites. The ITRF2008 is specified by the following frame parameters:

- Origin: The ITRF2008 origin is defined in such a way that there are null translation parameters at epoch 2005.0 and null translation rates with respect to the ILRS SLR time series.
- Scale: The scale of the ITRF2008 is defined in such a way that there are null scale factor at epoch 2005.0 and null scale rate with respect to the mean scale and scale rate of VLBI and SLR time series.
- Orientation: The ITRF2008 orientation is defined in such a way that there are null rotation parameters at epoch 2005.0 and null rotation rates between ITRF2008 and ITRF2005. These two conditions are applied over a set of 179 reference stations located at 131 sites as illustrated by Figure 2. The reference sites include 107 GPS, 27 VLBI, 15 SLR and 12 DORIS.

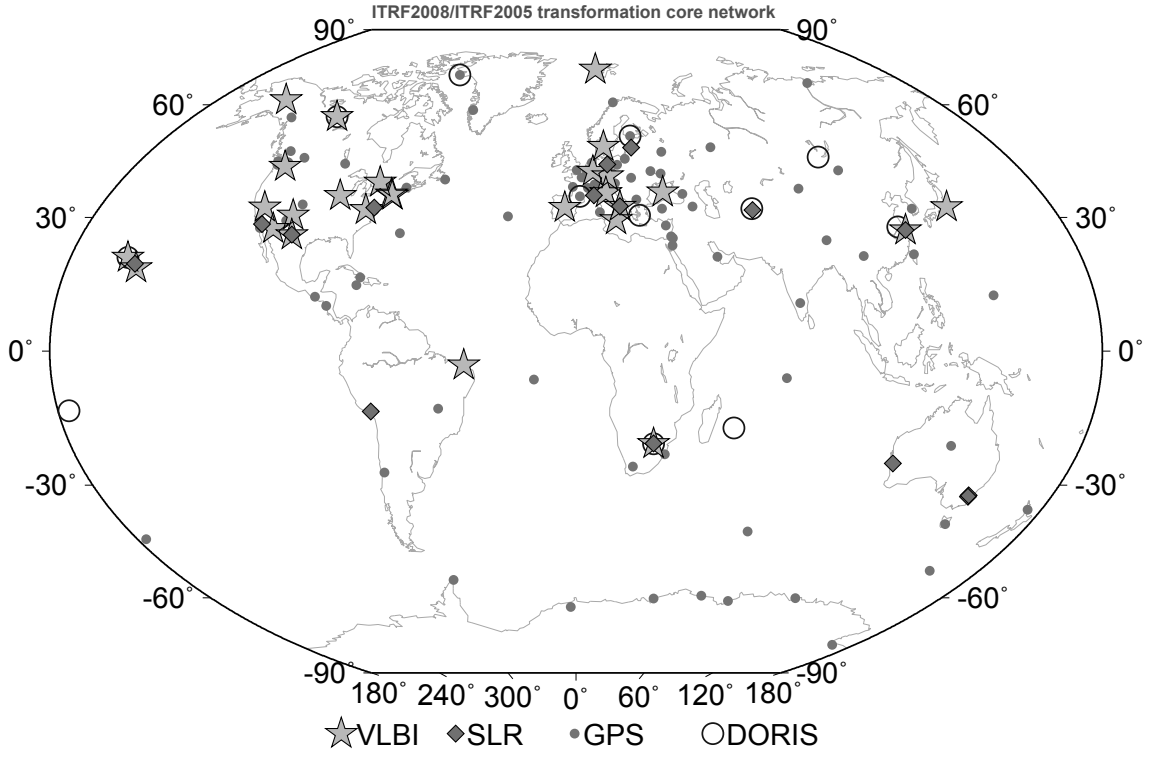


Figure 2. Location of the core sites used in the estimation of the 14 transformation parameters between ITRF2008 and ITRF2005 and their orientation alignment

III.ITRF2008 Results

III.1. ITRF2008 origin and scale

The submitted ILRS SLR solution was used to define the ITRF2008 origin, by fixing to zero (and consequently eliminating from the normal equation) the 6 parameters (translations and rates) of its corresponding long-term cumulative solution. An estimate of the translation components from ITRF2008 to ITRF2005 indicates differences at epoch 2005.0, namely: -0.5, -0.9 and -4.7 mm along X, Y and Z-axis, respectively. The translation rate differences are zero for Y and Z, while we observe an X-translation rate of 0.3 mm/yr (see III.3).

The ITRF2008 scale is specified by the average of VLBI and SLR scales, i.e. ITRF2008 scale is defined to be in the middle of the scales of VLBI and SLR long-term solutions. As results from the final ITRF2008 combination we found that the scale and scale rate differences between VLBI and SLR solutions are 1.05 ($\pm$0.13) ppb at epoch 2005.0 and 0.049 ($\pm$0.010) ppb/yr, respectively. This indicates an improvement compared to the past ITRF2005 results. This improvement is particularly due to the reprocessing effort of both IVS and ILRS. In addition, for some SLR co-located stations, we introduced offsets in the station position time series to account for significant discontinuities (but constraining the velocities to be equal) which improved the agreement of the estimated vertical velocities with GPS and consequently the scale rate agreement with VLBI. Propagating the scale discrepancy between SLR and VLBI at the start and end epochs of the time-span of VLBI data, leads to a maximum discrepancy of 1.2 ppb (8 mm at the equator), which could be considered as the level of the scale accuracy achievable today. Therefore defining the ITRF2008 scale to be in the middle of both technique solutions is the most appropriate choice that minimizes the scale impact for these two techniques when using the ITRF2008 products.

III.2. ITRF2008 adjusted parameters

The ITRF2008 adjusted parameters are:

- Station positions at epoch 2005.0 and velocities. These values are split into four tables corresponding to the four techniques: VLBI, SLR, GPS and DORIS. They are also provided in SINEX files with full variance covariance information. All the corresponding files are available through the ITRF2008 web and ftp sites. See next Chapter for access to these files.
- Transformation parameters between the individual technique solutions and ITRF2008. Note that the parameters defining the ITRF2008 origin, scale and orientation are eliminated from the normal equation.
- Earth orientation parameters. Consistent series of polar motion and its daily rates, universal time (UT1-UTC) and Length of Day (LOD), with the latter being determined by VLBI uniquely. The reason for using LOD values from VLBI only is to avoid contaminating the VLBI estimates by biased determinations from satellite techniques. The EOP series are also available through the ITRF2008 web and ftp sites (see below).

III.3. Transformation Parameters Between ITRF2008 and ITRF2005

For many applications and in order to ensure the link between ITRF2008 and ITRF2005, it is essential to assess consistently the transformation parameters between the two frames. The same 179 stations that were used to ensure the alignment of the ITRF2008 orientation and its rate to the ITRF2005, were also used to estimate the transformation parameters between the two

frames. The main criteria for selection of these 179 stations are (1) to have the best possible site distribution; (2) to involve as many as possible VLBI, SLR, GPS and DORIS stations and (3) to have the best agreement between the two frames in terms of post-fit residuals of the 14-parameter transformation. Regarding this third criteria, the WRMS values of the 14-parameter similarity transformation fit are 2.4, 2.9 and 3.9 mm in position (at epoch 2005.0) and 0.4, 0.4, 0.7 mm/yr in velocity, in east, north and vertical components, respectively. Table 4 lists the transformation parameters from ITRF2008 to ITRF2005, to be used with the transformation formula given by equation (III.1).

$$\begin{cases} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} + T + D \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} + R \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} \\ \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i05} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i08} + \dot{T} + \dot{D} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} + \dot{R} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} \end{cases} \quad \text{(III.1)}$$

where $i05$ designates ITRF2005 and $i08$ ITRF2008, T is the translation vector, $T = (T_x, T_y, T_z)^T$, D is the scale factor and R is 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 dotted parameters designate their time derivatives. The values of the 14 parameters are those listed in Table 4. Note that the inverse transformation from ITRF2005 to ITRF2008 follows by interchanging (i08) with (i05) and changing the sign of the transformation parameters.

Table 4. Transformation Parameters at epoch 2005.0 and their rates from ITRF2008 to ITRF2005, to be used with equation (III.1)

	Tx	Ty	Tz	D	Rx	Ry	Rz
	mm	mm	mm	ppb	mas	mas	mas
	$\dot{T}x$	$\dot{T}y$	$\dot{T}z$	$\dot{D}$	$\dot{R}x$	$\dot{R}y$	$\dot{R}z$
	mm/y	mm/y	mm/y	ppb/y	mas/y	mas/y	mas/y
	-0.5	-0.9	-4.7	0.94	0.00	0.00	0.00
$\pm$	0.2	0.2	0.2	0.03	0.08	0.08	0.08
	0.3	0.0	0.0	0.00	0.00	0.00	0.00
$\pm$	0.2	0.2	0.2	0.03	0.08	0.08	0.08

III.4. Consistency between local ties and space geodesy estimates

One of the most important by-products of the ITRF2008 combination is the assessment of the level of agreement between local ties and space geodesy estimates, through the availability of the post-fit residuals at co-location sites. In case of large discrepancies, discriminating between local ties and space geodesy estimates is a very delicate exercise, because the reasons for these discrepancies could be due to errors in local ties, in space geodesy estimates or in both. However quantifying the level of agreement between the two ensembles is very critical for further investigation and hopefully for identifying the error sources. At co-location sites, not only station position residuals are computed, but also velocity residuals. Therefore in order to take into

account velocity disagreements between the technique solutions, it is more effective to compute the tie discrepancies at their measurement epochs. In order to identify the most performing co-location sites, we list in Table 2 the tie vectors where the discrepancies are less than 6 mm (corresponding to the level of scale consistency between VLBI and SLR solutions) in all three components: North, East and Up. As the GPS is playing the major role of connecting the three techniques together, the vectors listed in Table 2 are from GPS to other technique reference markers. With some exceptions, the geodetic instruments at the co-location sites listed in this table are still in operation in 2010. If we count the percentage of these sites listed in Table 2 over the total currently operating co-locations, we find approximately: 47%, 43% and 34% for GPS-VLBI, GPS-SLR and GPS-DORIS, respectively. However, using this sub-set of local ties only, would result in a non-optimal combination. Indeed a test combination was performed involving these co-location sites only yielded an increase of the uncertainties of the estimated parameters by a factor of 3.4, compared to the results of the ITRF2008 combination. In particular the obtained scale factor between VLBI and SLR would be 0.83 ppb, but with an increase of its uncertainty: ± 0.44 versus ± 0.13 ppb. In addition, we found the following percentages of co-location sites where tie discrepancies are larger than 10 mm: 29%, 28% and 54% for GPS-VLBI, GPS-SLR and GPS-DORIS, respectively. Rejecting these co-location sites from the ITRF2008 combination increases the uncertainties of the estimated parameters by a factor of 2. Table 3 summarizes the tie discrepancy percentages following three categories: less than 6 mm, between 6 and 10 mm and larger than 10 mm.

The full list of discrepancies between ITRF2008 local tie and space geodesy estimates, as results from the ITRF2008 global adjustment is available in the appendix.

Table 2. ITRF2008 tie discrepancies less than 6 mm at tie epochs in (E)ast, (N)orth and (U)p : Residuals = Space Geodesy - Terrestrial Tie (in mm). The tie vectors are listed from GPS to other technique reference markers.

CODE DOMES #	CODE DOMES #	East	North	Up	Epoch	Technique
GRAS 10002M006	7835 10002S001	1.3	-3.6	-5.6	99:284	SLR
GRAS 10002M006	7845 10002S002	-1.1	-1.2	-0.6	99:284	SLR
TLSE 10003M009	TLSA 10003S001	-1.2	0.7	2.3	4: 34	DORIS
NYA1 10317M003	SPIB 10317S004	-1.2	5.7	2.2	3:228	DORIS
NYA1 10317M003	SPJB 10317S005	-1.9	-0.8	-0.9	3:228	DORIS
NYA1 10317M003	7331 10317S003	2.9	-2.7	1.2	3:228	VLBI
ONSA 10402M004	7213 10402S002	5.4	-0.6	-5.2	2:193	VLBI
GRAZ 11001M002	7839 11001S002	1.4	-0.6	-5.9	92:319	SLR
BOR1 12205M002	7811 12205S001	0.5	1.7	-2.9	94: 10	SLR
YSSK 12329M003	SAKA 12329S001	-0.4	-2.3	-2.9	4:231	DORIS
YSSK 12329M003	SAKB 12329S002	2.3	-5.0	-2.3	4:231	DORIS
MATE 12734M008	7941 12734S008	-3.7	-4.7	-1.6	4:300	SLR
HERS 13212M007	7840 13212S001	-1.2	-3.1	-2.4	8:177	SLR
ZIMM 14001M004	7810 14001S007	-1.9	-2.2	-5.2	96: 95	SLR
WTZZ 14201M014	7224 14201S004	-1.4	-4.1	-0.3	2:266	VLBI
BJFS 21601M001	7249 21601S004	0.6	2.2	5.9	3:171	SLR
TSKB 21730S005	7345 21730S007	-2.9	-0.8	-3.0	8: 16	VLBI
HRAO 30302M004	7232 30302S001	-1.6	3.2	2.0	3:214	VLBI
HRAO 30302M004	7501 30302M003	-2.2	2.6	3.5	3:214	SLR
HRAO 30302M004	HBKB 30302S006	5.4	-1.0	-4.2	3:214	DORIS
NKLG 32809M002	LIBB 32809S003	2.9	0.2	2.7	99: 36	DORIS
STJO 40101M001	7625 40101M003	0.3	0.1	1.6	99:269	VLBI
YELL 40127M003	7285 40127M001	-3.9	-3.9	-1.0	1:285	VLBI
PIE1 40456M001	7234 40456S001	-3.1	-2.8	-0.3	92:336	VLBI
NLIB 40465M001	7612 40465S001	-3.4	-2.0	-5.2	93: 64	VLBI
MKEA 40477M001	7617 40477S001	-3.7	-1.1	0.8	96:221	VLBI
MONP 40497M004	MONB 40497S008	3.1	-4.7	-0.8	5:335	DORIS
MONP 40497M004	7110 40497M001	3.2	-2.5	5.7	99:280	SLR
FORT 41602M001	7297 41602S001	-0.6	-4.0	2.3	93:264	VLBI
GLPS 42005M002	SCRB 42005S001	-2.8	-1.0	-1.1	5: 92	DORIS
CRO1 43201M001	7615 43201S001	-1.5	2.2	1.6	94: 16	VLBI
HOB2 50116M004	7242 50116S002	4.7	-3.0	-2.0	2: 81	VLBI
STR1 50119M002	7849 50119S001	4.1	0.1	4.0	1:209	SLR
CHAT 50207M001	CHAB 50207S001	0.1	0.6	-3.3	99: 56	DORIS
SYOG 66006S002	7342 66006S004	0.8	3.8	0.6	0: 1	VLBI
KERG 91201M002	KERB 91201S003	-3.2	-2.2	2.0	7:101	DORIS
DUM1 91501M001	ADEB 91501S002	-0.2	-0.2	1.3	8: 39	DORIS
DUM1 91501M001	ADFB 91501S003	-5.0	-3.0	3.3	8: 39	DORIS
THTI 92201M009	PAPB 92201S007	-1.3	1.7	4.4	7:278	DORIS
NOUM 92701M003	NOUB 92701S002	0.5	5.8	2.2	5:236	DORIS
REUN 97401M003	REUB 97401S002	0.4	2.5	-1.0	3:335	DORIS

Table 3. Tie discrepancy percentage

Discrepancy	GPS-VLBI	GPS-SLR	GPS-DORIS
$<$ 6 mm	47	43	34
6-10 mm	24	29	12
$>$ 10 mm	29	28	54

IV. Access to the ITRF2008 files

All the ITRF2008 related files are available at the ITRF2008 web site

http://itrf.ign.fr/ITRF_solutions/2008/

The ITRF2008 SINEX files are available via anonymous ftp :

ftp itrf.ign.fr

username: anonymous
password: e-mail address

move to the itrf2008 directory (cd pub/itrf/itrf2008)

- compressed full ITRF2008 SINEX file (ITRF2008.SNX.gz, available on request)
- ITRF2008-TRF.SNX.gz ITRF2008 Station positions and velocities
- ITRF2008-EOP-IVS.SNX.gz VLBI Station positions, velocities and EOPs starting from 1980.0
- ITRF2008-TRF-IVS.SNX.gz VLBI Station positions and velocities
- ITRF2008-EOP-ILRS.SNX.gz SLR Station positions, velocities and EOPs starting from 1983.0
- ITRF2008-TRF-ILRS.SNX.gz SLR Station positions and velocities
- ITRF2008-EOP-IGS.SNX.gz GPS Station positions, velocities and EOPs starting from 1997.0
- ITRF2008-TRF-IGS.SNX.gz GPS Station positions and velocities
- ITRF2008-EOP-IDS.SNX.gz DORIS Station positions, velocities and EOPs starting from 1993.0
- ITRF2008-TRF-IDS.gz DORIS Station positions and velocities

Other files

- ITRF2008_EOP-F1.DAT. Complete EOP list file: one line per day (MJD) listing all parameter of that day.
- ITRF2008_EOP-F2.DAT. Complete EOP list file: one parameter per line.
- ITRF2008-RESIDUALS.DAT. Station position, velocity and local tie residuals of the ITRF2008 combination

References

Altamimi Z, Sillard P, Boucher C (2002) ITRF2000: A New Release of the International Terrestrial Reference Frame for Earth Science Applications, J Geophys Res 107(B10):2214, doi:10.1029/2001JB000561.

Altamimi Z, Collilieux X, Legrand J, Garayt B, Boucher C (2007) ITRF2005: A New Release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters, 2007, J Geophys Res 112 (B09401), doi:10.1029/2007JB004949.

Altamimi Z, Collilieux X, Métivier L (2011) ITRF2008: an improved solution of the international terrestrial reference frame, Journal of Geodesy, 85 (8) (457-473), DOI: 10.1007/s00190-011-0444-4, DOI: 10.1007/s00190-011-0444-4.

Appendix

A1. ITRF2008 tie and space geodesy discrepancies

A2. ITRF2008 Article

Altamimi Z, Collilieux X, Métivier L (2011) ITRF2008: an improved solution of the international terrestrial reference frame, Journal of Geodesy, 85 (8) (457-473), DOI: 10.1007/s00190-011-0444-4, DOI: 10.1007/s00190-011-0444-4.

A3. Description of Technique Center solutions

- IVS solution description (auth. S. Bckmann, A. Nothnagel)
- ILRS solution description (auth. E. Pavlis, V. Luceri, C. Sciarretta, R. Kelm)
- IGS solution description (auth. R. Ferland)
- IDS solution description (auth. J.J. Valette, F. Lemoine)

ITRF2008 tie and space geodesy discrepancies

ITRF2008 tie discrepancies at tie epochs in (E)ast, (N)orth, (U)p and (D)istance : Residuals = Space Geodesy - Terrestrial Tie (in mm). Each tie vector component is flagged by '-' if the residual is less than 5 mm and by '*' otherwise. (Sol)ution number that identifies the reference coordinates.

