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Analysis and results of ITRF2020

Z. Altamimi, P. Rebischung, X. Collilieux, L. Métivier, K. Chanard

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1 Summary

The ITRF2020 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 involves two main innovations dealing with the modeling of station non-linear motions, namely seasonal (annual and semi-annual) signals present in the time series of station positions and post-seismic deformations for 118 sites that were subject to major earthquakes. The ITRF2020 combination is achieved through a one-step procedure, that is, by accumulating the time series of the four space geodetic techniques all together, adding local ties and co-motion constraints at co-location sites in a single process. The Technique Centers' solutions incorporated in the ITRF2020 combination are free from any external constraints, thus preserving the actual space geodesy estimates of station positions and Earth Orientation Parameters (EOPs). The ITRF2020 long-term origin follows linearly with time the Earth's Center of Mass (CM) as sensed by SLR, based on observations collected over the time span 1993.0-2021.0. The ITRF2020 long-term scale is defined by a rigorous weighted average of selected VLBI sessions up to 2013.75 and SLR weekly solutions covering the 1997.75 - 2021.0 time span. For the first time of the ITRF history, the scale agreement between SLR and VLBI long-term solutions is at the level of 0.15 ppb (1 mm at the equator) at epoch 2015.0, with no drift. The orientation of the ITRF2020 long-term frame is defined in such a way that there are zero rotation parameters at epoch 2015.0 and zero rotation rates between the ITRF2020 and ITRF2014, using 131 stations of high geodetic quality.

The ITRF2020 includes the coordinates and their temporal variations of 1835 stations located at 1243 sites. Figure 1 shows the coverage of these sites, underlying the co-located space geodesy techniques.

This technical note describes the main ITRF2020 products: station positions and velocities, seasonal signals, the post fit residuals of the least squares adjustment as well as the transformation parameters between ITRF2020 and ITRF2014. The main technical procedure used to generate the ITRF2020, a thorough discussion of its quality as well as most important geodetic and geophysical results were published in an open-access article [Altamimi et al., 2023], appended to this Technical Note.

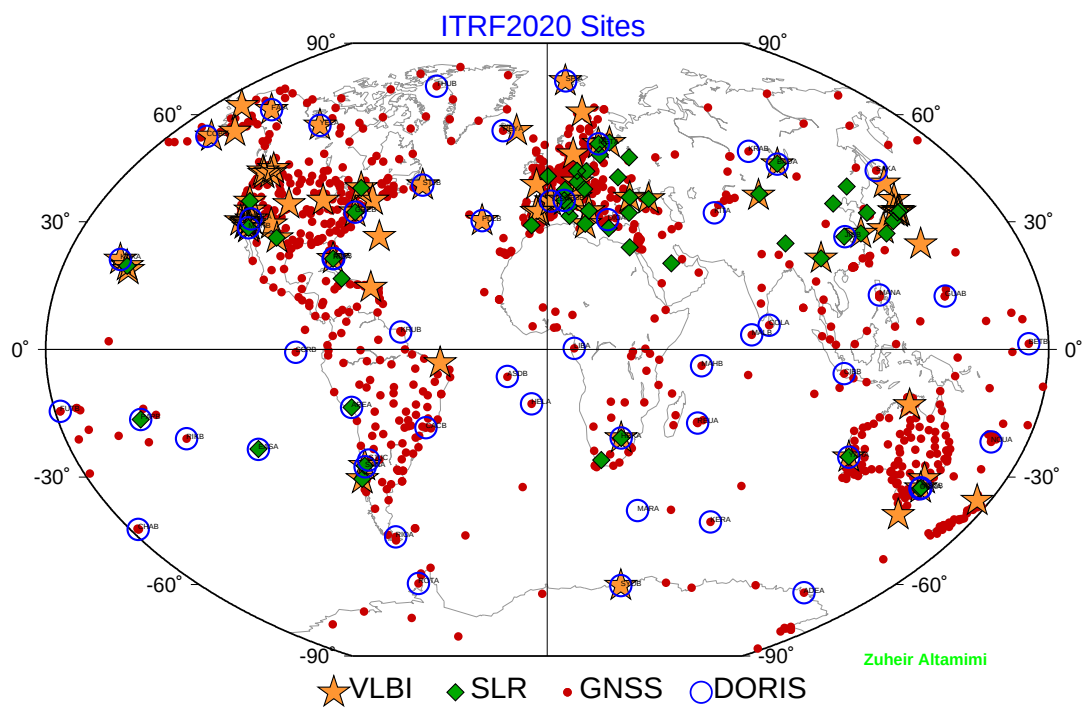


Fig. 1: ITRF2020 network

2 ITRF2020 input data

As for any ITRF solution, the ITRF2020 relies not only on space geodesy solutions (station position time series and Earth Orientation Parameters (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 ITRF2020 construction.

2.1 Space geodesy solutions

We recall that the ITRF input time series solutions are provided on a daily basis for GNSS, session-wise for VLBI, weekly for DORIS and fortnightly and weekly for SLR, by the International Association of Geodesy (IAG) technique services: International GNSS Service (IGS), International Laser Ranging Service (ILRS), International DORIS Service (IDS) and 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, the solution type, the constraints applied by the technique combination centers, and the estimated EOPs. The IDS/DORIS contribution contains 1456 weekly combined solutions involving four ACs [Moreaux et al., 2023], and including 201 stations located at 87 sites.

The IGS/GNSS contribution to ITRF2020 consists of 9861 daily combined terrestrial frame solutions in SINEX (Solution INdependent EXchange) format from the third IGS reprocessing campaign (repro3) [Rebischung et al., 2024]. Those were obtained by combining the contributions from 10 Analysis Centers (ACs), and include 1905 stations, of which 1344, located at 1159 sites, have been retained in ITRF2020. The observations used cover the time period 1994.0 - 2021.0 for GPS, 2002.0 - 2021.0 for GLONASS and 2013.0 - 2021.0 for GALILEO. One of the novelties of the IGS solutions is their scale definition based on the calibrated Galileo satellite phase center offsets (z-PCOs) published by the European GNSS Service Center [GSC, 2022]. Note that GPS and GLONASS satellite z-PCOs were corrected to become consistent with the Galileo satellite z-PCOs [Rebischung, 2020].

The ILRS/SLR contribution consists of 244 fortnightly solutions, with polar motion and Length of Day (LOD) estimated every three days for the period 1983.0-1993.0, using LAGEOS I satellite data, and 1459 weekly solutions with daily polar motion and LOD estimates afterwards, using data acquired on LAGEOS I and II and ETALON I and II satellites

[Pavlis and Luceri, 2022]. The main feature of the ILRS submission worth mentioning here is the careful handling of station range biases, which has an impact on the scale of the SLR frame [Pavlis et al., 2021]. The IVS contribution to the ITRF2020 is a combination of session-wise solutions of 11 different IVS Analysis Centers [Hellmers et al., 2022]. The number of the IVS/VLBI session-wise solutions included in the ITRF2020 combination is 6178, spanning in total 41 years of observations, involving 154 stations in 117 sites, but with only 14 sites in the southern hemisphere. The majority of sessions (86%) includes a small number of stations, ranging between 3 to 9. 842 sessions (13%) involve 10 to 19 stations, 8 sessions involve 20 stations, while one session exceptionally includes 31 stations. The solutions include the full set of EOPs, in addition to station positions.

More detailed descriptions of the submitted solutions are available in the appendix of this technical note.

Figure 1 illustrates the full ITRF2020 network, comprising 1835 stations located in 1243 sites, where about 10% of them are co-located with 2, 3, or 4 distinct space geodetic instruments. Over the entire ITRF2020 observation history, we used local ties available for 101 co-location sites (10 more sites than in ITRF2014) with two or more technique instruments which were or are currently operating.

Table 1: Summary of Submitted Solutions to ITRF2020^a

TC	Data-Span	Sampling	Solution Type	Constraints	EOPs
IVS	1980.0 - 2021.0	Daily	Normal Eq.	None	PM, PMr, LOD, UT1-UTC
ILRS	1983.0 - 1993.0	Fortnightly	Var-Cov	Loose	PM, LOD
	1993.0 - 2021.0	Weekly	Var-Cov	Loose	PM, LOD
IGS	1994.0 - 2021.0	Daily	Var-Cov	Minimum	PM, PMr, LOD
IDS	1993.0 - 2021.0	Weekly	Var-Cov	Minimum	PM

^aPM: Polar Motion, PMr: Polar Motion rate, LOD: Length of Day, UT1-UTC: UT1 minus UTC.

2.2 Local ties in co-location sites

The ITRF combination fundamentally depends on the availability of co-location sites where (1) two or more geodetic instruments of different techniques are operated and (2) local surveys between instrument measuring points are available. Local surveys are usually conducted

using terrestrial measurements (angles, distances, and spirit leveling) or the GNSS technique. Least squares adjustments of local surveys are performed by national agencies operating ITRF co-location sites to provide differential coordinates (local ties) connecting the instrument reference points.

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 (1):

$$\begin{pmatrix} \Delta x_s^{i,j} \\ \Delta y_s^{i,j} \\ \Delta z_s^{i,j} \end{pmatrix} = \begin{pmatrix} x^j - x^i \\ y^j - y^i \\ z^j - z^i \end{pmatrix} \quad (1)$$

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 :

$$\sigma_{computed} = \sqrt{\sigma_1^2 + \sigma_2^2} \quad (2)$$

where,

$$\sigma_1 = 3 \text{ mm} \quad \text{and} \quad \sigma_2 = 10^{-6} \times \sqrt{(\Delta x_s^{i,j})^2 + (\Delta y_s^{i,j})^2 + (\Delta z_s^{i,j})^2}$$

The equation system (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.

All past and newly submitted local ties to the ITRF2020 were used. After the ITRF2014 release, 32 new surveys were conducted and their results, including local tie SINEX files were submitted and included in the ITRF2020 computation. All the DORIS co-location site survey data were re-adjusted by the IGN survey department in order to generate full SINEX files, including the most recent surveys operated at these sites. All the local tie SINEX files used in the ITRF2020 combination are available at <https://itrf.ign.fr/en/local-ties>.

We recall here that the local ties used in the ITRF combination are provided in SINEX format with known measurement epochs (with the

exception of few old ties), and 80% of them are available with full variance-covariance information.

The number of co-location sites between DORIS, SLR and VLBI, taken by pair, is insufficient to allow for a reliable combination of these three techniques alone: 12 DORIS-SLR, 10 DORIS-VLBI and 8 SLR-VLBI. However, almost all SLR and VLBI sites are co-located with GNSS, and a significant number of well distributed DORIS sites are co-located with GNSS. We count in total 253 tie vectors between GNSS and the three other technique reference points: 77 for VLBI, 53 for SLR and 123 for DORIS. 66 additional tie vectors were also used between old and current DORIS beacon reference points in DORIS-only sites, but almost half of them are the results of repeated surveys.

3 ITRF2020 data analysis

Up to ITRF2014, the general strategy adopted for the ITRF formation involved a two-step procedure described in [Altamimi et al., 2002, 2007, 2011]: (1) stacking the individual time series to estimate a long-term solution per technique comprising station positions at a reference epoch, station velocities and daily EOPs; and (2) combining the resulting long-term solutions of the four techniques together with the local ties at co-location sites.

For the first time in the ITRF history, the ITRF2020 accumulates the time series of the four space geodetic techniques all together, adding local ties and co-motion constraints at co-location sites in a single process.

The seasonal (annual and semi-annual) signals were modeled using a sinusoidal function, while the Post-Seismic Deformations (PSDs) were accounted for, before the stacking, by applying parametric models that were first fitted to GNSS daily station position time series.

3.1 Combination model

The CATREF combination model used for the ITRF combination is extensively described in previous publications, e.g. [Altamimi et al., 2002, 2007, 2011, 2016]. For the ITRF2020 generation, we followed the same analysis strategy used for the ITRF2014 combination, but enhanced by modeling the nonlinear station motions, for both seasonal (annual and semi-annual) signals and PSDs.

The full equations of the combination model used in the ITRF2020 global adjustment are available in the appendix of the open-access article [Altamimi et al., 2023], appended to this Technical Note.

3.2 ITRF2020 Frame and Seasonal Signals Definition

In the global ITRF2020 combination, the frame and seasonal signals defining parameters were specified as follows:

Origin The origin of the ITRF2020 long-term frame is defined in such a way that there are zero translation parameters at epoch 2015.0 and zero translation rates between the ITRF2020 and the ILRS SLR long-term frame over the 1993.0-2021.0 time span, using the concept of internal constraints.

The origin of the ITRF2020 seasonal signals expressed in the CM (as sensed by SLR) frame is defined in such a way that there is no seasonal translation between the ITRF2020 seasonal signals and the input

SLR solutions over the 1993.0-2021.0 time span, using the concept of internal constraints.

Scale The scale of the ITRF2020 long-term frame is determined using the revised concept of internal constraints (for more details, see Appendix B of [Altamimi et al. \[2023\]](#) provided in Appendix 2 of this Technical Note), in such a way that there are zero scale and scale rate between ITRF2020 and the scale and scale rate averages of VLBI selected sessions up to 2013.75 and SLR weekly solutions covering the 1997.75 - 2021.0 time span.

The scale of the ITRF2020 seasonal signals is determined using internal constraints, in such a way that the average of the seasonal scale variations between the selected SLR solutions and ITRF2020 is zero.

Orientation The orientation of the ITRF2020 long-term frame is defined in such a way that there are zero rotation parameters at epoch 2015.0 and zero rotation rates between the ITRF2020 and ITRF2014. These two conditions were applied over a set of 131 reference stations located at 105 sites as illustrated by Figure 2.

The orientation of the ITRF2020 seasonal signals is defined in such a way that there is no net seasonal rotation of that same core network.

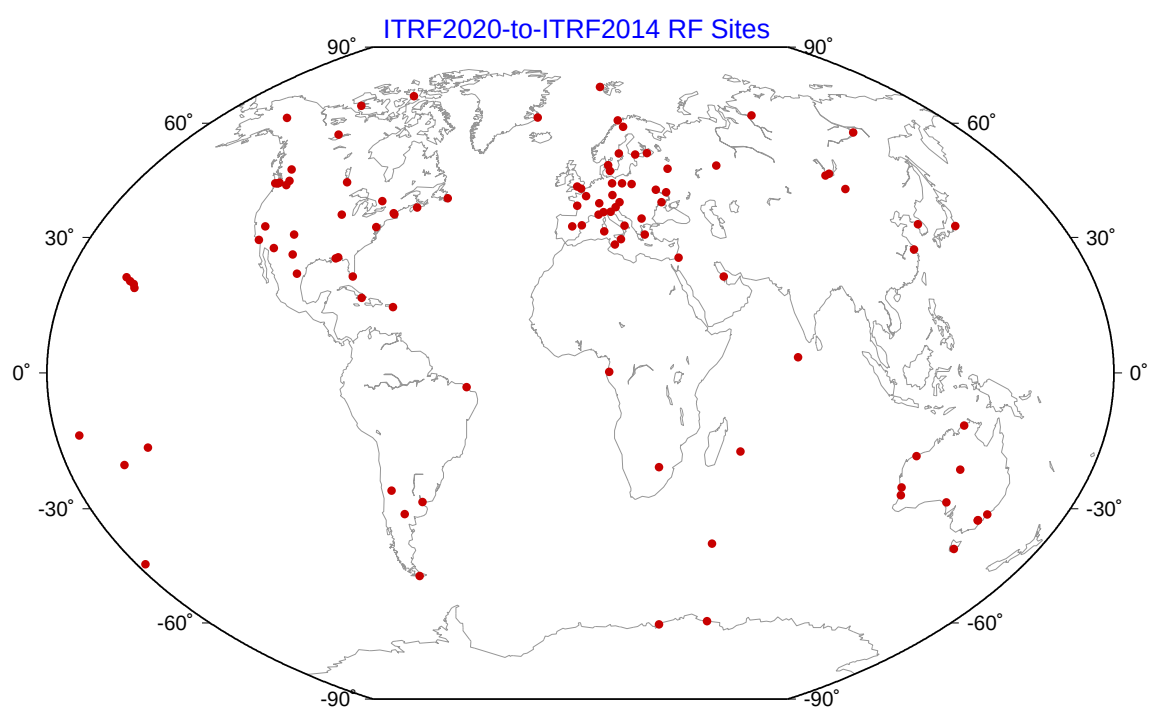


Fig. 2: Location of the reference frame sites used in the estimation of the 14 transformation parameters between ITRF2020 and ITRF2014 and their orientation alignment

4 ITRF2020 Results

We refer the reader to the open-access article [Altamimi et al., 2023], appended to this Technical Note, for more details regarding not only the analysis strategy, but also the usage of the kinematic model and discussion of ITRF2020 results.

4.1 ITRF2020 products

The ITRF2020 main products are:

- Station positions at epoch 2015.0 and velocities. For each station, several pairs of coordinates (position at epoch 2015.0, velocities) may be available. In this case, each pair is valid for specific time interval which is indexed by an integer number named solution number (soln). Their values are split into four tables corresponding to the four techniques: VLBI, SLR, GNSS and DORIS. They are also provided in SINEX files with full variance covariance information. All the corresponding files are available through the ITRF2020 web and FTP sites. See next Chapter for access to these files.
- The Post-Seismic Deformation parametric models, which are an integral part of the ITRF2020 products. The users should be aware that they must compute the model corrections, using the equations supplied in Appendix D of Altamimi et al. [2023], see Appendix 2 of this Technical Note, and add them to the ITRF2020 coordinates if the needed position epoch occurs during the post-seismic relaxation period. Failing to do so would introduce position errors at the decimeter level for many stations impacted by PSD. More information and some useful subroutines in Fortran are provided at the ITRF2020 web site:
<https://itrf.ign.fr/en/solutions/ITRF2020>.
- Annual and semi-annual signals provided in the Center of Mass (CM) frame as sensed by SLR, as well as the Center of Figure (CF) frame.
- 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 ITRF2020 web and FTP sites (see below).

4.2 Usage of the ITRF2020 kinematic model

Depending on the user need, the ITRF2020 coordinates of a given station at epoch t can be computed using equation (3):

$$X(t) = X(t_0) + \dot{X} \cdot (t - t_0) + \delta X_{PSD}(t) + \delta X_f(t), \quad (3)$$

where $\delta X_{PSD}(t)$ is the total sum of PSD corrections at epoch t and $\delta X_f(t)$ is the total sum of the seasonal signal corrections.

The seasonal coordinate variations $\delta X_f(t)$ can be computed using equation (4), to be added to the station coordinates at epoch t , using equation (3).

$$\delta X_f(t) = \sum_{i=1}^2 \begin{pmatrix} a_x^i \\ a_y^i \\ a_z^i \end{pmatrix} \cos(2i\pi \cdot t) + \begin{pmatrix} b_x^i \\ b_y^i \\ b_z^i \end{pmatrix} \sin(2i\pi \cdot t) \quad (4)$$

where t is the decimal year and $(a_x^i, a_y^i, a_z^i, b_x^i, b_y^i, b_z^i)$ are the cosine and sine coefficients at frequency i (annual: $i=1$; semi-annual: $i=2$) provided in ITRF2020 for the given station. The main motivation for publishing seasonal signals consistent with the ITRF2020 is to provide users, e.g., those dealing with satellite precise orbit determination, with a means of referring the ITRF2020 coordinates to the quasi-instantaneous Earth's Center of mass (CM), a point around which an artificial satellite is naturally orbiting. The ITRF2020 seasonal signals are provided to the users in both the CM frame, as sensed by SLR, and in the Center of Figure (CF) frame, together with the corresponding seasonal geocenter motion, that is the seasonal motion of the Center of Mass with respect to the Center of Figure of the solid Earth's surface. When using the ITRF2020 station position kinematic model (3), the user should decide, depending on their application, if the seasonal signals, i.e. adding $\delta X_f(t)$, should be considered, and if so, whether the seasonal signals referred to CM or CF should be used. Discussion on the usage of the ITRF2020 seasonal signals depending on the user application can be found in [Altamimi et al. \[2023\]](#).

4.3 Transformation parameters between ITRF2020 and ITRF2014

For many applications and in order to ensure the link between ITRF2020 and ITRF2014, it is essential to assess consistently the transformation parameters between the two frames. The same 131 stations displayed in Figure 2 that were used to ensure the alignment of the ITRF2020 orientation and rate parameters to the ITRF2014, were also used to estimate the transformation parameters between the two frames. The main criterion for the selection of these 131 stations were (1) to have the best possible site distribution; (2) to involve as many as possible VLBI, SLR, GNSS 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 1.6, 1.8 and 3.4 mm in position (at epoch 2015.0) and 0.2, 0.1, 0.3 mm/yr in velocity, in East, North and Vertical components, respectively. Table 2 lists the transformation parameters from ITRF2020 to ITRF2014, to be used with the transformation formula given by equation (5).

$$\left\{ \begin{array}{l} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i14} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} + T + D \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} + R \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} \\ \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i14} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i20} + \dot{T} + \dot{D} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} + \dot{R} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} \end{array} \right. \quad (5)$$

where $i14$ designates ITRF2014 and $i20$ ITRF2020, 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 2. Note that the inverse

transformation from ITRF2014 to ITRF2020 follows by interchanging (i20) with (i14) and changing the sign of the transformation parameters.

Table 2: Transformation Parameters at epoch 2015.0 and their rates from ITRF2020 to ITRF2014, to be used with equation (5)

	T_x	T_y	T_z	D	R_x	R_y	R_z
	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
	-1.4	-0.9	1.4	-0.42	0.00	0.00	0.00
±	0.2	0.2	0.2	0.03	0.07	0.06	0.07
	0.0	-0.1	0.2	0.00	0.00	0.00	0.00
±	0.2	0.2	0.2	0.03	0.07	0.06	0.07

4.4 Consistency between local ties and space geodesy estimates

One of the most important scientific by-products of the ITRF2020 combination is the assessment of the level of agreement between local ties and space geodesy estimates of station positions, 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 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.

The complete list of the residuals (or tie discrepancies) is available in [Appendix 1](#). If we count the percentage of sites where the tie discrepancy is less than 5 mm, we find approximately: 50%, 36% and 32% for GNSS-VLBI, GNSS-SLR and GNSS-DORIS, respectively.

5 Access to the ITRF2020 files

All the ITRF2020 related files are accessible through the ITRF2020 web site:

<https://itrf.ign.fr/en/solutions/ITRF2020>

as well as via anonymous FTP:

ftp itrf-ftp.ign.fr

cd pub/itrf/itrf2020

5.1 ITRF2020 SINEX files

- ITRF2020.SNX.gz. Full ITRF2020 SINEX file (available on request)
- ITRF2020-TRF.SNX.gz. ITRF2020 station positions and velocities
- ITRF2020-EOP-IVS.SNX.gz. VLBI station positions, velocities and EOPs starting from 1980.0
- ITRF2020-TRF-IVS.SNX.gz. VLBI station positions and velocities
- ITRF2020-EOP-ILRS.SNX.gz. SLR station positions, velocities and EOPs starting from 1983.0
- ITRF2020-TRF-ILRS.SNX.gz. SLR station positions and velocities
- ITRF2020-EOP-IGS.SNX.gz. GNSS station positions, velocities and EOPs starting from 1994.0
- ITRF2020-TRF-IGS.SNX.gz. GNSS station positions and velocities
- ITRF2020-EOP-IDS.SNX.gz. DORIS station positions, velocities and EOPs starting from 1993.0
- ITRF2020-TRF-IDS.gz. DORIS station positions and velocities

5.2 ITRF2020 other files

EOP files

- ITRF2020_EOP-F1.DAT. Complete EOP list file: one line per day (MJD) listing all parameters of that day

- ITRF2020_EOP-F2.DAT. Complete EOP list file: one parameter per line

Residuals

- ITRF2020-RESIDUALS.DAT. Station position, velocity and local tie residuals of the ITRF2020 combination

Discontinuity files: 4 files (one per technique) of station position discontinuities, in SINEX format

- ITRF2020-soln-vlbi.snz
- ITRF2020-soln-slr.snz
- ITRF2020-soln-gnss.snz
- ITRF2020-soln-doris.snz

Post-Seismic Deformation files: 4 files (one per technique) of post-seismic deformation model parameters, in SINEX format

- ITRF2020-psd-vlbi.snz
- ITRF2020-psd-slr.snz
- ITRF2020-psd-gnss.snz
- ITRF2020-psd-doris.snz

and in CATREF internal format:

- ITRF2020-psd-vlbi.dat
- ITRF2020-psd-slr.dat
- ITRF2020-psd-gnss.dat
- ITRF2020-psd-doris.dat

ITRF2020 annual and semi-annual signals

8 files are available for the coefficients of the annual and semi-annual signals in XYZ and ENU, expressed in SLR CM frame, as well as in the Center of Figure (CF) frame, provided in tables and SINEX format.

The ITRF2020 seasonal geocenter motion model [Rebischung et al., 2024] is also provided in a text file and in SINEX format.

5.3 Post-seismic deformation

Equations for post-seismic deformation models and their variance propagation are available through the ITRF2020 web site (<https://itrf.ign.fr/>)

<ftp/pub/itrf/itrf2020/ITRF2020-PSD-model-eqs-IGN.pdf>) but also in Appendix D of Altamimi et al. [2023] appended to this Technical Note as Appendix 2.

Subroutines in Fortran for PSD computations are also available:

- parametric.f: Compute the post-seismic deformation correction "d" using CATREF internal files ITRF2020-psd*.dat
- psd-example.f: EXAMPLE of user subroutine to add "d" by calling parametric.f to X Y Z at epoch t, using CATREF internal files ITRF2020-psd*.dat
- psdmatc.f : Compute the two terms of the matrix C (see pdf file ITRF2020-psd-model-eqs-IGN.pdf) of the parametric model necessary for the variance computation.

The user should read the model parameters (earthquake epoch, model type, LOG or/and EXP, amplitude and relaxation time) in one of the following two files:

- SINEX file (ITRF2020-psd*.snx). These SINEX files provided per technique contain the full information of the parametric models used in the ITRF2020 generation, including the variance-covariance information. It is strongly recommended to use these SINEX files, especially if the user needs to compute the variance of the estimated corrections. Please refer to the equations in the pdf file "ITRF2020-PSD-model-eqs-IGN.pdf". A Fortran subroutine called "psdmatc.f" is provided which allows to compute the terms of the matrix used in the variance-covariance propagation equations.
- CATREF internal file (ITRF2020-psd*.dat). In this case a subroutine called "parametric.f" is provided that allows computing $\delta X(t)_{PSD}$. A usage example called "psd-example.f" is also provided. Please read the commentary lines in the provided Fortran files. Note that using CATREF internal files does not allow computing the variance-covariance matrix of $\delta X(t)_{PSD}$.