Code	DOMES #	Sol	Code	DOMES #	Sol	E	N	U	D	Epoch	ENU	Tech	D
YELL	40127M003	3	7285	40127M001	1	-3.9	-3.9	-1.0	-2.2	1:285	---	VLBI	
WTZZ	14201M014	1	7224	14201S004	1	-1.4	-4.1	-0.3	-1.6	2:266	---	VLBI	
SYOG	66006S002	1	7342	66006S004	1	0.8	3.8	0.6	2.8	0: 1	---	VLBI	
HOB2	50116M004	1	7242	50116S002	1	4.7	-3.0	-2.0	1.4	2: 81	---	VLBI	
TSKB	21730S005	3	7345	21730S007	1	-2.9	-0.8	-3.0	-0.5	8: 16	---	VLBI	
CRO1	43201M001	2	7615	43201S001	1	-1.5	2.2	1.6	-1.9	94: 16	---	VLBI	
HRAO	30302M004	1	7232	30302S001	1	-1.6	3.2	2.0	2.3	3:214	---	VLBI	
STJO	40101M001	5	7625	40101M003	1	0.3	0.1	1.6	-0.3	99:269	---	VLBI	
FORT	41602M001	1	7297	41602S001	1	-0.6	-4.0	2.3	3.9	93:264	---	VLBI	
MKEA	40477M001	1	7617	40477S001	1	-3.7	-1.1	0.8	-3.7	96:221	---	VLBI	
DRAO	40105M002	2	7283	40105M001	1	-0.7	-0.7	-0.5	-0.7	89:234	---	VLBI	
PIE1	40456M001	1	7234	40456S001	1	-3.1	-2.8	-0.3	3.7	92:336	---	VLBI	
NYA1	10317M003	2	7331	10317S003	1	2.9	-2.7	1.2	3.9	3:228	---	VLBI	
TIDB	50103M108	2	1545	50103S010	1	-0.5	0.6	9.2	1.1	95:263	--*	VLBI	
WES2	40440S020	2	7209	40440S003	1	0.6	-3.7	10.2	2.6	96:278	--*	VLBI	
MEDI	12711M003	2	7230	12711S001	2	-2.4	-2.7	6.3	-1.2	7:241	--*	VLBI	
YEBE	13420M001	1	7333	13420S001	1	-3.6	-1.1	-6.0	2.7	99:322	--*	VLBI	
NLIB	40465M001	1	7612	40465S001	1	-3.4	-2.0	-5.2	-3.8	93: 64	--*	VLBI	
VNDP	40420M007	6	7223	40420M002	1	2.3	-1.3	-7.0	1.7	91:335	--*	VLBI	
CONZ	41719M002	1	7640	41719S001	1	1.4	-4.2	7.8	-4.3	3: 80	--*	VLBI	
ALGO	40104M002	5	7282	40104S001	1	-2.9	-4.0	9.0	5.7	99: 1	--*	VLBI	*
OHI2	66008M005	1	7245	66008S001	1	-0.8	8.4	3.4	-1.4	2: 43	-*-	VLBI	
SHAO	21605M002	2	7227	21605S009	1	-2.1	-10.1	-4.9	7.1	3:332	-*-	VLBI	*
FAIR	40408M001	2	7225	40408S002	1	-2.3	-8.2	2.1	-5.7	1:274	-*-	VLBI	*
MDO1	40442M012	1	7613	40442S017	1	-0.2	-7.6	16.5	3.6	93: 76	-**	VLBI	
WTZZ	14201M014	1	7593	14201S100	1	-1.7	-5.6	7.8	-0.7	2:266	-**	VLBI	
KSMV	21701S007	1	1856	21701S001	1	-1.3	11.0	99.2	0.1	99:292	-**	VLBI	
YELL	40127M003	3	7296	40127M004	1	-3.1	-6.6	-8.3	0.4	1:285	-**	VLBI	
MDO1	40442M012	1	7216	40442S003	1	2.0	-9.8	7.3	7.1	93: 76	-**	VLBI	*
WES2	40440S020	2	7205	40440S002	1	9.0	-0.7	-2.8	2.5	96:278	*--	VLBI	
MADR	13407S012	8	1565	13407S010	1	-9.1	-1.0	1.0	6.0	99: 1	*--	VLBI	*
SANT	41705M003	2	1404	41705S006	1	16.1	4.9	9.4	-1.6	92:192	*-*	VLBI	
ZECK	12351M001	2	7381	12351S001	1	-25.5	-3.5	13.9	2.2	5: 1	*-*	VLBI	
ONSA	10402M004	2	7213	10402S002	1	5.4	-0.6	-5.2	2.1	2:193	*-*	VLBI	
NOT1	12717M004	1	7547	12717S001	1	-9.1	-3.4	7.2	8.9	5:264	*-*	VLBI	*
MATE	12734M008	4	7243	12734S005	1	-6.9	-6.8	-2.0	-0.9	4:300	**-	VLBI	
KOKB	40424M004	4	1311	40424S001	1	17.4	38.2	1.8	-10.4	2:319	**-	VLBI	*
KOKB	40424M004	4	7298	40424S007	1	18.1	36.6	3.3	26.6	2:319	**-	VLBI	*
SVTL	12350M001	2	7380	12350S001	1	-5.6	-10.7	-10.2	2.3	5: 1	***	VLBI	
BRFT	41602M002	1	7297	41602S001	1	-5.7	-5.1	12.1	7.8	6: 78	***	VLBI	*
ZIMM	14001M004	1	7810	14001S001	1	0.5	-1.3	0.9	-1.6	96: 95	---	SLR	
GRAS	10002M006	1	7845	10002S002	1	-1.1	-1.2	-0.6	-0.9	99:284	---	SLR	
STR1	50119M002	3	7849	50119S001	1	4.1	0.1	4.0	-0.8	1:209	---	SLR	
HERS	13212M007	5	7840	13212S001	1	-1.2	-3.1	-2.4	-0.6	8:177	---	SLR	
MATE	12734M008	4	7941	12734S008	1	-3.7	-4.7	-1.6	3.6	4:300	---	SLR	
BOR1	12205M002	1	7811	12205S001	2	0.5	1.7	-2.9	0.6	94: 10	---	SLR	
MAUI	40445S008	1	7120	40445M002	1	0.6	-1.0	-3.9	-0.5	6:260	---	SLR	
HRAO	30302M004	1	7501	30302M003	1	-2.2	2.6	3.5	2.9	3:214	---	SLR	
GODE	40451M123	2	7105	40451M105	1	-3.2	1.2	-6.1	0.4	8: 1	--*	SLR	
CAGL	12725M003	1	7545	12725M002	1	2.1	3.0	6.7	-3.0	95:161	--*	SLR	
MAUI	40445S008	1	7210	40445M001	3	2.8	-0.7	-8.7	1.8	6:260	--*	SLR	
MAUI	40445S008	1	7119	40445M004	1	0.0	-1.4	-6.7	2.9	6:260	--*	SLR	
MDO1	40442M012	1	7850	40442M008	1	2.1	0.8	21.5	-2.8	93: 76	--*	SLR	
AREQ	42202M005	5	7403	42202M003	6	1.3	-0.3	-6.6	-0.6	7:123	--*	SLR	
GRAZ	11001M002	1	7839	11001S002	1	1.4	-0.6	-5.9	-2.2	92:319	--*	SLR	
ALGO	40104M002	5	7410	40104M003	1	1.6	-4.5	7.1	2.3	99: 1	--*	SLR	

YAR1	50107M004	3	7090	50107M001	1	3.3	-1.9	14.4	-3.7	3:305	--*	SLR	
MONP	40497M004	2	7110	40497M001	1	3.2	-2.5	5.7	-1.6	99:280	--*	SLR	
THTI	92201M009	2	7124	92201M007	1	3.0	0.8	9.9	1.6	7:278	--*	SLR	
ZIMM	14001M004	1	7810	14001S007	1	-1.9	-2.2	-5.2	0.1	96: 95	--*	SLR	
POTS	14106M003	1	7836	14106S009	1	2.7	-0.2	6.8	-2.7	94:221	--*	SLR	
GRAS	10002M006	1	7835	10002S001	1	1.3	-3.6	-5.6	1.3	99:284	--*	SLR	
WTZZ	14201M014	1	8834	14201S018	2	-1.4	-4.2	7.6	-0.2	2:266	--*	SLR	
BJFS	21601M001	1	7249	21601S004	1	0.6	2.2	5.9	-2.5	3:171	--*	SLR	
METS	10503S011	1	7806	10503S014	1	-2.3	-3.2	-10.8	7.3	0:299	--*	SLR	*
CONZ	41719M002	1	7405	41719M001	1	1.4	-4.6	6.9	-5.2	3: 80	--*	SLR	*
EISL	41703M003	1	7097	41703M002	1	-2.1	-21.1	-3.0	-17.1	1: 46	-*-	SLR	*
AREQ	42202M005	1	7403	42202M003	1	3.9	-6.9	9.8	3.0	95: 1	-**	SLR	
MDO1	40442M012	1	7080	40442M006	2	4.4	-8.3	17.5	4.0	93: 76	-**	SLR	
KGNI	21704S005	1	7308	21704S002	1	-1.9	-6.0	34.8	-0.4	99:285	-**	SLR	
SHAO	21605M002	2	7837	21605S001	2	4.5	-5.0	-20.3	-3.1	3:332	-**	SLR	
KSMV	21701S007	1	1857	21701S004	1	-2.2	18.5	72.5	9.4	99:292	-**	SLR	*
KSMV	21701S007	1	7335	21701M002	1	4.6	8.6	70.3	14.1	99:292	-**	SLR	*
AJAC	10077M005	1	7848	10077M002	1	-6.1	-3.8	14.5	-4.0	0: 1	*-*	SLR	
SUTH	30314M002	1	7502	30314M001	1	12.6	3.6	7.6	-12.5	97:340	*-*	SLR	*
POTS	14106M003	1	7841	14106S011	1	-20.0	-1.4	-8.7	11.3	94:221	*-*	SLR	*
URUM	21612M001	1	7355	21612M002	1	-18.2	-3.3	24.6	-18.4	99: 1	*-*	SLR	*
STR1	50119M002	3	7825	50119S003	1	6.5	-5.4	1.0	3.9	1:209	**-	SLR	
METS	10503S011	1	7805	10503S001	1	23.2	57.8	0.6	-41.7	0:299	**-	SLR	*
WUHN	21602M001	2	7231	21602S004	1	-8.6	-31.8	36.0	-4.0	3:342	***	SLR	
TIDB	50103M108	2	7843	50103S007	1	9.2	10.7	10.8	-11.6	95:263	***	SLR	*
KGNI	21704S005	1	7328	21704M001	1	-5.5	-8.2	67.4	-16.0	99:285	***	SLR	*
SFER	13402M004	6	7824	13402S007	1	7.1	-10.0	-16.5	-9.6	9:192	***	SLR	*
LHAS	21613M001	2	7356	21613M003	1	11.5	13.8	-35.5	-15.5	0: 56	***	SLR	*
QUIN	40433M004	2	7109	40433M002	1	-9.6	5.2	24.7	9.0	85:247	***	SLR	*
REUN	97401M003	1	REUB	97401S002	1	0.4	2.5	-1.0	-2.4	3:335	---	DORIS	
TLSE	10003M009	2	TLSA	10003S001	1	-1.2	0.7	2.3	-0.8	4: 34	---	DORIS	
NYA1	10317M003	2	SPJB	10317S005	1	-1.9	-0.8	-0.9	-1.3	3:228	---	DORIS	
YSSK	12329M003	2	SAKA	12329S001	4	-0.4	-2.3	-2.9	1.3	4:231	---	DORIS	
DIOA	12602S011	1	DIOB	12602S012	1	-0.1	0.8	-0.2	0.8	6:136	---	DORIS	
NKLG	32809M002	1	LIBB	32809S003	1	2.9	0.2	2.7	0.6	99: 36	---	DORIS	
DJIA	39901S002	1	DJIB	39901S003	1	0.0	0.2	-0.1	-0.2	0:183	---	DORIS	
THTI	92201M009	2	PAPB	92201S007	1	-1.3	1.7	4.4	1.3	7:278	---	DORIS	
DUM1	91501M001	2	ADFB	91501S003	1	-5.0	-3.0	3.3	1.3	8: 39	---	DORIS	
DUM1	91501M001	2	ADEB	91501S002	1	-0.2	-0.2	1.3	0.1	8: 39	---	DORIS	
DJIA	39901S002	1	DJIB	39901S003	1	-0.1	0.3	0.0	-0.2	6:178	---	DORIS	
GOMA	40405S005	1	GOMB	40405S037	1	2.1	0.1	-2.8	-2.8	96:244	---	DORIS	
MONP	40497M004	5	MONB	40497S008	1	3.1	-4.7	-0.8	4.0	5:335	---	DORIS	
AMSA	91401S001	1	AMTB	91401S003	1	-1.2	2.3	3.4	-2.5	3:326	---	DORIS	
CROB	91301S001	1	CRPB	91301S002	1	-1.2	1.1	0.4	0.4	7: 96	---	DORIS	
GLPS	42005M002	1	SCRB	42005S001	1	-2.8	-1.0	-1.1	1.4	5: 92	---	DORIS	
CHAT	50207M001	1	CHAB	50207S001	1	0.1	0.6	-3.3	-0.6	99: 56	---	DORIS	
KERG	91201M002	2	KERB	91201S003	1	-3.2	-2.2	2.0	-2.9	7:101	---	DORIS	
BELB	66018S001	1	BEMB	66018S002	1	-0.3	0.3	-5.0	-0.3	5: 42	---	DORIS	
ROTA	66007S001	1	ROTB	66007S002	1	1.1	0.9	0.2	-1.3	5: 54	---	DORIS	
DIOA	12602S011	1	7515	12602M002	1	3.5	-4.7	1.8	-5.5	6:136	---	DORIS	*
SYOG	66006S002	1	SYOB	66006S001	1	-3.4	0.4	-47.5	3.1	0: 1	--*	DORIS	
NYA1	10317M003	2	SPIA	10317S002	1	-3.7	-1.8	-7.2	-2.3	3:228	--*	DORIS	
NOUM	92701M003	3	NOUA	92701S001	1	-0.9	0.2	6.0	0.1	5:236	--*	DORIS	
METS	10503S011	1	META	10503S013	1	4.3	0.1	-11.0	-0.7	0:299	--*	DORIS	
METS	10503S011	1	METB	10503S015	1	-3.1	2.6	-7.8	3.3	0:299	--*	DORIS	
TLSE	10003M009	2	TLHA	10003S003	1	-2.5	-1.6	-8.0	0.9	4: 34	--*	DORIS	
THTI	92201M009	2	PATB	92201S010	1	-3.2	0.2	6.4	-1.4	7:278	--*	DORIS	
AOML	49914S001	1	MIAB	49914S003	1	4.5	-3.5	-11.1	2.0	5: 36	--*	DORIS	
AMTB	91401S003	1	AMUB	91401S004	1	-0.5	-4.6	-7.9	-7.8	7:108	--*	DORIS	*
THTI	92201M009	2	PAQB	92201S008	1	1.6	4.9	10.1	5.6	7:278	--*	DORIS	*
SEY1	39801M001	3	MAHB	39801S005	1	-2.3	-1.2	-94.1	7.2	1:152	--*	DORIS	*
NYA1	10317M003	2	SPIB	10317S004	1	-1.2	5.7	2.2	-3.6	3:228	-*-	DORIS	
YSSK	12329M003	2	SAKB	12329S002	2	2.3	-5.0	-2.3	5.0	4:231	-*-	DORIS	
REYK	10202M001	4	REZB	10202S003	1	2.9	-6.2	1.0	0.7	4:248	-*-	DORIS	

```
NOUM 92701M003  3 NOUB 92701S002  1    0.5   5.8   2.2   0.1  5:236 -*- DORIS
KIT3 12334M001  1 KIUB 12334S006  1    1.1   7.7  -2.6  -6.0  1:115 -*- DORIS *
MANA 22006S001  1 MANB 22006S002  1    4.7 -11.7   0.7  -7.1  3: 54 -*- DORIS *
RIOG 41507M004  2 RIPB 41507S005  1    3.3  -7.0   3.9   7.4  1: 15 -*- DORIS *
HRAO 30302M004  1 HBKA 30302S202  1    2.5 -15.6  -7.9  -0.6  3:214 -** DORIS
RIOG 41507M004  2 RIOB 41507S004  1   -4.4  11.0  -6.0  -4.4  1: 15 -** DORIS
STR1 50119M002  3 MSPB 50119S004  1   -4.3   5.3   6.8  -4.3  1:209 -** DORIS
STJO 40101M001  5 STJB 40101S002  1    3.0  14.2   7.6   2.5 99:269 -** DORIS
RIOG 41507M004  2 RIOA 41507S003  1    0.1   5.5  18.7  -2.8  1: 15 -** DORIS
YAR1 50107M004  3 YARB 50107S010  1    0.9  15.6  13.4   9.2  3:305 -** DORIS *
YAR1 50107M004  3 YASB 50107S011  1   -2.8  10.0   6.7  10.5  3:305 -** DORIS *
RIDA 40499S016  1 7295 40499M002  1    2.4  -9.5 -41.5   9.8 93:  4 -** DORIS *
MONP 40497M004  5 MOOB 40497S009  1   -2.4 -12.3 -11.4  11.6  5:335 -** DORIS *
AREQ 42202M005  1 AREA 42202S005  1    1.2 -15.2  40.8  13.4 95:  1 -** DORIS *
TRIA 30604S001  2 TRIB 30604S002  1    4.0 -15.3 -22.2  16.5  2: 23 -** DORIS *
BADA 12338S001  1 BADB 12338S002  1    2.5  -5.5  -8.2  -8.1  4:224 -** DORIS *
STR1 50119M002  3 MSOB 50119S002  3   -1.7   8.3   5.1  -7.7  1:209 -** DORIS *
MARA 30313S001  1 MATB 30313S003  1   -7.9   2.3   0.6   0.8  4:241 *-- DORIS
HRAO 30302M004  1 HBKB 30302S006  1    5.4  -1.0  -4.2   4.9  3:214 *-- DORIS
YELL 40127M003  3 YEMB 40127S009  1    9.6  -1.6   1.6   7.9  1:285 *-- DORIS *
YELL 40127M003  3 YELB 40127S008  1    9.1  -1.1  -4.3   7.5  1:285 *-- DORIS *
SYOG 66006S002  1 SYPB 66006S003  1    9.9   1.7  -2.4  -5.3  0:  1 *-- DORIS *
BAKO 23101M002  4 CIBB 23101S001  1   10.8  -1.8  49.9  -0.3  0:350 *-* DORIS
SANT 41705M003  2 SANA 41705S007  1    9.8   2.2 -22.6   2.0 96:339 *-* DORIS
REUN 97401M003  1 REUA 97401S001  1    5.7   4.0 -10.7  -4.3  3:335 *-* DORIS
SANT 41705M003  2 SAOB 41705S008  1   14.6   0.8  29.4   0.0 96:339 *-* DORIS
NKLG 32809M002  1 LIBA 32809S002  1   15.7  -2.6  22.3   1.0 99: 36 *-* DORIS
KERG 91201M002  2 KESB 91201S004  1    6.3   1.2   7.3  -1.7  7:101 *-* DORIS
GUAM 50501M002  1 GUAB 50501S001  1   14.6  -0.5  24.2  10.4 93:346 *-* DORIS *
THU3 43001M002  1 THUB 43001S005  1   26.1   1.2  -7.6  16.0  2:257 *-* DORIS *
FAIR 40408M001  2 FAIB 40408S005  1   14.6  -4.9 -16.5  -9.2  1:274 *-* DORIS *
BAKO 23101M002  4 CICB 23101S002  1   -9.4   1.2  43.3   6.0  0:350 *-* DORIS *
SANT 41705M003  2 SANB 41705S009  1   -8.7   4.9  38.6   6.5 96:339 *-* DORIS *
ASC1 30602M001  1 ASDB 30602S004  1   29.1   3.7 -17.0  28.3  3:350 *-* DORIS *
MARA 30313S001  1 MARB 30313S002  1  -19.8   7.8   3.7   4.7  4:241 **- DORIS
REYK 10202M001  4 REYA 10202S001  1  -10.7 -10.7   3.1   2.6  4:248 **- DORIS
REYK 10202M001  4 REYB 10202S002  1   14.5  -9.4   1.6 -17.3  4:248 **- DORIS *
PDEL 31906M004  1 PDLB 31906S001  1   16.1   9.7   3.6 -18.0  1: 79 **- DORIS *
EISL 41703M003  1 EASB 41703S009  1   18.6   7.0  -4.4  -6.2  1: 46 **- DORIS *
KIT3 12334M001  1 KITB 12334S005  1   -5.2  10.3  -1.5  -7.6  1:115 **- DORIS *
DUM1 91501M001  2 ADEA 91501S001  1   -8.8 -10.1   4.9  -9.3  8: 39 **- DORIS *
AREQ 42202M005  5 ARFB 42202S007  1  -28.8  28.4  -4.6  -5.1  7:123 **- DORIS *
ADEA 91501S001  1 ADEB 91501S002  1    8.5   9.5  -1.7  -8.7  2:104 **- DORIS *
KOKB 40424M004  4 KOKA 40424S008  1   12.6  10.9   0.1 -12.4  2:319 **- DORIS *
WUHN 21602M001  2 JIUB 21602S005  1   -6.6 -30.5  51.9  -2.2  3:342 *** DORIS
KSTU 12349M002  1 KRAB 12349S001  1    7.7   9.1  10.1  -4.9  0:  1 *** DORIS
KIT3 12334M001  1 KITA 12334S004  1  -11.6   7.7  -7.2  -3.1  1:115 *** DORIS
HRAO 30302M004  1 HBLA 30302S005  1    5.3  -6.2 -13.3   3.3  3:214 *** DORIS
TIDB 50103M108  2 ORRB 50103S202  1  -26.3 -33.6 -32.1  36.1 95:263 *** DORIS *
TIDB 50103M108  2 ORRA 50103S201  1  -30.1 -39.0 -29.4  42.1 95:263 *** DORIS *
MALD 22901S001  1 MALB 22901S002  1   -9.6  13.8  18.1   9.4  5: 14 *** DORIS *
RIDA 40499S016  1 7219 40499S001  1   10.3 -26.3 -60.7  28.0 93:  4 *** DORIS *
NOUM 92701M003  3 NOWB 92701S003  1    6.3  19.3  26.9  15.5  5:236 *** DORIS *
CHPI 41609M003  1 CACB 41609S001  1   20.6  -8.8 -48.5 -20.9  4: 85 *** DORIS *
CHPI 41609M003  1 CADB 41609S002  1   -6.5   9.6 -76.7  11.1  4: 85 *** DORIS *
PDEL 31906M004  1 PDMB 31906S002  1   10.9   8.2 -12.3 -11.4  1: 79 *** DORIS *
EISL 41703M003  1 EASA 41703S008  1  -11.7  10.5 -17.6  13.8  1: 46 *** DORIS *
MORA 51001S001  1 MORB 51001S002  1   -7.6  15.4  15.3   9.9  2: 79 *** DORIS *
KERG 91201M002  2 KETB 91201S005  1    6.7   8.6   8.9  -8.9  7:101 *** DORIS *
KOKB 40424M004  4 KOLB 40424S009  1    9.1  15.6 -12.4 -16.8  2:319 *** DORIS *
GODE 40451M123  2 GREB 40451S176  1    9.9 -17.0 -11.6  10.4  8:  1 *** DORIS *
HELA 30606S002  1 HELB 30606S003  1   19.1  25.2 -11.5 -14.8  3: 80 *** DORIS *
HELA 30606S002  1 HEMB 30606S004  1   10.5  41.0 -16.2 -32.0  3: 80 *** DORIS *
```

ITRF2008 Article

J Geod (2011) 85:457–473
DOI 10.1007/s00190-011-0444-4

ORIGINAL ARTICLE

ITRF2008: an improved solution of the international terrestrial reference frame

Zuheir Altamimi · Xavier Collilieux · Laurent Métivier

Received: 17 September 2010 / Accepted: 10 January 2011 / Published online: 3 February 2011
© The Author(s) 2011. This article is published with open access at Springerlink.com

Abstract ITRF2008 is a refined version of the International Terrestrial Reference Frame based on reprocessed solutions of the four space geodetic techniques: VLBI, SLR, GPS and DORIS, spanning 29, 26, 12.5 and 16 years of observations, respectively. The input data used in its elaboration are time series (weekly from satellite techniques and 24-h session-wise from VLBI) of station positions and daily Earth Orientation Parameters (EOPs). The ITRF2008 origin is defined in such a way that it has zero translations and translation rates with respect to the mean Earth center of mass, averaged by the SLR time series. Its scale is defined by nullifying the scale factor and its rate with respect to the mean of VLBI and SLR long-term solutions as obtained by stacking their respective time series. The scale agreement between these two technique solutions is estimated to be 1.05 ± 0.13 ppb at epoch 2005.0 and 0.049 ± 0.010 ppb/yr. The ITRF2008 orientation (at epoch 2005.0) and its rate are aligned to the ITRF2005 using 179 stations of high geodetic quality. An estimate of the origin components from ITRF2008 to ITRF2005 (both origins are defined by SLR) indicates differences at epoch 2005.0, namely: -0.5, -0.9 and -4.7 mm along X, Y and Z-axis, respectively. The translation rate differences between the two frames are zero for Y and Z, while we observe an X-translation rate of 0.3 mm/yr. The estimated formal errors of these parameters are 0.2 mm and 0.2 mm/yr, respectively. The high level of origin agreement between ITRF2008 and ITRF2005 is an indication of an imprecise ITRF2000 origin that exhibits a Z-translation drift of 1.8 mm/yr with respect to ITRF2005. An evaluation of the ITRF2008 origin accuracy based on the level of its agreement with ITRF2005 is believed to be at the level of 1 cm over the time-span of the SLR observations. Considering the level of scale consistency between VLBI and SLR, the ITRF2008 scale accuracy is evaluated to be at the level of 1.2 ppb (8 mm at the equator) over the common time-span of the observations of both techniques. Although the performance of the ITRF2008 is demonstrated to be higher than ITRF2005, future ITRF improvement resides in improving the consistency between local ties in co-location sites and space geodesy estimates.