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Appendices

Appendix 1 ITRF2020 terrestrial tie and space geodesy discrepancies

ITRF2020 tie discrepancies at tie epochs in (E)ast, (N)orth and (U)p.

Tie Discrepancies = Space Geodesy - Terrestrial Tie (in mm)

Each tie vector component is flagged by '-' if the residual is less than 5 mm and by '*' otherwise.

GNSS GNSS Tie Discrepancies

Id	DOMES	Soln	Id	DOMES	Soln	East North		Up	Tie	-----Technique Epochs-----				-----Spans-----	
						mm	mm	mm	Epoch Flg	Start	End	Start	End		
GRAS	10002M006	4	GRAC	10002M010	5	-5.7	-2.2	-8.2	13:205 **	04:296	21:001	15:070	21:001	16.19	5.81
GRAS	10002M006	4	GRAC	10002M010	5	-6.6	-2.5	-9.0	21: 84 **	04:296	21:001	15:070	21:001	16.19	5.81
METS	10503S011	1	METZ	10503M005	1	0.3	-0.7	-5.7	0:299 --	94:002	10:195	98:290	12:131	16.53	13.56
KIT3	12334M001	2	KITG	12334M004	1	3.5	2.0	16.9	16:162 --	12:291	20:241	16:187	21:001	7.86	4.49
WTZR	14201M010	1	WTZA	14201M013	1	5.0	1.5	6.9	12:153 **	95:040	09:020	97:329	21:001	13.95	23.10
WTZR	14201M010	1	WTZZ	14201M014	3	2.2	1.0	-2.1	12:153 ---	95:040	09:020	11:036	21:001	13.95	9.90
WTZR	14201M010	1	WTZA	14201M013	1	4.9	2.3	7.2	18:344 --	95:040	09:020	97:329	21:001	13.95	23.10
WTZR	14201M010	1	WTZZ	14201M014	3	1.9	0.6	-3.1	18:344 ---	95:040	09:020	11:036	21:001	13.95	9.90
WTZR	14201M010	1	WTZS	14201M015	4	-1.0	-0.4	-3.6	18:344 ---	95:040	09:020	10:182	20:366	13.95	10.50
HRAO	30302M004	3	HARB	30302M009	1	1.5	3.4	-1.0	3:214 ---	00:118	04:324	00:225	11:334	4.56	11.30
STJO	40101M001	6	STJ2	40101M004	1	-1.1	4.2	7.0	13:190 --	00:148	13:031	10:137	21:001	12.68	10.63
STJO	40101M001	6	STJ2	40101M004	1	-1.1	4.2	7.0	13:190 --	00:148	13:031	10:137	21:001	12.68	10.63
STJO	40101M001	7	STJ3	40101M005	3	-3.8	4.7	5.0	19:175 --	13:032	21:001	18:278	21:001	7.92	2.24
STJO	40101M001	7	STJ2	40101M004	1	-5.2	2.2	10.4	19:175 **	13:032	21:001	10:137	21:001	7.92	10.63
YAR2	50107M004	7	YARR	50107M006	2	-0.8	-1.3	-7.7	3:305 --	13:171	21:001	99:067	07:157	7.53	8.25
YAR2	50107M004	7	YARR	50107M006	3	-3.9	-0.1	2.4	10:201 ---	13:171	21:001	09:265	12:103	7.53	2.56
YAR2	50107M004	7	YAR3	50107M008	3	-1.5	1.5	11.9	10:201 --	13:171	21:001	12:103	21:001	7.53	8.72

GNSS VLBI Tie Discrepancies

Id	DOMES	Soln	Id	DOMES	Soln	East North		Up	Tie	-----Technique Epochs-----				-----Spans-----	
						mm	mm	mm	Epoch Flg	Start	End	Start	End		
GRAS	10002M006	4	7605	10002M003	1	-2.6	-1.3	-1.0	9:238 ---	04:296	21:001	89:256	89:258	16.19	0.01
GRAS	10002M006	4	7605	10002M003	1	-2.8	-0.3	-3.1	13:205 ---	04:296	21:001	89:256	89:258	16.19	0.01
NYA1	10317M003	3	7331	10317S003	1	2.7	-1.8	2.4	3:228 ---	04:186	16:233	94:277	20:294	12.13	26.05
ONSA	10402M004	3	7213	10402S002	1	6.0	2.0	-9.7	2:193 **	99:033	19:092	80:208	20:357	20.16	40.41
ONSA	10402M004	3	7636	10402S014	1	0.2	0.6	-7.4	10: 1 --	99:033	19:092	19:007	20:175	20.16	1.46
ONSA	10402M004	3	7637	10402S015	1	0.8	-0.5	1.2	10: 1 ---	99:033	19:092	19:007	20:191	20.16	1.50
ONSA	10402M004	3	7213	10402S002	1	2.4	-0.5	1.6	14:173 ---	99:033	19:092	80:208	20:357	20.16	40.41

METS	10503S011	4	7385	10503S002	1	-0.2	-3.9	-0.6	15:245	---	13:180	21:001	04:321	19:087	7.51	14.36
SVTL	12350M001	2	7380	12350S001	1	-6.1	-3.5	-31.0	5: 1	***	08:298	19:276	03:065	20:365	10.94	17.82
ZECK	12351M001	4	7381	12351S001	1	-25.7	-2.3	10.4	5: 1	***	11:231	21:001	05:356	07:124	9.37	1.36
MEDI	12711M003	2	7230	12711S001	1	1.0	-0.1	10.4	7:241	--*	00:320	21:001	87:093	20:346	20.13	33.69
MEDI	12711M003	2	7230	12711S001	1	3.1	-4.2	11.2	13:165	--*	00:320	21:001	87:093	20:346	20.13	33.69
NOT1	12717M004	1	7547	12717S001	1	-3.7	-2.1	5.8	5:264	--*	00:252	15:282	89:154	20:357	15.08	31.56
NOT1	12717M004	1	7547	12717S001	1	1.4	2.0	-1.6	13:193	---	00:252	15:282	89:154	20:357	15.08	31.56
MATE	12734M008	5	7243	12734S005	1	-2.1	-5.2	-1.2	4:300	*-	99:170	08:329	90:277	20:364	9.44	30.24
MADR	13407S012	4	1565	13407S010	1	-4.2	7.6	-2.0	99: 1	*-	03:316	11:018	88:244	96:341	7.18	8.27
YEBE	13420M001	1	7389	13420S003	1	2.1	-0.2	-4.2	16:313	---	00:274	21:001	15:047	20:063	20.25	5.04
YEBE	13420M001	1	7386	13420S002	1	3.3	-3.9	-19.2	16:313	---	00:274	21:001	08:255	11:287	20.25	3.09
YEBE	13420M001	1	7333	13420S001	1	0.2	1.0	-14.9	99:322	---	00:274	21:001	95:159	03:197	20.25	8.10
WTZR	14201M010	1	7224	14201S004	1	-0.9	-2.9	-1.4	12:153	---	95:040	09:020	83:320	20:365	13.95	37.12
WTZR	14201M010	1	7387	14201S043	1	-0.5	-3.3	-1.3	12:153	---	95:040	09:020	15:160	20:358	13.95	5.54
WTZR	14201M010	1	7388	14201S044	1	1.5	-2.9	-2.2	12:153	---	95:040	09:020	17:337	20:191	13.95	2.60
WTZR	14201M010	1	7224	14201S004	1	0.7	-2.5	-3.6	18:344	---	95:040	09:020	83:320	20:365	13.95	37.12
WTZR	14201M010	1	7387	14201S043	1	1.7	-2.5	-0.6	18:344	---	95:040	09:020	15:160	20:358	13.95	5.54
WTZR	14201M010	1	7388	14201S044	1	1.8	-1.6	0.3	18:344	---	95:040	09:020	17:337	20:191	13.95	2.60
SHAO	21605M002	8	7227	21605S009	1	-3.5	6.9	4.5	3:332	*-	11:071	21:001	88:100	04:342	9.81	16.66
TSKB	21730S005	7	7345	21730S007	5	-1.1	-2.1	0.5	8: 16	---	05:293	08:129	08:133	11:067	2.55	2.82
TSKB	21730S005	11	7345	21730S007	6	0.4	3.6	-1.5	11:192	---	11:243	18:167	11:094	16:363	6.79	5.74
TSKB	21730S005	11	7345	21730S007	6	1.4	-6.1	1.1	16:290	*-	11:243	18:167	11:094	16:363	6.79	5.74
ISHI	21791M001	3	7369	21791S001	1	-4.1	-1.6	-3.7	18:320	---	18:177	20:366	15:050	20:191	2.52	5.39
ISHI	21791M001	3	7369	21791S001	1	2.1	-2.0	-5.3	20:253	--*	18:177	20:366	15:050	20:191	2.52	5.39
SEJN	23907M001	1	7368	23907S001	1	2.5	-0.9	-12.6	20:290	--*	13:331	20:363	14:272	20:364	7.09	6.25
HRAO	30302M004	3	7232	30302S001	1	0.7	3.8	-3.8	3:214	---	00:118	04:324	86:009	20:324	4.56	34.86
STJO	40101M001	6	7625	40101M003	1	1.8	1.2	2.9	99:269	---	00:148	13:031	02:317	05:279	12.68	2.90
STJO	40101M001	6	7625	40101M003	1	0.6	0.6	-2.2	13:190	---	00:148	13:031	02:317	05:279	12.68	2.90
ALGO	40104M002	4	7282	40104S001	1	-2.6	-2.1	8.6	99: 1	--*	97:016	12:344	84:241	06:216	15.90	21.93
YELL	40127M003	3	7296	40127M004	1	-3.5	-5.2	-5.7	1:285	---	96:235	13:199	91:181	06:215	16.90	15.09
FAIR	40408M001	2	7225	40408S002	1	-1.5	-6.6	0.8	1:274	*-	96:108	02:308	84:203	02:304	6.55	18.28
VNDP	40420M007	4	7223	40420M002	1	2.7	-1.8	0.7	91:335	---	03:357	12:032	83:234	91:210	8.11	7.93
KOKB	40424M004	5	1311	40424S001	1	-0.9	-1.7	-6.1	2:319	---	04:149	21:001	84:203	94:074	16.59	9.65
KOKB	40424M004	5	7298	40424S007	1	1.1	-0.3	2.7	2:319	---	04:149	21:001	93:159	20:365	16.59	27.56
KOKB	40424M004	5	7298	40424S007	1	3.3	-1.5	3.6	14: 81	---	04:149	21:001	93:159	20:365	16.59	27.56
KOKB	40424M004	5	7298	40424S007	1	2.9	-0.9	0.3	18:161	---	04:149	21:001	93:159	20:365	16.59	27.56
KOKB	40424M004	5	7623	40424S010	1	8.4	0.2	-1.5	18:161	---	04:149	21:001	17:337	20:191	16.59	2.60

WES2	40440S020	13	7209	40440S003	1	1.0	-0.6	11.9	19:137	--*	01:208	14:175	81:133	20:191	12.91	39.16
WES2	40440S020	13	7205	40440S002	1	18.1	3.3	2.7	96:278	***	01:208	14:175	79:329	92:182	12.91	12.60
WES2	40440S020	13	7209	40440S003	1	10.5	0.4	15.1	96:278	***	01:208	14:175	81:133	20:191	12.91	39.16
MD01	40442M012	1	7613	40442S017	1	-0.7	-6.8	11.9	93: 76	***	94:002	02:339	92:013	20:324	8.92	28.85
MD01	40442M012	5	7613	40442S017	1	4.3	-5.3	8.6	13: 54	***	17:045	19:255	92:013	20:324	2.57	28.85
PIE1	40456M001	4	7234	40456S001	3	1.0	-5.2	-1.2	16:139	--*	07:024	20:135	01:302	20:324	13.30	19.06
PIE1	40456M001	1	7234	40456S001	1	-0.6	-2.3	-5.5	92:336	***	94:002	97:132	88:252	97:240	3.36	8.97
NLIB	40465M001	1	7612	40465S001	1	-2.0	0.4	-7.8	93: 64	***	94:002	02:254	92:241	20:324	8.69	28.23
BREW	40473M001	1	7614	40473S001	1	1.0	-1.8	-0.7	11:209	---	01:320	21:001	93:111	20:324	19.13	27.58
BREW	40473M001	1	7614	40473S001	1	1.4	-2.4	2.9	18:228	---	01:320	21:001	93:111	20:324	19.13	27.58
MKEA	40477M001	2	7617	40477S001	2	1.0	0.8	-2.4	15:193	---	06:289	14:291	06:312	17:346	8.01	11.09
MKEA	40477M001	4	7617	40477S001	2	-7.9	9.5	5.2	20: 19	***	18:125	20:366	06:312	17:346	2.66	11.09
MKEA	40477M001	1	7617	40477S001	1	-1.8	3.2	-1.3	96:221	---	96:234	06:289	93:200	06:257	10.15	13.16
BRFT	41602M002	3	7297	41602S001	1	2.7	-1.4	-0.8	6: 78	---	07:177	11:005	93:111	20:322	3.53	27.58
FORT	41602M001	2	7297	41602S001	1	-0.6	-0.3	-0.9	93:264	---	97:256	00:080	93:111	20:322	2.52	27.58
SANT	41705M003	3	1404	41705S006	1	15.4	7.4	-7.8	92:192	***	98:010	10:058	91:324	96:327	12.13	5.01
CONZ	41719M002	2	7640	41719S001	1	4.2	-0.7	23.3	3: 80	***	03:108	05:134	02:133	10:057	2.07	7.79
CONZ	41719M002	8	7640	41719S001	5	1.2	-1.5	7.7	12:337	***	11:201	15:076	11:045	14:150	3.66	3.29
CRO1	43201M001	9	7615	43201S001	1	1.7	-5.2	-4.8	17:134	***	10:189	15:237	93:176	20:324	5.13	27.41
CRO1	43201M001	1	7615	43201S001	1	-2.1	3.5	0.5	94: 16	---	95:287	99:233	93:176	20:324	3.85	27.41
TIDB	50103M108	4	1545	50103S010	1	-3.4	3.4	-20.0	7:254	***	04:353	16:218	88:212	16:237	11.63	28.07
TIDB	50103M108	2	1545	50103S010	1	-0.3	3.5	3.0	95:263	---	96:178	00:176	88:212	16:237	3.99	28.07
YAR2	50107M004	7	7376	50107S012	1	-0.9	0.2	-3.1	10:201	---	13:171	21:001	11:146	20:357	7.53	9.58
HOB2	50116M004	5	7242	50116S002	1	2.6	-0.2	-2.6	2: 81	---	04:359	16:326	89:269	20:350	11.91	31.22
HOB2	50116M004	5	7242	50116S002	1	2.2	0.4	-1.4	9:330	---	04:359	16:326	89:269	20:350	11.91	31.22
HOB2	50116M004	5	7374	50116S007	1	6.7	3.8	-13.7	9:330	***	04:359	16:326	10:280	20:338	11.91	10.16
WARK	50243M001	1	7377	50243S001	1	-1.4	-1.4	11.4	12:338	***	09:039	16:319	11:059	20:344	7.77	9.78
WARK	50243M001	1	7377	50243S001	1	-0.7	1.3	3.5	17:153	---	09:039	16:319	11:059	20:344	7.77	9.78
KAT1	59968M001	1	7375	59968S001	1	-8.7	7.6	19.0	11:153	***	10:072	21:001	11:167	20:226	10.81	9.16
SYOG	66006S002	3	7342	66006S004	1	-1.9	5.4	3.2	0: 1	***	99:319	07:025	99:312	19:310	7.20	19.99
OHI2	66008M005	2	7245	66008S001	1	2.3	2.6	0.6	13: 41	---	03:054	09:028	93:027	19:345	5.93	26.87
OHI2	66008M005	2	7245	66008S001	1	-1.8	3.4	-3.5	2: 43	---	03:054	09:028	93:027	19:345	5.93	26.87

GNSS SLR Tie Discrepancies

Id	DOMES	Soln Id	DOMES	Soln	East	North	Up	Tie	-----Technique Epochs-----	Spans-----
					mm	mm	mm	Epoch Flg	Start	End

GRAS	10002M006	4	7835	10002S001	2	-3.9	-9.6	-5.3	99:284	---	04:296	21:001	90:079	99:338	16.19	9.71
GRAS	10002M006	4	7845	10002S002	1	-6.7	-4.1	-1.0	99:284	*--	04:296	21:001	97:327	20:358	16.19	23.08
GRAS	10002M006	4	7845	10002S002	1	-5.5	-3.2	-3.8	9:238	*--	04:296	21:001	97:327	20:358	16.19	23.08
GRAS	10002M006	4	7845	10002S002	1	-4.1	-4.7	-0.8	13:205	---	04:296	21:001	97:327	20:358	16.19	23.08
GRAS	10002M006	4	7845	10002S002	1	-6.2	-2.9	-4.0	21: 84	*--	04:296	21:001	97:327	20:358	16.19	23.08
AJAC	10077M005	1	7848	10077M002	1	0.2	-0.0	1.4	0: 1	---	00:024	08:222	02:041	05:302	8.54	3.71
METS	10503S011	1	7806	10503S014	1	0.2	-2.6	3.1	0:299	---	94:002	10:195	98:064	04:310	16.53	6.67
GRAZ	11001M002	7	7839	11001S002	1	2.9	-1.4	9.9	92:319	---	10:139	16:295	83:252	20:361	6.43	37.30
BOR1	12205M002	2	7811	12205S001	2	-0.1	5.0	3.7	94: 10	---	99:152	16:279	02:303	20:354	17.35	18.14
RIGA	12302M002	5	1884	12302S002	1	-3.4	0.6	-8.6	20: 84	---	13:346	21:001	94:240	20:273	7.06	26.09
SVTL	12350M001	2	1888	12350S002	1	-7.1	5.8	-7.6	96: 74	***	08:298	19:276	12:036	20:354	10.94	8.87
CAGL	12725M003	2	7545	12725M002	1	0.2	0.6	0.9	95:161	---	01:192	13:263	85:311	94:071	12.19	8.34
MATE	12734M008	5	7541	12734M004	1	-1.0	2.1	-4.3	4:300	---	99:170	08:329	86:010	94:167	9.44	8.43
MATE	12734M008	5	7941	12734S008	1	1.5	0.7	-6.4	4:300	---	99:170	08:329	01:183	21:002	9.44	19.50
HERT	13212M010	2	7840	13212S001	1	-1.0	4.2	1.5	8:177	---	07:339	15:062	83:101	20:366	7.24	37.73
SFER	13402M004	9	7824	13402S007	1	7.3	-0.1	4.0	9:192	*--	08:152	14:029	99:102	20:207	5.66	21.29
ZIMM	14001M004	2	7810	14001S007	1	-0.4	5.0	0.2	96: 95	*--	98:311	21:001	97:362	20:362	22.15	23.00
POTS	14106M003	3	7836	14106S009	1	3.3	3.2	15.4	94:221	---	99:232	09:105	93:003	04:164	9.65	11.44
POTS	14106M003	3	7841	14106S011	1	-19.5	3.3	-1.1	94:221	*--	99:232	09:105	04:050	21:002	9.65	16.87
WTZR	14201M010	1	8834	14201S018	1	-0.1	0.5	3.4	12:153	---	95:040	09:020	90:365	20:198	13.95	29.54
WTZR	14201M010	1	7827	14201S045	1	0.2	0.1	1.5	18:344	---	95:040	09:020	14:107	20:319	13.95	6.58
WTZR	14201M010	1	8834	14201S018	1	1.1	0.3	2.3	18:344	---	95:040	09:020	90:365	20:198	13.95	29.54
SOLA	20101M001	2	7832	20101S001	1	-0.1	-1.3	13.1	12: 35	---	04:140	15:300	01:017	10:247	11.44	9.63
BJFS	21601M001	1	7249	21601S004	1	2.0	6.2	-10.9	3:171	---	99:294	05:288	99:230	11:042	5.98	11.49
WUHN	21602M001	8	7231	21602S004	1	-10.7	-7.9	-6.8	3:342	---	04:362	08:134	00:117	04:345	3.38	4.62
SHAO	21605M002	8	7837	21605S001	2	-5.1	12.3	3.3	3:332	---	11:071	21:001	95:303	05:106	9.81	9.46
SMST	21726M001	6	7838	21726S001	4	-1.9	3.9	10.2	20:318	---	16:273	20:049	16:096	20:361	3.39	4.73
SMST	21726M001	2	7838	21726S001	2	5.5	-25.7	9.5	7: 1	---	04:250	11:070	04:250	11:049	6.51	6.45
SEJN	23907M001	1	7394	23907S002	1	5.0	-5.1	-4.7	20:290	---	13:331	20:363	16:032	20:312	7.09	4.77
HRAO	30302M004	3	7501	30302M003	1	-0.6	3.9	4.4	3:214	---	00:118	04:324	93:180	12:098	4.56	18.78
MD01	40442M012	1	7080	40442M006	1	1.4	-7.1	10.9	93: 76	---	94:002	02:339	88:032	15:339	8.92	27.84
MD01	40442M012	5	7080	40442M006	1	0.6	-3.5	-0.3	13: 54	---	17:045	19:255	88:032	15:339	2.57	27.84
MAUI	40445S008	1	7119	40445M004	1	2.7	4.0	-4.9	6:260	---	99:001	20:366	06:309	20:366	22.00	14.16
MAUI	40445S008	1	7210	40445M001	4	2.4	1.5	-0.1	6:260	---	99:001	20:366	00:268	04:156	22.00	3.69

MAUI	40445S008	1	7119	40445M004	1	1.6	3.3	-6.1	19:	70	---	99:001	20:366	06:309	20:366	22.00	14.16
GODE	40451M123	2	7105	40451M105	1	-0.3	6.6	-5.0	8:	1	---	98:262	12:220	82:364	20:365	13.89	38.00
GODE	40451M123	2	7105	40451M105	1	0.4	3.3	-5.4	12:	196	---	98:262	12:220	82:364	20:365	13.89	38.00
MONP	40497M004	3	7110	40497M001	1	1.6	1.8	-1.7	99:	280	---	95:214	99:290	82:362	99:289	4.21	16.80
MONP	40497M004	9	7110	40497M001	3	1.9	-2.3	1.7	18:	137	---	14:210	19:188	10:102	19:187	4.94	9.23
OAFA	41508M001	1	7406	41508S003	1	24.3	26.1	48.6	18:	326	***	13:111	15:250	06:058	10:051	2.38	3.98
EISL	41703M003	1	7097	41703M002	1	-2.5	-14.1	18.0	1:	46	---	94:123	03:027	87:329	95:091	8.74	7.35
CONZ	41719M002	2	7405	41719M001	1	4.8	-2.1	21.5	3:	80	---	03:108	05:134	04:304	10:058	2.07	5.33
CONZ	41719M002	8	7405	41719M001	5	15.2	-19.1	22.4	12:	337	***	11:201	15:076	11:072	14:088	3.66	3.04
AREQ	42202M005	3	7403	42202M003	3	0.0	-0.0	1.1	95:	1	---	96:318	01:175	96:322	01:166	4.61	4.57
AREQ	42202M005	6	7403	42202M003	6	2.4	-3.2	-6.3	13:	12	---	07:228	14:092	07:233	14:093	6.63	6.62
AREQ	42202M005	5	7403	42202M003	5	0.1	3.4	-8.7	7:	123	---	01:189	07:228	01:267	07:230	6.11	5.90
YAR2	50107M004	7	7090	50107M001	1	0.4	-1.7	10.1	3:	305	---	13:171	21:001	83:011	21:002	7.53	37.98
YAR2	50107M004	7	7090	50107M001	1	-0.6	-1.4	6.1	10:	201	---	13:171	21:001	83:011	21:002	7.53	37.98
STR1	50119M002	5	7825	50119S003	1	-0.3	-3.7	2.4	9:	317	---	03:311	21:001	04:214	21:001	17.15	16.42
STR1	50119M002	5	7849	50119S001	1	0.2	-0.3	-0.1	1:	209	---	03:311	21:001	98:186	03:018	17.15	4.54
STR1	50119M002	5	7825	50119S003	1	0.5	-5.0	3.6	1:	209	---	03:311	21:001	04:214	21:001	17.15	16.42
THTI	92201M009	2	7124	92201M007	2	-4.2	-6.8	4.0	7:	278	---	04:013	12:171	01:303	20:353	8.43	19.14
THTI	92201M009	2	7822	92201M017	1	-4.2	-12.2	11.9	11:	128	---	04:013	12:171	11:170	11:274	8.43	0.28
OAFA	41508M001	1	7406	41508S003	1	24.3	26.1	48.6	18:	326	***	13:111	15:250	06:058	10:051	2.38	3.98
EISL	41703M003	1	7097	41703M002	1	-2.5	-14.1	18.0	1:	46	---	94:123	03:027	87:329	95:091	8.74	7.35
CONZ	41719M002	2	7405	41719M001	1	4.8	-2.1	21.5	3:	80	---	03:108	05:134	04:304	10:058	2.07	5.33
CONZ	41719M002	8	7405	41719M001	5	15.2	-19.1	22.4	12:	337	***	11:201	15:076	11:072	14:088	3.66	3.04
AREQ	42202M005	3	7403	42202M003	3	0.0	-0.0	1.1	95:	1	---	96:318	01:175	96:322	01:166	4.61	4.57
AREQ	42202M005	6	7403	42202M003	6	2.4	-3.2	-6.3	13:	12	---	07:228	14:092	07:233	14:093	6.63	6.62
AREQ	42202M005	5	7403	42202M003	5	0.1	3.4	-8.7	7:	123	---	01:189	07:228	01:267	07:230	6.11	5.90
YAR2	50107M004	7	7090	50107M001	1	0.4	-1.7	10.1	3:	305	---	13:171	21:001	83:011	21:002	7.53	37.98
YAR2	50107M004	7	7090	50107M001	1	-0.6	-1.4	6.1	10:	201	---	13:171	21:001	83:011	21:002	7.53	37.98
STR1	50119M002	5	7825	50119S003	1	-0.3	-3.7	2.4	9:	317	---	03:311	21:001	04:214	21:001	17.15	16.42
STR1	50119M002	5	7849	50119S001	1	0.2	-0.3	-0.1	1:	209	---	03:311	21:001	98:186	03:018	17.15	4.54
STR1	50119M002	5	7825	50119S003	1	0.5	-5.0	3.6	1:	209	---	03:311	21:001	04:214	21:001	17.15	16.42
THTI	92201M009	2	7124	92201M007	2	-4.2	-6.8	4.0	7:	278	---	04:013	12:171	01:303	20:353	8.43	19.14
THTI	92201M009	2	7822	92201M017	1	-4.2	-12.2	11.9	11:	128	---	04:013	12:171	11:170	11:274	8.43	0.28

GNSS DORIS Tie Discrepancies

Id	DOMES	Soln	Id	DOMES	Soln	East North		Up	Tie	-----Technique Epochs-----	Spans-----					
						mm	mm									
						mm	mm	mm	Epoch	Flg	Start	End	Start	End		
GRAS	10002M006	4	GR3B	10002S018	1	-4.1	-2.2	-4.7	9:238	---	04:296	21:001	08:321	13:209	16.19	4.69
GRAS	10002M006	4	GR3B	10002S018	1	-4.2	-1.5	-2.6	13:205	---	04:296	21:001	08:321	13:209	16.19	4.69

GRAS	10002M006	4	GR4B	10002S019	1	-4.0	-1.4	-2.6	13:205	---	04:296	21:001	14:012	21:003	16.19	6.98
GRAS	10002M006	4	GR4B	10002S019	1	-5.5	-2.5	0.3	21: 84	*--	04:296	21:001	14:012	21:003	16.19	6.98
TLSE	10003M009	2	TLHA	10003S003	1	1.9	2.6	-5.7	4: 34	---	03:336	10:056	97:228	07:189	6.23	9.89
TLSE	10003M009	2	TLSA	10003S001	1	1.5	17.1	7.6	4: 34	---	03:336	10:056	93:009	97:229	6.23	4.60
TLSE	10003M009	4	TLSE	10003S005	2	0.0	-0.4	-3.5	14: 43	---	12:249	16:072	12:308	21:003	3.52	8.16
REYK	10202M001	4	REYA	10202S001	1	-7.9	0.7	0.1	4:248	*--	03:165	07:262	93:003	98:242	4.27	5.65
REYK	10202M001	4	REYB	10202S002	3	-2.6	0.1	0.3	4:248	---	03:165	07:262	00:176	04:249	4.27	4.20
REYK	10202M001	4	REZB	10202S003	1	-7.6	-0.1	0.0	4:248	*--	03:165	07:262	04:304	05:079	4.27	0.38
NYA1	10317M003	3	SPIA	10317S002	1	-3.5	2.3	0.9	3:228	---	04:186	16:233	93:003	99:080	12.13	6.21
NYA1	10317M003	3	SPIB	10317S004	1	-1.3	0.4	1.3	3:228	---	04:186	16:233	99:212	03:229	12.13	4.05
NYA1	10317M003	3	SPJB	10317S005	1	-3.2	0.0	2.3	3:228	---	04:186	16:233	03:242	14:061	12.13	10.50
METS	10503S011	1	META	10503S013	1	-2.5	0.8	-0.6	0:299	---	94:002	10:195	93:003	00:303	16.53	7.82
METS	10503S011	1	METB	10503S015	1	-3.3	6.0	-4.4	0:299	*--	94:002	10:195	00:316	12:183	16.53	11.64
METG	10503M002	1	MEUB	10503S016	1	1.4	-0.4	0.5	12:184	---	12:199	16:293	12:182	21:003	4.26	8.51
METG	10503M002	1	METB	10503S015	1	-5.9	2.3	1.4	12:184	*--	12:199	16:293	00:316	12:183	4.26	11.64
YSSK	12329M003	4	SAKA	12329S001	4	-7.8	5.7	3.9	4:231	***	07:215	11:071	04:024	04:235	3.61	0.58
YSSK	12329M003	4	SAKB	12329S002	1	-9.9	6.7	6.7	4:231	***	07:215	11:071	04:241	05:324	3.61	1.23
KIT3	12334M001	1	KITA	12334S004	1	-26.5	10.6	1.7	1:115	***	94:274	12:291	93:003	96:147	18.05	3.39
KIT3	12334M001	1	KITB	12334S005	1	-14.3	9.0	0.8	1:115	***	94:274	12:291	96:146	01:119	18.05	4.93
KIT3	12334M001	1	KIUB	12334S006	1	2.1	6.1	-4.7	1:115	***	94:274	12:291	01:147	16:171	18.05	15.07
KIT3	12334M001	2	KIVC	12334S007	1	5.9	0.8	10.0	16:162	*--	12:291	20:241	16:170	21:003	7.86	4.54
KIT3	12334M001	2	KIUB	12334S006	1	11.3	0.6	1.7	16:162	*--	12:291	20:241	01:147	16:171	7.86	15.07
KSTU	12349M002	4	KRAB	12349S001	2	-4.7	6.2	6.4	0: 1	***	01:026	04:264	99:135	03:278	3.65	4.39
DYNG	12602M006	3	DIOB	12602S012	1	0.9	1.7	-1.2	11:131	---	15:269	20:345	06:161	20:362	5.21	14.55
DYNG	12602M006	3	DIOB	12602S012	1	0.7	1.8	-0.8	18:296	---	15:269	20:345	06:161	20:362	5.21	14.55
WTZR	14201M010	1	WEUC	14201S046	1	0.2	-6.2	3.8	18:344	*--	95:040	09:020	16:268	21:003	13.95	4.27
WUHN	21602M001	8	JIUB	21602S005	1	-13.2	-11.6	-18.9	3:342	***	04:362	08:134	05:071	12:288	3.38	7.59
WUHN	21602M001	8	JIUB	21602S005	1	-4.5	-4.2	-41.7	12:285	---	04:362	08:134	05:071	12:288	3.38	7.59
WUHN	21602M001	8	JIVB	21602S006	1	-4.5	4.5	-34.5	12:285	---	04:362	08:134	13:152	15:109	3.38	1.88
PTAG	22006M005	2	MANB	22006S002	4	-3.7	6.2	2.0	14:339	*--	12:103	17:027	12:168	21:003	4.79	8.55
MALD	22901S001	2	MALB	22901S002	1	6.4	-12.6	-7.3	5: 14	***	00:150	04:360	05:204	21:003	4.57	15.45
BAKO	23101M002	7	CICB	23101S002	2	-0.4	0.1	1.8	0:350	---	02:252	04:362	02:292	05:002	2.30	2.21
HARB	30302M009	1	HBMB	30302S008	1	0.7	3.1	0.5	14: 58	---	00:225	11:334	07:062	21:003	11.30	13.84
HRAO	30302M004	3	HBKB	30302S006	1	-0.5	4.9	-0.8	3:214	---	00:118	04:324	00:225	05:254	4.56	5.08
HRAO	30302M004	3	HBKA	30302S202	1	-3.7	-3.9	7.1	3:214	---	00:118	04:324	93:003	97:152	4.56	4.41
HRAO	30302M004	3	HBLA	30302S005	1	-4.0	-0.5	-1.3	3:214	---	00:118	04:324	97:158	00:226	4.56	3.19
ASCG	30602M004	1	ASEB	30602S005	1	-10.9	5.8	8.1	15:217	***	15:261	21:001	10:219	15:326	5.29	5.29
ASCG	30602M004	1	ASDB	30602S004	3	-20.3	10.5	-6.7	15:217	***	15:261	21:001	03:081	09:081	5.29	6.00

PDEL	31906M004	1	PDLB	31906S001	1	9.7	3.0	-0.0	1: 79	***	00:108	06:347	98:346	01:238	6.65	2.70
PDEL	31906M004	1	PDMB	31906S002	1	7.9	1.7	-0.7	1: 79	***	00:108	06:347	01:286	08:356	6.65	7.19
PDEL	31906M004	4	PDNC	31906S003	1	0.5	-2.3	-2.5	14:268	---	12:292	20:366	15:108	15:340	8.20	0.64
PDEL	31906M004	4	PDMB	31906S002	2	0.6	-3.6	-3.9	14:268	---	12:292	20:366	09:164	14:271	8.20	5.29
NKLG	32809M002	1	LIBA	32809S002	1	10.1	2.5	11.2	99: 36	***	00:090	10:124	93:003	99:038	10.09	6.10
NKLG	32809M002	1	LIBB	32809S003	1	6.6	4.4	-5.0	99: 36	***	00:090	10:124	99:087	05:331	10.09	6.67
NKLG	32809M002	1	LICB	32809S004	1	-3.9	5.6	1.8	10:125	***	00:090	10:124	05:337	08:223	10.09	2.69
NKLG	32809M002	2	LICB	32809S004	3	-7.5	-2.4	13.2	19:235	***	10:126	21:001	11:359	21:003	10.66	9.03
CPVG	39601M001	4	SAPC	39601S003	1	1.5	-7.2	-0.0	15:296	***	15:297	21:001	16:234	16:248	5.19	0.04
CPVG	39601M001	4	SALB	39601S002	2	1.3	-8.1	0.1	15:296	***	15:297	21:001	08:194	15:298	5.19	7.28
SEY1	39801M001	6	MAHB	39801S005	2	-9.1	-2.8	-2.4	12:168	***	07:180	16:064	09:101	12:344	8.68	3.67
SEY1	39801M001	6	MAIB	39801S006	1	-4.9	-1.2	0.1	12:168	---	07:180	16:064	13:061	21:003	8.68	7.84
STJO	40101M001	6	STJB	40101S002	1	-6.4	13.4	1.7	99:269	***	00:148	13:031	99:275	12:344	12.68	13.19
STJO	40101M001	6	STJB	40101S002	1	-4.0	9.0	1.6	13:190	***	00:148	13:031	99:275	12:344	12.68	13.19
STJO	40101M001	6	STKB	40101S003	1	-28.7	20.8	-7.4	13:190	***	00:148	13:031	13:264	19:174	12.68	5.75
STJO	40101M001	7	STKC	40101S004	1	-3.1	1.9	5.8	19:175	***	13:032	21:001	19:180	21:003	7.92	1.52
YELL	40127M003	3	YELB	40127S008	1	1.2	-0.2	-2.0	1:285	---	96:235	13:199	01:300	07:140	16.90	5.56
YELL	40127M003	3	YEMB	40127S009	1	1.6	1.2	-2.0	1:285	---	96:235	13:199	07:146	21:003	16.90	13.61
YELL	40127M003	3	YEMB	40127S009	1	-0.4	-1.4	1.5	13:198	---	96:235	13:199	07:146	21:003	16.90	13.61
FAIR	40408M001	2	FAIB	40408S005	1	6.8	-1.0	-11.9	1:274	***	96:108	02:308	00:009	02:314	6.55	2.84
KOKB	40424M004	5	KOLB	40424S009	1	-12.8	-25.0	-6.3	2:319	***	04:149	21:001	02:341	21:003	16.59	18.07
KOKB	40424M004	5	KOKA	40424S008	1	-11.0	-31.8	6.9	2:319	***	04:149	21:001	93:003	02:308	16.59	9.84
KOKB	40424M004	5	KOLB	40424S009	1	1.6	-5.6	4.0	14: 81	***	04:149	21:001	02:341	21:003	16.59	18.07
KOKB	40424M004	5	KOLB	40424S009	1	2.1	-5.1	2.8	18:161	***	04:149	21:001	02:341	21:003	16.59	18.07
GODE	40451M123	2	GREB	40451S176	1	2.4	-1.3	-8.8	8: 1	***	98:262	12:220	00:183	12:134	13.89	11.87
GODE	40451M123	2	GRFB	40451S178	1	1.6	-6.7	-12.0	12:196	***	98:262	12:220	12:147	21:003	13.89	8.61
MONP	40497M004	5	MONB	40497S008	1	-0.3	0.5	0.4	5:335	---	04:291	10:095	05:344	07:350	5.46	2.02
MONP	40497M004	5	MOOB	40497S009	1	-0.6	0.3	0.3	5:335	---	04:291	10:095	07:356	10:038	5.46	2.13
RIOG	41507M004	2	RIOA	41507S003	1	-2.1	0.4	-0.1	1: 15	---	99:338	07:027	93:003	95:022	7.15	2.05
RIOG	41507M004	2	RIOB	41507S004	2	-1.0	12.8	-9.8	1: 15	***	99:338	07:027	98:087	01:014	7.15	2.80
RIOG	41507M004	2	RIPB	41507S005	1	-0.3	0.5	1.7	1: 15	---	99:338	07:027	01:069	08:111	7.15	7.11
RIO2	41507M006	2	RIRB	41507S007	1	-0.1	2.5	-0.1	14:142	---	12:284	15:259	12:105	15:347	2.93	3.66
OAFA	41508M001	1	SJUC	41508S004	1	-87.2	-1.3	43.5	18:326	***	13:111	15:250	18:272	19:349	2.38	1.21
CHPI	41609M003	1	CACB	41609S001	1	-31.4	-2.6	-45.1	4: 85	***	03:128	10:059	93:311	03:075	6.81	9.35
CHPI	41609M003	1	CADB	41609S002	1	-7.2	15.3	-71.0	4: 85	***	03:128	10:059	04:101	06:022	6.81	1.78
EISL	41703M003	1	EASB	41703S009	1	5.2	5.6	-15.1	1: 46	***	94:123	03:027	01:237	06:274	8.74	5.10
EISL	41703M003	1	EASA	41703S008	1	-1.8	15.2	-6.4	1: 46	***	94:123	03:027	93:003	01:014	8.74	8.03
SANT	41705M003	3	SAOB	41705S008	1	-18.5	-10.8	-9.5	96:339	***	98:010	10:058	97:019	00:331	12.13	3.85
SANT	41705M003	3	SANB	41705S009	1	-59.6	-32.2	-27.0	96:339	***	98:010	10:058	01:188	10:052	12.13	8.63
GLPS	42005M002	1	SCRB	42005S001	1	-0.3	-0.4	1.2	5: 92	---	03:007	08:051	05:099	09:158	5.12	4.16

AREQ	42202M005	6	ARFB	42202S007	2	-3.6	6.5	12.1	13: 12	---	07:228	14:092	07:230	14:082	6.63	6.59
AREQ	42202M005	5	ARFB	42202S007	2	-5.2	6.9	9.7	7:123	***	01:189	07:228	07:230	14:082	6.11	6.59
THU3	43001M002	1	THUB	43001S005	1	17.7	3.4	-6.6	2:257	***	01:240	06:098	02:327	06:127	4.61	3.45
AOML	49914S001	1	MIAB	49914S003	1	1.9	2.2	0.1	5: 36	---	97:324	03:220	05:078	15:235	5.72	10.43
YAR2	50107M004	7	YARB	50107S010	1	0.7	14.6	12.9	3:305	---	13:171	21:001	99:310	03:334	7.53	4.07
YAR2	50107M004	7	YASB	50107S011	1	-4.6	4.5	12.1	3:305	---	13:171	21:001	03:354	21:003	7.53	17.04
YAR2	50107M004	7	YASB	50107S011	1	-3.9	4.5	9.0	10:201	---	13:171	21:001	03:354	21:003	7.53	17.04
STR1	50119M002	5	MSPB	50119S004	1	-6.3	3.1	2.5	9:317	---	03:311	21:001	04:108	21:003	17.15	16.71
STR1	50119M002	5	MSOB	50119S002	1	-4.8	4.1	1.7	1:209	---	03:311	21:001	99:072	03:019	17.15	3.85
STR1	50119M002	5	MSPB	50119S004	1	-5.1	0.9	0.2	1:209	---	03:311	21:001	04:108	21:003	17.15	16.71
CHAT	50207M001	1	CHAB	50207S001	1	-0.9	9.2	15.3	99: 56	---	95:277	01:332	99:065	06:218	6.15	7.42
GUAM	50501M002	1	GUAB	50501S001	1	10.8	-1.9	10.6	93:346	---	95:018	02:117	94:176	00:226	7.27	6.14
SYOG	66006S002	3	SYOB	66006S001	1	-7.7	7.3	-42.8	0: 1	---	99:319	07:025	93:121	98:116	7.20	4.99
SYOG	66006S002	3	SYPB	66006S003	1	1.2	5.8	-8.3	0: 1	---	99:319	07:025	99:101	08:202	7.20	9.28
ROTH	66007M003	1	ROTB	66007S002	1	-0.1	2.1	-24.9	11: 33	---	10:037	16:278	05:085	07:189	6.66	2.28
ROTH	66007M003	1	ROUB	66007S003	1	3.7	4.3	-16.8	11: 33	---	10:037	16:278	07:321	11:037	6.66	3.22
ROTH	66007M003	1	ROVB	66007S004	1	6.0	2.3	0.7	11: 33	---	10:037	16:278	11:106	15:018	6.66	3.76
ROTH	66007M003	2	ROXC	66007S006	1	2.0	-3.7	-3.7	18: 22	---	16:282	20:276	18:055	19:083	3.98	1.08
ROTH	66007M003	2	ROWC	66007S005	1	0.4	6.7	-4.0	18: 22	---	16:282	20:276	15:045	18:021	3.98	2.93
GUUG	82301M001	3	MLAC	82301S001	1	-0.0	-0.3	1.1	18: 97	---	11:178	19:161	18:104	21:003	7.95	2.72
KERG	91201M002	4	KERB	91201S003	1	-27.7	-11.3	4.8	7:101	---	08:251	21:001	94:330	01:091	12.32	6.35
KERG	91201M002	4	KESB	91201S004	1	-12.0	-4.6	16.6	7:101	---	08:251	21:001	01:112	04:039	12.32	2.80
KERG	91201M002	4	KETB	91201S005	1	-15.9	-0.4	12.6	7:101	---	08:251	21:001	07:118	15:039	12.32	7.78
KERG	91201M002	4	KETB	91201S005	1	-13.8	-11.3	9.0	12: 89	---	08:251	21:001	07:118	15:039	12.32	7.78
DUM1	91501M001	5	ADEA	91501S001	1	-9.5	-7.8	5.6	8: 39	---	04:191	14:365	93:003	98:088	10.48	5.23
DUM1	91501M001	5	ADEB	91501S002	1	-4.0	-3.7	2.6	8: 39	---	04:191	14:365	04:080	08:041	10.48	3.89
DUM1	91501M001	5	ADFB	91501S003	1	-6.3	-5.6	9.3	8: 39	---	04:191	14:365	08:055	10:248	10.48	2.53
THTI	92201M009	2	PAPB	92201S007	1	-3.6	-29.3	6.8	7:278	---	04:013	12:171	95:217	98:102	8.43	2.69
THTI	92201M009	2	PAQB	92201S008	1	-7.0	-4.7	12.3	7:278	---	04:013	12:171	98:325	07:273	8.43	8.86
THTI	92201M009	2	PATB	92201S010	1	-2.5	-3.6	4.4	7:278	---	04:013	12:171	07:300	09:319	8.43	2.05
THTI	92201M009	2	PATB	92201S010	1	-2.5	-3.1	4.3	11:128	---	04:013	12:171	07:300	09:319	8.43	2.05
GAMB	92301M003	4	RILB	92301S003	1	-0.7	2.1	-1.2	11:218	---	14:282	21:001	09:094	11:100	6.23	2.02
GAMB	92301M003	4	RIMB	92301S004	1	-0.3	1.4	-0.6	11:218	---	14:282	21:001	11:239	21:003	6.23	9.35
NOUM	92701M003	3	NOUB	92701S002	1	-1.2	3.8	1.5	5:236	---	03:362	07:080	02:082	02:293	3.23	0.58
NOUM	92701M003	3	NOWB	92701S003	1	1.6	21.8	25.7	5:236	---	03:362	07:080	05:246	11:205	3.23	5.89
NOUM	92701M003	3	NOUA	92701S001	1	-3.8	15.6	-1.3	5:236	---	03:362	07:080	93:016	00:191	3.23	7.48
FTNA	92902S002	1	FUUB	92902S003	1	9.4	-16.2	-7.2	12:139	---	98:268	05:347	12:259	19:356	7.22	7.27
FTNA	92902S002	1	FUTB	92902S001	1	4.1	-3.5	0.7	12:139	---	98:268	05:347	01:027	08:349	7.22	7.88
LMMF	97205M001	3	LAOB	97205S001	1	4.2	-14.1	-6.1	13:183	---	13:176	21:001	13:264	21:003	7.52	7.29

KOUG	97301M402	1	KRWB	97301S006	1	4.0	-15.3	17.9	11: 56	---	11:079	21:001	11:148	15:333	9.79	4.51
KOUG	97301M402	1	KRUB	97301S004	1	6.3	-15.4	10.1	11: 56	---	11:079	21:001	93:003	97:005	9.79	4.01
REUN	97401M003	2	REUA	97401S001	1	-10.3	7.1	3.4	3:335	---	03:148	08:338	93:003	98:347	5.52	5.94
REUN	97401M003	2	REUB	97401S002	2	-10.6	7.9	6.7	3:335	---	03:148	08:338	02:012	19:104	5.52	17.25
REUN	97401M003	4	REUC	97401S003	1	-4.9	12.2	15.8	20: 42	---	15:274	21:001	20:046	21:003	5.25	0.88
REUN	97401M003	4	REUB	97401S002	2	-17.2	-3.4	21.4	20: 42	---	15:274	21:001	02:012	19:104	5.25	17.25

SLR VLBI Tie Discrepancies

Id	DOMES	Soln	Id	DOMES	Soln	East	North	Up	Tie	-----Technique		Epochs-----		-----Spans-----		
						mm	mm	mm	Epoch	Flg	Start	End	Start	End		
7845	10002S002	1	GR3B	10002S018	1	1.4	1.0	-1.0	9:238	---	97:327	20:358	08:321	13:209	23.08	4.69
7845	10002S002	1	GR3B	10002S018	1	-0.1	3.3	-1.8	13:205	---	97:327	20:358	08:321	13:209	23.08	4.69
7845	10002S002	1	GR4B	10002S019	1	0.1	3.3	-1.8	13:205	---	97:327	20:358	14:012	21:003	23.08	6.98
7845	10002S002	1	GR4B	10002S019	1	0.7	0.4	4.4	21: 84	---	97:327	20:358	14:012	21:003	23.08	6.98
7806	10503S014	1	META	10503S013	1	-2.7	3.3	-3.8	0:299	---	98:064	04:310	93:003	00:303	6.67	7.82
7806	10503S014	1	METB	10503S015	1	-3.5	8.6	-7.5	0:299	---	98:064	04:310	00:316	12:183	6.67	11.64
8834	14201S018	1	WEUC	14201S046	1	-0.8	-6.4	1.4	18:344	---	90:365	20:198	16:268	21:003	29.54	4.27
7231	21602S004	1	JIUB	21602S005	1	-2.5	-3.7	-12.1	3:342	---	00:117	04:345	05:071	12:288	4.62	7.59
7501	30302M003	1	HBKB	30302S006	1	0.0	0.9	-5.2	3:214	---	93:180	12:098	00:225	05:254	18.78	5.08
7501	30302M003	1	HBKA	30302S202	1	-3.1	-7.8	2.7	3:214	---	93:180	12:098	93:003	97:152	18.78	4.41
7501	30302M003	1	HBLA	30302S005	1	-3.4	-4.4	-5.7	3:214	---	93:180	12:098	97:158	00:226	18.78	3.19
7105	40451M105	1	GREB	40451S176	1	2.7	-7.9	-3.9	8: 1	---	82:364	20:365	00:183	12:134	38.00	11.87
7406	41508S003	1	SJUC	41508S004	1	-111.5	-27.4	-5.1	18:326	---	06:058	10:051	18:272	19:349	3.98	1.21
7097	41703M002	1	EASB	41703S009	1	7.6	19.6	-33.1	1: 46	---	87:329	95:091	01:237	06:274	7.35	5.10
7097	41703M002	1	EASA	41703S008	1	0.6	29.2	-24.4	1: 46	---	87:329	95:091	93:003	01:014	7.35	8.03
7403	42202M003	6	ARFB	42202S007	2	-6.0	9.7	18.4	13: 12	---	07:233	14:093	07:230	14:082	6.62	6.59
7403	42202M003	5	ARFB	42202S007	2	-5.3	3.5	18.4	7:123	---	01:267	07:230	07:230	14:082	5.90	6.59
7090	50107M001	1	YARB	50107S010	1	0.3	16.4	2.8	3:305	---	83:011	21:002	99:310	03:334	37.98	4.07
7090	50107M001	1	YASB	50107S011	1	-5.1	6.2	2.0	3:305	---	83:011	21:002	03:354	21:003	37.98	17.04
7090	50107M001	1	YASB	50107S011	1	-3.2	5.9	3.0	10:201	---	83:011	21:002	03:354	21:003	37.98	17.04
7825	50119S003	1	MSPB	50119S004	1	-6.1	6.8	0.2	9:317	---	04:214	21:001	04:108	21:003	16.42	16.71
7849	50119S001	1	MSOB	50119S002	1	-5.1	4.3	1.9	1:209	---	98:186	03:018	99:072	03:019	4.54	3.85
7849	50119S001	1	MSPB	50119S004	1	-5.4	1.2	0.3	1:209	---	98:186	03:018	04:108	21:003	4.54	16.71
7124	92201M007	2	PAPB	92201S007	1	0.6	-22.5	2.8	7:278	---	01:303	20:353	95:217	98:102	19.14	2.69
7124	92201M007	2	PAQB	92201S008	1	-2.8	2.0	8.2	7:278	---	01:303	20:353	98:325	07:273	19.14	8.86
7124	92201M007	2	PATB	92201S010	1	1.7	3.1	0.3	7:278	---	01:303	20:353	07:300	09:319	19.14	2.05
7822	92201M017	1	PATB	92201S010	1	1.7	9.1	-7.6	11:128	---	11:170	11:274	07:300	09:319	0.28	2.05