Keywords Reference systems · Reference frames · ITRF · Earth rotation

Z. Altamimi (✉) · X. Collilieux · L. Métivier
Institut Géographique National, LAREG,
6-8 Avenue Blaise Pascal, 77455 Marne-la-Vallée, France
e-mail: zuheir.altamimi@ign.fr

L. Métivier
Institut de Physique du Globe de Paris,
Universite Paris-Diderot, Batiment Lamarck,
case 7011, 35 rue Helene Brion, 75013 Paris, France

1 Introduction

Precisely determining satellite orbits or quantifying Earth rotation, tectonic plate motion or mean sea level rise and its variability in space and time fundamentally depend on the availability of a truly global Terrestrial Reference System (TRS) that only space geodesy is able to realize. Following the established terminology on reference systems (Kovalevsky et al. 1989), we distinguish between a TRS and its realization by a Terrestrial Reference Frame (TRF). The former is being ideal and conventional, with specified mathematical and physical properties, while the latter is constructed using space geodesy observations (hence with uncertainties) and is being accessible to the users through numerical values (e.g. positions as a function of time of a network of Earth crust-based points). The main physical and mathematical properties of a TRS (at the theoretical level) or of a TRF (at the realization level) are the origin, the scale, the orientation and their time evolution.

The International Terrestrial Reference System (ITRS), realized and maintained by the International Earth Rotation and Reference Systems Service (IERS) has been formally adopted and recommended for Earth science applications (IUGG 2007). For more details regarding the ITRS description and definition, the reader may refer to Chapter 4 of the IERS Conventions (Petit and Luzum 2010). The ITRS realization, through the International Terrestrial Reference Frame (ITRF) is regularly updated to take into account not only new accumulated data, but also improved analysis strategies applied by the analysis centers of the contributed techniques. Eleven ITRF versions were hence published, starting with the ITRF88 and ending with ITRF2008 described in this article. The space geodetic techniques that contribute to the ITRF construction are Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS). These techniques are organized as scientific services within the International Association of Geodesy (IAG) and known by the IERS as Technique Centers (TCs): the International VLBI Service (IVS), (Schlüter and Behrend 2007), the International Laser Ranging Service (ILRS), (Pearlman et al. 2002), the International GNSS Service, formerly the International GPS Service (IGS), (Dow et al. 2009) and the International DORIS Service (IDS), (Willis et al. 2010).

Although ITRF2005 (Altamimi et al. 2007) was an improved solution compared to past ITRF versions, in terms of internal consistency and robustness, it, however, shed light on some deficiencies of the four technique solutions as well as their co-locations. In preparation for the ITRF2008, the IAG technique services, together with their respective Analysis and Combination Centers invested considerable effort to improve their solutions. Without being exhaustive, we can cite that the reprocessed IGS solution involves new absolute phase center offsets and variations models for satellites and stations (Schmid et al. 2007) and a new tropospheric model (Boehm et al. 2006a, 2007); the reanalysis solution from IVS accounts for the mean pole tide correction following the IERS Conventions (Petit and Luzum 2010) and a more advanced troposphere modeling (Boehm et al. 2006b) and corrections for antenna thermal deformations (Nothnagel 2009); the improved ILRS solution takes into account new range bias values, a new tropospheric modeling (Mendes et al. 2002; Mendes and Pavlis 2004) and other station-dependent corrections, and for the first time the DORIS combined solution involves seven IDS Analysis Centers (Valette et al. 2010).

Each time an ITRF solution is prepared, one of the fundamental aspects of its formation is to ensure the optimal frame definition and its stability as a function of time. While the origin and the scale (having physical properties) are critical parameters of interest to Earth science applications, the orientation and its time variation (arbitrary and conventionally defined) are of importance to ensure the continuity of Earth rotation determination. Any bias or drift in these components will inevitably propagate into the geophysical results that depends on the usage of the ITRF, as for instance mean sea level assessment and its variability in space and time (Morel and Willis 2005; Beckley et al. 2007; Collilieux and Wöppelmann 2010). As it will be shown by the discussion of the ITRF2008 results, the current achievable accuracy of the ITRF scale is probably not better than 1 part-per-billion (ppb) and its temporal stability at the range of 0.05 ppb/yr. The total error budget includes systematic errors of not only VLBI and SLR, but also GPS that is crucially needed to tie the three other techniques together, as well as local tie errors.

The space geodetic technique solutions and local ties at co-location sites used to generate ITRF2008 are first presented in Sect. 2. Section 3 describes the combination strategy that has been applied to these data. The output results of this combination and ITRF2008 quality evaluation are described in Sect. 4. The main ITRF2008 results and performance are synthesized in the conclusion.

All the ITRF2008 files and results are available at the ITRF web site: http://itrf.ign.fr/ITRF_solutions/2008/

2 ITRF2008 input data

As for any ITRF solution, the ITRF2008 relies not only on space geodesy solutions, but also on local ties at co-location sites. In the following two sub-sections we describe the two sets of data used in the ITRF2008 construction.

2.1 Space geodesy solutions

We recall that the ITRF input time series solutions are provided on a weekly basis by the IAG International Services of satellite techniques: IGS, ILRS and IDS and on a daily (VLBI session-wise) basis by the IVS. Each per-technique time series is already a combination of the individual Analysis Center (AC) solutions of that technique. Table 1 summarizes the submitted solutions by the IAG services, specifying the time span, solution type and the constraints applied by the TCs as well as the estimated Earth Orientation Parameters (EOPs). For more details regarding the type of constraints applied by the techniques, and the minimum constraints concept in general, the reader may refer to Dermanis (2000, 2003); Sillard and Boucher (2001); Altamimi et al. (2002a, 2004) or to Chapt. 4 of the IERS Conventions (Petit and Luzum 2010). The submitted VLBI solution involves more than 4,000 session-wise SINEX files spanning the entire VLBI observation history (Bockmann et al. 2010). The SLR solution covers also its full observation history, and comprises fortnightly SINEX files, with polar motion and Length of Day (LOD) estimated each three days between 1983.0 and

Table 1 Summary of submitted solutions to ITRF2008

TC	Data-span	Solution type	Constraints	EOPs
IVS	1980.0–2009.0	Normal equation	None	Polar motion, rate, LOD, UT1-UTC
ILRS	1983.0–2009.0	Variance–covariance	Loose	Polar motion, LOD
IGS	1997.0–2009.5	Variance–covariance	Minimum	Polar motion, rate, LOD
IDS	1993.0–2009.0	Variance–covariance	Minimum	Polar motion, rate, LOD

1993.0 and weekly SINEX files with daily polar motion and LOD estimates afterwards (Pavlis et al. 2010). The GPS submitted solution represents a large part of the first reprocessed solution by the IGS and covers the time period 1997.0–2009.5 (Ferland 2010; Ferland and Piraszewski 2008). Note that a very small portion of GLONASS observations were used by some IGS ACs that contributed to the reprocessing effort. For the first time the DORIS contribution is a combined time series involving seven ACs and covers its full observation history, using data from all available satellites with onboard DORIS receiver, except Jason-2 (Valette et al. 2010).

The ITRF2008 network comprises 934 stations located at 580 sites, with 463 sites in the northern hemisphere and 117 in the southern hemisphere. The ITRF2008 combination involves 84 co-location sites where two or more technique instruments were or are currently operating and for which local ties are available. Figure 1 illustrates the full ITRF2008 network where we superimposed the VLBI, SLR and DORIS sites co-located with GPS. In fact all the 84 co-location sites comprise permanent GPS stations, except two sites: Dionysos (Greece) where DORIS and an old mobile SLR were co-located, and Richmond (Virginia, USA) where VLBI, SLR and DORIS systems were co-located.

2.2 Local ties in co-location sites

The local ties used in the ITRF2008 combination are provided in SINEX format with known measurement epochs, and 63% of them are available with full variance covariance information. Most of the local ties used in the ITRF2005 combination are used here with some updates, e.g., Tahiti (GPS, SLR, DORIS), Tsukuba (GPS, VLBI), Herstmonceux (GPS, SLR), Medicina and Noto (GPS, VLBI), Greenbelt (GPS, VLBI, SLR, DORIS), Maui/ Haleakala (GPS, SLR), San Fernando (GPS, SLR), Onsala (GPS, VLBI). Most of

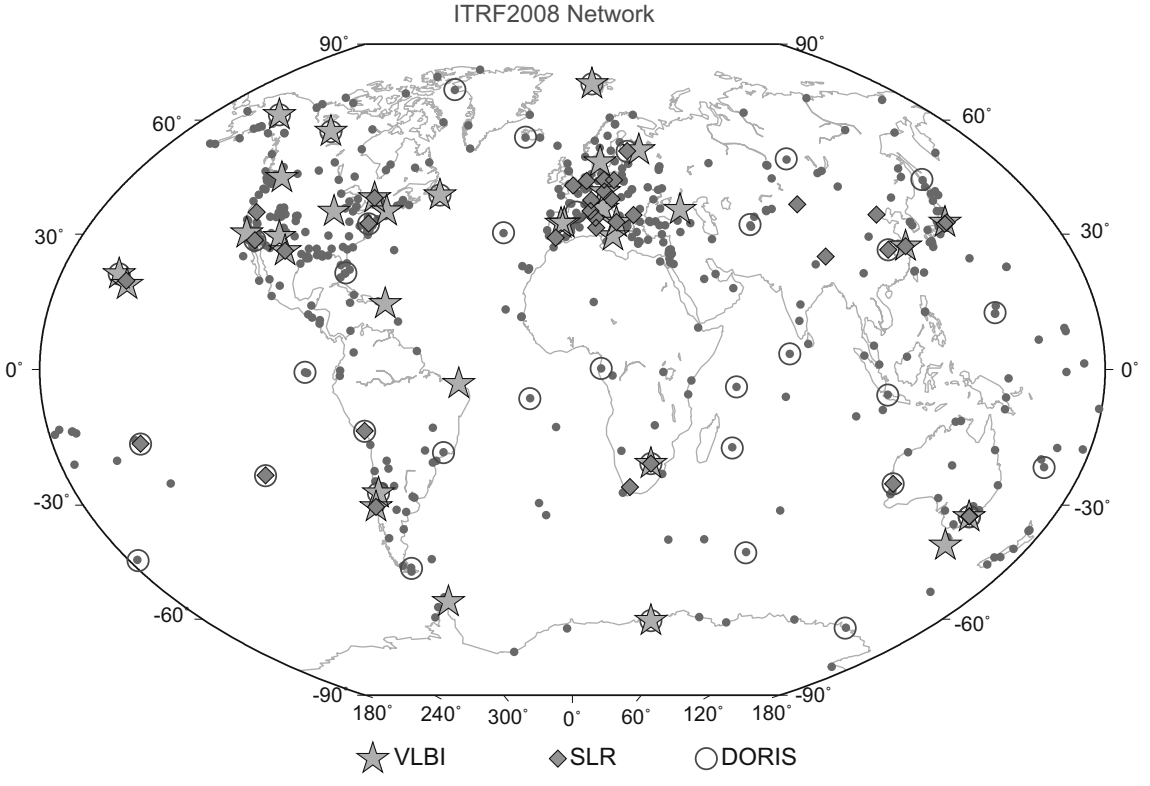


Fig. 1 ITRF2008 network highlighting VLBI, SLR and DORIS sites co-located with GPS

the local tie SINEX files were provided by the national agencies operating co-location sites, all sites in Australia (Johnston and Dawson 2004); three sites in Italy: Medicina, Noto (Sarti et al. 2004) and Matera (Bianco 2006); Wettzell and Concepcion (Schlüter et al. 2004a,b); Tsukuba (GSI 2010); Onsala (Haas 2010); and all the DORIS co-location sites were re-adjusted by the IGN survey department in order to generate full SINEX files, using the most recent surveys operated at these sites. All the local tie SINEX files used in the ITRF2008 combination are available at http://itrf.ign.fr/local_surveys.php.

Counting the number of co-locations between VLBI, SLR and DORIS, taken by pairs, we find eight VLBI-SLR, ten VLBI-DORIS and ten SLR-DORIS. These are very poor numbers of co-locations to allow a reliable combination of these three techniques alone. Therefore, the GPS is playing a major role in the ITRF combination by linking together the three other techniques (Altamimi and Collilieux 2009). We count in total 137 tie vectors between GPS and the three other techniques: 44 for VLBI, 48 for SLR and 45 for DORIS. 15 additional ties were also used between old and current DORIS beacon reference points in DORIS-only sites.

3 ITRF2008 data analysis

The CATREF combination model used for the ITRF combination is extensively described in previous publications and in particular (Altamimi et al. 2002b, 2007). For the ITRF2008 generation, we followed the same analysis strategy used for the ITRF2005 combination (Altamimi et al. 2007). We recall here that two steps are currently used for the ITRF construction: (1) stacking the individual time series to estimate a long-term solution per technique comprising station positions at a reference epoch, velocities and daily EOPs; and (2) combining the resulting long-term solutions of the four techniques together with the local ties in co-location sites. The main two equations of the combination model are given below for completeness. They involve a 14-parameter similarity transformation, station positions and velocities and EOPs and are written as

$$\begin{cases} X_s^i = X_c^i + (t_s^i - t_0)\dot{X}_c^i \\ \qquad + T_k + D_k X_c^i + R_k X_c^i \\ \qquad + (t_s^i - t_k)\left[\dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i\right] \\ \dot{X}_s^i = \dot{X}_c^i + \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i \end{cases} \quad (1)$$

$$\begin{cases} x_s^p = x_c^p + R2_k \\ y_s^p = y_c^p + R1_k \\ UT_s = UT_c - \frac{1}{f} R3_k \\ \dot{x}_s^p = \dot{x}_c^p \\ \dot{y}_s^p = \dot{y}_c^p \\ LOD_s = LOD_c \end{cases} \quad (2)$$

where for each point i, X_s^i (at epoch t_s^i) and $\dot{X}_s^i$ are positions and velocities of technique solution s and X_c^i (at epoch t_0) and $\dot{X}_c^i$ are those of the combined solution c. For each individual frame k, as implicitly defined by solution s, D_k is the scale factor, T_k the translation vector and R_k the rotation matrix. The dotted parameters designate their derivatives with respect to time. The translation vector T_k is composed of three origin components, namely T_x, T_y, T_z and the rotation matrix of three small rotation parameters: R_x, R_y, R_z, following the three axes, respectively X, Y, Z. t_k is a conventionally selected epoch of the seven transformation parameters. In addition to Eq. (1) involving station positions (and velocities), the EOPs are added by Eq. (2), following (Zhu and Mueller 1983), making use of pole coordinates x_s^p, y_s^p and universal time UT_s as well as their daily rates $\dot{x}_s^p$, $\dot{y}_s^p$ and LOD_s. The link between the combined frame and the EOPs is ensured via the three rotation parameters appearing in the first three lines of Eq. (2).

Note that Eq. (1) uses the linearized form of the general similarity transformation formula, neglecting second and higher order terms. For more details regarding the mathematical derivation of Eq. (1), the reader may refer to Chapt. 4 of the IERS Conventions (Petit and Luzum 2010), and to Altamimi and Dermanis (2010).

The reader should note that in past publications, e.g., (Altamimi et al. 2007), we considered the three last lines of Eq. (2) as the time derivatives of the first three lines of the same equation, and so rotation rate terms have been added. However, the conventional EOP representation provided by the techniques is in the form of daily offset (at noon) and drift (or rate), while other types of EOP representation could also be considered, such as continuous piece-wise linear function where no EOP rates would appear. Therefore, the daily EOP rates are independent from the orientation time evolution of the reference frame, although they should be correlated with the daily EOP offset values. In case of time series stacking, the addition of such rotation rates has no impact on the results because they are not introduced in the normal equation. However, their addition in case of combining long-term solutions (which contain EOPs) yields biased frame rotation rates of the individual solutions with respect to (but without altering) the combined frame.

3.1 ITRF2008 time series analysis

The first line of Eq. 1 and the entire Eq. 2 are used to estimate long-term solutions for each technique, by accumulating (rigorously stacking) the individual technique time series of station positions and EOPs. In this process, the second line of Eq. 1 and the rates of the translation, scale and rotation parameters are not included because station velocities are not available/estimable at the weekly (daily) basis. Moreover, a precise definition of the reference frame associated with the

resulting long-term solution (comprising station positions at a reference epoch, station velocities and EOPs) has to be clearly specified. As transformation parameters are estimated between each weekly (or session-wise) frame and the long-term frame, it becomes necessary to define the long-term frame origin, scale, orientation and their time evolution and therefore to complete the rank deficiency of the constructed normal equation. It is essential that the long-term solutions be representative of the mean origin and mean scale information of the space geodesy techniques. The particular type of minimal constraints introduced in Altamimi et al. (2007) have been designed for such purpose and are consequently used here to preserve the long-term solution origin (for SLR and DORIS) and scale (for VLBI, SLR and DORIS). As the input GPS weekly frames have been explicitly expressed in the IGS05 (derived from ITRF2005), GPS long-term solution has been expressed with respect to ITRF2005 and was not used for the ITRF2008 origin and scale definition.

One of the main advantages of using time series as input data for the ITRF combination is the ability to identify station position discontinuities which are mostly due to earthquakes and equipment changes. There are in total 638 discontinuities; 550 of them are GPS-related. In the generation of the long-term technique solutions, we consider different station positions before and after each event. Nearby stations within the same site and multiple segments (in case of discontinuities) are constrained to have the same velocity, except for sites where geophysical events such as large earthquakes occur.

As a by-product of the time series analysis we evaluate the internal precision (or repeatability) of each technique solution, through the computation of the Weighted Root Mean Scatter (WRMS) over the time series of weekly or daily residuals. Figure 2 displays the WRMS in East, North and Up components of the four technique solutions submitted to ITRF2008, with respect to the estimated long-term solutions. We computed the median values of these WRMS for the four technique solutions over the three components which are for GPS: 1.6, 1.7 and 4.4; for VLBI: 2.9, 3.0 and 7.4; for SLR: 7.9, 9.4, 7.9 and for DORIS: 11.9, 10.9 and 13.3 mm over the East, North and Up components, respectively. These median values are representative of the intrinsic precision (or repeatability) of each technique solution computed using the full time series, including the early less-precise observations, as well as all (less and well performing) stations. An inspection of the WRMS plotted in Fig. 2 indicates a precision improvement in the three components at recent dates for GPS, SLR and DORIS. It is interesting to note that for DORIS in particular the precision improves when observations from four to five satellites are used.