VLBI VLBI Tie Discrepancies

Id	DOMES	Soln	Id	DOMES	Soln	East	North	Up	Tie	-----Technique	Epochs	-----Spans
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						mm	mm	mm	Epoch	Flg	Start	End	Start	End		
7386	13420S002	1	7389	13420S003	1	-1.0	3.7	15.0	16:313	---	08:255	11:287	15:047	20:063	3.09	5.04
7224	14201S004	1	7387	14201S043	1	0.4	-0.2	0.1	12:153	---	83:320	20:365	15:160	20:358	37.12	5.54
7224	14201S004	1	7388	14201S044	1	2.5	0.1	-0.8	12:153	---	83:320	20:365	17:337	20:191	37.12	2.60
7224	14201S004	1	7387	14201S043	1	1.1	-0.0	3.0	18:344	---	83:320	20:365	15:160	20:358	37.12	5.54
7224	14201S004	1	7388	14201S044	1	1.1	0.9	3.9	18:344	---	83:320	20:365	17:337	20:191	37.12	2.60
7232	30302S001	1	7378	30302S009	1	-1.5	5.2	-1.2	14: 58	---	86:009	20:324	12:285	20:358	34.86	8.20
1311	40424S001	1	7298	40424S007	1	1.9	1.3	8.8	2:319	---	84:203	94:074	93:159	20:365	9.65	27.56
7298	40424S007	1	7623	40424S010	1	5.5	-0.2	-2.5	16:103	---	93:159	20:365	17:337	20:191	27.56	2.60
7298	40424S007	1	7623	40424S010	1	5.4	1.0	-1.9	18:161	---	93:159	20:365	17:337	20:191	27.56	2.60
7205	40440S002	1	7209	40440S003	1	-7.7	-2.9	12.4	96:278	---	79:329	92:182	81:133	20:191	12.60	39.16
7242	50116S002	1	7374	50116S007	1	4.5	3.4	-12.3	9:330	---	89:269	20:350	10:280	20:338	31.22	10.16
DORIS DORIS Tie Discrepancies																
Id	DOMES	Soln	Id	DOMES	Soln	East	North	Up	Tie	-----Technique		Epochs-----		-----Spans-----		
						mm	mm	mm	Epoch	Flg	Start	End	Start	End		
GR3B	10002S018	1	GR4B	10002S019	1	0.2	0.1	0.0	13:205	---	08:321	13:209	14:012	21:003	4.69	6.98
TL5A	10003S001	1	TL5A	10003S003	1	0.4	-14.5	-13.3	4: 34	---	93:009	97:229	97:228	07:189	4.60	9.89
REYA	10202S001	1	REYA	10202S002	3	5.3	-0.6	0.1	4:248	---	93:003	98:242	00:176	04:249	5.65	4.20
REYA	10202S001	1	REYA	10202S003	1	0.3	-0.8	-0.1	4:248	---	93:003	98:242	04:304	05:079	5.65	0.38
SPIA	10317S002	1	SPIA	10317S004	1	2.2	-1.9	0.4	3:228	---	93:003	99:080	99:212	03:229	6.21	4.05
SPIA	10317S002	1	SPIA	10317S005	1	0.3	-2.2	1.4	3:228	---	93:003	99:080	03:242	14:061	6.21	10.50
META	10503S013	1	META	10503S015	1	-0.7	5.3	-3.7	0:299	---	93:003	00:303	00:316	12:183	7.82	11.64
META	10503S015	1	META	10503S016	1	7.4	-2.7	-0.9	12:184	---	00:316	12:183	12:182	21:003	11.64	8.51
SAKA	12329S001	4	SAKA	12329S002	1	-2.1	1.0	2.8	4:231	---	04:024	04:235	04:241	05:324	0.58	1.23
KITA	12334S004	1	KITA	12334S005	1	12.2	-1.5	-1.0	1:115	---	93:003	96:147	96:146	01:119	3.39	4.93
KITA	12334S004	1	KITA	12334S006	1	28.6	-4.5	-6.5	1:115	---	93:003	96:147	01:147	16:171	3.39	15.07
KIUB	12334S006	1	KIUB	12334S007	1	-5.4	0.1	8.3	16:162	---	01:147	16:171	16:170	21:003	15.07	4.54
BADA	12338S001	1	BADA	12338S002	1	3.7	-2.7	-7.1	4:224	---	93:003	02:202	04:234	21:003	9.54	16.37
DIOA	12602S011	1	DIOA	12602S012	1	-5.7	8.7	1.4	6:136	---	94:093	05:261	06:161	20:362	11.46	14.55
JIUB	21602S005	1	JIUB	21602S006	1	-0.1	8.7	7.2	12:285	---	05:071	12:288	13:152	15:109	7.59	1.88
MANA	22006S001	1	MANA	22006S002	1	0.1	-8.4	-5.2	3: 54	---	93:044	03:019	03:088	04:200	9.93	1.31
HBKA	30302S202	1	HBKA	30302S006	1	3.2	8.7	-7.9	3:214	---	93:003	97:152	00:225	05:254	4.41	5.08
HBKA	30302S202	1	HBKA	30302S005	1	-0.3	3.4	-8.4	3:214	---	93:003	97:152	97:158	00:226	4.41	3.19

ASDB 30602S004	1	ASEB 30602S005	1	-6.3	2.1	3.1	10:164	***	99:101	01:070	10:219	15:326	1.92	5.29
ASDB 30602S004	3	ASEB 30602S005	1	9.4	-4.7	14.7	15:217	***	03:081	09:081	10:219	15:326	6.00	5.29
TRIA 30604S001	2	TRIB 30604S002	1	-1.7	-10.5	-16.5	2: 23	***	99:205	01:140	02:047	04:214	1.82	2.46
TRIB 30604S002	3	TRJB 30604S003	1	-0.1	-0.5	0.4	12:164	---	09:234	10:024	13:061	16:136	0.43	3.21
HELA 30606S002	1	HELB 30606S003	1	11.9	19.8	-6.9	3: 80	***	93:009	97:103	98:116	00:037	4.26	1.78
HELA 30606S002	1	HEMB 30606S004	1	11.3	26.9	-2.6	3: 80	***	93:009	97:103	03:102	08:216	4.26	5.31
PDLB 31906S001	1	PDMB 31906S002	1	-1.8	-1.3	-0.6	1: 79	---	98:346	01:238	01:286	08:356	2.70	7.19
PDMB 31906S002	2	PDNC 31906S003	1	-0.1	1.3	1.4	14:268	---	09:164	14:271	15:108	15:340	5.29	0.64
LIBA 32809S002	1	LIBB 32809S003	1	-3.5	1.9	-16.3	99: 36	---	93:003	99:038	99:087	05:331	6.10	6.67
SALB 39601S002	2	SAPC 39601S003	1	0.2	0.9	-0.1	15:296	---	08:194	15:298	16:234	16:248	7.28	0.04
MAHB 39801S005	2	MAIB 39801S006	1	4.2	1.6	2.6	12:168	---	09:101	12:344	13:061	21:003	3.67	7.84
DJIA 39901S002	1	DJIB 39901S003	1	0.9	10.9	0.6	0:183	***	93:003	98:333	06:189	21:003	5.90	14.49
DJIA 39901S002	1	DJIB 39901S003	1	0.8	11.0	0.7	6:178	***	93:003	98:333	06:189	21:003	5.90	14.49
STJB 40101S002	1	STKB 40101S003	1	-24.7	11.9	-9.0	13:190	***	99:275	12:344	13:264	19:174	13.19	5.75
YELB 40127S008	1	YEMB 40127S009	1	0.4	1.5	0.0	1:285	---	01:300	07:140	07:146	21:003	5.56	13.61
KOKA 40424S008	1	KOLB 40424S009	1	-1.7	6.7	-13.2	2:319	***	93:003	02:308	02:341	21:003	9.84	18.07
MONB 40497S008	1	MOOB 40497S009	1	-0.3	-0.3	-0.1	5:335	---	05:344	07:350	07:356	10:038	2.02	2.13
RIOA 41507S003	1	RIOB 41507S004	2	1.2	12.4	-9.6	1: 15	***	93:003	95:022	98:087	01:014	2.05	2.80
RIOA 41507S003	1	RIPB 41507S005	1	1.8	0.0	1.9	1: 15	---	93:003	95:022	01:069	08:111	2.05	7.11
CACB 41609S001	1	CADB 41609S002	1	24.2	17.9	-25.9	4: 85	***	93:311	03:075	04:101	06:022	9.35	1.78
EASA 41703S008	1	EASB 41703S009	1	7.0	-9.6	-8.7	1: 46	***	93:003	01:014	01:237	06:274	8.03	5.10
SAOB 41705S008	1	SANB 41705S009	1	-41.1	-21.4	-17.5	96:339	***	97:019	00:331	01:188	10:052	3.85	8.63
YARB 50107S010	1	YASB 50107S011	1	-5.4	-10.2	-0.8	3:305	***	99:310	03:334	03:354	21:003	4.07	17.04
MSOB 50119S002	1	MSPB 50119S004	1	-0.3	-3.1	-1.4	1:209	---	99:072	03:019	04:108	21:003	3.85	16.71
MORA 51001S001	1	MORB 51001S002	1	-16.5	3.6	-1.4	2: 79	***	93:009	02:076	02:110	08:216	9.18	6.29
SYOB 66006S001	1	SYPB 66006S003	1	8.9	-1.5	34.5	0: 1	***	93:121	98:116	99:101	08:202	4.99	9.28
ROTA 66007S001	1	ROTB 66007S002	1	0.2	7.8	-4.9	5: 54	***	93:003	02:020	05:085	07:189	9.05	2.28
ROTB 66007S002	1	ROUB 66007S003	1	3.8	2.1	8.2	11: 33	***	05:085	07:189	07:321	11:037	2.28	3.22
ROTB 66007S002	1	ROVB 66007S004	1	6.1	0.2	25.6	11: 33	***	05:085	07:189	11:106	15:018	2.28	3.76
ROWC 66007S005	1	ROXC 66007S006	1	1.6	-10.4	0.3	18: 22	***	15:045	18:021	18:055	19:083	2.93	1.08
BELB 66018S001	1	BEMB 66018S002	1	-0.1	0.0	-0.2	5: 42	---	04:073	04:130	05:127	21:003	0.16	15.66

KERB 91201S003	1	KESB 91201S004	1	15.7	6.7	11.8	7:101	***	94:330	01:091	01:112	04:039	6.35	2.80
KERB 91201S003	1	KETB 91201S005	1	11.8	11.0	7.8	7:101	***	94:330	01:091	07:118	15:039	6.35	7.78
CROB 91301S001	1	CRPB 91301S002	1	0.2	0.3	0.1	7: 96	---	04:045	07:098	07:090	09:088	3.15	1.99
AMSA 91401S001	1	AMTB 91401S003	1	14.6	18.1	11.5	3:326	***	93:009	96:007	01:111	05:254	2.99	4.39
AMTB 91401S003	1	AMUB 91401S004	1	0.3	0.4	-0.1	7:108	---	01:111	05:254	07:153	09:102	4.39	1.86
ADEA 91501S001	1	ADEB 91501S002	1	5.5	3.7	-1.1	2:104	---	93:003	98:088	04:080	08:041	5.23	3.89
ADEA 91501S001	1	ADEB 91501S002	1	5.5	4.1	-3.0	8: 39	---	93:003	98:088	04:080	08:041	5.23	3.89
ADEA 91501S001	1	ADFB 91501S003	1	3.2	2.2	3.7	8: 39	---	93:003	98:088	08:055	10:248	5.23	2.53
PAPB 92201S007	1	PAQB 92201S008	1	-3.4	24.6	5.4	7:278	---	95:217	98:102	98:325	07:273	2.69	8.86
PAPB 92201S007	1	PATB 92201S010	1	1.0	25.7	-2.5	7:278	---	95:217	98:102	07:300	09:319	2.69	2.05
RILB 92301S003	1	RIMB 92301S004	1	0.3	-0.7	0.6	11:218	---	09:094	11:100	11:239	21:003	2.02	9.35
NOUA 92701S001	1	NOUB 92701S002	1	2.5	-11.8	2.9	5:236	---	93:016	00:191	02:082	02:293	7.48	0.58
NOUA 92701S001	1	NOWB 92701S003	1	5.4	6.2	27.1	5:236	***	93:016	00:191	05:246	11:205	7.48	5.89
FUTB 92902S001	1	FUUB 92902S003	1	5.2	-12.7	-8.0	12:139	***	01:027	08:349	12:259	19:356	7.88	7.27
KRUB 97301S004	1	KRWB 97301S006	1	-2.3	0.1	7.8	11: 56	---	93:003	97:005	11:148	15:333	4.01	4.51
REUA 97401S001	1	REUB 97401S002	2	-0.3	0.8	3.3	3:335	---	93:003	98:347	02:012	19:104	5.94	17.25
REUB 97401S002	2	REUC 97401S003	1	12.3	15.6	-5.6	20: 42	***	02:012	19:104	20:046	21:003	17.25	0.88

Appendix 2 ITRF2020 Journal of Geodesy paper



ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions

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Abstract

To better describe the shape of the constantly deforming Earth's surface, the ITRF2020 is provided as an augmented terrestrial reference frame that precisely models nonlinear station motions for both seasonal (annual and semi-annual) signals present in the station position time series and Post-Seismic Deformation (PSD) for sites impacted by major earthquakes. Reprocessed solutions in the form of station position time series and Earth Orientation Parameters using the full observation history provided by the four space geodetic techniques (DORIS, GNSS, SLR and VLBI) were used as input data, spanning 28, 27, 38 and 41 years of observations, respectively. The ITRF2020 long-term origin follows linearly with time the Earth's Center of Mass (CM) as sensed by SLR, based on observations collected over the time span 1993.0–2021.0. We evaluate the accuracy of the ITRF2020 long-term origin position and time evolution by comparison to previous solutions, namely ITRF2014, ITRF2008 and ITRF2005, to be at the level of or better than 5 mm and 0.5 mm/yr, respectively. The ITRF2020 long-term scale is defined by a rigorous weighted average of selected VLBI sessions up to 2013.75 and SLR weekly solutions covering the 1997.75–2021.0 time span. For the first time of the ITRF history, the scale agreement between SLR and VLBI long-term solutions is at the level of 0.15 ppb (1 mm at the equator) at epoch 2015.0, with no drift. To accommodate most of ITRF2020 users, the seasonal station coordinate variations are provided in the CM as well as in the Center of Figure frames, together with a seasonal geocenter motion model. While the PSD parametric models were determined by fitting GNSS data only, they also fit the station position time series of the three other techniques that are colocated with GNSS, demonstrating their high performance in describing site post-seismic trajectories.

Keywords Reference systems · Reference frames · Nonlinear station motions · ITRF

1 Introduction

Solid Earth science and operational geodesy applications require the availability of a long-term global terrestrial ref-

erence frame, as a unique standard reference, to ensure inter-operability and consistency of geodetic products and to adequately exploit various measurements collected by ground-based sensors, or via artificial satellites. The International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF) are recommended by a number of international scientific organizations, such as the International Association of Geodesy and the International Union of Geodesy and Geophysics (IUGG 2007, 2019).

The ITRF is a collaborative international effort, starting with the investments of national mapping agencies, space agencies and research groups in implementing and operating geodetic observatories, followed by Data Centers (DCs) who collect and archive geodetic observations, and then by Analysis Centers (ACs) and Combination Centers (CCs) of the four space geodetic techniques that contribute to the ITRF computation: Doppler Orbitography and Radiopositioning

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Integrated by Satellite (DORIS), Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI). These techniques are organized as scientific services and are part of the structure of the International Association of Geodesy (IAG) and known by the International Earth Rotation and Reference Systems Service (IERS) as Technique Centers (TCs): the International DORIS Service (IDS; Willis et al. 2016), the International GNSS Service, formerly the International GPS Service (IGS; Johnston et al. 2017), the International Laser Ranging Service (ILRS; Pearlman et al. 2019), and the International VLBI Service (IVS; Nothnagel et al. 2017).

By precisely combining individual reference frame solutions of the four techniques, the ITRF greatly benefits from their specific strengths while integrating all of them into a single reference frame with a unique origin, scale and orientation.

Each ITRF solution is demonstrated to be of higher quality than past versions, as new and extended data are used, but also thanks to improved analysis strategies at both the technique and ITRF combination levels.

The ITRF2020 provided the opportunity to improve the modeling of nonlinear station motions and, in turn, better characterize the shape of the deforming Earth's surface. It is an augmented reference frame where the temporal station positions are modeled by piecewise linear functions, parametric models describing annual and semi-annual deformation, as well as Post-Seismic Deformation (PSD) for stations subject to major earthquakes.

The ITRS Center of the IERS, hosted by the Institut National de l'Information Géographique et Forestière (IGN) France, is responsible for the maintenance of the ITRS/ITRF and official ITRF solutions. Two other ITRS combination centers are also generating combined solutions using ITRF input data: Forschungsinstitut at the Technische Universität München (DGFI-TUM; Seitz et al. 2022), and Jet Propulsion Laboratory (JPL; Abbondanza et al. 2017; Wu et al. 2015).

All the ITRF2020 products presented and discussed in this paper are available at a dedicated website: <https://itrf.ign.fr/en/solutions/ITRF2020> (Altamimi et al. 2022).

2 ITRF2020 input data

The following two subsections describe the two data sets used in the computation of the ITRF2020 that is fundamentally based on the availability of colocation sites where two or more space geodesy instruments were or are currently operating.

2.1 Space geodesy solutions

The ITRF2020 benefits from reprocessed solutions, using the full history of observations of the four space geodetic techniques (DORIS, GNSS, SLR and VLBI). Table 1 lists the ITRF2020 input data of the four techniques: weekly solutions for IDS/DORIS and ILRS/SLR, daily solutions for IGS/GNSS and session-wise solutions for IVS/VLBI. It specifies the solution type (Normal Equations or Variance-Covariance), the constraints applied for the reference frame definition (free, loose or minimum constraints), and the Earth Orientation Parameters (EOPs) provided in addition to station positions. The reader may refer to (Altamimi et al. 2002, 2004; Dermanis 2001, 2004; Sillard and Boucher 2001) or to Chapter 4 of the IERS Conventions (Petit and Luzum 2010, Ch. 4) for more details regarding reference frame constraints and the minimum constraints concept in general. The submitted time series per technique are combined solutions of the individual AC solutions of that technique.

The IDS/DORIS contribution contains 1456 weekly combined solutions involving four ACs (Moreaux et al. 2022), and including 201 stations located at 87 sites.

The IGS/GNSS contribution to ITRF2020 consists of 9861 daily combined terrestrial frame (SINEX) solutions from the third IGS reprocessing campaign (repro3; Rebischung 2022). Those were obtained by combining the contributions from 10 (ACs), and include 1905 stations, of which 1344, located at 1159 sites, have been retained in ITRF2020. The observations used cover the time period 1994.0–2021.0 for GPS, 2002.0–2021.0 for GLONASS and 2013.0–2021.0 for GALILEO. One of the novelties of the IGS submission is the fact that the scale of the IGS frame is based on the calibrated Galileo satellite phase center offsets (z-PCOs) published by the European GNSS Service Center (GSC 2022) and that GPS and GLONASS satellite z-PCOs were corrected to become consistent with the Galileo satellite z-PCOs (Rebischung 2020).

The ILRS/SLR contribution consists of 244 fortnightly solutions, with polar motion and Length of Day (LOD) estimated every three days for the period 1983.0–1993.0, using LAGEOS I satellite data, and 1459 weekly solutions with daily polar motion and LOD estimates afterwards, using data acquired on LAGEOS I and II and ETALON I and II satellites (Pavlis and Luceri 2022). The main feature of the ILRS submission worth mentioning here is the careful handling of station range biases, which has an impact on the scale of the SLR frame (Pavlis et al. 2021).

The IVS contribution to the ITRF2020 is a combination of session-wise solutions of 11 different IVS Analysis Centers (Hellmers et al. 2022a,b). The number of the IVS/VLBI

session-wise solutions included in the ITRF2020 combination is 6178, spanning in total 41 years of observations, involving 154 stations in 117 sites, but with only 14 sites in the southern hemisphere. The majority of sessions (86%) includes a small number of stations, ranging between 3 and 9. 842 (13%) sessions involve 10–19 stations, 8 sessions involve 20 stations, while one session exceptionally includes 31 stations. The solutions include the full set of EOPs, in addition to station positions.

2.2 Local ties at colocation sites

In order to integrate and connect the networks of the four techniques together, and subsequently form the ITRF, it is fundamental to have a sufficient number of well-distributed sites where two or more independent geodetic instruments are observing and where local surveys between instrument measuring points are available. Local surveys are usually conducted using terrestrial measurements (angles, distances, and spirit leveling) or/and GNSS observations. Least squares adjustments of local surveys are performed by national agencies operating ITRF colocation sites to provide relative coordinates (local ties) connecting the instrument reference points.

Figure 1 illustrates the full ITRF2020 network, comprising 1835 stations located in 1243 sites, where about 10% of them are colocated with 2, 3, or 4 distinct space geodetic instruments. Over the entire ITRF2020 observation history, we used local ties available for 101 colocation sites (10 more sites than in ITRF2014) with two or more technique instruments which were or are currently operating.

All past and newly submitted local ties to the ITRF2020 were used. After the ITRF2014 release, 32 new surveys were conducted and their results, including local tie SINEX files were submitted and included in the ITRF2020 computation. All the DORIS colocation site survey data were re-adjusted by the IGN survey department in order to generate full SINEX files, including the most recent surveys operated at these sites. All the local tie SINEX files used in the ITRF2020 combination are available at <https://itrf.ign.fr/en/local-ties>.

We recall here that the local ties used in the ITRF combination are provided in SINEX (Solution-INdependent EXchange) format with known measurement epochs (with the exception of few old ties), and 80% of them are available with full variance-covariance information.

The number of colocation sites between DORIS, SLR and VLBI, taken by pair, is insufficient to allow for a reliable combination of these three techniques alone: 12 DORIS-SLR, 10 DORIS-VLBI and 8 SLR-VLBI. However, almost all SLR and VLBI sites are colocated with GNSS, and a significant number of well-distributed DORIS sites are colocated with GNSS. We count in total 253 tie vectors between GNSS and the three other technique reference points: 77 for VLBI, 53

for SLR and 123 for DORIS. 66 additional tie vectors were also used between old and current DORIS beacon reference points in DORIS-only sites, but almost half of them are the results of repeated surveys.

There are six 4-technique colocation sites in the ITRF2020: Metsahovi (Finland), Wettzell (Germany), Badary (Russia), Hartebeesthoek (South Africa), Greenbelt (USA), and Yarragadee (Australia).

3 ITRF2020 analysis strategy

Among a number of other innovations and analysis improvements, for the first time of the ITRF history, the ITRF2020 accumulates the time series of the four space geodetic techniques all together, adding local ties and co-motion constraints at colocation sites in a single process. In preparation for such a global stacking, intermediates steps, as detailed in the following subsections, were performed in order to mainly identify and reject outliers, introduce discontinuities in station position time series and determine parametric models for stations subject to post-seismic deformation.

3.1 Time series analysis

Although the full equations of the combination model implemented in the CATREF Software that is used for the ITRF computations were published in past articles, see for instance (Altamimi et al. 2016), they are detailed in the appendix of this stand-alone paper for the convenience of the reader.

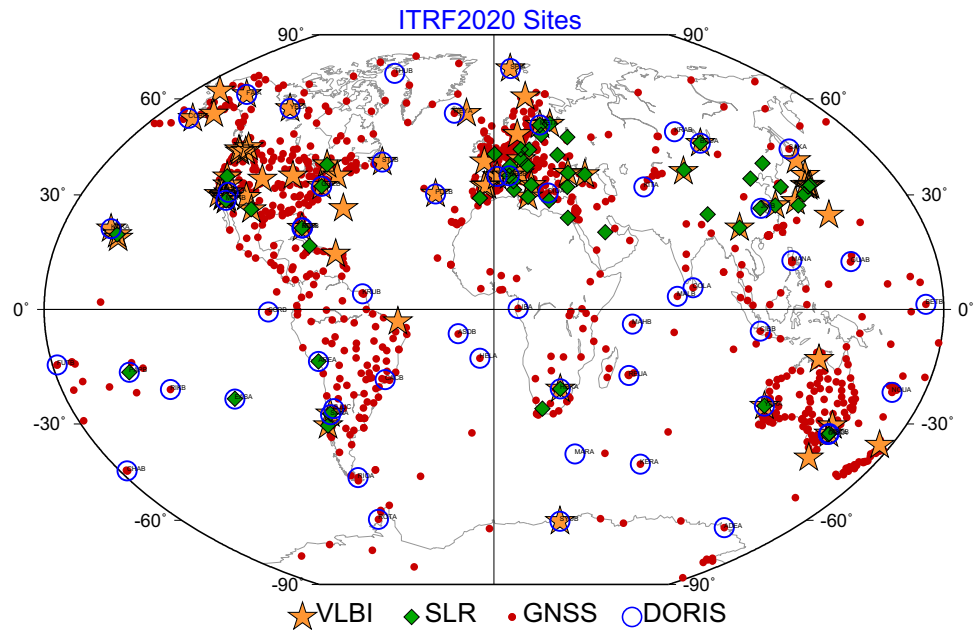
In preparation for the global overall ITRF2020 combination described in Sect. 4, intermediate analysis steps and stacking of the individual technique time series were conducted, including the following:

- Apply No-Net-Rotation constraints to all SLR loosely constrained solutions, thus preserving the origin and the scale of each weekly solution;
- Apply No-Net-Translation and No-Net-Rotation constraints to IVS solutions, thus preserving the scale of each session-wise solution provided in the form of normal equations;
- Use as they are minimally constrained solutions: this is the case of IGS daily and IDS weekly solutions where the GNSS scale and DORIS origin and scale information are preserved;
- Determine PSD parametric models using GNSS/IGS data (see Subsect. 3.4 for more details), then apply them to all technique time series at colocation sites impacted by earthquake-induced displacements/deformation, prior to the next step;
- Form per-technique long-term solutions, by rigorously stacking the time series, solving for station positions,

Table 1 Summary of submitted solutions to ITRF2020

TC	Data-span	Sampling	Solution type	Constraints	EOPs
IVS	1980.0–2021.0	Daily	Normal Eq	None	PM, PMr, LOD, UT1-UTC, δX , δY
ILRS	1983.0–1993.0	Fortnightly	Var-Cov	Loose	PM, LOD
	1993.0–2021.0	Weekly	Var-Cov	Loose	PM, LOD
IGS	1994.0–2021.0	Daily	Var-Cov	Minimum	PM, PMr, LOD
IDS	1993.0–2021.0	Weekly	Var-Cov	Minimum	PM

PM Polar motion, *PMr* Polar motion rate, *LOD* Length of day, *UT1-UTC* UT1 minus UTC, δX and δY : Nutation offsets

Fig. 1 ITRF2020 network highlighting VLBI, SLR, and DORIS sites colocated with GNSS

velocities, EOPs and 7 transformation parameters for each input solution with respect to the per-technique cumulative solution. During the iterative stacking process:

- Annual and semi-annual signals were estimated for stations with time spans greater than 2 years;
- Discontinuities were introduced in the station position time series as detailed in Subsect. 3.3. Each of the successive time intervals bounded by discontinuities is labelled with an integer called solution number (SOLN);
- For the particular case of IGS time series, in addition to the annual and semi-annual signals, periodic signals at the first 8 GPS draconitic harmonics (Ray et al. 2008) were estimated and then removed from the IGS time series.

During the stacking process of either of the individual technique time series, as well as in the global ITRF2020 combination described in Sect. 4, nearby stations, as well as the successive segments (SOLNs) of a given station, are constrained to have the same velocity and periodic signals

using the following two equations:

$$\dot{X}^{i1} = \dot{X}^{i2} \quad (\sigma_v) \quad (1)$$

$$F_j^{i1} = F_j^{i2} \quad (\sigma_f) \quad (2)$$

where $i1$ and $i2$ are two close-by stations or two consecutive segments (SOLNs) of a station with discontinuities. $\dot{X}^{i1}$ and $\dot{X}^{i2}$ are the corresponding velocities. $F_j^{i1} = [ax_j^{i1}, ay_j^{i1}, az_j^{i1}, bx_j^{i1}, by_j^{i1}, bz_j^{i1}]^T$ and $F_j^{i2} = [ax_j^{i2}, ay_j^{i2}, az_j^{i2}, bx_j^{i2}, by_j^{i2}, bz_j^{i2}]^T$ are the coefficients of the cosine and sine functions describing the periodic station displacements at frequency j (see Appendix A for more details). σ_v and σ_f are the uncertainties at which the constraints (1) and (2) are imposed, which are chosen to be 10^{-6} m/yr and 10^{-6} m in case of the stacking of the individual technique time series, and as a function of the level of agreement between techniques at collocation sites in case of the global ITRF2020 combination. For some stations, different velocities were estimated before and after the discontinuity events in case of apparent slope change (i.e., no velocity equality constraints were applied in those cases). This also holds for some (not all) stations with post-seismic deformation.

3.2 Periodic signals

The periodic signals observed in the station position time series are due not only to geophysical or climatological phenomena, e.g., loading (van Dam and Wahr 1998), or thermal effects (Xu et al. 2017), but also due to technique systematic errors, such as the draconitic signals for satellite techniques, as evidenced by Ray et al. (2008) for GPS.

In the particular case of the ITRF computation, it is necessary to estimate the periodic signals embedded in the input data that are in the form of time series. Doing so is expected to improve the linear station velocity estimation, especially for stations with large seasonal signals and/or relatively short time series (Blewitt and Lavallée 2002). Estimating the periodic signals during the stacking process, along with station position and velocities also helps detecting discontinuities in the time series more easily, and consequently improves the offset determination.

The fact that the ITRF combination / stacking model described in Appendix A includes a 7-parameter similarity transformation between each individual daily / weekly solution and the cumulative long-term solution offers a number of options for the definition / specification of not only the long-term linear reference frame, but also the seasonal signals, in origin, scale and orientation (Collilieux et al. 2018).

Appendix C provides the equations implemented in the CATREF software that are used for the definition / specification of the periodic signals, distinguishing between minimum and internal constraints. In the stacking process, we need to specify how to separate seasonal variations of the transformation parameters from seasonal variations of the station positions. To that end, we generally chose the internal constraint approach for the origin and scale components, that is, to constrain to zero the periodic signals embedded in the time series of the corresponding transformation parameters. This approach is justified by the fact that it avoids the absorption of part of the station motions by the time series of translation and scale factor parameters. In regard to the rotation parameters, we usually chose the minimum constraint approach, i.e., to impose no net periodic rotation conditions on a set of well-distributed reference stations. More details are provided in Sect. 4 regarding the options used in the ITRF2020 global combination.

3.3 Handling of discontinuities

To identify the discontinuities present in the GNSS station position time series provided by the IGS, we inspected them visually, as manual offset detection tends to perform better than automated methods (Gazeaux et al. 2013). A model composed of a piecewise linear function, annual and semi-annual signals and, when needed, functions describing post-seismic deformation (see following subsection) was

adjusted to each of the time series. Position and velocity discontinuities were iteratively added to the model until no more offset nor trend change was visible in the residual time series. To help the identification of offsets and relate them to known events, we used as auxiliary data the equipment changes recorded in the station log files, as well as a list of co-seismic offsets predicted using the approach of Métivier et al. (2014). In the 1344 GNSS station position time series used in ITRF2020, a total of 2939 position and/or velocity discontinuities were identified. 1505 could be related to equipment changes or malfunction, 677 to earthquakes, 6 to volcanic activity, 185 were introduced to describe trend changes (e.g., in response to current ice melting), while the remaining 566 have unknown causes. This corresponds to one discontinuity every 6.4 years in average.

For colocation sites impacted by earthquakes, and in order to ensure consistency between the four technique time series, we adopted the same discontinuity epochs for DORIS, SLR and VLBI as for GNSS. The number of position discontinuities due to earthquakes are 37 (out of 86), 29 (out of 41), and 46 (out of 50), for DORIS, SLR and VLBI, respectively. Discontinuities unrelated to earthquakes were identified by visual inspection of the station position residual time series, resulting from the individual per-technique stacking where seasonal signals were estimated.

3.4 Post-seismic deformation

Initiated at the occasion of the ITRF2014 (Altamimi et al. 2016), the parametric models describing PSD for sites impacted by major earthquakes were refined using the extended ITRF2020 input data. In addition to the four PSD models introduced with ITRF2014, a fifth model is now added: (1) (Log)arithmic, (2) (Exp)ponential, (3) Log+Exp, (4) Exp+Exp, and (5) Log+Log. Each PSD model may or may not be accompanied by a velocity change.

The ITRF2020 PSD models were adjusted to the input IGS station position time series after all offsets were identified. For every earthquake followed by visible PSD, a single exponential function and a single logarithmic function were first separately tested. The function yielding the smallest weighted sum of squared residuals was retained. In case residual PSD was still visible in the residuals from this first model, a second exponential or logarithmic function was added to the PSD model, according to the same criterion.

Figure 2 displays in red the locations, extracted from the global Centroid-Moment-Tensor catalog (Dziewonski et al. 1981; Ekström et al. 2012), of the 65 earthquake epicenters that caused significant PSD in the ITRF2020 input time series, and in green the 118 impacted ITRF2020 sites. Figure 3 shows the histograms of the residuals from the trajectory models adjusted to the IGS repro3 station position time series without (in black) and with (in red) PSD. From this figure,

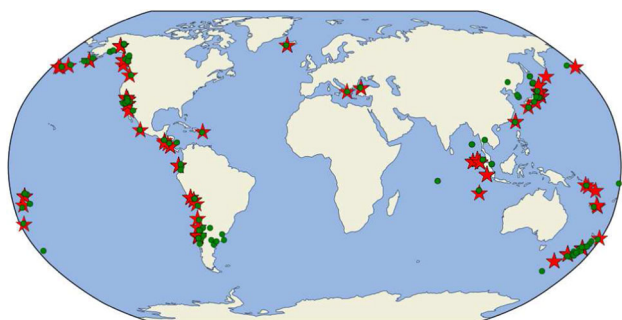


Fig. 2 Distribution of earthquake epicenters (red), extracted from the global Centroid-Moment-Tensor catalog (Dziewonski et al. 1981; Ekström et al. 2012) and ITRF2020 sites (green) impacted by Post-Seismic Deformation

we can see that the distributions are similar whether or not PSD models are part of the trajectory models, indicating that the presence of PSD models or not has little influence on the goodness of fit of the overall trajectory models.

The corrections predicted by the GNSS-fitted models were then applied not only to the IGS station position time series, but also to the colocated stations of the three other techniques, before stacking their respective time series. We verified that the ITRF2020 PSD parametric models determined using IGS/GNSS data fit also the station position time series of the three other techniques that are sharing the same colocation sites. Thus, we inspected the post-fit residuals of these colocated station position time series to verify that no residual post-seismic deformation was visible. As an example, Fig. 4 illustrates the performance of the PSD parametric model for the colocated GNSS and VLBI stations at Tsukuba (Japan). It shows in blue the raw station position time series, in green the piecewise linear trajectories given by the ITRF2020 coordinates and in red the trajectories obtained when adding the parametric PSD model. In that figure, one can see the remarkable fit of the PSD model, not only to the GNSS, but also to the VLBI data.

4 ITRF2020 global combination

Past ITRF combinations up to ITRF2014 were operated using a two-step procedure (Altamimi et al. 2007, 2011, 2016): (1) stacking the individual time series to estimate a long-term solution per technique comprising station positions at a reference epoch, station velocities and daily EOPs; and (2) combining the resulting long-term solutions of the four techniques together with the local ties at colocation sites.

For the ITRF2020 computation, we opted for a one-step procedure, that is, to accumulate the full time series of the four techniques all together. Seven transformation parameters are estimated for each single daily, weekly, or VLBI

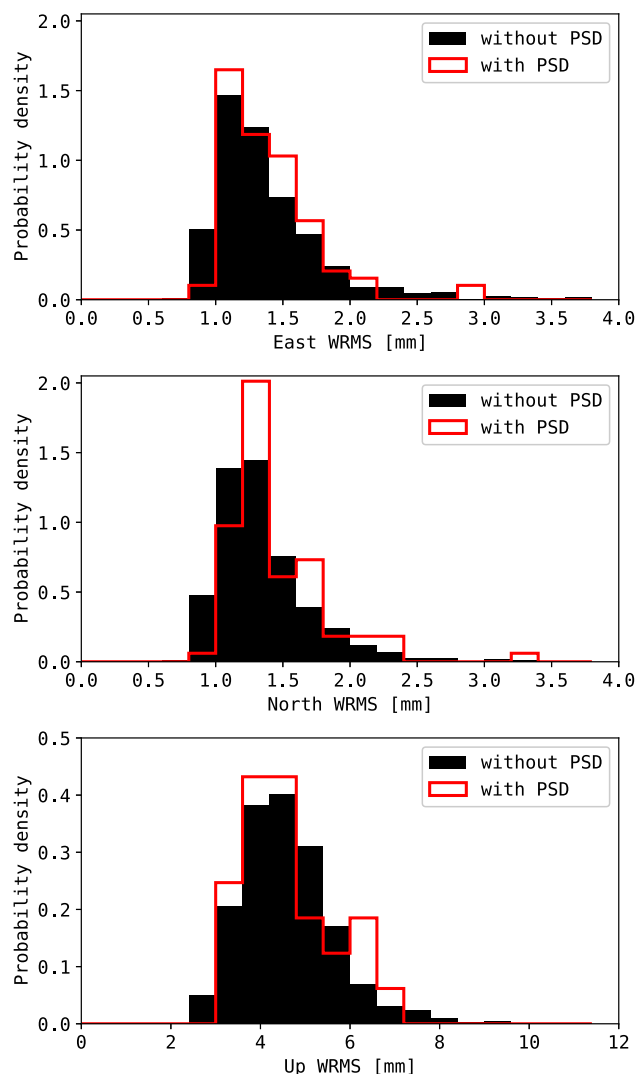


Fig. 3 Histogram of the WRMS of the residuals from the trajectory models adjusted to the IGS repro3 station position time series without (in black) and with (in red) PSD

session-wise solution with respect to the ITRF2020 global combined solution.

This strategy has multiple advantages, including the ease of imposing co-motion constraints between points of different techniques at colocation sites, but also the ease of transferring the instantaneous Center of Mass information as sensed by SLR to the three other technique networks, using the internal constraints approach. However, we also operated the two-step procedure and verified that we obtain the same results with both approaches, as it should mathematically be the case, provided that the same weighting is used for both space geodesy solutions and local ties. Indeed, the weighting is an important aspect in the ITRF combination analysis, as we deal with observations and constraints: global space geodesy solutions, local ties and co-motion constraints at colocation sites (cf. Eqs. 1 and 2). In addition, there

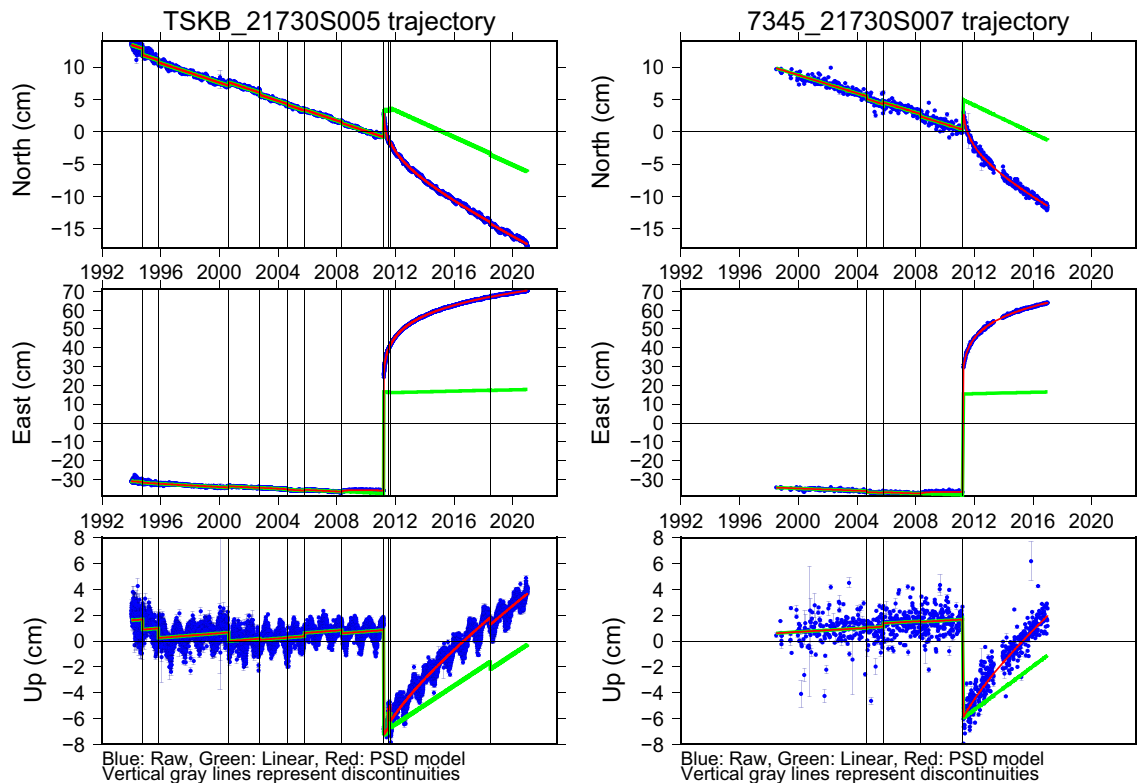


Fig. 4 Trajectory of Tsukuba (Japan) site. Left GNSS and right VLBI. In blue raw data, in green the piecewise linear trajectories from ITRF2020 coordinates, and in red the trajectories obtained when adding the parametric PSD model

are significant tie, velocity and seasonal signal discrepancies between technique solutions at a number of colocation sites that necessitate an iterative combination and empirical weighting process.

For the global ITRF2020 combination and to determine the relative weighting of the individual space geodetic technique solutions and the local ties, as well as the uncertainties of the velocity and seasonal signal constraints (σ_v and σ_f of Eqs. 1 and 2), we operated the following consecutive steps:

1. The weighting of the space geodesy solutions was determined by re-scaling the individual variance-covariance matrices by the following two factors:
 - The a posteriori variance factors obtained from the individual stacking of each technique station position time series, whose square roots are: 2.92, 2.60, 3.93 and 11.56 for DORIS, GNSS, SLR and VLBI, respectively;
 - Corrective factors aiming at accounting for the presence of time-correlated noise in the station position time series. While geodetic station position time series are known to exhibit time-correlated noise (Abbondanza et al. 2015; Williams et al. 2004; Williams and Willis 2006), the CATREF stacking model indeed assumes variable white noise only, and the above

variance factors are consequently under-estimated. To obtain corrective factors, we adjusted the ITRF2020 kinematic model of every station to its position time series together with either a variable white noise (only) model, or a variable white noise + power-law noise model. The parameters of the noise models (variances and spectral index) were estimated by restricted maximum likelihood, an unbiased alternative to classical maximum likelihood (Gobron et al. 2022; Harville 1977). The ratio between the formal velocity uncertainty obtained with the white + power-law noise model and the formal velocity uncertainty obtained with the white noise only model was then computed for each station and component. The corrective factors we applied in the ITRF2020 computation are the per-technique medians of the obtained ratios: 7.75 for GNSS, 2.12 for SLR and 2.69 for VLBI. For DORIS, although the median ratio is 2.00, we found empirically that it was necessary to use a corrective factor of 5.00. We noticed that selecting a corrective factor smaller than 5 would lead to an increase of normalized residuals exceeding the adopted threshold of 3 for a significant number of DORIS colocation sites.

2. For the purpose of equating station velocities at colocation sites, an iterative combination process of the four

technique velocity fields was operated as detailed in Subsect. 4.1.

3. Using the weighting determined in steps 1 and 2, an iterative combination process of the four long-term solutions, adding local tie SINEX files at colocation sites, was performed. During this step, the uncertainties of local ties were re-evaluated and discrepant ties were down-weighted as described in Subsect. 4.2. Once the combination was stabilized, i.e., no normalized residual was larger than 3 in any component of both space geodesy estimates and local ties, the EOPs were then added to the combination. At this stage, the combination was iterated as necessary, and at each iteration EOP estimates were rejected if their normalized residuals were larger than 3. We also faced the situation where, when adding EOPs to the combination, small distortions of the SLR and VLBI frames appeared, namely an increase of position residuals for some stations, up to 4 mm, with normalized residuals exceeding the threshold of 3. We suspect this behavior to be caused by some mismatch between station position and polar motion estimates. In order to get the best of SLR and VLBI, and avoid these small distortions in the two corresponding frames, we down-weighted the ILRS and IVS polar motion estimates by a factor of 2. Doing so actually stabilized the two frames within the combination, and the small distortions were mitigated.
4. The global and final ITRF2020 combination was operated by accumulating the full time series of the four techniques all together, adopting the weighting for space geodesy time series and local ties as determined in the previous steps, and adding co-motion constraints where the σ_v and σ_f for the velocity and seasonal signals constraints, respectively, were chosen as described in Subsect. 4.1.

4.1 Co-motion constraints at colocation sites

4.1.1 Equating station velocities at colocation sites

In order to evaluate the level of the velocity agreement between techniques at colocation sites, and consequently adopt the appropriate σ_v for the velocity constraint (Eq. 1) between collocated reference points, we conducted an iterative combination process of the four technique velocity fields embedded in the long-term solutions resulting from the individual stacking of the corresponding time series. In this analysis, we have chosen to constrain the couples of GNSS and reference points of the collocated instruments of the three other techniques that are available at these sites. For sites with multiple points (or segments in case of discontinuities) of the same technique, we constrained one couple of GNSS and other technique points, given the fact that the velocities of these multiple points (with some exceptions) are constrained technique per technique. Moreover, we

have chosen the longest and most stable time series of these constrained points by inspecting their respective detrended residuals. The initial σ_v was chosen to be 0.1 mm/yr per component between GNSS/SLR and GNSS/VLBI collocated points, while 1 mm/yr was selected for the GNSS/DORIS pairs. Using σ_v smaller than 1 mm/yr for GNSS/DORIS pairs leads to an increase of the normalized residuals exceeding the adopted threshold of 3 for a significant number of DORIS colocation sites. At each iteration of this combination of the velocity fields, the σ_v of Eq. 1 was increased for sites where the velocity normalized residual exceeded the threshold of 3 in any of the three components.

4.1.2 Equating station seasonal signals at colocation sites

In the ITRF2020 global stacking of the four technique time series, we equated the seasonal signals (annual and semi-annual) of the same chosen couples of GNSS and reference points of the collocated instruments that were constrained to have the same velocity. The initial σ_f of Eq. 2 was set to 0.1 mm per coefficient of the cosine and sine functions. In case of seasonal signal discrepancies between techniques at colocation sites larger than 1 mm in amplitude, σ_f was increased to the level of their agreements.

In order to evaluate the benefit of estimating the seasonal signals, we operated an ITRF2020-like global combination without estimating the seasonal signals. We found that the horizontal velocity differences are almost all negligible for all stations and are less than 0.1 mm/yr, while the largest vertical velocity differences range between 0.5 and 1 mm/yr for about 20 poorly determined stations, with short time span of observations. The reduction of the velocity formal errors of about 10% when estimating the seasonal signals could be regarded as an improvement of the velocity determination.

4.2 Handling of local ties

In the same way as we use space geodesy solutions, local ties at colocation sites are used as observations, with full variance-covariance information provided in SINEX format. Note that the local ties are introduced in the combination with their corresponding survey epochs, as provided in their respective SINEX files. For the ITRF2020 computation, the variances of the used local ties were re-evaluated, in such a way that the uncertainty in any of the three components (East, North and Vertical) should not be below 2 mm (versus 3 mm in ITRF2014) using two scaling factors: one for the horizontal and one for the vertical components. The local tie lower bound uncertainty of 2 mm was adopted after a number of test combinations where we varied that threshold between 1 and 4 mm and found more coherent results with better agreement between space geodesy estimates and terrestrial ties, compared with ITRF2014 results as discussed at the end of

this subsection. The reason why we adopted two factors to re-scale the local tie variances is that the local tie vertical component is usually more precise than the horizontal ones, as it is determined using spirit leveling methods, independently from the horizontal components (Poyard et al. 2017).

Considering the number of station position discontinuities of the four techniques at colocation sites, but especially in case of GNSS time series, we had to adopt a comprehensive approach in selecting the segments to be tied together. For that purpose and as we did for the ITRF2014, we assigned the tie vectors to the longest and most stable segments, judging from their time series of residuals free from the linear trend and seasonal signals.

During the combination process of the long-term solutions of the four techniques, as described in Step 3 of Sect. 4, we iteratively down-weighted discrepant ties whose normalized residuals were exceeding the threshold of 3 in any of the three components. As in previous ITRF solutions, we chose to down-weight the local ties rather than space geodesy estimates in order to mainly maximize the consistency between individual technique solutions and ITRF2020.

Table 2 summarizes the main statistics of the local tie discrepancies in the ITRF2020 combination, in comparison with ITRF2014 results. Note that “Tie discrepancy” means difference between terrestrial ties and space geodesy estimates. As it can be seen in that table, ITRF2020 includes more tie vectors (from GNSS to other techniques reference points) and performs better than ITRF2014, as the percentage of tie discrepancies less than 5 mm is higher for all three techniques tied to GNSS. The reader can access the full list of tie discrepancies available at the ITRF2020 website.

4.3 ITRF2020 frame and seasonal signals definition

In the global ITRF2020 combination, the frame and seasonal signals defining parameters were specified as follows, noting that we used the concept of internal constraints for the origin and the scale, and the concept of minimum constraints for the orientation.

4.3.1 Origin

The origin of the ITRF2020 long-term frame is defined in such a way that there are zero translation parameters at epoch 2015.0 and zero translation rates between the ITRF2020 and the ILRS SLR long-term frame over the 1993.0–2021.0 time span, using the concept of internal constraints.

The origin of the ITRF2020 seasonal signals expressed in the CM (as sensed by SLR) frame is defined in such a way that there is no seasonal translation between the ITRF2020 seasonal signals and the input SLR solutions over the 1993.0–2021.0 time span, using the concept of internal constraints.

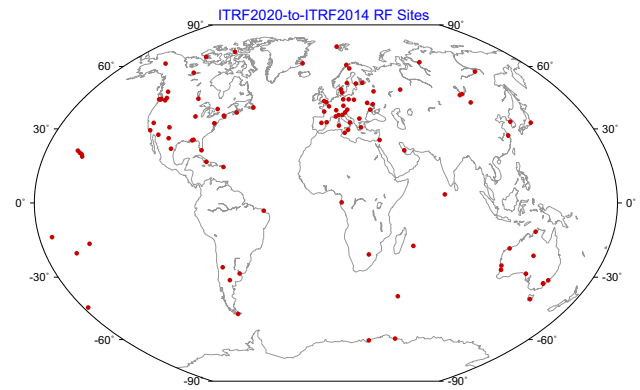


Fig. 5 Location of the reference frame sites used in the estimation of the 14 transformation parameters between ITRF2020 and ITRF2014 and their orientation alignment

4.3.2 Scale

The scale of the ITRF2020 long-term frame is determined using the revised concept of internal constraints (see Appendix B for more details), in such a way that there are zero scale and scale rate between ITRF2020 and the scale and scale rate averages of VLBI selected sessions up to 2013.75 and SLR weekly solutions covering the 1997.75–2021.0 time span.

The scale of the ITRF2020 seasonal signals is determined using internal constraints, in such a way that the average of the seasonal scale variations between the selected SLR solutions and ITRF2020 is zero.

4.3.3 Orientation

The orientation of the ITRF2020 long-term frame is defined in such a way that there are zero rotation parameters at epoch 2015.0 and zero rotation rates between the ITRF2020 and ITRF2014. These two conditions were applied over a set of 131 reference stations located at 105 sites as illustrated by Fig. 5.

The orientation of the ITRF2020 seasonal signals is defined in such a way that there is no net seasonal rotation of that same core network.

5 ITRF2020 results

5.1 Station position kinematic model

The ITRF2020 is an augmented terrestrial reference frame comprising in addition to the classical parameters (station positions at a reference epoch $t_0 = 2015.0$ and station velocities), parametric models describing the trajectory of stations subject to post-seismic deformation, as well as annual and

Table 2 Statistics of local tie discrepancies

GNSS to	# of tie vectors		# of tie discrepancies < 5 mm		% of tie discrepancies < 5 mm	
	ITRF2014	ITRF2020	ITRF2014	ITRF2020	ITRF2014	ITRF2020
VLBI	60	77	27	38	45	50
SLR	49	53	14	19	29	36
DORIS	103	123	23	39	22	32

semi-annual periodic terms expressed in the CM (as sensed by SLR) frame, and in the Center of Figure (CF) frame.

Depending on the user need, the coordinates of a given station at epoch t can be computed using Eq. 3.

$$X(t) = X^i(t_0) + \dot{X}^i(t - t_0) + \delta X_{PSD}(t) + \delta X_f^i(t) \quad \forall t \in [t_i, t_{i+1}] \quad (3)$$

where the couple $(X^i(t_0), \dot{X}^i)$ are the station position and velocity for segment (SOLN) i bounded by dates (t_i, t_{i+1}) , $\delta X_{PSD}(t)$ is the total sum of the PSD corrections—the PSD corrections of successive earthquakes are cumulative, and $\delta X_f^i(t)$ is the total sum of the seasonal signal corrections for segment (SOLN) i . The following two subsections provide more details on how to compute $\delta X_{PSD}(t)$ and $\delta X_f^i(t)$.