Seasonal signals can be noticed in the WRMS time series, and in particular for GPS. It has been shown that some of these variations, especially the annual, are related to loading effects (Altamimi and Collilieux 2009). Indeed, the Earth is continuously deforming due to non-tidal loading effects

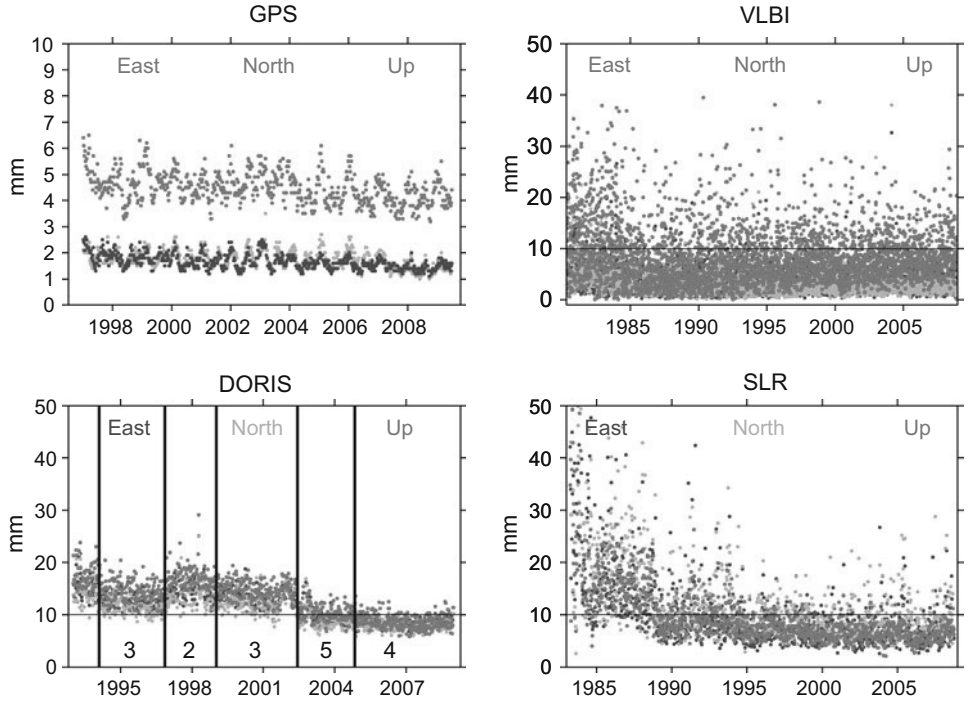


Fig. 2 WRMS (internal precision) of weekly (or session-wise for VLBI) station position time series with respect to the long-term solution along the East, North and the Height components for GPS (*top left*); VLBI (*top right*); DORIS (*bottom left*) and SLR (*bottom right*). For DORIS, the number of satellites used is indicated on the plot

(Farrell 1972) but modeling of these phenomena is not yet integrated in the processing of geodetic observables for all the effects and all the techniques. It was decided not to incorporate the modeling of any non-tidal loading effects in the processing of geodetic data submitted by the TCs since not all available loading models have been fully evaluated. For instance, it was discovered recently that neglecting high-resolution topography changes induce errors in the atmospheric loading models (van Dam et al. 2010). However, it is worth noting that loading effects are not expected to affect ITRF frame parameters, especially the origin and scale (Collilieux et al. 2010), although the coordinates of the stations with few observations are impacted by this neglected effect. Therefore for the future, it becomes necessary that loading models, if they are accurate enough, be recommended by the IERS to be homogeneously and consistently used by the four techniques, since neglected effects, as the atmospheric tides, may be aliased into low frequencies signals (Tregoning and Watson 2009).

3.2 ITRF2008 multi-technique combination

The second step of the ITRF2008 analysis consists in combining the long-term solutions of the four technique solutions together with local ties at co-location sites. The ITRF2008 is specified by the following frame parameters:

- Origin: The ITRF2008 origin is defined in such a way that there are null translation parameters at epoch 2005.0 and null translation rates with respect to the ILRS SLR time series.
- Scale: The scale of the ITRF2008 is defined in such a way that there are null scale factor at epoch 2005.0 and null scale rate with respect to the mean scale and scale rate of VLBI and SLR time series.
- Orientation: The ITRF2008 orientation is defined in such a way that there are null rotation parameters at epoch 2005.0 and null rotation rates between ITRF2008 and ITRF2005. These two conditions are applied over a set of 179 reference stations located at 131 sites as illustrated by Fig. 3. The reference sites include 107 GPS, 27 VLBI, 15 SLR and 12 DORIS.

Special attention was devoted to the important issue of relative weighting of the space geodesy technique solutions and local ties. Several test combinations were performed by varying the weighting of all input data solutions in order to reach and adopt a statistically satisfactory ITRF2008 combination. The weighting of the individual solutions is operated by estimating an appropriate variance factor per data set and iterating as necessary. Because of the imbalance between the space geodesy technique solutions (which are global by nature)

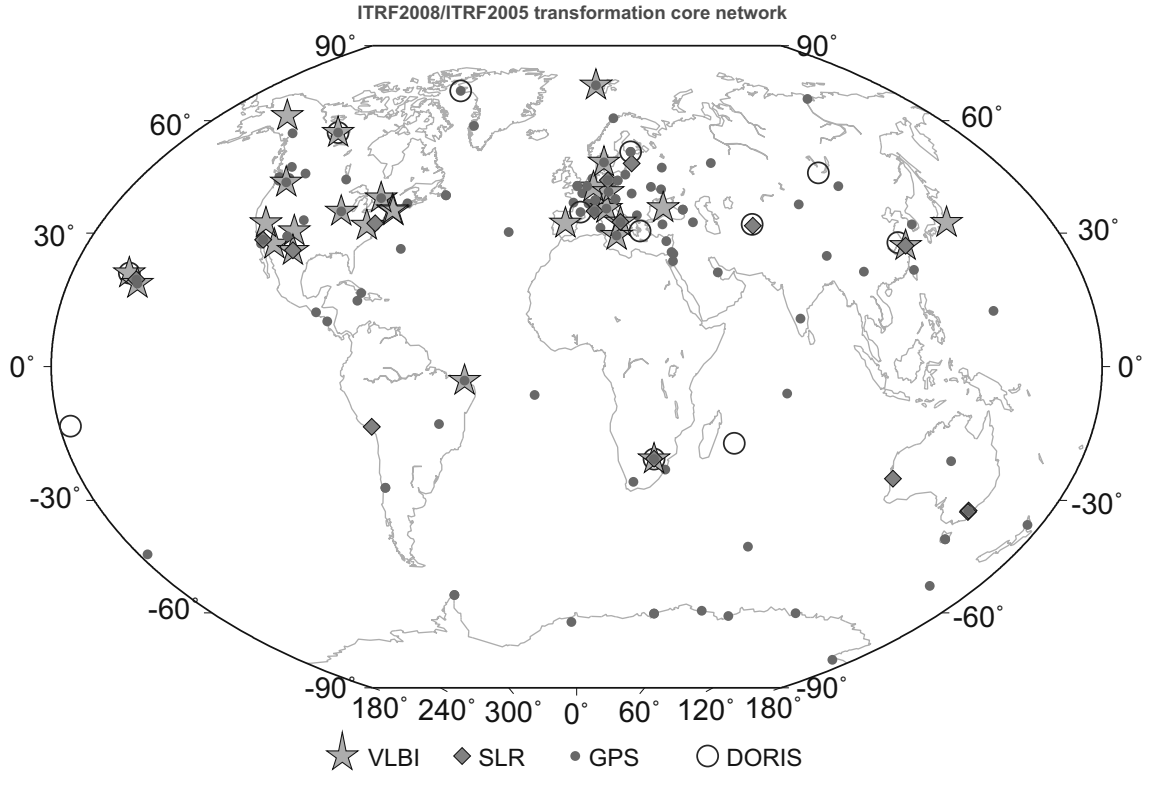


Fig. 3 Location of the core sites used in the estimation of the 14 transformation parameters between ITRF2008 and ITRF2005 and their orientation alignment

and the small, local-by-nature networks of co-location sites, it is very difficult to adequately use a mathematically or statistically prescribed method of variance component estimation as the degree of freedom or Helmert methods (Bähr et al. 2007). Therefore, the overall weighting process used in the ITRF2008 combination is a mixture of the degree of freedom method as described in (Altamimi et al. 2002b), Appendix A, Sect. A5, Eq. A16 and an empirical weighting. The long-term solutions of the four techniques are first properly weighted as a function of the variance factors (VF) obtained during the process of the individual stacking of the technique time series and computed as

$$VF = \frac{\sum_s^S v_s^T P_s v_s}{f} \quad (3)$$

where v_s is the vector of the station coordinates post fit residuals of solution s, P_s its weight matrix (the inverse of the variance-covariance matrix) and S is the total number of solutions included in the stacking. f is the number of degrees of freedom of the least squares adjustment, which is equal to the difference between the number of observations and the number of unknowns. Being a function of the residuals, normalized by the weight matrices, the VF is considered as a statistical indicator of the overall quality of the combination. Adequately weighting the individual solutions should lead to a variance factor close to unity. Therefore, an increase of the VF is a strong indication of the increase of the normalized residuals (raw residuals divided by their observation a priori errors), implying an inappropriate weighting of the individual solutions included in the combination or/and large outliers.

From this first step analysis, the following individual variance factors were obtained: 0.69 for GPS, 2.95 for SLR, 3.37 for VLBI and 2.20 for DORIS, respectively. As results of several ITRF2008 multi-technique test combinations, it was necessary to rescale the variance factors of VLBI and DORIS, by 1.2 and 2.5, respectively. In order to judge the appropriateness of this weighting scheme, we performed three main test combinations: a combination of the four technique velocity fields (downweighting station positions and local ties), and two combinations with and without EOPs. The obtained global variance factors of unit weight are in all cases close to unity, with variations less than 10%.

In the ITRF combination, local ties at co-location sites, provided in SINEX format, are used as observations with proper weighting as described in detail in Altamimi et al. (2002b). An empirical variance factor per local tie SINEX file is estimated during the combination process in such a way that (1) the normalized residual should not exceed a threshold of 3 and (2) the uncertainty per tie vector component should not be below 3 mm. The reasons for these two conditions are that (1) we believe a local tie between physically inaccessible instrumental measurement reference points is unlikely to be precise to better than 3 mm, and (2) the agreement between local ties and space geodesy estimates are by far larger than 3 mm for most of the co-location sites and consequently (3) the local ties should be properly weighted in order to avoid contaminating the combined frame defining parameters by local tie and space geodesy discrepancies and at the same time to preserve consistency between individual technique solutions and ITRF2008. However, the discrepancies mean that either local ties or space geodesy estimates (or both) are imprecise or in error. One of the local survey difficulties is to precisely determine the eccentricity between the intersection of axes of VLBI or SLR telescopes and the ground physical markers. As an example, Sarti et al. (2009) estimated that the action of gravity on the structure of the Medicina (Italy) VLBI antenna biases the estimate of the instrument's reference point up to 1 cm.

A detailed analysis of the consistency between local ties and space geodesy estimates is discussed in Sect. 4.5.

4 ITRF2008 results

In the following subsections we discuss the main results of the ITRF2008 analysis as obtained from the two steps: time series stacking and multi-technique combination.

4.1 ITRF2008 origin

The submitted ILRS SLR solution was used to define the ITRF2008 origin, by fixing to zero (and consequently eliminating from the normal equation) the six parameters (translations and rates) of its corresponding long-term cumulative solution. Figure 4 illustrates the temporal behavior of the weekly SLR origin components with respect to ITRF2008, showing as expected (Dong et al. 1997) seasonal variations, but no shift or drift are visible. In order to evaluate the performance of the SLR origin determination, it is then important to compare the origin components between ITRF2008 and ITRF2005. An estimate of the translation components from ITRF2008 to ITRF2005 indicates differences at epoch 2005.0, namely -0.5, -0.9 and -4.7 mm along X, Y and Z-axes, respectively. The translation rate differences are zero for Y and Z, while we observe an X-translation rate of 0.3 mm/yr. These numbers suggest that the origin agreement between the two frames is at the level of or better than one centimeter over the entire time span of the SLR observations, and may be regarded as the level of the origin accuracy achievable today. We recall that there is a significant Z-translation rate of 1.8 mm/yr between ITRF2000 and ITRF2005 (Altamimi et al. 2007). A few studies (Greff-Lefftz 2000; Greff-Lefftz et al. 2010; Métivier et al. 2010) have shown that geophysical phenomena, such as present day ice melting or postglacial rebound, cannot lead to an

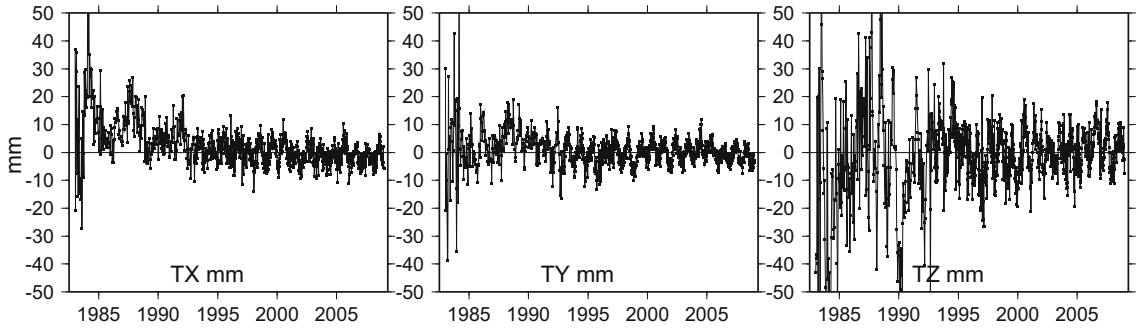


Fig. 4 Weekly translation components of the SLR ILRS solution with respect to ITRF2008, in millimeter along the *X*, *Y* and *Z*-axes: *left*, *middle* and *right*, respectively

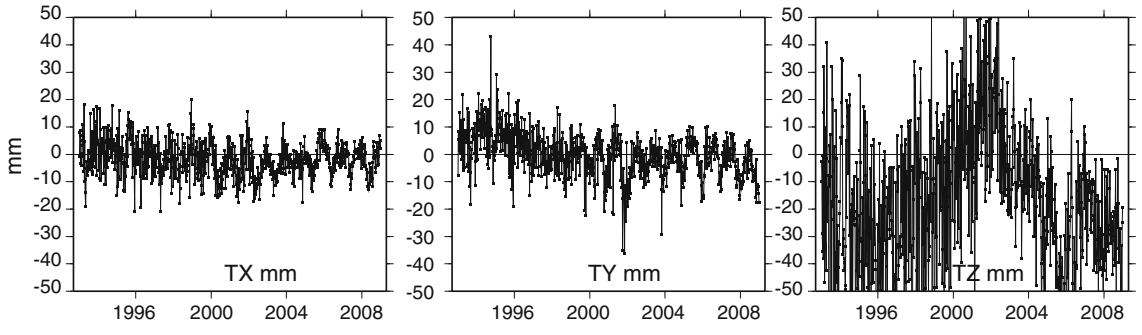


Fig. 5 Weekly translation components of the DORIS IDS-3 solution with respect to ITRF2008, in millimeter along the *X*, *Y* and *Z*-axes: *left*, *middle* and *right*, respectively

increase of the geocenter velocity along the *Z*-axis larger than 0.3 mm/yr in a decade. Given the fact that the ITRF2008 results show negligible translation rates with respect to ITRF2005, the *Z*-translation rate between ITRF2005 and ITRF2000 is most likely an indication of an imprecise origin determination of the ITRF2000 solution. This statement is also supported by the fact that both ITRF2005 and ITRF2008, being based on rigorous time series analysis, are by far more precise than ITRF2000.

While detailed analyses of the IDS submitted solution to ITRF2008 were published in (Altamimi and Collilieux 2010; Valette et al. 2010), for completeness Fig. 5 illustrates the temporal origin components of the DORIS IDS-3 solution with respect to ITRF2008. This plot shows a rather stable Tx, a slope change in Ty after 2002.0 and a very scattered Tz behavior.

4.2 ITRF2008 scale

The level of agreement of the scale and scale rate between VLBI and SLR solutions used in the ITRF2005 combination were 1.4 (±0.11) ppb at epoch 2005.0 and 0.08 (±0.01) ppb/yr, respectively. This low level of consistency was due to several factors, including uncorrected mean pole tide effect of the VLBI and probably station range biases of the SLR, together with their poor co-locations and the degradation of their network with time.

As results from the final ITRF2008 combination we found that the scale and scale rate agreement between VLBI and SLR solutions are 1.05 (±0.13) ppb at epoch 2005.0 and 0.049 (±0.010) ppb/yr, respectively. This indicates an improvement compared to the past ITRF2005 results. This improvement is particularly due to the reprocessing effort of both IVS and ILRS. In addition, for some SLR co-located stations, we introduced breaks in the time series to account for significant discontinuities which improved the agreement of the estimated vertical velocities with GPS and consequently the scale rate agreement with VLBI. Propagating the scale discrepancy between SLR and VLBI at the start and end epochs of the time-span of VLBI data leads to a maximum discrepancy of 1.2 ppb (8 mm at the equator), which could be considered as the level of the scale accuracy achievable today. Therefore, defining the ITRF2008 scale to be in the middle of both technique solutions is the most appropriate choice that minimizes the scale impact for these two techniques when using the ITRF2008 products.

Figure 6 illustrates the daily scales of VLBI, and weekly scales of SLR and DORIS solutions with respect to ITRF2008 using the full time series. From that figure, we can distinguish

the level of agreement, scattering and temporal behavior of the scale factors of the three techniques. The estimated uncertainties (formal error at one sigma) of the scale and scale rates as results from the ITRF2008 combination are 0.10, 0.13, 0.19 ppb at epoch 2005.0 and 0.01, 0.01 and 0.03 ppb/yr for VLBI, SLR and DORIS, respectively.

The scale factor of the DORIS IDS-3 solution with respect to ITRF2008 is 0.70 ppb at epoch 2005.0, and so it is closer to VLBI than to SLR. As discussed in (Altamimi and Collilieux 2010), IDS-3 has a fairly stable scale (with negligible drift) during 1993–2002, and then displays uneven non-linear behavior afterward. This behavior is most likely to be related to the change of the number of satellites used.

4.3 Origin and scale seasonal variations

In order to evaluate the origin and scale seasonal variations visible in the time series plotted in Figs. 4, 5 and 6, we fitted annual amplitudes and phases (listed in Table 2) to the SLR and DORIS translation and scale components as well as to the scale of VLBI. For comparison, Table 2 reproduces also the values which were obtained using ITRF2005 data, published in (Altamimi et al. 2007). We restrict our discussion here to the quantification of the apparent geocenter motion and scale seasonal variation. The variations of the translation time series derived from the satellite techniques are expected to be close to the opposite of the non-linear part of the geocenter motion (Collilieux et al. 2009). The difference between the "true" geocenter motion and the translation

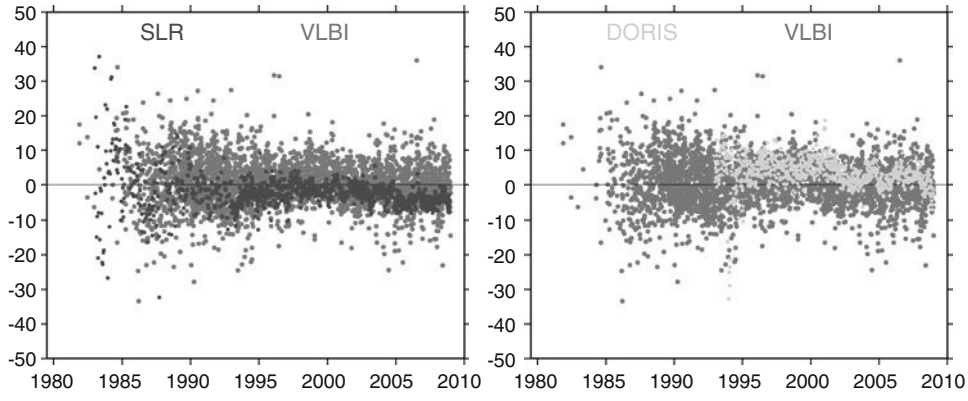


Fig. 6 Scale factors, in millimeters, of the VLBI, SLR and DORIS solutions with respect to ITRF2008

Table 2 Annual amplitude (A) and phase (ϕ) of the translation components and scale factor, according to the model $A\cos(\omega \cdot t - \phi)$ with t in decimal year

TC	TX		TY		TZ		scale	
	A (mm)	ϕ (deg)	A (mm)	ϕ (deg)	A (mm)	ϕ (deg)	A (mm)	ϕ(deg)
ITRF2008								
IVS	–	–	–	–	–	–	2.2	241
±							0.1	3
ILRS	2.6	222	3.1	135	5.5	202	0.6	255
±	0.1	3	0.1	2	0.3	10	0.1	10
IDS	3.9	327	4.6	160	4.4	115	0.3	206
±	0.2	3	0.3	3	1.1	14	0.1	27
ITRF2005 (Altamimi et al. 2007)								
IVS	–	–	–	–	–	–	2.7	220
±							0.1	3
ILRS	3.0	216	3.3	147	2.5	186	1.7	231
±	0.2	4	0.2	3	0.4	11	0.2	7
IDS-IGN	5.8	351	4.6	117	29.0	165	4.5	161
±	0.5	5	0.5	6	2.5	5	0.3	4
IDS-LCA	5.4	329	2.1	46	12.0	165	2.4	248
±	0.5	5	0.5	13	1.8	9	0.4	9

variations includes not only systematic errors related to orbit mis-modeling but also the aliasing of the loading effects (network effect) into the translation components (Collilieux et al. 2009; Lavallée et al. 2006). Scale annual variations also partly reflect this aliasing and can be interpreted as the mean vertical motion of the network (Collilieux et al. 2010). As all the geodetic networks are different, there is no reason to expect identical signals for all the techniques in the scale factor time series.

Comparing the annual amplitudes and phases of the SLR translations with those of ITRF2005 published in (Altamimi et al. 2007), we notice very similar estimates (i.e. within the uncertainties), except for the *Z*-translation amplitude which is two times larger here (5.5 mm). We checked that this *Z*-translation high amplitude is not significantly influenced by the pre 1993 SLR scattered data, being determined with only one satellite (Lageos 1). Contrariwise, while the SLR scale phase is statistically similar to ITRF2005 result, the amplitude here is smaller by 1 mm. Compared to ITRF2005 results, the VLBI scale factor annual phase is changed by about 20° and its annual amplitude is smaller by 0.5 mm, but this difference may be explained by the modeling of the antenna thermal deformation (Bockmann et al. 2010). Regarding DORIS, we note a more realistic annual amplitude in the *Z* component (4.4 mm), compared to the very large values exhibited by the two solutions used in the ITRF2005. This improvement is most likely to be related to the improvement of the solar radiation pressure treatment by some IDS analysis centers, leading to better estimate of the *Z*-geocenter (Gobindass et al. 2009). The DORIS *X* and *Y* amplitudes are higher by 1.5 mm than SLR, while only the phase in *Y* is closer to SLR. The DORIS scale annual amplitude is very small (0.3 mm), but the DORIS network has also the most homogeneous distribution over the Earth surface.

4.4 Impact of local ties on the ITRF2008 combination

Given the importance of local ties in the ITRF combination, we chose here to evaluate their impact on one of the most critical estimated parameters, namely the scale, being determined for the ITRF2008 by the mean of VLBI and SLR solutions. For this purpose, we performed different combination tests whose results are listed in Table 3. We evaluate the quality of these tests by discussing the obtained scale bias between VLBI and SLR solutions, as well as the variance factor of each adjustment. In reference to Eq. (3), an increase of the variance factor is the consequence of the increase of the normalized residuals (discrepancies between space geodesy estimates and local ties), implying an inappropriate relative weighting between space geodesy solutions and local ties.

Table 3 displays for each test, the scale factors (at epoch 2005.0) of SLR, GPS and DORIS with respect to VLBI solution, the global variance factor of each adjustment and the different cases of local ties handling. The first line of Table 3 lists the results of the final ITRF2008 combination where all available local tie SINEX files were properly weighted. Note that 63% of the local tie SINEX files are available with full variance–covariance information. The second combination is similar to the ITRF2008, but where the EOPs are not included and involves local ties vectors instead of SINEX files, weighted by their diagonal terms only. In addition, the epochs of these tie vectors were assumed to be all the same, namely 2005.0. This combination shows slight changes of the estimated scale factors of SLR, GPS and DORIS with an increase of their uncertainties as well as the variance factor. The next combination test (Case-1) involves a selection of good ties that agree with space geodesy estimates to better than 1 cm (for the worst cases), but with a uniform weighting of 1 mm over all ties and components. Although the increase of the variance factor to 4.0 indicating that the weight given to

Table 3 Scale factors (at epoch 2005.0) from VLBI long-term solution to SLR, DORIS and GPS using different weighting and selection of local ties at co-location sites

Case	SLR	DORIS	GPS	VF[a]	Tie handling
ITRF2008	−1.05	0.18	0.67	0.90	All tie SINEX files, weighted
	±0.13	±0.20	±0.10		
ITRF2008	−1.11	0.04	0.41	1.66	All tie vectors, weighted
without EOPs	±0.26	±0.31	±0.19		
Case-1	−1.20	−0.31	0.49	4.00	Selection of local ties, σ = 1 mm
	±0.16	±0.34	±0.14		
Case-2	−1.02	−0.30	0.52	31.70	Selection of local ties, σ = 0.1 mm
	±0.31	±0.84	±0.31		
Case-3	0.0[b]	0.48	1.28	4.28	Same as Case-1
		±0.32	±0.08		

[a] Variance factor
[b] parameter eliminated from the normal equation; assumed to be equal to VLBI scale

the local ties is too optimistic, this combination test increases the scale discrepancy between SLR and VLBI. The Case-2 test is the same as the previous one, but the local ties were given more weight by a factor of 10. It yields a very large variance factor and still shows a scale discrepancy of 1.02 ppb between SLR and VLBI solutions. The large variance factor obtained here is a clear indication that the heavy weight given to local ties increases considerably the normalized residuals, reflecting the discrepancies between space geodesy estimates and local ties that completely dominate this combination. The last test combination (Case-3) listed in Table 3 involves the same tie selection and weighting (1 mm) as Case-1, but where the SLR scale parameter was eliminated from the normal equation system (i.e. assuming zero scale difference with VLBI), this combination not only increases the variance factor, but it also insidiously transfers the SLR and VLBI scale discrepancy to GPS and DORIS. These test examples demonstrate that the adopted ITRF2008 final combination is the most statistically satisfactory combination. In addition, they show that the level of the scale agreement between VLBI and SLR solutions is not better than 1 ppb.

4.5 Consistency between local ties and space geodesy estimates

One of the most important by-products of the ITRF2008 combination is the assessment of the level of agreement between local ties and space geodesy estimates, through the availability of the post-fit residuals at co-location sites. In case of large discrepancies, discriminating between local ties and space geodesy estimates is a very delicate exercise, because the reasons for these discrepancies could be due to errors in local ties, in space geodesy estimates or in both. However, quantifying the level of agreement between the two ensembles is very critical for further investigation and hopefully for identifying the error sources. At co-location sites, not only station position residuals are computed, but also velocity residuals. Therefore, in order to take into account velocity disagreements between the technique solutions, it is more effective to compute the tie discrepancies at their measurement epochs. In order to identify the most performing co-location sites, we list in Table 4 the tie vectors where the discrepancies are less than 6 mm (corresponding to the level of scale consistency between VLBI and SLR solutions) in all three components: North, East and Up. As the GPS is playing the major role of connecting the three techniques together, the vectors listed in Table 4 are from GPS to other technique reference markers. With some exceptions, the geodetic instruments at the co-location sites listed in this table are still in operation in 2010. If we count the percentage of these sites listed in Table 4 over the total currently operating co-locations, we find approximately: 47, 43 and 34% for GPS-VLBI, GPS-SLR and GPS-DORIS, respectively. However, using this sub-set of local ties only, would result in a non-optimal combination. Indeed, a test combination that was performed involving these co-location sites only yielded an increase of the uncertainties of the estimated parameters by a factor of 3.4, compared to the results of the ITRF2008 combination. In particular, the obtained scale factor between VLBI and SLR is 0.83 ppb, but with an increase of its uncertainty: ± 0.44 versus ± 0.13 ppb. In addition, we found the following percentages of co-location sites where tie discrepancies are larger than 10 mm: 29, 28 and 54% for GPS-VLBI, GPS-SLR and GPS-DORIS, respectively. Rejecting these co-location sites from the ITRF2008 combination increases the uncertainties of the estimated parameters by a factor of 2. Table 5 summarizes the tie discrepancy percentages following three categories: less than 6 mm, between 6 and 10 mm and larger than 10 mm.

The drawback of the GPS being the connecting technique is that any intrinsic GPS error would be transferred to the ITRF2008 estimated parameters. Therefore, properly weighting the local ties as a function of their agreement with space geodesy estimates is fundamental in order to ensure consistency between ITRF2008 results and individual technique solutions. Inspecting ITRF2008 local tie residuals, we found that some large discrepancies in the height component might be related to un-calibrated radomes covering the GPS antennas (Jim Ray and Ralf Schmid, personal communication). Examples of these cases include for GPS-VLBI co-locations: Onsala (Sweden), Tidbinbilla (Australia), Santiago (Chile), Fort Davis (USA), and for GPS-SLR co-locations: Greenbelt (USA), Yarragadee (Australia). Another patent example of the radome effect is the case of Forteleza (Brazil) GPS-VLBI co-location site. Using the original local tie values obtained from the adjustment of the survey conducted in 1994 exhibited a tie discrepancy of 19 mm in the height component. Correction was then applied for the apparent height shift due to the neglected effect of the conical radome covering the GPS antenna as reported by Ray et al. (2007) which reduced the discrepancy to 2.3 mm (see Table 4, line "FORT"). However, there are sites with GPS radomes where the discrepancies are within the tie uncertainties, such as CRO1 (Saint-Croix, Virgin Islands, USA) and NYA1 (Ny-Alesund, Norway) as listed in Table 4.

There most probably are other technique-specific errors related to the mis-modeling of the instrumental measurement reference points, not only for GPS (Schmid et al. 2007), but also for the other techniques. Sarti et al. (2010) for instance evaluated the impact of signal path variations caused by VLBI antenna gravitational deformations for Medicina and Noto (Italy) telescopes. They found that applying an elevation-dependent model of the gravitational deformations in VLBI data analysis for these two antennas shift the reference point positions upward by 8.9 and 6.7 mm, respectively. Applying this kind of elevation-dependent model to all VLBI

Table 4 ITRF2008 tie discrepancies less than 6 mm at tie epochs in (E)ast, (N)orth and (U)p: Residuals = Space geodesy − terrestrial tie (in mm)

CODE DOMES #	CODE DOMES #	East	North	Up	Epoch	Technique
GRAS 10002M006	7835 10002S001	1.3	−3.6	−5.6	99:284	SLR
GRAS 10002M006	7845 10002S002	−1.1	−1.2	−0.6	99:284	SLR
TLSE 10003M009	TLSA 10003S001	−1.2	0.7	2.3	4:34	DORIS
NYA1 10317M003	SPIB 10317S004	−1.2	5.7	2.2	3:228	DORIS
NYA1 10317M003	SPJB 10317S005	−1.9	−0.8	−0.9	3:228	DORIS
NYA1 10317M003	7331 10317S003	2.9	−2.7	1.2	3:228	VLBI
ONSA 10402M004	7213 10402S002	5.4	−0.6	−5.2	2:193	VLBI
GRAZ 11001M002	7839 11001S002	1.4	−0.6	−5.9	92:319	SLR
BOR1 12205M002	7811 12205S001	0.5	1.7	−2.9	94:10	SLR
YSSK 12329M003	SAKA 12329S001	−0.4	−2.3	−2.9	4:231	DORIS
YSSK 12329M003	SAKB 12329S002	2.3	−5.0	−2.3	4:231	DORIS
MATE 12734M008	7941 12734S008	−3.7	−4.7	−1.6	4:300	SLR
HERS 13212M007	7840 13212S001	−1.2	−3.1	−2.4	8:177	SLR
ZIMM 14001M004	7810 14001S007	−1.9	−2.2	−5.2	96:95	SLR
WTZZ 14201M014	7224 14201S004	−1.4	−4.1	−0.3	2:266	VLBI
BJFS 21601M001	7249 21601S004	0.6	2.2	5.9	3:171	SLR
TSKB 21730S005	7345 21730S007	−2.9	−0.8	−3.0	8:16	VLBI
HRAO 30302M004	7232 30302S001	−1.6	3.2	2.0	3:214	VLBI
HRAO 30302M004	7501 30302M003	−2.2	2.6	3.5	3:214	SLR
HRAO 30302M004	HBKB 30302S006	5.4	−1.0	−4.2	3:214	DORIS
NKLG 32809M002	LIBB 32809S003	2.9	0.2	2.7	99:36	DORIS
STJO 40101M001	7625 40101M003	0.3	0.1	1.6	99:269	VLBI
YELL 40127M003	7285 40127M001	−3.9	−3.9	−1.0	1:285	VLBI
PIE1 40456M001	7234 40456S001	−3.1	−2.8	−0.3	92:336	VLBI
NLIB 40465M001	7612 40465S001	−3.4	−2.0	−5.2	93:64	VLBI
MKEA 40477M001	7617 40477S001	−3.7	−1.1	0.8	96:221	VLBI
MONP 40497M004	MONB 40497S008	3.1	−4.7	−0.8	5:335	DORIS
MONP 40497M004	7110 40497M001	3.2	−2.5	5.7	99:280	SLR
FORT 41602M001	7297 41602S001	−0.6	−4.0	2.3	93:264	VLBI
GLPS 42005M002	SCRB 42005S001	−2.8	−1.0	−1.1	5:92	DORIS
CRO1 43201M001	7615 43201S001	−1.5	2.2	1.6	94:16	VLBI
HOB2 50116M004	7242 50116S002	4.7	−3.0	−2.0	2:81	VLBI
STR1 50119M002	7849 50119S001	4.1	0.1	4.0	1:209	SLR
CHAT 50207M001	CHAB 50207S001	0.1	0.6	−3.3	99:56	DORIS
SYOG 66006S002	7342 66006S004	0.8	3.8	0.6	0:1	VLBI
KERG 91201M002	KERB 91201S003	−3.2	−2.2	2.0	7:101	DORIS
DUM1 91501M001	ADEB 91501S002	−0.2	−0.2	1.3	8:39	DORIS
DUM1 91501M001	ADFB 91501S003	−5.0	−3.0	3.3	8:39	DORIS
THTI 92201M009	PAPB 92201S007	−1.3	1.7	4.4	7:278	DORIS
NOUM 92701M003	NOUB 92701S002	0.5	5.8	2.2	5:236	DORIS
REUN 97401M003	REUB 97401S002	0.4	2.5	−1.0	3:335	DORIS

The tie vectors are listed from GPS to other technique reference markers

antennas would probably increase its scale bias with respect to SLR. Appleby et al. (2009) reported that the introduction of a high-accuracy event timer at Herstmonceux (UK) SLR site in February 2007 has caused an apparent discontinuity in the laser range data, suggesting that the data prior to this date of equipment change is biased by 12 mm. An appropriate correction was then applied by the ILRS for their ITRF2008 submission (Pavlis et al. 2010). As it can be seen in Table 4

Table 5 Tie discrepancy percentage

Discrepancy (mm)	GPS-VLBI	GPS-SLR	GPS-DORIS
<6	47	43	34
6–10	24	29	12
>10	29	28	54

(line HERS), the agreement between the local survey operated in June 2008 (IGN 2008) and space geodesy estimate is at the level of 3 mm.

4.6 ITRF2008 earth orientation parameters

Similar to the ITRF2005 experience, ITRF2008 provides consistent series of polar motion and its daily rates, universal time (UT1-UTC) and Length of Day (LOD), with the latter being determined by VLBI uniquely. The reason for using LOD values from VLBI only is to avoid contaminating the VLBI estimates by biased determinations from satellite techniques (Ray 1996, 2009). In order to evaluate the EOP consistency between the four technique solutions, Fig. 7 displays the post fit polar motion residuals as result from the ITRF2008 combination, where it can be seen that GPS is dominating the three other techniques. It is worth noting that GPS polar motion helps tieing the three other technique solutions, via the two frame rotation parameters around the *X* and *Y*-axes. The WRMS values computed over the post fit residuals between the combined and the individual polar motion time series are (for the couple *x* and *y* components): (10,10), (142,120), (144,128), (239, 353) in micro-arc-seconds, for GPS, VLBI, SLR and DORIS, respectively.

4.7 ITRF2008 performance in station positions and velocities

In order to evaluate the ITRF2008 performance in station positions and velocities determination, we show the precision gain of these estimated parameters, compared to ITRF2005 results. Figure 8 illustrates for both frames the spherical

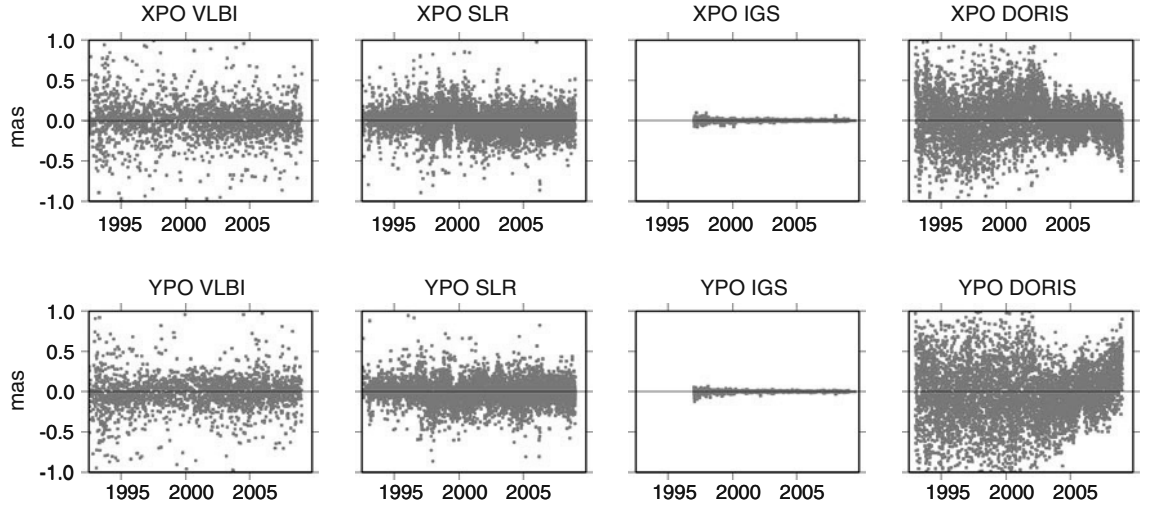


Fig. 7 ITRF2008 post fit residuals of polar motion in milli-arc-seconds

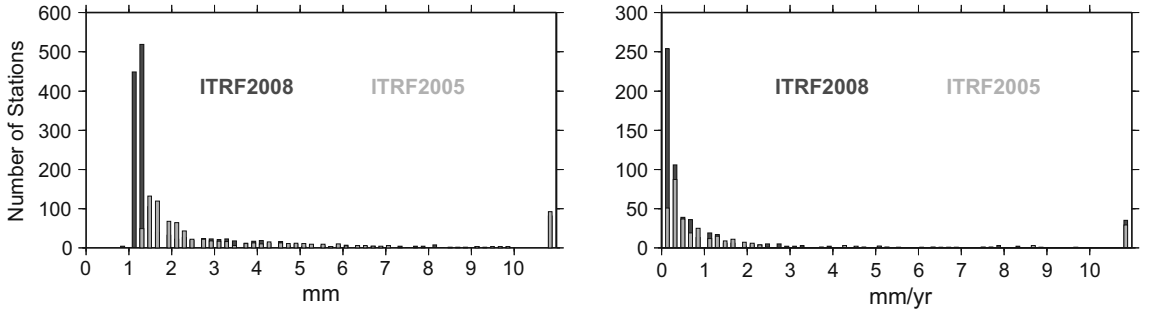


Fig. 8 Histogram of the ITRF2008 and ITRF2005 station position and velocity spherical errors

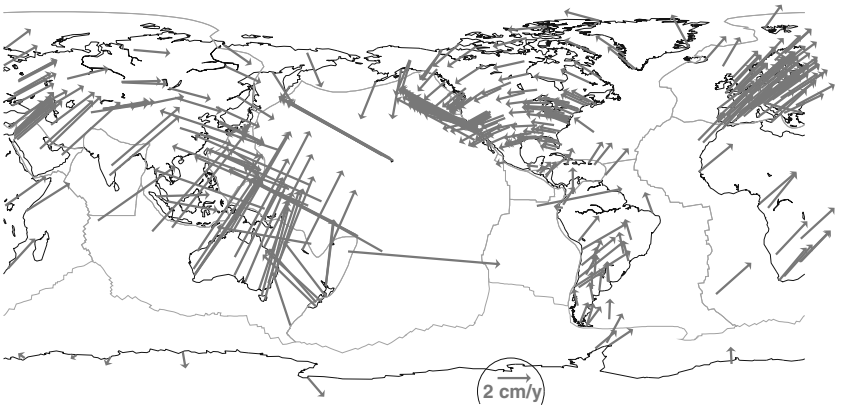


Fig. 9 ITRF2008 horizontal velocities with formal error less than 0.2 mm/yr. Major plate boundaries are shown according to Bird (2003)

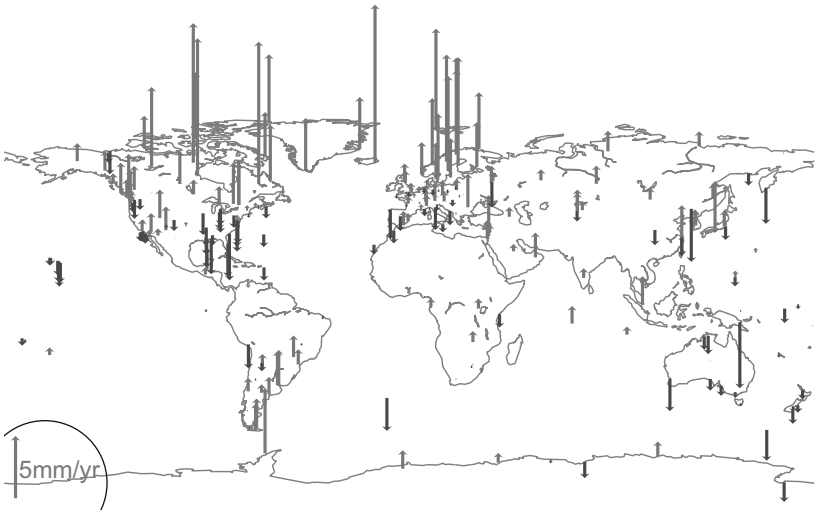


Fig. 10 ITRF2008 vertical velocities with formal error less than 0.2 mm/yr. Positive velocities are shown in *red* and negative in *blue*

errors (computed following Altamimi et al. (2002b), Appendix A7) in station positions and velocities, showing the improvement achieved by ITRF2008. The station position spherical errors are computed at the epochs of minimum variances, following Altamimi et al. (2002b), Appendix A6, Eq. A22. They correspond, for each point position and velocity, to the square root of the square sum of the formal errors along the three components. Although these errors are very often believed to be optimistic (Williams et al. 2004), the proportion of ITRF2008 sites having greater precision as indicted by this figure is relatively high to demonstrate the well performance of ITRF2008 determination. The velocity error histogram shows a number of stations with errors greater than 10 mm/yr which are due to short data spans for mostly old SLR and VLBI stations.

In addition, Figs. 9 and 10 show the ITRF2008 horizontal and vertical velocity fields, respectively, with formal error less than 0.2 mm/yr. At this high level of precision, ITRF2008 contains 406 sites in horizontal and 278 sites in vertical, versus 150 and 30 sites for ITRF2005.