5.2 Post-seismic deformation models

The full equations of the parametric models and their variance propagation used in the ITRF2020 generation are provided in Appendix D of this paper. While the ITRF2020 solution provides the usual/classical estimates (station positions at epoch 2015.0, station velocities and EOPs), the PSD models are also part of the ITRF2020 products. The users should be aware that they must compute the total sum of PSD corrections, $\delta X_{PSD}(t)$, using the equations supplied in Appendix D, to be then added to the ITRF2020 coordinates using Eq. 3 if the epoch of the needed position occurs during the post-seismic relaxation period. Failing to do so would introduce position errors at the decimeter level for many stations impacted by PSD. Full information regarding the PSD models fitted for stations subject to major earthquakes, and some useful subroutines in Fortran are available through the ITRF2020 website: <https://itrf.ign.fr/en/solutions/ITRF2020>.

5.3 ITRF2020 seasonal signals and geocenter motion

The seasonal (annual and semi-annual) signals were estimated for stations with time spans longer than 2 years, together with station positions, velocities and EOPs in the global ITRF2020 combination and expressed in the CM frame of SLR.

Figure 6 illustrates the ITRF2020 station annual signals, following East, North and Up components, respectively. They are expressed in the SLR-based CM frame where, as expected, geographically common mode patterns are evidenced, primarily due to the geocenter motion. In addition, it is well known that station seasonal displacements are spatially correlated (Collilieux et al. 2007; Dong et al. 2002).

The main motivation of estimating the seasonal signals consistent with the ITRF2020 whose long-term origin is inherited from SLR data is to provide to users, e.g., those dealing with satellite precise orbit determination, a means to refer the ITRF2020 coordinates to the quasi-instantaneous Earth CM, a point around which an artificial satellite is naturally orbiting.

To use this new feature, user should compute the seasonal coordinate variations $\delta X_f(t)$ using Eq. 4 and add it to the station coordinates at epoch t , using Eq. 3.

$$\delta X_f(t) = \sum_{i=1}^2 \begin{pmatrix} a_x^i \\ a_y^i \\ a_z^i \end{pmatrix} \cos(2i\pi \cdot t) + \begin{pmatrix} b_x^i \\ b_y^i \\ b_z^i \end{pmatrix} \sin(2i\pi \cdot t) \quad (4)$$

where t is the decimal year and $(a_x^i, a_y^i, a_z^i, b_x^i, b_y^i, b_z^i)$ are the cosine and sine coefficients at frequency i (annual: $i = 1$; semi-annual: $i = 2$) provided in ITRF2020 for the given station.

Note that the seasonal motion of an ITRF2020 station provided in the CM frame is the sum of a net translation term that affects all stations equally and the station individual seasonal motion with respect to the center of figure of the solid Earth (CF). Recall that, by definition, the integral of seasonal deformation over the Earth's surface with respect to CF is zero (Blewitt 2003) and the net translation term is the opposite of the geocenter motion, namely the motion of CF with respect to CM.

Based on these concepts, it follows that from the ITRF2020 CM station seasonal signals, one can derive both seasonal geocenter motion and the CF station seasonal signals. To do so, we started by selecting a subset of ITRF2020 CM seasonal station motion coefficients. The selected subset excludes stations with poorly determined and abnormal seasonal coefficients and retains one single point per site with multiple stations that were constrained to have the same seasonal coefficients: the one for which the trace of the formal

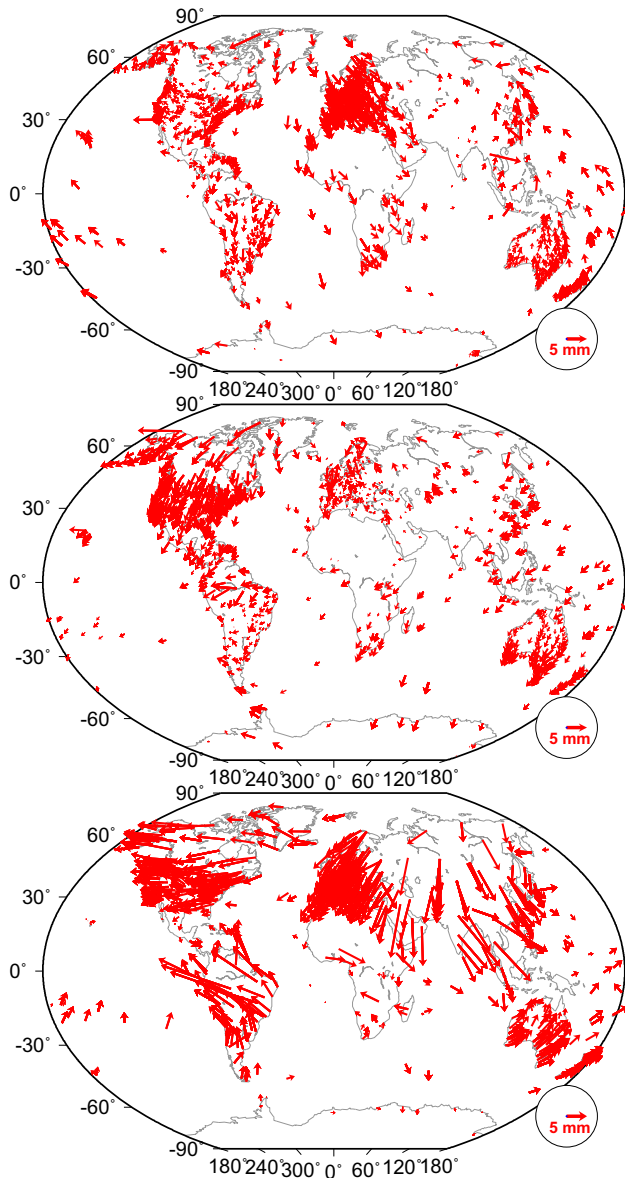


Fig. 6 ITRF2020 station annual signals following the three components: East (top), North (middle) and Up (bottom). The amplitudes (A) and phases (ϕ) are represented by the arrow lengths and orientations (counted from the north), respectively, following the model $A \cdot \cos(2\pi \cdot t - \phi)$, with t in decimal year

covariance matrix of the seasonal coefficients is minimal. The final selection contains a cleaned ensemble of 1124 stations. We then computed a weighted sum of the selected CM station seasonal signals aiming at approximating the integral of the Earth's surface seasonal deformation with respect to CM. The adopted weights are the areas of the stations' spherical Voronoi cells (Caroli et al. 2010), spatially smoothed so that nearby stations have similar weights. From the arguments above, it follows that this weighted sum approximates the seasonal motion of CF with respect to CM, hereafter noted $\Delta X_{CF/CM}$.

Table 3 Seasonal displacement of CF with respect to CM = opposite of the seasonal geocenter motion

	Amplitude mm	Phase degrees
Annual x	1.23	-123.2
$\pm$	0.16	7.2
Annual y	3.48	152.9
$\pm$	0.15	2.5
Annual z	2.76	-139.5
$\pm$	0.33	6.8
Semi-annual x	0.49	107.2
$\pm$	0.15	18.1
Semi-annual y	0.22	1.6
$\pm$	0.15	39.0
Semi-annual z	1.19	30.5
$\pm$	0.33	15.5

The obtained ITRF2020 seasonal coefficients of vector $\Delta X_{CF/CM}$ are given in Table 3. Subtracting this model from the ITRF2020 CM station seasonal signals yields the ITRF2020 CF station seasonal signals, which are also provided at the ITRF2020 website. More details on the derivation of the ITRF2020 geocenter motion model will be given in a follow-up paper.

Following Table 3, the seasonal motion of CF with respect to CM, along any x , y , z axis, say $\Delta x_{CF/CM}$ along x , is obtained by Eq. 5.

$$\Delta x_{CF/CM}(t) = A_1 \cos\left(2\pi t - \frac{\pi}{180} \cdot \phi_1\right) + A_2 \cos\left(4\pi t - \frac{\pi}{180} \cdot \phi_2\right) \quad (5)$$

where t is the time in decimal years, A_1 and A_2 are the annual and semi-annual amplitudes, ϕ_1 and ϕ_2 are the annual and semi-annual phases expressed in degrees, respectively, as listed in Table 3. This equation is valid for each one of the three axes x , y , z .

The reader should note that by convention, the IERS Conventions (Petit and Luzum 2010, Ch. 4) defines seasonal geocenter motion as the motion of the Earth's CM with respect to CF. To obtain seasonal geocenter motion as defined in the IERS Conventions, the user can either add 180 degrees to the phase values listed in Table 3, or change sign of Eq. (5).

5.4 Usage of the ITRF2020 seasonal signals

When using the ITRF2020 station position kinematic model (3), the user should decide, depending on his application, if the seasonal signals, i.e., adding $\delta X_f(t)$, should be considered, and if so, whether the seasonal signals referred to CM

or CF should be used. In this regard, it should be noted that, in principle:

- The origin of the *linear* ITRF2020 coordinates reflects CM on secular time scale, but CF on shorter (inter-annual, seasonal, sub-seasonal, etc.) time scales, as a consequence of the linear kinematic model used to represent station motions. Linear coordinates can indeed not account for net nonlinear translations of the Earth's surface, and CF is by definition the point with respect to which there is no net translation of the Earth's surface (see full development of this argument in (Dong et al. 2003));
- If the ITRF2020 seasonal signals referred to CF are added, the origin of the resulting coordinates remains the same as in the purely linear case: it still reflects CM on the long term, but CF at both the annual and semi-annual periods (by construction of the ITRF2020 CF seasonal signals) and all other frequencies (since they are not represented in the kinematic model). However, compared to the purely linear case, the resulting coordinates additionally account for the individual seasonal station motions with respect to CF;
- On the other hand, if the ITRF2020 seasonal signals referred to CM are added, the origin of the resulting coordinates changes compared to the purely linear case: it now reflects CM on both the long term and at the annual and semi-annual periods, but still reflects CF on all other time scales (e.g., inter-annual, sub-seasonal).

In practice, different usage scenarios could be the following:

- *Precise orbit determination:* In this application, the reference station positions should describe as well as possible the instantaneous shape of the Earth, and be referred as closely as possible to the instantaneous CM. Hence, using as reference positions the linear ITRF2020 coordinates augmented with the seasonal signals referred to CM, rather than the linear ITRF2020 coordinates only, can be expected to be beneficial. This would indeed make the reference positions fit the Earth's shape and follow CM not only on the long term, but also at the annual and semi-annual periods.
- *Alignment of global solutions:* When aligning series of global instantaneous solutions derived from space geodetic data to a long-term linear reference frame by means of Helmert transformations, part of the nonlinear station motions aliases into the estimated Helmert parameters (Collilieux et al. 2012). The incorporation of annual and semi-annual signals in the target reference frame does however resolve this aliasing at the annual and semi-annual frequencies. Hence, aligning global instantaneous

solutions to the linear ITRF2020 frame augmented with seasonal signals (referred to either CM or CF), rather than to the linear ITRF2020 frame only, can be expected to be beneficial and result in seasonal station motions more accurately retained in the aligned solutions. This holds equally true whether the ITRF2020 seasonal signals referred to CM or CF are used. Employing the ITRF2020 seasonal signals referred to one or the other origin would only change the origin of seasonal station motions in the aligned solutions. Namely, if the ITRF2020 seasonal signals referred to CM are used, the seasonal station motions in the aligned solutions will also be referred to CM, and will include a seasonal translational motion common to all stations (i.e., seasonal geocenter motion). On the other hand, if the ITRF2020 seasonal signals referred to CF are used, the seasonal station motions in the aligned solutions will also be referred to CF, and will be free of this global seasonal translational common mode. Whether the ITRF2020 seasonal signals referred to CM or CF should be used does thus depend on the usage intended for the aligned solutions. For instance, if the station positions in the aligned solutions are intended to serve as reference station positions for precise orbit determination, then the ITRF2020 seasonal signals referred to CM should be preferred (see also previous item). On the other hand, if the aligned solutions are mainly intended to study the Earth's surface deformation, it seems more natural to have them free of a global seasonal common mode, hence to use the ITRF2020 seasonal signals referred to CF. Note finally that if an instantaneous solution was aligned to "linear ITRF2020 + CM seasonal signals", it is straightforward to align it to "linear ITRF2020 + CF seasonal signals" instead: for that purpose, the offset $\Delta x_{CF/CM}(t)$ given by Eq. (5) should simply be removed from all station positions. The inverse transformation is achieved by adding this offset instead of removing it.

- *Alignment of local or regional GNSS solutions:* In this case, since seasonal displacements are spatially correlated (Collilieux et al. 2007; Dong et al. 2002), an alignment to the linear ITRF2020 frame augmented with seasonal signals (referred to either CM or CF) would introduce a seasonal common mode in the resulting station position time series. If the user wishes to avoid such a regional, seasonal common mode, he should use as a reference the linear ITRF2020 frame without adding seasonal signals.

It is also worth mentioning here that non-tidal loading corrections were not applied to the ITRF2020 input data, nor during the ITRF2020 computation, so that part of the ITRF2020 seasonal signals reflects seasonal loading deformation. As a consequence, station displacements predicted by a non-tidal loading model should not be added to the lin-

Table 4 Translation parameters from ITRF2020 to past ITRF solutions at epoch 2015.0 and their rates in mm and mm/yr

Solution	TX	TY	TZ
ITRF2014	−1.4	−0.9	1.4
Rates	0.0	−0.1	0.2
ITRF2008	0.2	1.0	3.3
Rates	0.0	−0.1	0.1
ITRF2005	2.7	0.1	−1.4
Rates	0.3	−0.1	0.1

ear ITRF2020 coordinates augmented with seasonal signals, unless mean annual and semi-annual variations are removed from the predicted loading displacements beforehand. Otherwise, seasonal loading deformation would be accounted twice.

5.5 ITRF2020 long-term origin

As stated earlier in this article, the long-term origin of the ITRF2020 is defined by the ILRS SLR input data only, and satisfies the conditions of no translation and no translation rate between ITRF2020 and the SLR long-term frame. Figure 7 illustrates the full time series of the ILRS SLR origin components with respect to the ITRF2020, as result of the global stacking. From that figure, one can see no discernable offset or drift, nor seasonal signals as these were constrained to zero (over the 1993.0–2021.0 time span), using the internal constraints approach, in order to express the ITRF2020 station seasonal signals in the CM frame as sensed by SLR.

One way to evaluate the accuracy and performance of the ITRF2020 origin is to estimate the translation components with respect to past ITRF solutions, namely ITRF2014, ITRF2008 and ITRF2005 whose origins were also defined by SLR data submitted in the form of time series. Table 4 lists the translation components and their rates from ITRF2020 to the past three frames. In that table, we can see variations between −1.4 and 3.3 mm for the translations at epoch 2015.0, and between −0.1 and 0.3 mm/yr for the translation rates. In other words, we can stipulate that the origins of the successive ITRF solutions stand roughly within a sphere of 5 mm in diameter and 0.5 mm/yr for their time variation. These figures are an indication of the level of the ITRF origin intrinsic accuracy achievable today using SLR data, dominated by LAGEOS I and II observations (Pavlis and Luceri 2022) and are consistent with previous independent analyses (Collilieux et al. 2014).

Figure 8 displays the time series of the DORIS geocenter components with respect to ITRF2020, as obtained from the ITRF2020 global stacking of all technique time series. The estimated DORIS long-term origin component offsets with respect to SLR are small: −2.7, 1.1 and 5.4 mm, at epoch 2015.0, for X, Y and Z, respectively, with almost zero drifts.

However, we can clearly see in Fig. 8 significant seasonal variations in X, but more pronounced in Y, suggesting that SLR (which defines the ITRF2020 origin on the seasonal term) and DORIS seasonal geocenter motions are inconsistent for these two components. The DORIS Z-geocenter component is very scattered and still suffering from systematic errors, such as solar radiation pressure mis-modeling (Gobinddass et al. 2009).

5.6 ITRF2020 long-term scale

This is the first time of the ITRF history where we are in presence of independent and competitive scales stemming from the 4 techniques (VLBI, SLR, GNSS and DORIS) that contributed input data for the ITRF2020. Note that as stated earlier, the IGS/GNSS scale is based on the calibrated z-Phase Center Offsets (z-PCOs) of the Galileo satellites published by GSC (GSC 2022), consistently to which the GPS and GLONASS satellite z-PCOs have been re-evaluated (Rebischung 2020). This is also the first time where the ILRS did a great effort in handling and estimating the station-dependent range biases (Luceri et al. 2019) that greatly impact the scale of the SLR frame by up to 1 ppb (about 6 mm at the equator), as demonstrated by (Appleby et al. 2016).

The left panel of Fig. 9 illustrates in orange and red the full time series of VLBI session-wise scales and in light and dark blue the fortnightly/weekly SLR scales with respect to ITRF2020. As it can be seen in that figure, we detected an unexpected VLBI scale drift after around epoch 2014.0, but also an offset in the SLR scale before epoch 1997.75, as well as poor and scattered scale determinations before 1993.0 when only LAGEOS I satellite data were available. The reasons for these VLBI scale drift and SLR scale offset are not clear to the authors and are under investigation by the IVS and ILRS. In order to use the best and most stable scale time series of both techniques for the ITRF2020 scale definition, we retained the ILRS weekly solutions from 1997.75 on (dark blue dots at Fig. 9), and considered only the VLBI sessions before 2013.75 for which station networks have convex hulls with volumes larger than 10^{19} m^3 . To empirically localize the epoch of the VLBI scale drift, we operated 8 test combinations involving the 4 technique long-term solutions where we varied the starting epoch of the VLBI scale drift between 2012.0 and 2021.0 and ended up by finding that assigning the start of the VLBI scale drift at epoch 2013.75 gives the best scale agreement between SLR and VLBI, namely a 0.15 ppb offset (equivalent to 1 mm at the equator) at epoch 2015.0 and zero drift. This is the first time of the ITRF history where the scale agreement between the two techniques reaches that level, compared with the ITRF2014 results (Altamimi et al. 2016) where the agreement was at the level of 1.39 ppb (about 8 mm at the equator).

Fig. 7 Time series of SLR geocenter components with respect to ITRF2020, in mm

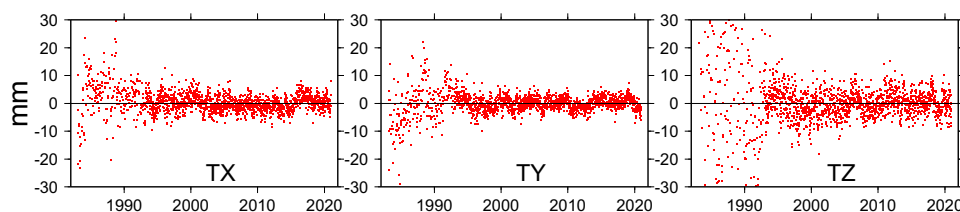


Fig. 8 Time series of DORIS geocenter components with respect to ITRF2020, in mm

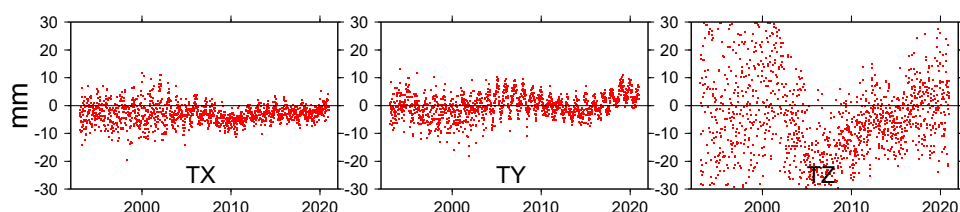


Fig. 9 SLR and VLBI scale time series with respect to ITRF2020 (left), adding DORIS and GNSS (right), in mm. Light blue and orange: all SLR and VLBI solutions, dark blue and red: selected solutions whose average defines the ITRF2020 scale, black: DORIS and green: GNSS

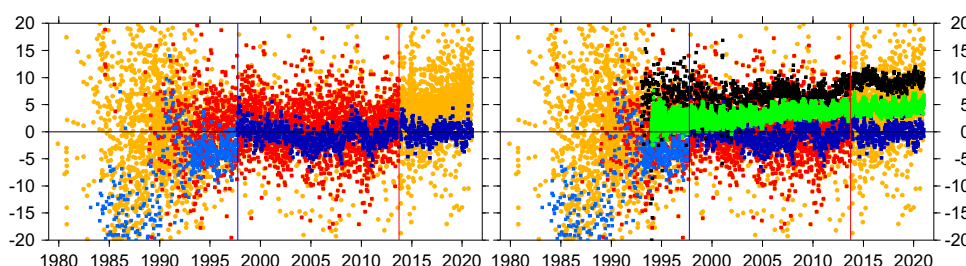


Table 5 Scale offsets and rates with respect to ITRF2020

Solution	Scale at 2015.0 ppb	Scale rate ppb/yr
IDS/DORIS	1.386	0.028
±	0.037	0.003
IGS/GNSS	0.682	0.018
±	0.018	0.001
ILRS/SLR	−0.075	0.000
±	0.038	0.004
IVS/VLBI	0.075	0.000
±	0.040	0.003

Note that using the full scale time series of SLR and VLBI would introduce a scale discrepancy between these two techniques of 0.3 ppb at epoch 2015.0 and a significant rate of 0.03 ppb/yr.

The right panel of Fig. 9 displays the scale time series of IGS/GNSS in green and IDS/DORIS in black, respectively, superimposed over the SLR and VLBI time series, where one can see their behaviors, offsets and rates with respect to ITRF2020. The estimated scale offsets at epoch 2015.0 and rates with respect to ITRF2020 of the four technique solutions are listed in Table 5. The DORIS and GNSS scale time series were not used in the ITRF2020 scale definition, given their significant offsets and rates (see the values listed in Table 5 and Fig. 9) compared with the high level agreement between SLR and VLBI.

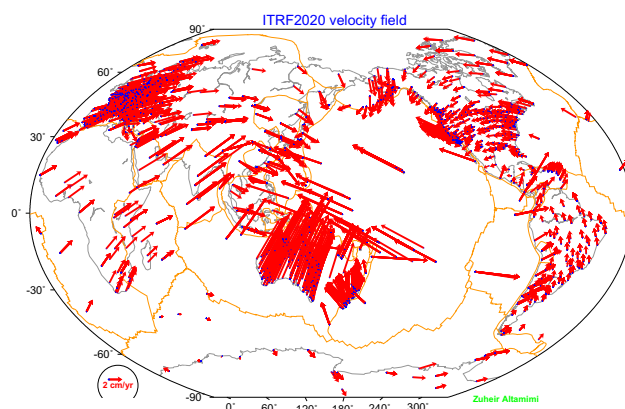


Fig. 10 ITRF2020 horizontal site velocities with formal error less than 1 mm/yr. Major plate boundaries are shown according to (Bird 2003)

5.7 ITRF2020 velocities

The ITRF2020 site velocities with formal errors less than 1 mm/yr are illustrated by Fig. 10 for the horizontal and by Fig. 11 for the vertical components, respectively. Compared with the ITRF2014 horizontal velocity field, ITRF2020 contains more sites in some large tectonic plates, such as North and South Americas, Australia, and to some extent Antarctica. The angular velocities of these plates are expected to be improved in the ITRF2020 Plate Motion Model which is under preparation at the time of writing this article, compared to the one published in (Altamimi et al. 2017).

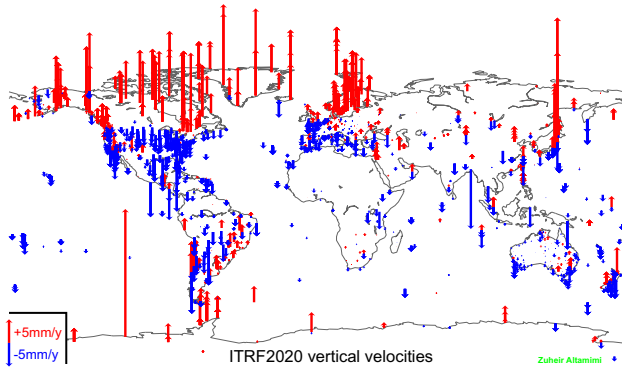


Fig. 11 ITRF2020 vertical site velocities with formal error less than 1 mm/yr

Inspecting Fig. 11, one can easily distinguish regional patterns in the ITRF2020 vertical velocities, especially in North America, Greenland, Fennoscandia and Antarctica, reflecting the uplift caused by not only Glacial Isostatic Adjustment, but also recent ice melting, in particular in Greenland (Métivier et al. 2020). Thanks to the density of ITRF2020 sites in North America, the vertical velocity pattern clearly shows the significant subsidence belt, right south of the Canadian uplift area, consistent with the results discussed in (Kreemer et al. 2018).

In order to assess the overall velocity agreement between techniques at colocation sites, Fig. 12 shows the histograms of the velocity differences between GNSS and the three other techniques, following the three components (East, North and Up). As a statistical estimator, we computed the standard deviation (SD) of the different distributions illustrated in Fig. 12. For the horizontal components, we found that the SD is about 0.7 mm/yr for VLBI and SLR and 1.2 mm/yr for DORIS, respectively. The SD values for the vertical components range between 1.3 mm/yr and 1.6 mm/yr for the three techniques (VLBI, SLR, DORIS), compared with GNSS.

5.8 ITRF2020 earth orientation parameters

The ITRF2020 global stacking of the four technique time series rigorously combines station positions, velocities and seasonal signals, together with EOPs: Polar Motion (PM) components and their daily rates (PM-rate), as well as Universal Time (UT1-UTC) and Length of Day (LOD). The EOPs are thus well integrated and rigorously referenced in the ITRF2020 frame. ITRF2020 PM components are the results of the combination of the four technique time series, PM-rate values are determined by combining GNSS and VLBI results, while UT1-UTC and LOD are determined using VLBI data uniquely, in order to avoid possible biased estimates from satellite techniques (Ray 1996, 2009). The full consistency between the ITRF2020 frame and EOPs is ensured via the three rotation parameters appearing in the first three lines

of Eq. 8 of Appendix A. In particular, PM coordinates play a significant “colocation” role in linking the four technique frames, via the rotation parameters around the X and Y axes.