4.8 Transformation parameters between ITRF2008 and ITRF2005

For many applications and in order to ensure the link between ITRF2008 and ITRF2005, it is essential to assess consistently the transformation parameters between the two frames. The same 179 stations (Fig. 3) that were used to ensure the alignment of the ITRF2008 orientation and its rate to the ITRF2005 were also used to estimate the transformation parameters between the two frames. The main criteria for selection of these 179 stations are (1) to have the best possible site distribution; (2) to involve as many as possible VLBI, SLR, GPS and DORIS stations and (3) to have the best agreement between the two frames in terms of post-fit residuals of the 14-parameter transformation. Regarding this third criteria, the WRMS values of the 14-parameter similarity transformation fit are 2.4, 2.9 and 3.9 mm in position (at epoch 2005.0) and 0.4, 0.4, 0.7 mm/yr in velocity, in east, north and vertical components, respectively. Table 6 lists the transformation parameters from ITRF2008

Table 6 Transformation Parameters at epoch 2005.0 and their rates from ITRF2008 to ITRF2005, to be used with Eq. 4

	Tx (mm) $\dot{T}x$ (mm/yr)	Ty (mm) $\dot{T}y$ (mm/yr)	Tz (mm) $\dot{T}z$ (mm/yr)	D (ppb) $\dot{D}$ (ppb/yr)	Rx (mas) $\dot{R}x$ (mas/yr)	Ry (mas) $\dot{R}y$ (mas/yr)	Rz (mas) $\dot{R}z$ (mas/yr)
±	−0.5	−0.9	−4.7	0.94	0.00	0.00	0.00
	0.2	0.2	0.2	0.03	0.08	0.08	0.08
±	0.3	0.0	0.0	0.00	0.00	0.00	0.00
	0.2	0.2	0.2	0.03	0.08	0.08	0.08

to ITRF2005, to be used with the transformation formula given by Eq. (4).

$$\begin{cases} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i05} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} + T + D \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} + R \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} \\ \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i05} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i08} + \dot{T} + \dot{D} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} + \dot{R} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i08} \end{cases} \quad (4)$$

where $i05$ designates ITRF2005 and $i08$ ITRF2008, T is the translation vector, $T = (T_x, T_y, T_z)^T$, D is the scale factor and R is 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 dotted parameters designate their time derivatives. The values of the 14 parameters are those listed in Table 6. Note that the inverse transformation from ITRF2005 to ITRF2008 follows by interchanging (i08) with (i05) and changing the sign of the transformation parameters.

5 Conclusion

The ITRF2008 follows the series of constantly improved ITRF solutions thanks to the continuous improvements of the input data provided by the technique services and the combination strategy. The results presented in this paper demonstrate the high performance of the ITRF2008, compared with past solutions including the ITRF2005, not only in terms of precision of station positions and velocities, but also the improvement of its defining parameters, specifically the origin and the scale. While the accuracy of the ITRF2008 origin is difficult to assess, being determined by SLR only, we believe that its agreement with the ITRF2005 origin at the level of or better than 1 cm (at any epoch covering the time-span of the SLR observations) could be regarded as the level of the origin accuracy attainable today. An assessment of the scale discrepancy between the two independent techniques (VLBI and SLR) solutions, and hence the current scale accuracy, is believed to be at the level of 1.2 ppb (8 mm) over the common time-span of their observations covering about 26 years.

Thorough analysis and several test combinations have been undertaken during the ITRF2008 project to evaluate the impact of the local ties and their usage on the results and in particular on the frame defining parameters. We showed that using the local ties at their measurement epochs as observations and properly weighted with full variance covariance information provides the most statistically satisfactory combination. Although newly reprocessed solutions of the four techniques were used for the ITRF2008 generation, discrepancies between local surveys and space geodesy estimates still exist: 50% of the available SLR and VLBI tie vectors to GPS exhibit residuals larger than 6 mm, and about 30% have residuals larger than 10 mm. We identified that some large tie discrepancies might be due to the effect of un-calibrated radomes covering the GPS antennas in some IGS sites. However, including all available local ties properly weighted and if possible with full variance covariance information has been shown to lead to the best inter-technique combination.

As results from the ITRF2008 combination, we evaluate the uncertainty of the transfer of SLR origin and SLR and VLBI mean scale to GPS frame to be at the level of 0.6 mm at epoch 2005.0. This uncertainty would certainly be improved if we had a better geometry of co-location network with better agreement between space geodesy and local tie estimates. Therefore, the prerequisite for improving the ITRF is to start by improving the geodetic infrastructure.

Acknowledgments The ITRF activities are funded by the Institut Géographique National (IGN), France and partly by Centre National d'Etudes Spatiales (CNES). We are indebted to all Analysis and Combination Centers of the Technique Services of the four techniques who constantly provide data for ITRF solutions which would not exist without their valuable contributions. We are particularly grateful to all the institutions who provide the necessary budgets for the space geodesy observatories, which constitute the main ITRF foundation. Fruitful discussions and exchanges with DGFI group have been found very valuable for the benefit of the ITRF2008 project. We are grateful to R. Ferland, J-J. Valette, J. Griffith, S. McClusky and the DGFI group for their contribution to the GPS discontinuity list. Part of the work of Laurent Métivier is an IPGP contribution number 3125. We acknowledge useful comments and suggestions provided by two anonymous

reviewers and Athanasios Dermanis which improved the content of this article.

Open Access This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

References

Altamimi Z, Boucher C, Sillard P (2002) New trends for the realization of the international terrestrial reference system. Adv Space Res 30(2):175–184

Altamimi Z, Sillard P, Boucher C (2002) ITRF2000: a new release of the international terrestrial reference frame for earth science applications. J Geophys Res 107(B10):2214. doi:10.1029/2001JB000561

Altamimi Z, Sillard P, Boucher C (2004) ITRF2000: from theory to implementation. In: Sansò F (ed) V Hotine–Marussi symposium on mathematical geodesy. International association of geodesy, 127. Springer, Berlin, pp 157–163

Altamimi Z, Collilieux X, Legrand J, Garayt B, Boucher C (2007) ITRF2005: a new release of the international terrestrial reference frame based on time series of station positions and earth orientation parameters 2007. J Geophys Res 112(B09401). doi:10.1029/2007JB004949

Altamimi Z, Collilieux X (2009) IGS contribution to the ITRF. J Geodesy 83(3–4):375–383. doi:10.1007/s00190-008-0294

Altamimi Z, Collilieux X (2010) Quality assessment of the IDS contribution to ITRF2008. In: Willis P (ed) DORIS: scientific applications in geodesy and geodynamics. Adv Space Res 45(12): 1500–1509. doi:10.1016/j.asr.2010.03.010

Altamimi Z, Dermanis A (2010) The choice of reference system in ITRF formulation. In: Proceedings of Hotine–Marussi symposium, Rome (in press)

Appleby GM, Wilkinson M, Luceri V, Gibbs P, Smith V (2009) Attempts to separate apparent observational range bias from true geodetic signals. In: Schilliak S (ed) Proceedings of the 16th international workshop on laser ranging. Posnan, Poland

Bähr H, Altamimi Z, Heck B (2007) Variance component estimation for combination of terrestrial reference frames. Universität Karlsruhe Schriftenreihe des Studiengangs Geodäsie und Geoinformatik 2007 6. ISBN:978-3-86644-206-1

Beckley BD, Lemoine FG, Luthcke SB, Ray RD, Zelensky NP (2007) A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised frame and orbits. Geophys Res Lett 34(L14608). doi:10.1029/2007GL030002

Bianco G (2006) Agenzia Spaziale Italiana, provided local tie SINEX file for Matera site (personal communication)

Bird P (2003) An updated digital model of plate boundaries. Geochem Geophys Geosyst 4(3):1027. doi:10.1029/2001GC000252

Böckmann S, Artz T, Nothnagel A (2010) VLBI terrestrial reference frame contributions to ITRF2008. J Geod 84(3):201–219. doi:10.1007/s00190-009-0357-7

Boehm J, Niell A, Tregoning P, Schuh H (2006) Global mapping function (GMF): a new empirical mapping function based on numerical weather model data. Geophys Res Lett 33(L07304). doi:10.1029/2005GL025546

Boehm J, Werl B, Schuh H (2006) Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data. J Geophys Res Solid Earth 111:2406. doi:10.1029/2005JB003629

Boehm J, Heinkelmann R, Schuh H (2007) Short note: a global model of pressure and temperature for geodetic applications. J Geod 81: 679–683. doi:10.1007/s00190-007-0135-3

Collilieux X, Altamimi Z, Ray J, van Dam T, Wu X, (2009) Effect of the satellite laser ranging network distribution on geocenter motion estimation. J Geophys Res 114(B04402). doi:10.1029/2008JB005727

Collilieux X, Wöppelmann G (2010) Global sea-level rise and its relation to the terrestrial reference frame. J Geod. doi:10.1007/s00190-010-0412-4

Collilieux X, Altamimi Z, Coulot D, van Dam T, Ray J (2010) Impact of loading effects on determination of the International Terrestrial Reference Frame. Adv Space Res 45:144–154. doi:10.1016/j.asr.2009.08.024

Dermanis A (2000) Establishing global reference frames, nonlinear, temporal geophysical and stochastic aspects. In: Sideris M (ed) Gravity, geoid and geodynamics IAG symposium 123. pp 35–42

Dermanis A (2003) The rank deficiency in estimation theory and the definition of reference systems. In: Sansò F (ed) Hotine–Marussi symposium on mathematical geodesy, IAG Symposia 127, pp 145–156

Dong D, Dickey JO, Chao Y, Cheng M (1997) Geocenter variations caused by atmosphere, ocean and surface ground water. Geophys Res Lett 24:1867–1870. doi:10.1029/97GL01849

Dow J, Neilan RE, Rizos C (2009) The International GNSS Service in a changing landcape of Global Navigation Satellite Systems. J Geod 83(3–4):191–198

Farrell WE (1972) Deformation of the earth by surface loads. Rev Geophys 10(3):761–797

Ferland R, Piraszewski RM (2008) The IGS combined station coordinates, earth rotation parameters and apparent geocenter. J Geod 83:385–392. doi:10.1007/s00190-008-0295-9

Ferland R (2010) Description of IGS submission to ITRF2008. Available at: http://itrf.ensg.ign.fr/ITRF_solutions/2008/doc/IGSsubmission4ITRF2008.txt

Geographical Survey Institute (GSI) (2010) VLBI Group, Space Geodesy Division, Tsukuba, Japan, provided local tie SINEX file for Tsukuba site (personal communication)

Gobinddass ML, Willis P, de Viron O, Sibthorpe A, Ries JC, Zelensky NP, Bar-Sever Y, Diament M, Ferland R (2009) Systematic biases in DORIS-derived geocenter time series related to solar pressure mis-modeling. J Geod 83(9):849–858. doi:10.1007/s00190-009-0303-8

Greff-Lefftz M (2000) Secular variation of the geocenter. J Geophys Res 105(B11):25685–25692

Greff-Lefftz M, Métivier L, Besse J (2010) Dynamic mantle density heterogeneities and global geodetic observables. Geophys J Int 180:1080–1094. doi:10.1111/j.1365-246X.2009.04490.x

Haas G (2010) Onsala Space Observatory, provided local tie SINEX file for Onsala site (personal communication)

Institut Géographique National (IGN) (2008) Herstmonceux Co-location Survey, Reports and Results. Available at: http://itrf.ensg.ign.fr/doc_ITRF/Herstmonceux_Colocation_Survey_aug08.pdf

IUGG (2007) Resolution number 2 of Perugia IUGG General Assembly

Johnston G, Dawson J (2004) The 2003 Yarragadee (Moblas 5) Local Tie Survey, Geoscience Australia Record 2004/19. Available at: http://www.ga.gov.au/image_cache/GA5651.pdf

Kovalevsky J, Mueller II, Kolaczek B (eds) (1989) Reference frames in astronomy and geophysics. Kluwer Academic Publisher, Dordrecht p 474

Lavallée D, van Dam T, Blewitt G, Clarke P (2006) Geocenter motions from GPS: a unified observation model. J Geophys Res 111(B10):B05405. doi:10.1029/2005JB003784

Mendes VB, Prates G, Pavlis EC, Pavlis D, Langley RB (2002) Improved mapping functions for atmospheric refraction correction in SLR. Geophys Res Lett 29(10). doi:10.1029/2001GL014394

Mendes VB, Pavlis EC (2004) High-accuracy zenith delay prediction at optical wavelengths. Geophys Res Lett 31:14602. doi:10.1029/2004GL020308

Morel L, Willis P (2005) Terrestrial reference frame effects on global sea level rise determination from TOPEX/Poseidon altimetric data. Adv Space Res 36:358–368. doi:10.1016/j.asr.2005.05.113

Métivier L, Greff-Lefftz M, Altamimi Z (2010) On secular geocenter motion: the impact of climate changes, Earth and Planet. Sci Lett 296(3–4):360–366. doi:10.1016/j.epsl.2010.05.021

Nothnagel A (2009) Conventions on thermal expansion modelling of radio telescopes for geodetic and astrometric VLBI. J Geod 83: 787–792. doi:10.1007/s00190-008-0284-z

Pavlis E, Luceri C, Sciarretta C, Kelm R (2010) The ILRS contribution to ITRF2008. Available at: http://itrf.ensg.ign.fr/ITRF_solutions/2008/doc/ILRSSubmission4ITRF2008.pdf

Pearlman MR, Degnan JJ, Bosworth JM (2002) The international laser ranging service. Adv Space Res 30(2):135–143

Petit G, Luzum B, (eds.) (2010) IERS Conventions (2010), IERS Technical Note 36, Verlagdes Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany. http://tai.bipm.org/iers/conv2010/

Ray JR (1996) Measurements of length of day using the Global Positioning System. J Geophys Res 101(B9):20141–20149

Ray JR, Crump D, Chin M (2007) New global positioning system reference station in Brazil. GPS Solut 11:1–10. doi:10.1007/s10291-006-0032-x

Ray JR (2009) A Quasi-optimal, consistent approach for combination of UT1 and LOD. In: Drewes H (ed) Geodetic reference frames. International association of geodesy symposia, 2009, 134(Part 4):239–243. Springer, Berlin. doi:10.1007/978-3-642-00860-3_37

Sarti P, Sillard P, Vittuari L (2004) Surveying co-located space-geodetic instruments for ITRF computation. J Geod 78(3): 210–222. doi:10.1007/s00190-004-0387-0

Sarti P, Abbondanza C, Vittuari L (2009) Gravity-dependent signal path variation in a large VLBI telescope modelled with a combination of surveying methods. J Geod 83(11):1115–1126. doi:10.1007/s00190-009-0331-4

Sarti P, Abbondanza C, Petrov L, and Negusini M (2010) Height bias and scale effect induced by antenna gravity deformations in geodetic VLBI data analysis. J Geod. doi:10.1007/s00190-010-0410-6

Schmid R, Steigenberger P, Gendt G, Ge M, Rothacher M (2007) Generation of a consistent absolute phase-center correction model for GPS receiver and satellite antennas. J Geod 81:781–798. doi:10.1007/s00190-007-0148-y

Schlüter W, Zernecke R, Becker S, Klügel Th, Thaller D (2004a) Local ties between the reference points at the fundamentalstation wettzell. In: Richter B, Dick WR, Schwegmann W (eds) IERS Technical Note 33. Verlag des Bundesamts für Kartographie und Geodäsie Frankfurt am Main, Germany

Schlüter W, Hase H, Zernecke R, Becker S, Klügel Th, Thaller D, (2004b) Local ties between the reference points at the transportable integrated geodetic observatory (TIGO) in Concepcion/Chile. In: Richter B, Dick WR, Schwegmann W (eds) IERS Technical Note 33. Verlag des Bundesamts für Kartographie und Geodäsie Frankfurt am Main, Germany

Schlüter W, Behrend D (2007) The international VLBI service for geodesy and astrometry (IVS). Current capabilities and future prospects. J Geod 81(6-8):379–387

Sillard P, Boucher C (2001) Review of algebraic constraints in terrestrial reference frame datum definition. J Geod 75:63–73

Tregoning P, Watson C (2009) Atmospheric effects and spurious signals in GPS analyses. J Geophys Res Solid Earth 114(B13):9403. doi:10.1029/2009JB006344

Valette JJ, Lemoine FG, Ferrage P, Yaya P, Altamimi Z, Willis P, Soudarin L (2010) IDS contribution to ITRF2008. In: Willis P (eds) DORIS: precise orbit determination and applications to the earth sciences. Adv Space Res. doi:10.1016/j.asr.2010.05.029

van Dam T, Altamimi Z, Collilieux X, Ray J (2010) Topographically induced height errors in predicted atmospheric loading effects. J Geophys Res 115(B07415) doi:10.1029/2009JB006810

Williams SDP, Bock Y, Fang P, Jamason P, Nikolaidis RM, Prawirodirdjo L, Miller M, Johnson DJ (2004) Error analysis of continuous GPS position time series. J Geophys Res 109(B03412). doi:10.1029/2003JB002741

Willis P, Fagard H, Ferrage P, Lemoine FG, Noll CE, Noomen R, Otten M, Ries JC, Rothacher M, Soudarin L, Tavernier G, Valette JJ (2010) The international DORIS service, toward maturity. In: Willis P (ed) DORIS: scientific applications in geodesy and geodynamics. Adv Space Res 45(12):1408–1420. doi:10.1016/j.asr.2009.11.018

Zhu SY, Mueller II (1983) Effects of adopting new precession, nutation and equinox corrections on the terrestrial reference frame. Bull Geod 57:29–42

Description of Technique Center solutions

Author: Sarah Böckmann, Axel Nothnagel

(boeckmann _at_ uni-bonn.de, nothnagel _at_ uni-bonn.de)

The official contribution of the International VLBI Service for Geodesy and Astrometry (IVS) to ITRF2008 consists of session-wise datum-free normal equations of altogether 4,539 daily 24h Very Long Baseline Interferometry (VLBI) network sessions from 1979.7 to 2009.0 including data of 115 different VLBI sites. It is the result of a combination of individual series of session-wise datum-free normal equations provided by seven analysis centers (ACs) of the IVS. All series are completely reprocessed following homogeneous analysis options according to the IERS Conventions 2003 and IVS Analysis Conventions. A correction for atmospheric pressure loading was not applied as it was approved by the IERS Directing Board. Unknown parameters contained in the normal equation systems are station positions and EOPs. Zenith wet delays, atmosphere gradients and clock parameters were (pre-)reduced by the individual ACs.
Source positions are handled by each AC independently under the premisses that they stay within the error boundaries of the ICRF. They are kept fixed to these values and are not contained in the normal equation systems.

1) Analysis strategy:

As for the IVS contribution to ITRF2005, the combination is performed at the normal equation level. The strategy for the intra-technique combination mainly consists of three steps.

1) The session-wise datum-free normal equation systems of the individual ACs are transformed to an identical reference epoch and to an equal set of a priori values.
2) Weights for the normal equation systems of each AC are estimated for each single session within a variance component estimation procedure.
3) The weighted equation systems of each contributing AC are stacked to combined session-wise normal equation systems.

These session-wise combined normal equation systems form the IVS input to the ITRF2008.

2) ACs Contribution:

7 ACs have contributed:

AC	Software	Time span	#sessions	#stations
BKG	Calc/Solve	1984.0-2009.0	4,424	94
GSFC	Calc/Solve	1979.7-2009.0	4,592	125
OPA	Calc/Solve	1979.7-2009.0	4,489	120
USNO	Calc/Solve	1979.7-2009.0	4,250	100
SHAO	Calc/Solve	1979.7-2009.0	4,465	120

IGGB	Calc/Solve	1979.7-2009.0	4,370	112
DGFI	OCCAM(LSM)	1984.0-2009.0	3,184	52

3) Combined Products:

AC	Software	Time span	#sessions	#stations
IVS	DOGS_CS	1979.7-2009.0	4,539	115

Consistency of the individual contributions to the IVS combination:

WRMS values computed from the single-session station position differences between the estimates of each individual contribution and the combined series for the north, east and height component.

AC - IVS comb.	North (mm)	East (mm)	Height (mm)
BKG	1.6	2.1	3.7
DGFI	1.6	2.0	3.1
GSFC	0.9	1.1	1.9
IGG	0.9	1.2	2.1
OPA	0.7	0.9	1.5
SHAO	0.7	0.8	1.5
USNO	1.0	1.4	2.2
average	1.1	1.4	2.2

WRMS values computed from the single-session EOP differences between the estimates of each individual contribution and the combined EOP series from 1984 to 2008 for polar motion, dUT1 and their first derivatives as well as nutation offsets.

AC - IVS comb.	X-pole (µas)	Y-pole (µas)	dUT1 (µs)	LOD (µs)	X-pole rate (µas/d)	Y-pole rate (µas/d)	dX (µas)	dY (µas)
BKG	56.2	55.3	3.5	6.2	174.3	170.2	46.0	48.0
DGFI	57.8	55.2	3.4	6.5	174.9	163.6	47.8	48.9
GFSC	34.4	34.2	2.7	3.5	103.5	98.5	28.8	30.5
IGG	37.1	32.7	2.9	4.4	113.9	106.8	32.5	33.2
OPA	30.6	31.2	2.8	3.8	93.5	92.6	29.1	29.9
SHAO	27.9	28.4	2.6	2.9	86.8	80.0	24.7	26.1
USNO	41.7	37.7	3.0	4.2	122.5	111.9	34.2	36.5
average	40.8	39.2	3.0	4.5	124.2	117.7	34.7	36.2

For detailed information on the IVS submission to ITRF2008 see:
Böckmann, S., T. Artz, A. Nothnagel (2010)
VLBI terrestrial reference frame contributions to ITRF2008.
J Geod 84:201-219, DOI 10.1007/s00190-009-0357-7.

The ILRS contribution to ITRF2008

E. Pavlis (GEST/UMBC & NASA Goddard)
V. Luceri (e-GEOS S.p.A., ASI/CGS)
C. Sciarretta (e-GEOS S.p.A., ASI/CGS)
R. Kelm (DGFI/München)

The ILRS contribution to ITRF2008 is a time series of weekly station coordinates and daily Earth Orientation Parameters (X-pole, Y-pole and excess Length-Of-Day (LOD)) estimated over 7-day arcs (15-day arcs for the period 1983-1992) aligned with calendar weeks (Sunday to Saturday), starting from January 1983. Each weekly solution is obtained through the combination of weekly solutions submitted by the official ILRS Analysis Centers (ASI, DGFI, GA, GFZ, GRGS, JCET and NSGF). Both the individual and combined solutions have followed strict standards agreed upon within the ILRS Analysis Working Group to provide products of the highest possible quality.

Individual solutions

SLR observations on LAGEOS 1, LAGEOS 2, and since mid-2002, Etalon 1 and Etalon 2, are analysed to generate the individual EOP and positions solutions; the measurements are retrieved from the CDDIS and/or EDC archive facilities. The observations are processed in intervals of 7 days to generate a loosely-constrained solution for station coordinates and EOP. The EOPs include X_p,Y_p and LOD, all computed as a daily average; daily UT parameters are also solved for, but they are of course considered as weakly-determined parameters by any satellite technique and are not included in the analysis product that is submitted to the combination centers. The station positions, with the midpoint of each 7-day (15-day for the period 1983-1992) interval as reference epoch, refer to the official station markers. Analysis contributors are generally free to follow their own computation model and/or analysis strategy, but a number of constraints must be followed for consistency:

1. The computation models follow the prevalent IERS Conventions as closely as possible.
2. The stations are included (positions estimated) in the weekly analysis if the number of observed LAGEOS 1 plus LAGEOS 2 ranges is greater than 10. Data weighting is applied according to the analyst's preference. However, the AWG has agreed to down-weight “non-core” sites significantly.
3. The tropospheric correction is applied using the IERS Conventions [Mendes-Pavlis, 2004], and there is no modeling of atmospheric pressure loading and no further estimation of tropospheric corrections.
4. The center-of-mass correction for each satellite is according to the ILRS standards. In this analysis a single correction for the two LAGEOS and another one for the two ETALON satellites were used, with the exception of the Herstmonceux station (7840), where for example the applied correction for LAGEOS is 245 mm (instead of the standard 251), to account for its (single-photon detection system) mode of operation.
5. Range corrections were modeled or estimated for a number of sites, based either on engineering reports from these sites or long-term analysis of their systematic behavior. All of the applied corrections are documented in the ILRS database (Data Handling file):

   http://www.dgfi.badw.de/typo3_ilrs/fileadmin/data_handling/ILRS_Data_Handling_File.snx

6. The weekly solutions are loosely constrained with an a priori standard deviation on station coordinates of ~1 meter and the equivalent of at least 1 m for EOPs.

Additional details on the individual AC analysis strategy can be found on the ILRS web page http://ilrs.gsfc.nasa.gov/science_analysis/analysis_centers.html

Intra-technique combination

The combined solution was produced by the primary Combination Center, ASI/CGS, and named ILRSA. The main lines of the combination methodology rely on the direct combination of loose constrained solutions; this straightforward method, "*Methodology for global geodetic time series estimation: A new tool for geodynamics*", [P. Davies and G. Blewitt, JGR, vol. 105, no. B5, pages 11083-11100, May 10, 2000], allows handling input solutions easily, with no inversion problems for the solution variance-covariance matrix and no need to know a priori values for the estimates. The reference frame is defined stochastically and it is undefined; no relative rotation between the reference frames is estimated or removed. The ASI/CGS s/w process, based on these loose combination algorithms, has been implemented in a completely general case, to handle site coordinates, EOP, and EOP-rates.

The combination is performed along the lines of the iterative Weighted Least Square technique, in which each contributing solution (and related variance-covariance matrix) plays the role of an 'observation' whose misclosure with respect to the combined solution must be minimized; each solution is stacked using its full covariance matrix rescaled by an estimated factor. A scaling of the covariance matrix of the *i*-th solution is required because the relative weights of the contributing solutions are arbitrary. Imposing $\chi^2=1$ for the combination residuals and requiring that each contribution to the total χ^2 is appropriately balanced, the relative scaling factors (σ_i) are estimated iteratively together with the combined solution. If R_i represents the solution residuals (with respect to the combined product) and Σ_i the solution covariance matrix, the imposed conditions are:

$$R_1^T(\sigma_1\Sigma_1)^{-1}R_1 = \ldots = R_i^T(\sigma_i\Sigma_i)^{-1}R_i \quad \text{and} \quad \chi^2 = R_1^T\Sigma_1^{-1}R_1 + \ldots + R_i^T\Sigma_i^{-1}R_i = 1$$

The first guess for the combination is obtained with $\sigma_i=1$ for each solution. Table 1 shows the mean value and its standard deviation, over the period 1983-2009, of the scale factors for each contributing agency.

Table 1. Mean scaling factors

	ASI	DGFI	GA	GFZ	GRGS	JCET	NSGF
Mean	5,6	16,7	3,9	11,8	6,0	8,3	7,5
Standard deviation	13,1	35,8	14,8	18,3	11,0	14,2	4,1

In ILRSA a rigorous editing has been introduced: any estimated parameter in the incoming solutions that is **not** site coordinates or EOP (e.g. range bias, ...) has been rigorously pre-eliminated ["Combination of solutions for geodetic and geodynamic applications....", E. Brockmann, PhD thesis, AIUB].

The same technique has been used to eliminate outliers with respect to the combined solution following a 5σ criterion for:

1. too weak sites (<10 NP) erroneously present in the contributing solutions
2. too weak site estimations in the contributing solutions, with uncertainties greater than 0.8m, in at least one component, after transformation to the *a priori* (SLRF2005)

3. too poor estimates in the contributing solutions, with discrepancy greater than 0.3m with respect to the *a priori* in at least one coordinate for the set of "Core Sites" (see below), 0.5m for the other sites (Arequipa excluded during the post-earthquake relaxation period).

The list of core sites has been officially defined, within the Analysis Working Group, considering the quality and stability of the entire set of network sites over several decades. This list was proposed by ASI at the AWG meeting in Grasse, France (September 2007) and accepted by the ILRS/AWG for the generation of the ILRS official products for contribution to ITRF2008.

List of core sites to be used for EOP referencing (June2009):

Site No.	dome	Wav	from	to (year included)	Notes
7080	40442M006	G	1988	--	
7090	50107M001	G	1979	--	
7105	40451M105	G	1981	--	
7109	40433M002	G	1981	1997	
7110	40497M001	G	1981	--	
7210	40445M001	G	feb 1994	2004	subset
7403	42202M003	G	1990	dec 2000	subset
7501	30302M003	G	2000	--	
7810	14001S007	B	1998	--	
7825	50119S003	G	2004	--	
7832	20101S001	G	2001	--	
7834	14201S002	G	1976	1991	
7835	10002S001	G	oct 1988	2005	subset
7836	14106S009	G	1993	2004	
7837	21605S001	G	1997	2005	subset
7839	11001S002	G	1983	--	
7840	13212S001	G	1983	--	
7849	50119S001	G	1998	2003	
7907	42202S001	G	1976	1992	
7939	12734S001	G	1983	2000	
7941	12734S008	G	2001	--	
8834	14201S018	G	may 1996	--	subset

The note "subset" identifies those sites tracking over a data span longer than the period they perform as core sites. In Fig. 1 below, the periods with low performance are indicated in yellow.

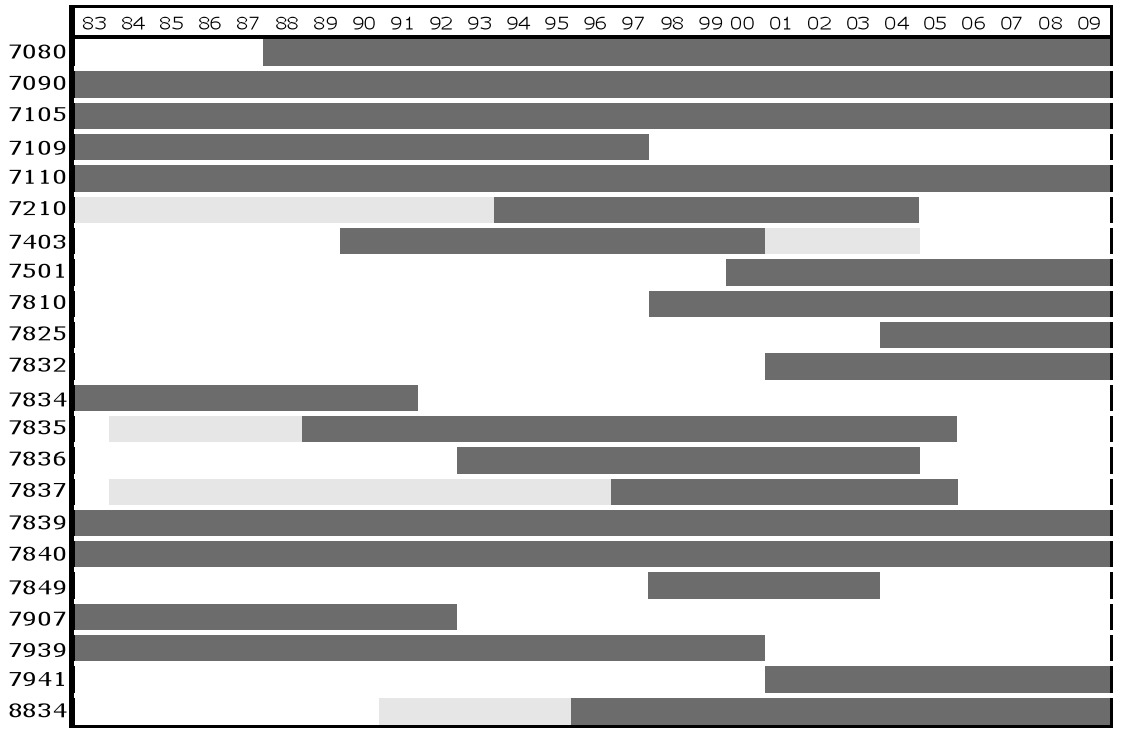


Figure 1. The selected "Core Sites" and their period of performance (yellow indicates operational period when the site is underperforming and remains excluded from the "Core Sites" list).

The mean values of the 3-dimensional weighted root mean square (WRMS) error of the site coordinate residuals with respect to the combined solution, obtained considering all the stations of the network and the entire time span 1983-2009, are shown in Table 2.

Table 2. 3D WRMS with respect to ILRSA

	ASI	DGFI	GA	GFZ	GRGS	JCET	NSGF
3D WRMS (mm)	10,7	19,8	11,8	13,0	9,2	11,9	20,2

The official ILRSA weekly solution is routinely compared with the backup combined solution ILRSB that is produced by DGFI (the official ILRS backup combination center) following a completely independent approach. The two solution series show an overall good agreement; eventual discrepancies are investigated to identify problems left. This comparison step has been performed also to check the results of the official ILRS contribution to ITRF2008.
The ILRSA solution has been extensively compared to SLRF2005; the two tables below show a limited comparison in terms of:

1) mean of the 3D WRMS of the site coordinates residuals w.r.t. SLRF2005 (see also Fig. 2)
2) translation and scale parameters of ILRSA w.r.t. SLRF2005

The evaluation of the results should take into consideration the different strength of the solution before and after 1993. The initial decade of the solution (1983-1992) consists of less precise estimates, based on 15-day arc data reduction. The weakness of the estimates is clearly visible both in the coordinate evaluation (Figure 2) and in the Helmert parameter time series (Figure 3). However, the old portion of the series is a valuable, unique contribution of the SLR to the long-term Terrestrial Reference Frame definition, contributing a number of sites from the early stages of space geodetic networks and strengthening the velocity estimates for sites that span both periods.

Table 3. 3D WRMS of the site coordinate residuals w.r.t. SLRF2005

Units are millimeters (mm)	ILRSA
All sites (mean)	12.3
Core sites (mean)	8.2
All sites (mean) 1993-2008	9.9
Core sites (mean) 1993-2008	6.5

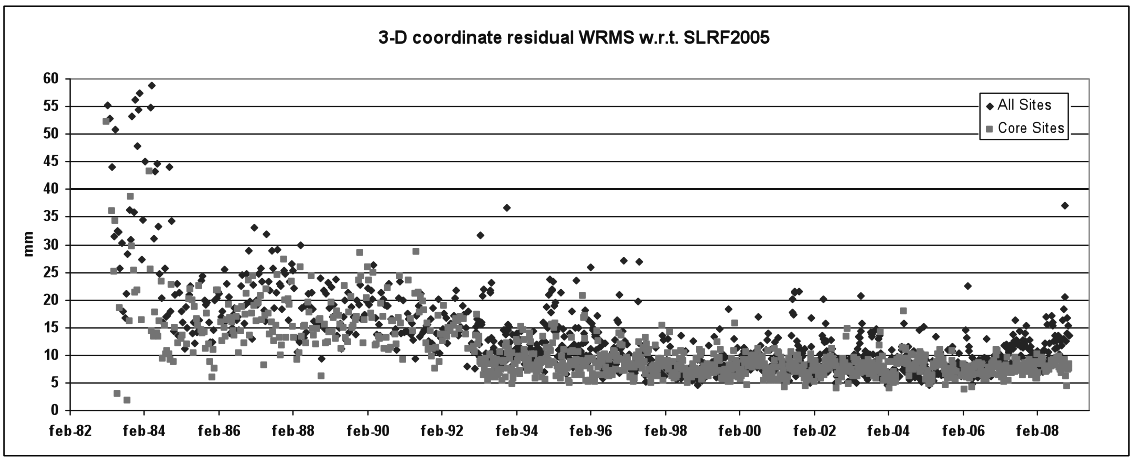


Figure 2. 3D WRMS of the core site coordinate residuals w.r.t. SLRF2005

Table 4. Translation and scale (w.r.t. SLRF2005)

	T_X	T_Y	T_Z	SCALE
Slope (mm/y)	-0.29±0.02	0.06±0.02	0.38±0.03	-0.30±0.01
Residual WRMS (mm)	4.16	3.82	7.45	3.15

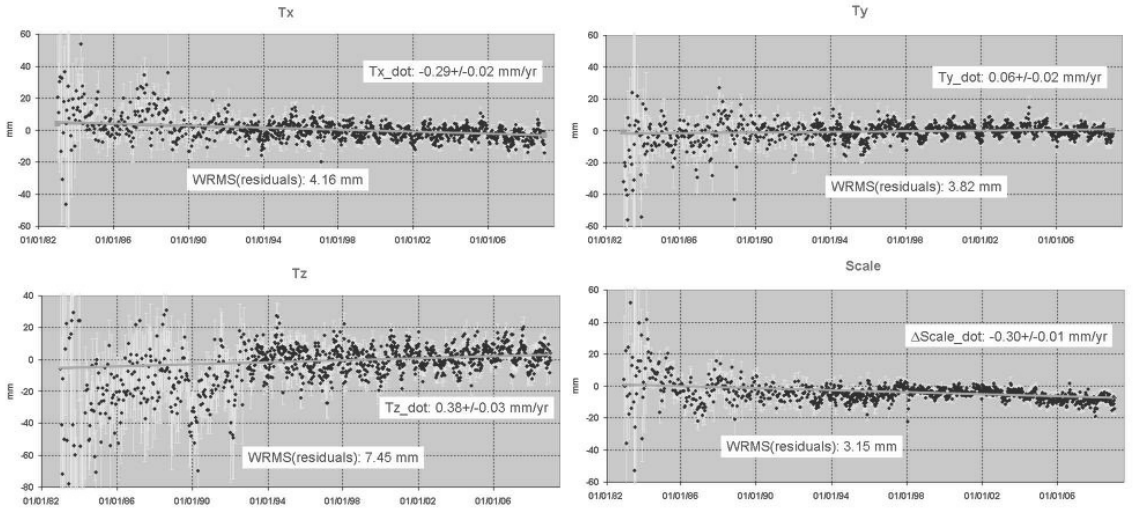


Figure 3. Helmert translation and scale w.r.t. SLRF2005

Additional information can be found on the ILRS web pages
http://ilrs.gsfc.nasa.gov/science_analysis/analysis_products.html

Author: Rémi Ferland

(Remi.Ferland _at_ NRCan-RNCan.gc.ca)
Extracted from IGS-ACS Mail Message Number 352

The IGS contribution spans the period 1997.0 - 2009.5 (563 weeks)
(GPS weeks 0886-1536) (1996/12/29 - 2009/07/04)
The pre-2008 solutions are based on the reprocessed products, while
the more recent solutions are based on the IGS official products.
Minor improvements were made to the official products before resubmission.
All weekly solution include weekly station coordinates and apparent
geocenter position estimates as well as daily (at the middle
of the day) pole position, pole rate, and LOD estimates. The weekly
solutions also include full variance-covariance estimate. All weekly
solutions are provided aligned to the IGS05 realization of ITRF2005.
The ACs LOD parameters are calibrated w.r.t. Bulletin A.

For detailed information on the reprocessing see:
http://acc.igs.org/reprocess.html

1) Analysis strategy:

The sequential procedures used to generate the official products
and the reprocessed products are almost identical. They differ in:
1) The official sequential analysis runs forward in time, while
the reprocessed runs backward.
2) The rejection criterion for the official products was set
at 5 sigmas, while the reprocessed rejection was set an 8 sigmas.

General strategy steps:
- Rescale covariance information (from previous iteration)
- Unconstrain
- Consistency check / Outlier rejection between AC (& GNAAC) and:
    - Reference frame,
    - AC,
    - Previous week (weekly & cumulative) combined solutions,
- Combine weekly solution,
- Update cumulative solution.

2) ACs & GNAACs Contribution:

11 ACs and 2 GNAACs have contributed:

AC	data span	Comments
co[d1]	1997.0 - 2009.5	Excluded ERPs
em[r1]	1997.0 - 2009.5	
es[a1]	1997.0 - 2009.5	
gf[z1]	1997.0 - 2009.5	Excluded apparent geocenter
gt1	1998.2 - 2002.0	Excluded apparent geocenter
jpl	2008.0 - 2009.5	
mi[t1]	1998.0 - 2009.5	
ng[s1]	1997.0 - 2009.5	
pdr	1997.0 - 2008.0	Excluded ERPs
si[o1]	1997.0 - 2009.5	Excluded pole rate

```
ul1     1997.0 - 2007.0   Excluded apparent geocenter (no ERPs)

GNAACs     data span       Comments
MIT     2008.0 - 2009.5   Comparison only
ncl     2008.0 - 2009.5   Comparison only

3) Combined Products:
=====================

560 stations with the following # of weekly solutions:
  Weeks
From  To # Stations
101 - 150   64
151 - 200   46
201 - 250   45
251 - 300   30
301 - 350   45
351 - 400   48
401 - 450   42
451 - 500   44
501 - 550   55
551 - 600   37
601 - 653  104
          ----
Total      560

There is a total of 222261 positions estimates resulting in
An average close to 395 stations estimates per weeks.
        Weekly *snx, *res, *sum, *res files are available at CDDIS.

As per the original submisson in Feb 2009, the
remarks concerning the statistics evolution:

- The North weekly weighted average residuals w.r.t. the
reference frame realization and the cumulative solution
have an annual signal with amplitude of 1-2mm.

- A similar annual signal can be seen in the estimated
scale offset w.r.t. the reference frame.

- The number of stations going back to 1997, is holding
at above 175 every week. By comparison, when the original
analysis was done for early 1997, there were ~95 stations
in the weekly combinations.

- The statistics of the residuals w.r.t. the reference
frame are generally best in the weeks 1200-1400 (2003-2006)
period.  The increase after 1400 is most likely due
to extrapolation of the reference frame and a decrease
number of available stations; and before 1200 it is
mostly due to a decrease of the number of available stations

The AC horizontal/vertical consistency is still about
(in mm) w.r.t.:

        IGS05           Combined        Combined
                        Weekly          Cumulative
```

2-3 / 7-9 1-2 / 3-4 2-3 / 5-7

The overall ERP consistency of the ACs w.r.t. weekly combination is still about:

LOD	15 us
XPO	0.05 mas
YPO	0.04 mas
XPOR	0.14 mas/d
YPOR	0.14 mas/d

The DORIS contribution to ITRF2008

Jean-Jacques Valette (CLS)
Frank Lemoine (GSFC)

DORIS data span

The DORIS data used for the IDS contribution to ITRF2008 are listed in Table 1. The data used in the combination started in January 1993, mainly because the DORIS station network was not completely implemented until the launch of TOPEX/Poseidon, and because a second satellite was necessary to strengthen the quality of the geodetic solutions. Data from three generations of DORIS instrument were considered. The first generation (1G) receiver could track only one DORIS beacon at a time. The main improvements in the following generation of instruments included miniaturization of the receiver and of interest for geodesy the number of ground beacons that could be tracked: The SPOT-2, SPOT-3 and SPOT-4 DORIS receivers also could only track one beacon at a time; The second-generation DORIS receivers on JASON-1, SPOT-5 and Envisat, can track two beacons; The Jason-2 third-generation DORIS receiver can track up to seven beacons.
Most of the available JASON-1 DORIS data were not used. The JASON-1 DORIS ultra-stable oscillator is unstable and is perturbed after passage through the South Atlantic Anomaly (SAA). These perturbations degrade the station and EOP positioning quality of JASON-1, and some Jason-1 was included early in 2002 to strengthen the solutions prior to the availability of data from Envisat and SPOT-5 launched later in that year.