The level of agreement between the four techniques in Polar Motion estimates is illustrated by the post-fit residuals in x and y components shown in Fig. 13, where one can see that the GNSS PM series dominates the other technique estimates. 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): (20, 20), (196, 204), (260, 251), (305, 294) in micro-arc-seconds, for GNSS, VLBI, SLR and DORIS, respectively. The reader should note that these WRMS values are computed over the full time series of the four techniques which makes SLR and VLBI values larger than what is observed during the last two decades.

5.9 Transformation parameters between ITRF2020 and ITRF2014

For a number of geodetic applications, the ITRF users need the transformation parameters between the new frame and past ITRF versions. For that purpose, the same 131 stations displayed in Fig. 5 that were used to ensure the alignment of the ITRF2020 orientation and orientation rate to the ITRF2014, were also used to estimate the transformation parameters between the two frames. The main criteria for the selection of these 131 stations are (1) to have the best possible site distribution; (2) to involve as many as possible VLBI, SLR, GNSS 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 1.6, 1.8 and 3.4 mm in position (at epoch 2015.0) and 0.2, 0.1, 0.3 mm/yr in velocity, in East, North and Vertical components, respectively. Table 6 lists the transformation parameters from ITRF2020 to ITRF2014, to be used with the transformation formula given by Eq. (6).

$$\begin{cases} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i14} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} + T + D \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} + R \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} \\ \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i14} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{i20} + \dot{T} + \dot{D} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} + \dot{R} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{i20} \end{cases} \quad (6)$$

where $i14$ designates ITRF2014 and $i20$ ITRF2020, T is the translation vector, $T = (T_x, T_y, T_z)^T$, D is the scale factor

Fig. 12 Histograms of the velocity differences between GNSS and the three other techniques at colocation sites: VLBI (top), SLR (middle), DORIS (bottom), following the three components (East, North, Up)

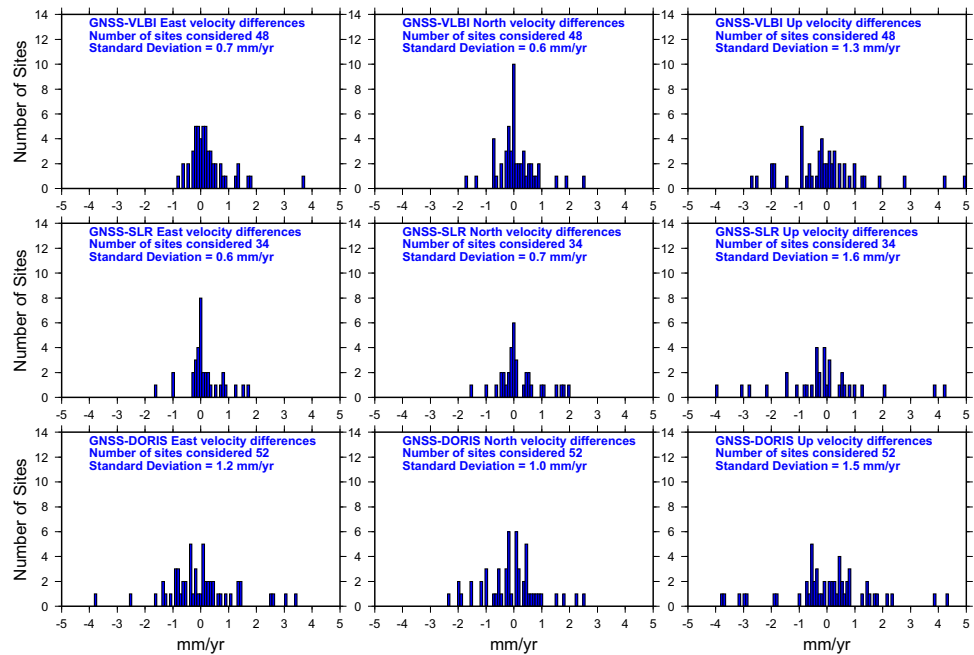
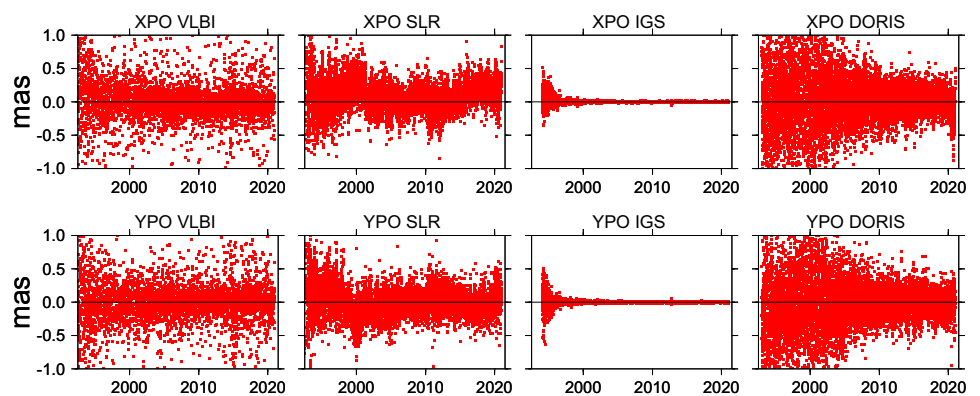


Fig. 13 ITRF2020 post-fit residuals of polar motion in milli-arc-seconds



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 ITRF2014 to ITRF2020 follows by interchanging (i20) with (i14) and changing the sign of the transformation parameters.

6 Conclusion

For the first time of the ITRF history, the ITRF2020 was generated by rigorously stacking the full time series of the four techniques all together, adding local ties and co-motion constraints at colocation sites. In addition to station posi-

tions and velocities and EOPs, refined parametric functions were also determined to accurately describe nonlinear station motions for both seasonal signals and post-seismic deformation, yielding an augmented ITRF2020 frame.

Using the concept of internal and minimum constraints, the ITRF2020 frame and seasonal signal parameters are comprehensively defined, thus preserving the ITRF2020 network shape which approximates the shape of the constantly deforming Earth's surface.

The ITRF2020 seasonal signals are provided in both the CM (as sensed by SLR) and the CF frames, together with a consistent new seasonal geocenter motion model, offering to the users several options to choose from, allowing to model seasonal deformations. We provided in Sect. 5.4 guidance to users to help choosing which options are the most suitable for their applications.

We verified that the ITRF2020 PSD parametric models determined using IGS/GNSS data fit also the station position time series of the three other techniques that are sharing the

Table 6 Transformation parameters at epoch 2015.0 and their rates from ITRF2020 to ITRF2014, to be used with Eq. (6)

	T_x <i>mm</i> $\dot{T}_x$ <i>mm/y</i>	T_y <i>mm</i> $\dot{T}_y$ <i>mm/y</i>	T_z <i>mm</i> $\dot{T}_z$ <i>mm/y</i>	D <i>ppb</i> $\dot{D}$ <i>ppb/y</i>	R_x <i>mas</i> $\dot{R}_x$ <i>mas/y</i>	R_y <i>mas</i> $\dot{R}_y$ <i>mas/y</i>	R_z <i>mas</i> $\dot{R}_z$ <i>mas/y</i>
$\pm$	−1.4 0.2	−0.9 0.2	1.4 0.2	−0.42 0.03	0.00 0.07	0.00 0.06	0.00 0.07
$\pm$	0.0 0.2	−0.1 0.2	0.2 0.2	0.00 0.03	0.00 0.07	0.00 0.06	0.00 0.07

same colocation sites. This is a key indicator of the high performance of the PSD parametric models in describing the trajectory of ITRF2020 sites impacted by major earthquakes.

By estimating the origin translational components between ITRF2020 and past ITRF solutions determined via station position time series, namely ITRF2005, ITRF2008 and ITRF2014, we conclude that the current accuracy and stability of the ITRF long-term origin achievable today using SLR data is at the level of or better than 5 mm in position and 0.5 mm/yr in time variation.

By filtering the scale time series of both SLR and VLBI solutions, and therefore using the best fit of the two series, we ended with a scale agreement at the level of 0.15 ppb (≈ 1 mm at the equator) at epoch 2015.0, with no significant rate, a key finding of the ITRF2020 analysis.

Compared to past ITRF solutions, ITRF2020 results show modest, but noticeable improvements in terms of agreement between terrestrial ties and space geodesy estimates at colocation sites. We still believe that most (if not all) of the tie discrepancies are caused by technique systematic errors rather than local ties. Improving the consistency between the two ensembles would not be possible without improving the geodetic infrastructure by investing in new generation of SLR and VLBI technologies, with a better distribution between the northern and southern hemispheres, but also by finding a mechanism to reduce, if not to eliminate, the IGS/GNSS station position discontinuities. Finally, as we stated in the ITRF2014 article (Altamimi et al. 2016): *VLBI in particular needs to evolve toward more frequent global observational session schedules, with increased number and well-distributed stations.*

Despite the high level results on reference frame determination presented in this paper, thanks to improved input data by the 4 techniques and the combination strategy, we are still far from the stringent science requirement of 1 mm accuracy and 0.1 mm/yr stability of the ITRF defining parameters. A factor of at least 5 will be needed to reach that goal.

As a final and important note, we repeat the last sentence of the ITRF2014 article (Altamimi et al. 2016), that is (with slight modification): *Improving the geodetic infrastructure is the prerequisite for the long-term sustainability and accuracy of the ITRF, as recognized by the United Nations General*

Assembly resolution (2015) on the global geodetic reference frame for sustainable development.

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Author contributions ZA conceptualized and designed the initial CATREF combination model used in the ITRF computation and wrote the full software code, with the help of XC for its updates. XC and PR greatly contributed to the CATREF equation improvements and updates. PR fitted the PSD parametric models using IGS/GNSS data, designed geocenter motion model estimation, and greatly contributed to the ITRF2020 analysis and validation of the results. LM developed the method to detect co-seismic discontinuities in station position time series and participated in the time series analysis. ZA operated the final ITRF2020 global combination and wrote the first draft of the paper. All authors contributed to regular discussions throughout the ITRF2020 project, read and commented on the final paper and provided contributions to the interpretation of the results.

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Data availability The input data used in the ITRF2020 computation are available at the NASA Crustal Dynamics Data Information System (CDDIS), <https://cddis.nasa.gov>, or through the Analysis Center Coordinators of the IAG Technique Services: <http://ids-doris.org>, <http://www.igs.org>, <http://ilrs.gsfc.nasa.gov>, <http://ivsc.gsfc.nasa.gov>. The local ties used in ITRF2020 are available at the ITRF2020 web site.

Code availability CATREF Software is available free of charge to research groups within institutions committed to sign an agreement with IGN for research, non-commercial activities.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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A Combination model

The main two equations of the combination model implemented in CATREF Software are given below. They involve a 14-parameter similarity transformation, station positions and velocities, periodic signals and EOPs and are written as:

$$\begin{cases} X_s^i = X_c^i + (t_s^i - t_0) \dot{X}_c^i \\ \quad + T_k + D_k X_c^i + R_k X_c^i \\ \quad + (t_s^i - t_k) [\dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i] \\ \quad + \sum_{j=1}^{n_f} a_j^i \cos[\omega_j (t_s^i - t_0)] + b_j^i \sin[\omega_j (t_s^i - t_0)] \end{cases} \quad (7)$$

$$\begin{cases} \dot{X}_s^i = \dot{X}_c^i + \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i \\ \begin{cases} x_s^p = x_c^p + R2_k \\ y_s^p = y_c^p + R1_k \\ UT_s = UT_c - \frac{1}{f} R3_k \end{cases} \\ \begin{cases} \dot{x}_s^p = \dot{x}_c^p \\ \dot{y}_s^p = \dot{y}_c^p \\ LOD_s = LOD_c \end{cases} \end{cases} \quad (8)$$

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 7 transformation parameters. In addition to station positions and velocities, Eq. 7 involves also the periodic terms modeled as a sine wave function, adding the total sum of the contributions of all the frequencies considered, n_f is the number of frequencies, $\omega_j = \frac{2\pi}{\tau_j}$, where τ_j is the period of the j th frequency, e.g., annual, semi-annual, etc.

In addition to the six station position and velocity parameters, each frequency adds six parameters per station, i.e., $(a_x^i, a_y^i, a_z^i, b_x^i, b_y^i, b_z^i)^T$.

EOPs are added by Eq. 8, 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 , where $f = 1.002737909350795$ is the conversion factor from UT into sidereal time. The link between the combined frame and the EOPs is ensured via the three rotation parameters appearing in the first three lines of Eq. 8.

Note that Eq. 7 uses the linearized form of the general similarity transformation formula, neglecting second and higher order terms (Petit and Luzum 2010, Ch. 4), (Altamimi and Dermanis 2012).

The first line of Eq. 7 and the entire Eq. 8 are used to estimate long-term solutions, by accumulating (rigorously stacking) time series of station positions and EOPs. They are also the ones used, together with local ties and co-motion constraints, in the global ITRF2020 combinations. The entire two equations are used to combine long-term solutions, e.g., in the step 3 described in Sect. 4.

B Concept of internal constraints revisited

We have introduced the concept of internal constraints at the occasion of the ITRF2005 (Altamimi et al. 2007) where we started to use as input data time series of station positions and EOPs. The fundamental property of the internal constraints is to preserve the intrinsic long-term frame physical parameters such as the origin and scale of SLR, and the scale of VLBI when stacking their corresponding time series, individually. We have extended the concept of internal constraints for the purpose of the ITRF2020 global combination, where the time series of several techniques are stacked all together, in order to ensure that the average of the selected SLR and VLBI scale time series is strictly zero. Denoting P_i the time series of a transformation parameter P (such as the scale) of technique i , and n the number of techniques involved, the generalized internal constraints condition can be written as:

$$\sum_{i=1}^n (A_i^T A_i)^{-1} A_i^T P_i = 0 \quad (9)$$

where $P_i = [P_{i,1}, \dots, P_{i,n_i}]^T$, n_i is the dimension of the time series of the parameter P of technique i , and A_i takes the form:

$$A_i = \begin{bmatrix} 1 & (t_{i,1} - t_0) \\ \vdots & \vdots \\ 1 & (t_{i,n_i} - t_0) \end{bmatrix}$$

C Periodic signals

The inclusion of the transformation parameters in the combination model offers a number of options for the reference frame definition, but also for the periodic signals, such as minimum or internal constraint approaches similar to those developed in (Altamimi et al. 2007).

C.1 Periodic signals: minimum constraints

In the stacking case, the equations of the minimum constraints approach take the form

$$(A^T A)^{-1} A^T \begin{pmatrix} \delta a_x^i \\ \delta a_y^i \\ \delta a_z^i \end{pmatrix} = (A^T A)^{-1} A^T \begin{pmatrix} a_{xR}^i - a_x^i \\ a_{yR}^i - a_y^i \\ a_{zR}^i - a_z^i \end{pmatrix} = 0 \quad (10)$$

$$(A^T A)^{-1} A^T \begin{pmatrix} \delta b_x^i \\ \delta b_y^i \\ \delta b_z^i \end{pmatrix} = (A^T A)^{-1} A^T \begin{pmatrix} b_{xR}^i - b_x^i \\ b_{yR}^i - b_y^i \\ b_{zR}^i - b_z^i \end{pmatrix} = 0 \quad (11)$$

where A is the well known design matrix of partial derivatives of the 7 transformation parameters, and $(a_{xR}^i, a_{yR}^i, a_{zR}^i, b_{xR}^i, b_{yR}^i, b_{zR}^i)^T$ are the reference values for each frequency i that could be taken from an external loading model, or as zeros over a set of well distributed stations.

C.2 Periodic signals: internal constraints

In the stacking case, one possibility is to constrain to zero, internally, the periodic signals embedded in the time series of a given transformation parameter $[P(t_1), \dots, P(t_K)]$. In such a case the internal constraint equation takes the form:

$$(B^T B)^{-1} B^T [P(t_1), \dots, P(t_K)]^T = 0 \quad (12)$$

where K is the number of the individual daily or weekly solutions, and B is the matrix of partial derivatives given by:

$$B = \begin{pmatrix} \cos(\omega_i t_1) & \sin(\omega_i t_1) \\ \vdots & \vdots \\ \cos(\omega_i t_K) & \sin(\omega_i t_K) \end{pmatrix} \quad (13)$$

D Equations of post-seismic deformation models

After an earthquake, the position of a station during the post-seismic trajectory at an epoch t is described by an additional term $\delta X_{PSD}(t)$ in Eq. 3.

ITRF2020 provides the PSD parameters in the local frame (Easting, Northing, Up) at epoch t . We remind that displacements in the local frame can be converted to displacements in the global frame with the following equation:

$$\begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} = R \cdot \begin{bmatrix} \delta E \\ \delta N \\ \delta U \end{bmatrix} \quad (14)$$

where R is the transformation (Jacobian) matrix from topocentric to geocentric frame.

For each component $L \in \{E, N, U\}$, the total PSD displacement in the local frame can be computed by:

$$\delta L(t) = \sum_{i=1}^{n^l} A_i^l \log \left(1 + \frac{t - t_i^l}{\tau_i^l} \right) + \sum_{i=1}^{n^e} A_i^e \left(1 - e^{-\frac{t - t_i^e}{\tau_i^e}} \right) \quad (15)$$

where:

n^l : Number of logarithmic terms of the parametric model

n^e : Number of exponential terms of the parametric model

A_i^l : Amplitude of the i th logarithmic term

A_i^e : Amplitude of the i th exponential term

τ_i^l : Relaxation time of the i th logarithmic term

τ_i^e : Relaxation time of the i th exponential term

t_i^l : earthquake time(date) corresponding to i th logarithmic term

t_i^e : earthquake time(date) corresponding to the i th exponential term

The variance of $\delta L(t)$ is given by:

$$\text{var}(\delta L) = C \cdot \text{var}(\theta) \cdot C^T \quad (16)$$

where θ is the vector of parameters of the post-seismic deformation model:

$$\theta = [A_1^l, \tau_1^l, \dots, A_{n^l}^l, \tau_{n^l}^l, A_1^e, \tau_1^e, \dots, A_{n^e}^e, \tau_{n^e}^e]$$

Note that the values of $\text{var}(\theta)$ of the parametric models are provided to the users in SINEX files available at the ITRF2020 web site.

The elements of the matrix $C = \frac{\partial \delta L}{\partial \theta}$ are computed by the following formulas:

$$\frac{\partial \delta L}{\partial A_i^l} = \log \left(1 + \frac{t - t_i^l}{\tau_i^l} \right) \quad (17)$$

$$\frac{\partial \delta L}{\partial \tau_i^l} = - \frac{A_i^l (t - t_i^l)}{(\tau_i^l)^2 \left(1 + \frac{t - t_i^l}{\tau_i^l} \right)} \quad (18)$$

$$\frac{\partial \delta L}{\partial A_i^e} = 1 - e^{-\frac{(t - t_i^e)}{\tau_i^e}} \quad (19)$$

$$\frac{\partial \delta L}{\partial \tau_i^e} = - \frac{A_i^e (t - t_i^e) e^{-\frac{(t - t_i^e)}{\tau_i^e}}}{(\tau_i^e)^2} \quad (20)$$

Note that the PSD models are determined and provided to the users per component $L \in \{E, N, U\}$, independently, and so there are NO cross-terms (or correlations) between components. However, cross-terms between amplitude and relaxation time for each LOG or/and EXP term should be taken into account in the variance calculation of Eq. (16). As an example, if for a given station there are 3 earthquakes that were taken into account in the estimation of the PSD models of its component E , and it has one EXP for the first EQ, one EXP for the 2nd EQ and LOG+EXP for the 3rd EQ, the one line matrix C for component E in Eq. (16) will have 8 terms.

Once the variances $\text{var}(\delta E)$, $\text{var}(\delta N)$, $\text{var}(\delta U)$ are computed, the transformation into cartesian coordinates is obtained by:

$$\text{var} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} = R \cdot \begin{bmatrix} \text{var}(\delta E) & 0 & 0 \\ 0 & \text{var}(\delta N) & 0 \\ 0 & 0 & \text{var}(\delta U) \end{bmatrix} \cdot R^T \quad (21)$$

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Appendix 3 IDS contribution

The DORIS contribution to ITRF2020

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Hugues Capdeville (CLS)
Frank Lemoine (GSFC)
Michiel Otten (ESA)

DORIS data span

The DORIS data used for the IDS contribution to ITRF2020 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 (August 1992), and because a second satellite (SPOT-2) was necessary to strengthen the quality of the geodetic solutions. Data from three generations of DORIS instrument were processed. 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 SPOT2, SPOT3 and SPOT4 DORIS receivers also could only track one beacon at a time; The second-generation DORIS receivers on JASON-1, SPOT5 and Envisat, could track two beacons; The Jason-2/3, Cryosat-2, HY-2A, Saral and Sentinel-3A/B third-generation (DGXX) DORIS receiver can track up to seven beacons (*Auriol and Tourain, 2010*).

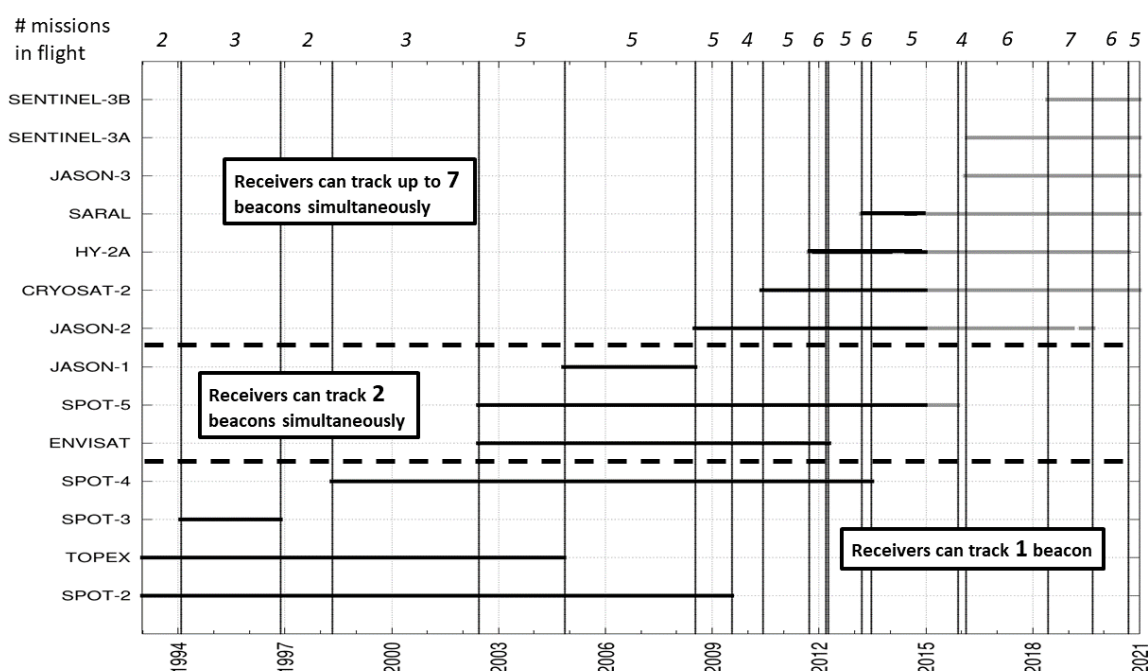


Figure 1 - Time evolution of the DORIS constellation for ITRF2020 (black = ITRF2014 constellation – gray + black = ITRF2020 constellation). Vertical lines correspond to starting and ending dates of the DORIS missions. Dashed lines divide DORIS receiver generations. From Moreaux et al., 2022.

The IDS recommended that Jason-1 be added in order to ensure that data from satellites at two different inclinations were incorporated into the solutions from November 2004 to July 2008, i.e. between the end of the TOPEX/Poseidon and through the start of the Jason-2 mission. The addition of data from the alternate inclination (66°) compared to the near-polar orbits of the other DORIS satellites improved the ground station observation geometry. The Jason-1 ultra-stable oscillator (USO) has been shown to exhibit high sensitivity to passage through the South Atlantic Anomaly (SAA). Thus, the analysis centers were required to use Jason-1 SAA-

corrected data obtained from the model of *Lemoine and Capdeville (2006)*. In addition, as for ITRF2014, due to the sensitivity of the SPOT-5 USO to the SAA demonstrated by *Štěpánek et al. (2014)*, the IDS asked all the AC's to use the SPOT-5 SAA-corrected data from the model of *Capdeville et al. (2016)* starting on 2005/12/27 (2005:261 – SPOT-5 cycle 138). Once *Willis et al. (2016)* revealed a possible sensitivity of the Jason-2 USO to the SAA, the IDS initiated several studies which confirmed that Jason-2 was also impacted by the SAA. Then, due to the lack of a Jason-2 data correction model at the start of the ITRF2020 reprocessing, the IDS suggested to locally solve (reduce) for the SAA stations using the Jason-2 normal equations or solutions so that the SAA-perturbed stations in the Jason-2 normal equations would not impact the multi-satellite solutions. The same strategy was also recommended for the Sentinel-3A/B missions after *Jalabert and Mercier (2018)* and *Štěpánek et al. (2020)* showed the sensitivity of these missions to the SAA.

AC contributions

Four IDS ACs contributed to the ITRF2020 DORIS combination. Among the standards for the analysis of the DORIS data and the satellite orbit dynamics model, all AC's used time-variable gravity models and applied DORIS ground beacon phase center variation corrections. For ITRF2020, the IDS AC's made a special effort was made to improve the non-conservative force modelling for the Jason-1, Jason-2 & Jason-3 satellites by using both spacecraft body and solar array quaternions to model the satellites' orientation for the force model & the measurement model in the different orbit determination software. In addition, "Cr" (solar radiation reflectivity coefficient) was adjusted per arc to further mitigate solar-radiation-pressure (SRP) induced errors. Compared to ITRF2014, the AC's updated the background ocean tide models (for dynamical modeling and ocean loading corrections) from FES2004, FES2012, GOT4.8 to EOT11a, FES2014 & GOT4.10c. For ITRF2020, all the AC's adopted the GRACE-FO RL06 AOD1B ocean-atmosphere dealiasing model to account for the short period atmosphere and ocean mass variations (*Dobslaw et al., 2017*). In addition, compared to ITRF2014, all the IDS ACs adopted more recent GRACE+GOCE-derived static and time-variable gravity models. As with ITRF2014, the IDS AC's employed a range of elevation cutoff angles for DORIS data (7-12°). For ITRF2020, all the IDS AC's employed a function to down-weight the DORIS data vs. elevation, since this was demonstrated to stabilize the derived scale. We also note that, compared to the ITRF2014 processing, a new Alcatel phase center variation model was used for the contribution to the ITRF2020. All SINEX deliveries were compliant with IERS call for participation to ITRF2020.