Satellite	DORIS receiver	Mean daily data	POE rms (mm/s)
SPOT 2	1 G	5500	0.44
TOPEX	1 G	7000	0.50
SPOT 3	1 G	5500	0,45
SPOT 4	1 G	6000	0.43
JASON 1	2 GM	13000	0.40
SPOT 5	2 GM	10000	0.41
ENVISAT	2 G	11000	0.47
JASON 2	DGXX	26000	0.42

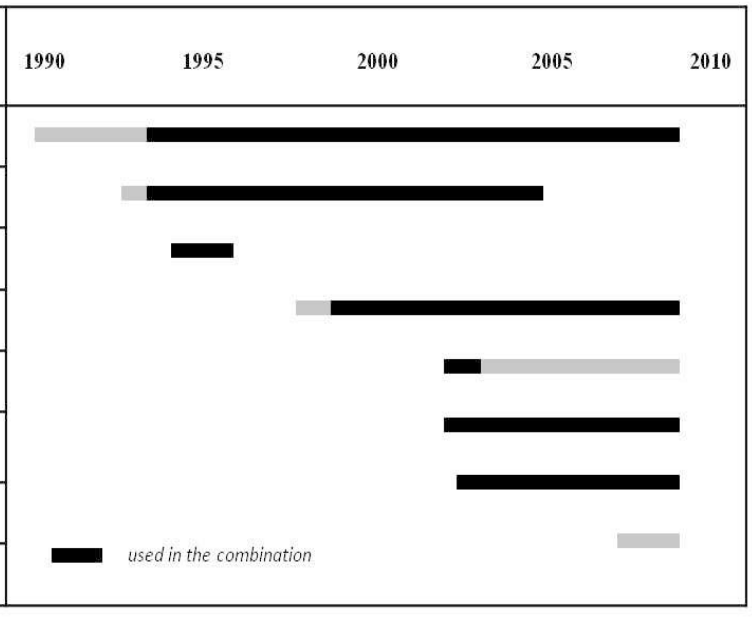


Table 1. DORIS dataset (POE=Precise Orbit Ephemeris from CNES)

ACs contributions

7 IDS ACs have contributed to the ITRF2008 DORIS combination. These ACs are listed in Table 2. More information about the analysts and the detailed processing strategies applied are available at the IDS website or in RD 1. Among the standards for the analysis of the DORIS data and the satellite orbit dynamics model, all ACs have used gravity models derived from the GRACE mission and most applied models for atmospheric gravity either from ECMWF or NCEP. All SINEX deliveries were compliant with IERS call for participation to ITRF2008. Details about the development of the individual AC contributions to ITRF2008 are provided in ITRF2008.

AC	AC solutions	Software	Sol. Id.	Type (1)	Data span	EOPs
Geodetic Observatory Pecny	**GOP**	BERNESE 5.0	**wd31**	var-cov	1993.0-2008.0 15 yrs	motion, rate
INASAN	**INA**	GYPSY/OASIS 4.03	**wd03**	var-cov	1997.0-2008.8 12 yrs	motion rate (constrained) LOD, UT1
LEGOS/CLS	**LCA**	GINS/DYNAMO	**wd21 to wd24**	var-cov	1993.0-2009.0 16 yrs	Motion
IGN/GPL	**IGN**	GYPSY/OASIS 5.0	**wd08**	var-cov	1993.0-2009.0 16 yrs	motion rate (constrained) LOD rate, UT1
Geoscience Australia	**GAU**	GEODYN	**wd06 to wd08**	var-cov	2002.1-2009.0 7 yrs	motion UT1
European Space Operations Center	**ESA**	NAPEOS	**wd03**	NEQ	1993.0-2009.0 16 yrs	motion, rate LOD
NASA Goddard Space Flight Center	**GSC**	GEODYN	**wd03 to wd10**	NEQ	1992.8-2008.9 16 yrs	Motion

Table 2. SINEX submissions for ITRF2008

SINEX Preprocessing analysis

The software used for the IDS combination is the IGN/LAREG CATREF package. As a validation step and before the weekly combination, each SINEX series is preprocessed with the following steps being applied:

(1) Verification of DORIS station identification (dome number, station mnemo),
(2) Rejection of stations over the whole time period (never used),
(3) Rejection of stations over specific periods (partially used),
(4) Verification/update of position discontinuities (but the solution number is set to 1 for the weekly combination),
(5) Inversion of the free singular normal equations for ESA and GSC.
(6) Projection using minimal constraints and rejection of perturbing stations,
(7) Comparison with ITRF2005 or a more recent datum at the epoch of each weekly solution.
(8) Analysis and rejection of high residual stations.

Loosely constrained network solutions are projected over its proper space using minimal constraints. Some partial or complete rejections of stations from the SINEX are done resulting from analysis in the SSALTO DORIS ground processing segment or from analysts. After this validation step, all the SINEX files of a series were expressed in the same DORIS reference system and spurious points were removed. A cumulative position/velocity DORIS solution was calculated including recent DORIS data and used as a datum in the projection.

Combination strategy

Three iterations were necessary to provide the best IDS combination of the AC solutions. Between them, the ACs improved their analysis strategies and submitted updated solutions to eliminate troposphere-derived biases in the solution scale, to reduce drag-related degradations in station positioning, and to reduce remaining periodic signals in the individual AC geocenter and scale solutions. The final combination strategy is summarized in the following table.

Iterations	Sinex Series & changes	Combination Strategy		
		Parameters	Weigths	EOPs
IDS-3 (Aug., 09)	gopwd31 (1998.0-2008.0) inawd06 (1997.0-2008.8) lcawd20 (1993.0-2008.8) lcawd21 : 1h Cd(1) (2002) lcawd24 : SRP(2) fixed ignwd08 (1993.0-2008.8) gauwd06 (2003.0-2008.8) gauwd08 : new tropo, 2h Cd(1) ,2002.0-2003.0 esawd03 (1993.0-2009.0) gscwd06 (2003.0-2008.8) gscwd10 : new tropo +2h Cd(1) , 1992.8-2003.0	Geocenter and Scale: GAU, INA, LCA estimated IC(3) for ESA, GOP, GSC,IGN (validation step for all series with 5 cm residual threshold)	var. factor no deweight	yes

Cd(1) Satellite drag coefficient estimated per 2 hours or higher during Sept.2001-March2002
SRP(2) Solar Radiation Pressure fixed to avoid TZ periodic signals at 118 days and 1 year
IC(3) Internal Constraints
Sinex series underlines show the version used per AC

Table 3. IDS combination inputs and strategy

The final IDS-3 combination includes solutions for 130 DORIS stations on 67 different sites of which 35 have occupations over 16 years (1993.0-2009.0).

TRF parameters

The intrinsic TRF parameters of IDS-3 series are compared in the next figures to ITRF2005 for an external validation. TX and TY remain most of the time within 20 mm in both cases. After 2002, when more than 3 satellites contribute to the data set, a clear annual signal is visible with amplitude of 3.0 mm for TX and 3.5 mm for TY. The translation parameter TZ has a more complex behaviour. Its amplitude variation range reaches ± 80 mm and several signals are apparent. A strong periodic signal appears with a period around 10-11 years with a 21 mm amplitude. The maximum in TZ is around 2002, and coincides with the peak of the solar cycle. The geophysical effects that are known to affect the Earth reference geocenter TZ component generate a 1 year but also 2 years period signals with an amplitude up to 6 mm.

They may be explained as well as residual solar radiation pressure mismodelling in the constituent AC solutions for IDS-3.

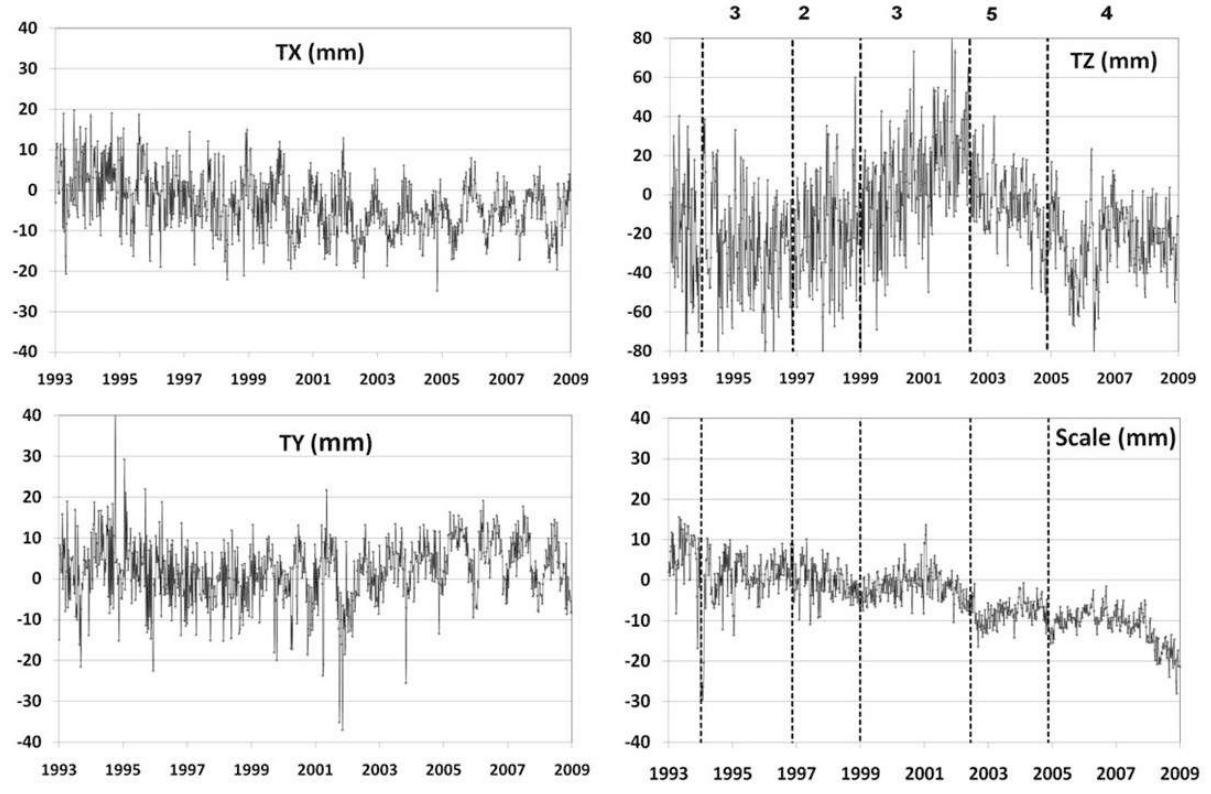


Figure 1. IDS-3 translation and scale parameters with respect to ITRF2005, dashes correspond to satellite constellation changes and figures to satellite number

Residuals

The final IDS-3 combination has an internal position consistency (WRMS) that is 15 to 20 mm before 2002 and 8 to 10 mm after 2002, when four or five satellites contribute to the weekly solutions (Figure 2).

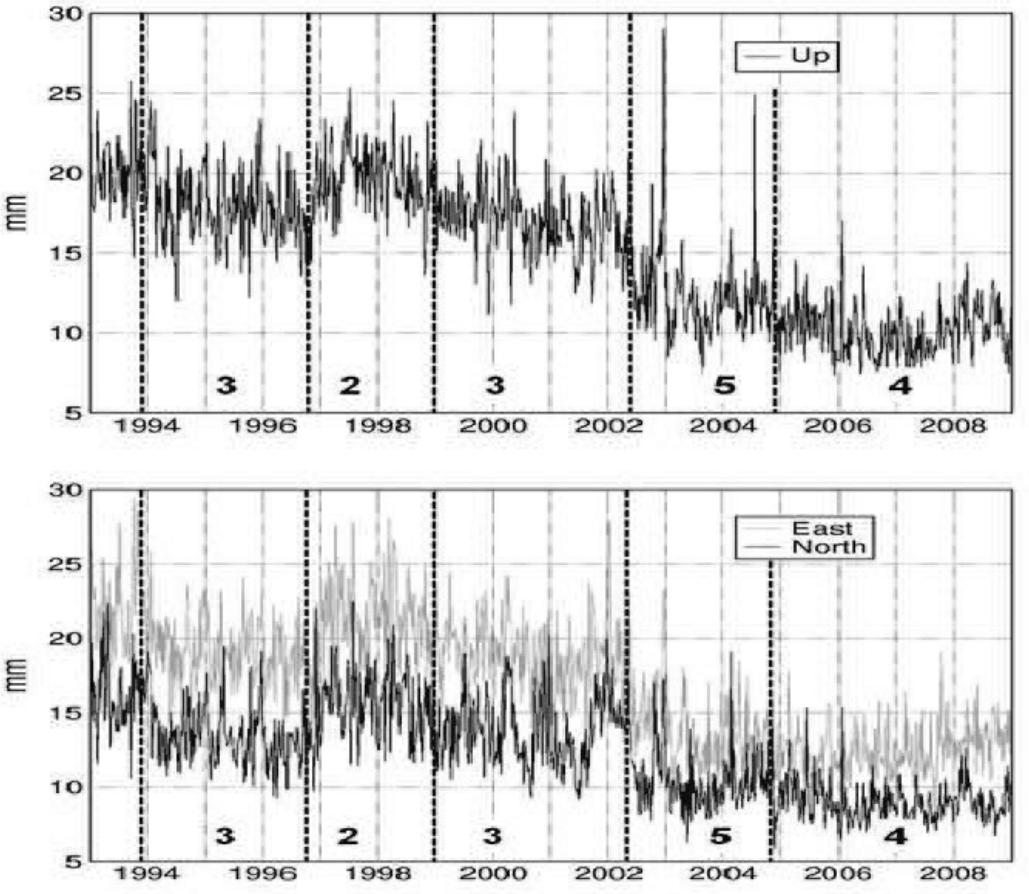
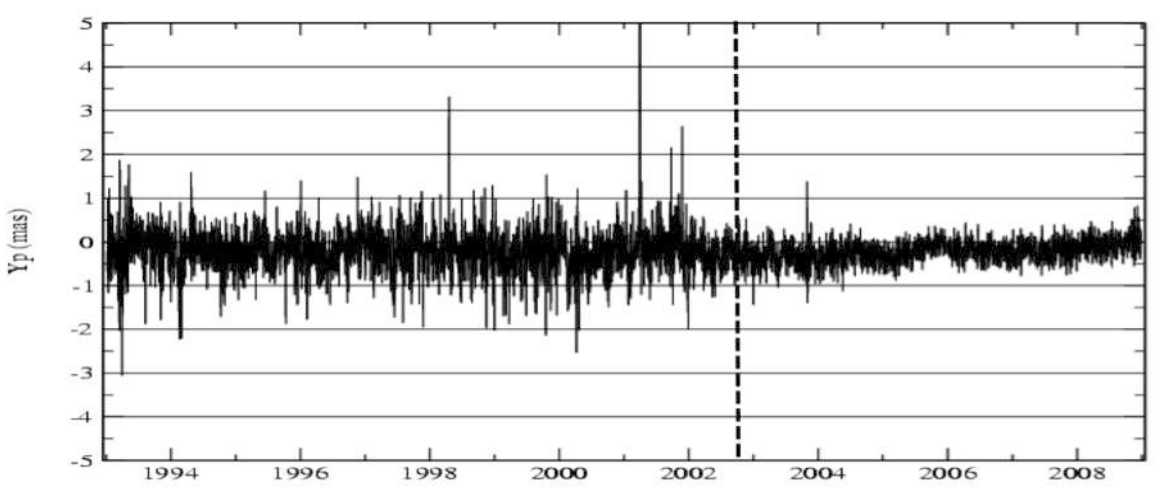


Figure 2. IDS-3 weekly solutions WRMS of the stations residuals, figures indicate the number of satellites used

Polar Motion

The EOPs from the IDS-3 combination were compared with the IERS 05 C04 time series and the RMS agreement was 0.24 mas and 0.35 mas for the X and Y components of polar motion (figure 3). It is also clear that the pole parameter precision is very sensitive to the satellite constellation. Before 2002.4 which corresponds to a constellation with more than 4 satellites the sigmas drop down from 0.32 to 0.16 mas on the X component and from 0.43 mas to 0.26 mas on the Y component.



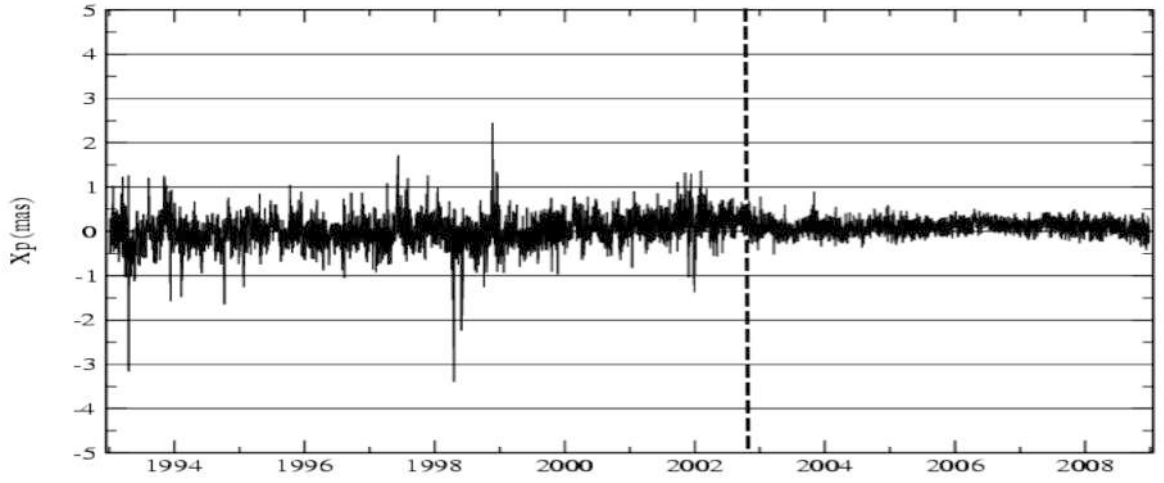


Figure 3. IDS-3 polar motion compared to the IERS 05 C04 series

Stations position and velocity

A cumulative combination of the IDS-3 weekly solutions was completed for validation. The comparison to ITRF2005 in station position shows an agreement of 6 to 8 mm RMS in horizontal and 10.3 mm in height. The RMS comparison to ITRF2005 in station velocity is at 1.8 mm/yr on the East component, to 1.2 mm/yr in North component and 1.6 mm/yr in height.

For more informationon the IDS-3 please contact
Guilhem Moreaux (CLS) at the IDS Combination Center (Email: Guilhem.Moreaux@cls.fr)
or the IDS Analysis Coordinator, Frank Lemoine (NASA) (Email: Frank.G.Lemoine@nasa.gov).

Reference Document

RD 1 : Valette, J.J.; Lemoine, F.G.; Ferrage, P.; Yaya, P.; Altamimi, Z.; Willis, P.; Soudarin, L., 2010. IDS contribution to ITRF2008, in DORIS Special Issue: Precise Orbit Determination and Applications to the Earth Sciences, P. Willis (Ed.), ADVANCES IN SPACE RESEARCH, 46(12):1614-1632, DOI: 10.1016/j.asr.2010.05.029.

Gobinddass, M.L.; Willis, P.; Sibthorpe, A.J.; Zelensky, N.P.; Lemoine, F.G.; Ries, J.C.; Ferland, R.; Bar-Sever, Y.E.; de Viron, O.; Diament, M., 2009. Improving DORIS geocenter time series using an empirical rescaling of solar radiation pressure models, Adv. Space Res., 44(11), 1279-1287, DOI: 10.1016/j.asr.2009.08.004

Gobinddass, M.L.; Willis, P.; Menvielle, M.; Diament, M., 2010. Refining DORIS atmospheric drag estimation in preparation of ITRF2008, in DORIS Special Issue: Precise Orbit Determination and Applications to the Earth Sciences, P. Willis (Ed.), ADVANCES IN SPACE RESEARCH, 46(12):1566-1577, DOI: 10.1016/j.asr.2010.04.004

Govind, R.J.; Lemoine, F.G.; Valette, J.J.; Chinn, D.S.; Zelensky, N., 2010. DORIS Geodesy: A dynamic determination of geocentre location, in DORIS Special Issue, Precise Orbit Determination and Applications to Earth Sciences, P. Willis (Ed.), ADVANCES IN SPACE RESEARCH, 46(12):1593-1605, DOI: 10.1016/j.asr.2010.08.025

Kuzin, S.P.; Tatevian, S.K.; Valeev, S.G.; Fashutdinova, V.A., 2010. Studies of the geocenter motion using 16-years of DORIS data, ADVANCES IN SPACE RESEARCH, 46(10):1292-1298, DOI: 10.1016/j.asr.2010.06.038

Le Bail, K.; Lemoine, F.G.; Chinn, D.S., 2010. GSFC contribution to ITRF2008, in DORIS Special Issue: Scientific Applications in Geodesy and Geodynamics, P. Willis (Ed.), ADVANCES IN SPACE RESEARCH, 45(12):1481-1499, DOI: 10.1016/j.asr.2010.01.030

Otten, M.; Flohrer, C.; Springer, T.; Dow, J., 2010. DORIS processing at the European Space Observations Centre, in DORIS Special Issue: Precise Orbit Determination and Applications to the Earth Sciences, P. Willis (Ed.), ADVANCES IN SPACE RESEARCH, 46(12):1606-1613, DOI: 10.1016/j.asr.2010.04.024

Stepanek, P.; Dousa, J.; Filler, V.; Hugentobler, U., 2010. DORIS data analysis at Geodetic Observatory Pecny using single-satellite and multi-satellite geodetic solutions, in DORIS Special Issue: Precise Orbit Determination and Applications to the Earth Sciences, P. Willis (Ed.), ADVANCES IN SPACE RESEARCH, 46(12):1578-1592, DOI: 10.1016/j.asr.2010.04.015