AC	AC solutions	Software	Sol. Id.	Type	Data span	EOPs
European Space Operations Center	ESA	NAPEOS	wd12/13	NEQ	1993.0-2021.0	Motion+rate+LOD
Geodetic Observatory Pecny	GOP	BERNESE	wd67	var-cov	1993.0-2021.0	Motion+rate
CNES/CLS	GRG	GINS/DYNAMO	wd43	var-cov	1993.0-2021.0	Motion
NASA Goddard Space Flight Center	GSC	GEODYN	wd51	NEQ	1993.0-2021.0	Motion

Table 1 - IDS Analysis Center submission summary using Normal Equations (NEQ) or variance–covariance output (COV).

SINEX Preprocessing analysis

The software used for the IDS combination was the IGN/LAREG CATREF package (*Altamimi et al., 2002*). As a validation step and before the weekly combination, each SINEX series was pre-processed with the following steps being applied:

- (1) Verification of DORIS station identification (dome number, station acronym),
- (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 intrinsic cumulative position and velocity solution from 1993.0 to 2021.0.
- (8) Analysis and rejection of high residual stations.

Loosely constrained network solutions were projected over their proper space using minimal constraints. Some partial or complete rejections of stations from the SINEX were made by using the results from the SSALTO DORIS ground processing segment or from other 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

Several iterations were necessary to provide the best IDS combination of the AC solutions. The combination process started with the individual series of solution files as output from the preprocessing step, i.e. with minimum constrained solutions. To strengthen the quality of the combined weekly solutions, we only computed solutions for weeks where we had contributions from at least two ACs. In addition, each week, we only estimated positions of stations which had been estimated by at least two ACs.

Analysis of differences of EOPs of the individual series with respect to the IERS C04 series (*Bizouard and Gambis, 2009*) showed that ESA series gave both larger differences and standard deviations compared to the performance of the three other IDS contributors. Therefore, the ESA contribution was not included in the estimation of the combined pole. Table 3 of *Moreaux et al. (2022)* summarizes the contribution of each AC to the IDS 16 combined solution. For more information on the combination strategy, please refer to *Moreaux et al. (2022)*.



The final IDS 16 combination included solutions for 201 DORIS stations on 87 different sites with 48 sites located in the northern hemisphere and 39 in the southern hemisphere (see Figure 2). For reference, the IDS network for ITRF2008 included 160 stations located at 71 sites. The sixteen new sites include both old sites with less than 2.5 years of observations which were rejected at the early stage of the IDS processing for the ITRF2014 (Ajaccio, Flores, Huanine, Iquique, Le Lamentin, Lifou, Ottawa, Owenga, Paramushir, Santa-Maria, Tana) and totally new sites, i.e. installed since 2015: Managua, Mangilao, Ny-Ålesund II, San Juan and Wettzell.

TRF parameters

The intrinsic TRF parameters of IDS 16 series are compared in Figure 3 to ITRF2014 for an external validation. From that figure we can observe that TX and TY remain most of the time within 20 mm while TZ presents higher variations (between -50 to +50 mm). We also see that the standard deviation of all the IDS 16 X- and Y-translations is lower than the IDS 09 (IDS contribution to the ITRF2014) ones thanks to the reduction of the amplitude of the annual and 118-day (draconitic period for the Jason satellites) signals by a factor of two. These reductions are the consequence of a better modelling of the non-conservative forces on the Jason satellites. The Z-translations of both IDS 09 and IDS 16 show similar performance and look highly correlated with the Sunspot number. Nevertheless, we observe a slight degradation of the IDS 16 TZ standard deviation after adding Jason-3 (early 2016) due to higher variations of that parameter for that mission.

Analysis of the IDS 16 scale with respect to the ITRF2014 showed a slope from 1993.0 to mid-2002. That pattern is explained in *Moreaux et al. (2022)* by the use of different Alcatel PCVs between ITRF2014 and the IDS ITRF2020 processing as well as by the gradual replacement over time of the Alcatel by Starec ground antennas. Compared to the IDS 09 scale parameter, the IDS 16 one does not show any more an increase in late 2011 thanks to the use of the correction of the Center-Of-Mass Center-Of-Phase vector for that mission and to more stable scales for the Cryosat-2 and Jason-2 single satellite solutions. Then, if we restrict scale values from mid-2002 to 2021.0, the scale slope of IDS 16 with respect to the ITRF2014 is about 0.062 mm/yr.

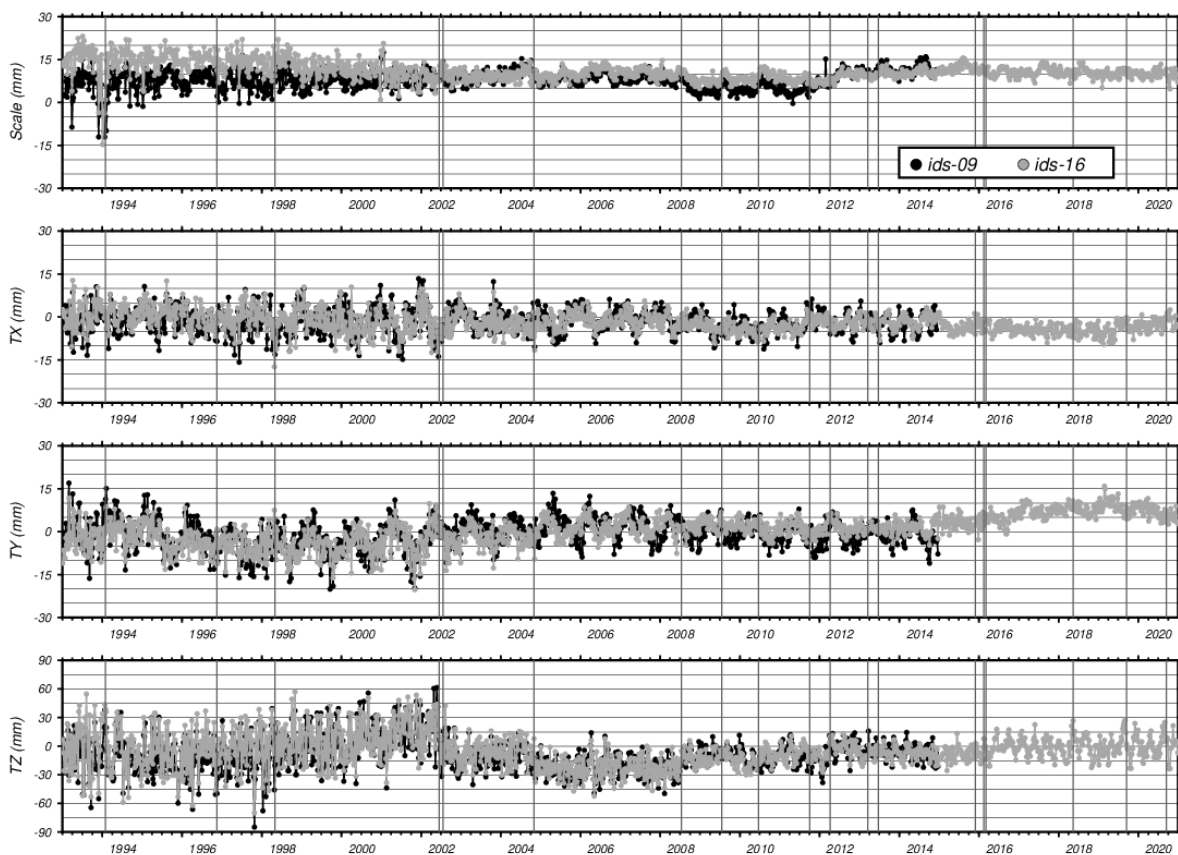


Figure 3 – IDS 09 (ITRF2014) and IDS 03 (ITRF2008) translation and scale parameters with respect to ITRF2008. Vertical lines correspond to DORIS satellite constellation changes and top numbers to satellites number. From Moreaux et al., 2022.

Residuals

From Figure 4, the North component is always the best determined, while the East is the worst one and whereas the Vertical is intermediate. This can be fully explained by the conjunction of two features of the DORIS technique: i) the Doppler technique provides observations that lack information in the direction perpendicular to the satellite track and, ii) except for TOPEX/Poseidon, Jason-1 and Jason-2, all the DORIS satellites have a near-polar orbit. In addition, we can see that the WRMS time series can be divided in three time periods: before mid-2002 (including of the first satellite with onboard the second generation of DORIS receiver), between mid-2002 and mid-2008 (including of the first satellite with onboard the third generation of DORIS receiver) and after mid-2008. This time decomposition emphasizes the impact of having more and more stations simultaneously received onboard allowing more observations by station. We can also notice that having since late 2015 a full constellation with onboard the third generation of DORIS receivers has only a very slight (but still) positive impact on the performance. In overall, the WRMS of the East/North/Up position residuals are below 6-7 mm since mid-2008.

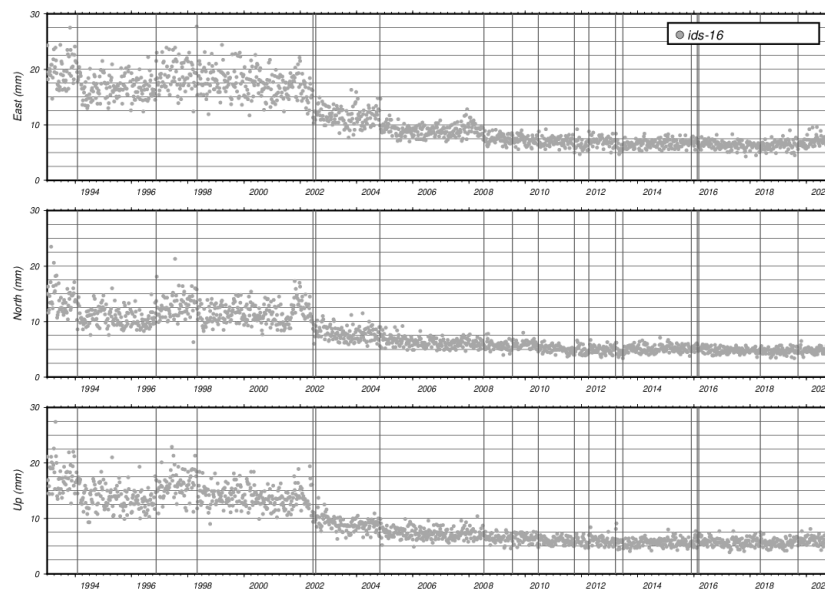


Figure 4 - IDS 16 weekly solutions WRMS of the station residuals wrt IDS 16 cumulative position and velocity solution. Vertical lines correspond to DORIS satellite constellation changes. From Moreaux et al., 2022.

Polar Motion

Figure 5 displays the difference of the IDS X and Y pole components with the IERS C04 pole series. As with the station positions residuals, the precision of the EOP significantly improves when the DORIS constellation has more than three satellites, i.e. after April 2002. Moreover, we also observe benefits of the satellite missions that include DGXX receivers, beginning with Jason-2 (July 2008) with a clear reduction of the standard deviations. From that figure, we also observe similar performance in the two pole components thanks to the relatively homogeneous distribution of the DORIS tracking network. Comparisons of IDS 16 and IDS 09 polar motion solutions show a substantial improvement of IDS 09 differences wrt the IERS C04 series even if the new series was obtained with fewer contributors.

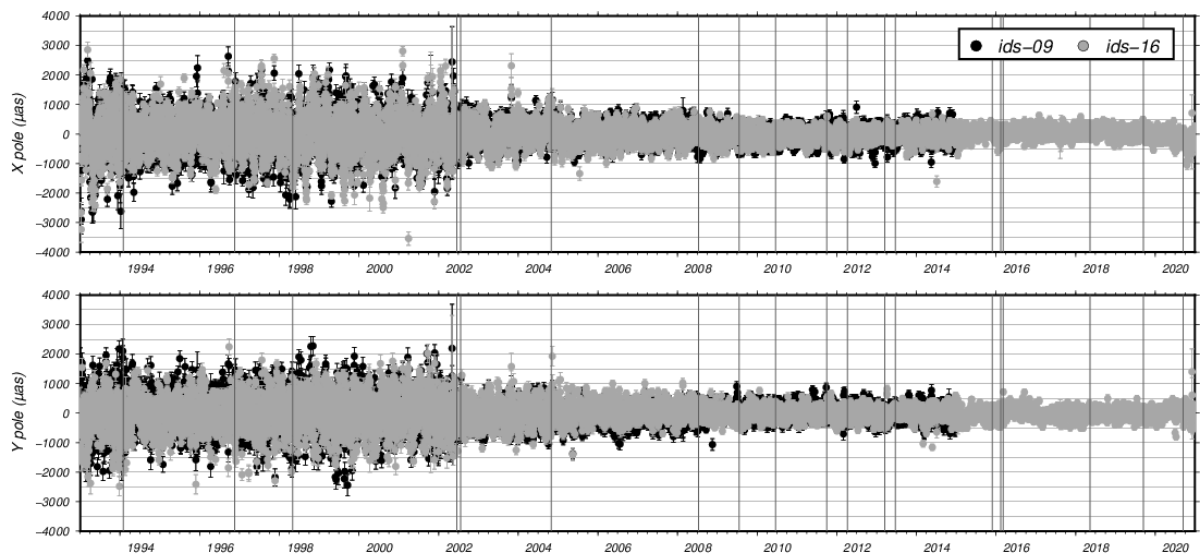


Figure 5 - IDS 16 (gray – IDS contribution to ITRF2020) and IDS 09 (black – IDS contribution to ITRF2014) polar motion compared to IERS C04 series. Vertical lines correspond to DORIS satellite constellation changes. From Moreaux et al., 2022.

For more information on the IDS-16 please contact

Guilhem Moreaux (CLS) at the IDS Combination Center (Email: Guilhem.Moreaux@cls.fr) and refer to Moreaux et al. 2022.

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Appendix 4 IGS contribution

IGS contribution to ITRF2020

Paul Rebischung, IGS Reference Frame Working Group Coordinator

The IGS contribution to ITRF2020 consists of the daily combined terrestrial frame (SINEX) solutions from the third IGS reprocessing campaign (repro3). Those were obtained by combining the contributions from 10 Analysis Centers (ACs) listed in the table below.

AC	Institution	GNSS	From	Till
COD	Center for Orbit Determination in Europe	GPS	1994-01-02	2020-12-31
		GLONASS	2002-01-01	2020-12-31
		GALILEO	2013-01-01	2020-12-31
ESA	European Space Operations Center	GPS	1995-01-01	2020-12-31
		GLONASS	2009-01-01	2020-12-31
		GALILEO	2015-01-01	2020-12-31
GFZ	GeoForschungsZentrum	GPS	1994-01-02	2020-12-31
		GLONASS	2012-01-01	2020-12-31
		GALILEO	2013-12-21	2020-12-31
GRG	Groupe de Recherche en Géodésie Spatiale	GPS	2000-05-03	2020-12-31
		GLONASS	2008-11-04	2020-12-31
		GALILEO	2016-12-31	2020-12-31
JPL	Jet Propulsion Laboratory	GPS	1994-01-02	2020-12-26
MIT	Massachusetts Institute of Technology	GPS	2000-01-02	2020-12-31
		GALILEO	2017-01-01	2020-12-31
NGS	National Geodetic Survey	GPS	1994-01-02	2020-12-31
TUG	Graz University of Technology	GPS	1994-01-02	2020-12-31
		GLONASS	2009-01-01	2020-12-31
		GALILEO	2013-01-01	2020-12-31
ULR	Université de la Rochelle	GPS	2003-01-01	2020-12-31
WHU	Wuhan University	GPS	2008-01-01	2019-12-31
		GLONASS	2010-09-28	2019-12-31

Available products

The IGS repro3 combined SINEX products follow the new [IGS long file name convention](#). They are prefixed "IGS1R03SNX". The available products are listed in the table below, where \${yyyy} stands for the 4-character year and \${doy} for the 3-character day of year (first day of the week in case of weekly files). Note that the opportunity of repro3 was taken to change the style of the SINEX combination residual and summary files and to make them additionally available in YAML format.

File name	Content
IGS1R03SNX_\${yyyy}\${doy}0000_01D_01D_SOL.SNX	Daily combined SINEX solution
IGS1R03SNX_\${yyyy}\${doy}0000_01D_01D_CRD.SNX	id., without covariance matrices
IGS1R03SNX_\${yyyy}\${doy}0000_01D_01D_RES.RES	Daily combination residuals
IGS1R03SNX_\${yyyy}\${doy}0000_01D_01D_RES.YML	id., in YAML format
IGS1R03SNX_\${yyyy}\${doy}0000_07D_07D_SOL.SNX	Weekly combined SINEX solution
IGS1R03SNX_\${yyyy}\${doy}0000_07D_07D_CRD.SNX	id., without covariance matrices
IGS1R03SNX_\${yyyy}\${doy}0000_07D_01D_ERP.ERP	Weekly ERP file
IGS1R03SNX_\${yyyy}\${doy}0000_07D_07D_SUM.SUM	Weekly combination summary
IGS1R03SNX_\${yyyy}\${doy}0000_07D_07D_SUM.YML	id., in YAML format

At present, those products are publicly available at the following URLs, where $\{\text{www}\}$ stands for the 4-character GPS week number:

- [https://cddis.nasa.gov/archive/gnss/products/\\${www}/repro3](https://cddis.nasa.gov/archive/gnss/products/${www}/repro3)
- [ftp://igs.ign.fr/pub/igs/products/\\${www}/repro3](ftp://igs.ign.fr/pub/igs/products/${www}/repro3)
- [ftp://igs-rf.ign.fr/pub/repro3/\\${www}](ftp://igs-rf.ign.fr/pub/repro3/${www})

Main modeling updates since repro2

Compared to the previous IGS reprocessing campaign and to current IGS operational products, a number of new models and conventions have been adopted in repro3. The main updates are detailed below together with their (expected) impact on terrestrial frame solutions.

Secular pole The new IERS secular pole model was adopted in repro3. It replaces the previous mean pole model of the original IERS 2010 Conventions, which was used in repro2 and is still used in the IGS operational products. The repro3 terrestrial frame solutions thus show a degree-2, order-1 deformation pattern with respect to repro2/operational solutions, but also ITRF2014/IGS14, whose amplitude is relatively small until ~2010, but then increases linearly. It reaches ~3 mm in vertical and ~1 mm in horizontal in 2020.

Satellite z-PCOs Compared to igs14.atx, the radial phase center offsets (z-PCOs) of all GPS and GLONASS satellites have been updated in the ANTEX file used in repro3, igsR3.atx. While the GPS and GLONASS satellite z-PCOs in igs14.atx had been estimated based on the ITRF2014 terrestrial scale, they were corrected in igsR3.atx to become consistent with the Galileo satellite z-PCOs measured and published by the European GNSS Agency. Details about these corrections can be found in the [2019 technical reports of the IGS Antenna and Reference Frame working groups](#) and in the header of [igsR3.atx](#). As a consequence, the terrestrial scale of the IGS repro3 solutions is independent of ITRF2014, and is instead based on the Galileo satellite antenna calibrations. It shows an offset of ~1.2 ppb at epoch 2010.0 and a drift of ~0.03 ppb/yr with respect to the ITRF2014 scale.

Ground antenna calibrations In order to enable the processing of Galileo data in repro3, the L1/L2-only calibrations of several ground antenna types in igs14.atx were replaced by new multi-GNSS calibrations in igsR3.atx (see details in the [2019 technical report of the IGS Antenna working group](#) and in the header of [igsR3.atx](#)). As usual, such ground antenna calibration updates induce antenna type- and station-dependent position offsets of a few mm in horizontal / up to ~1 cm in vertical. Those offsets were estimated for all affected stations that are part of the IGS14 reference frame (see below). The results can be found at: ftp://igs-rf.ign.fr/pub/IGSR3/igs14_to_igsR3_2077.txt

IGSR3 reference frame Because of the updates mentioned above, the repro3 solutions could not have been aligned to the IGS14 reference frame without systematic errors. A particular reference frame called IGSR3, consistent with the new IERS secular pole model, the igsR3.atx satellite PCOs and the igsR3.atx ground antenna calibrations, was thus used in repro3. It is available at:

- ftp://igs-rf.ign.fr/pub/IGSR3/IGSR3_2077.snx
- ftp://igs-rf.ign.fr/pub/IGSR3/IGSR3_2077.ssc (without covariance matrix)

Details about its computation can be found in the comment section of the SINEX file. Note that the daily and weekly repro3 solutions are aligned in orientation and origin to IGSR3, but not in scale. Their scale is a weighted average of those of the contributing AC solutions, and is thus based on the igsR3.atx satellite z-PCOs.

PCO/PCV rotations for antennas not oriented North Although certain ground GNSS antennas are not oriented North, the IGS practice until repro3 had been to ignore these mis-orientations and use the phase center corrections from the IGS ANTEX files as if all antennas were oriented North. In

repro3 however, the phase center corrections from igsR3.atx have been rotated when necessary to match the actual antenna orientations reported in the site logs. These PCO/PCV rotations have impacts of up to a few cm in horizontal / a few mm in vertical on the estimated positions of the affected stations. Antenna orientations, extracted from the site logs, are reported in an extra column in the SITE/ANTENNA blocks of the repro3 SINEX files.

Inclusion of GLONASS and Galileo While only two ACs had processed GLONASS data in repro2, a majority of ACs have processed GLONASS and also Galileo data in repro3. This may have a positive impact, which remains to be quantified, on the background noise in the repro3 station position time series. On the other hand, this leads to additional spurious signals at periods around 8 and 10 days.

Others

- ACs have used "modern" ocean tidal loading models in repro3 (FES2014 or equivalent). This can be expected to reduce spurious aliased tidal signals in the repro3 station position time series to some extent.
- ACs have refined their solar radiation pressure models since repro2. This may be expected to reduce draconitic signals in the repro3 station position time series to some extent.
- The sub-daily EOP tide model from [Desai & Sibois \(2016\)](#) was adopted in repro3 in replacement of the current IERS model. This has been shown to have practically no impact on station position estimates, but should reduce spurious aliased tidal signals in the repro3 polar motion [rate] time series to some extent ([Sibois, 2019](#)).
- Contrary to repro2, all ACs have used time-variable gravity field models in repro3. The expected impact on terrestrial frame solutions is sub-millimetric ([Amiri et al., 2016](#)).

Combination strategy

The daily combinations of the AC repro3 SINEX solutions follow essentially the same strategy as the one used in repro2 and described in [Rebischung et al. \(2016\)](#). Some minor changes are detailed below.

Terrestrial scale In the repro2 daily combinations, no scale factors were estimated between the AC solutions and the combined solutions. In repro3, the estimation of such scale factors was restored to study possible subtle differences between the terrestrial scales realized by the different AC solutions. The terrestrial scale is in practice handled in a similar way as geocenter coordinates during the repro3 daily combinations. Scale factors with respect to the IGSR3 reference frame are first made explicit in the unconstrained AC normal equations, by a similar re-parameterization as for geocenter coordinates. The preprocessed AC normal equations are then inverted using no-net-rotation, translation or scale (NNR+NNT+NNS) constraints with respect to IGSR3 (instead of NNR+NNT only in repro2). The AC scale factors are then combined together with station positions, ERPs and geocenter coordinates, and scale residuals are in particular provided in the combination residual files. The combined solution is at this step obtained using NNR+NNT+NNS constraints with respect to IGSR3 and includes combined geocenter coordinates as well as a combined scale factor with respect to IGSR3. In a last post-processing step, the combined normal equation is re-inverted with NNR+NNT constraints only while fixing the combined scale factor to 0. By doing so, the combined scale information (based on the igsR3.atx satellite z-PCOs) is brought back into station coordinates.

Station metadata errors Like in repro2, care has been taken to exclude from the repro3 combinations AC station position estimates for which incorrect metadata were reported in the AC SINEX files. The policy adopted in repro3 was to confront metadata in the AC SINEX files with site logs collected from different sources and systematically reject stations with either:

- an incorrect antenna type,

- an eccentricity error larger than 1 mm in either East, North or Up,
- an antenna orientation error larger than 10°.

This lead in particular to reject all stations with antenna mis-orientations larger than 10° from the solutions of COD, NGS and WHU, as these ACs did not apply PCO/PCV rotations and reported 0 or no mis-orientations in their SINEX files. All detected metadata errors are reported in Section 6 of the combination summary files, while rejected stations are listed in Section 4.

AC weighting and outliers The weighting of AC solutions in the combinations was refined compared to repro2. The same unbiased variance component estimator is used, but it is now iteratively applied until all AC variance factors have converged to better than 10^{-3} in a relative sense. (This explains why the global variance factors reported in the daily combined SINEX files are very close to 1.) The criterion for rejecting outliers from the AC solutions was also changed compared to repro2. Now, any AC station position estimate with a *normalized* residual larger than 5 in either East, North or Up is considered as an outlier. The overall iterative repro3 combination procedure can be described as follows:

- Assign a priori AC variance factors in the same way as in repro2.
- Perform an initial combination and re-weight AC solutions using unbiased variance component estimates. No outliers are rejected yet.
- Iteratively combine AC solutions. After each iteration, reject outliers and re-weight AC solutions again.
- Iterate until no outlier remains and AC variance factors have converged.

Weekly combined solutions The weekly combined repro3 solutions are obtained by iteratively stacking the 7 daily combined solutions of the week. The daily solutions are given a uniform a priori variance factor of 1, and a single common corrective variance factor is estimated. After each iteration, station position estimates with normalized residuals larger than 5 are removed from the corresponding daily solutions. Iterations are performed until no such outlier remains.

Appendix 5 ILRS contribution

The ILRS contribution to ITRF2020

E. Pavlis (GESTAR II/UMBC & NASA Goddard 61A)

V. Luceri (e-GEOS S.p.A., ASI/CGS)

The ILRS contribution to ITRF2020 consists of a pair of time series of weekly and bi-weekly station position estimates along with daily and 3-day averaged Earth Orientation Parameters (X-pole, Y-pole and excess Length-Of-Day (LOD)) estimated over 7-day arcs (1993.0 – 2021.0) and 15-day arcs for the period 1983.0-1993.0) aligned to the calendar weeks (Sunday to Saturday), starting from January 1983. Each solution is obtained through the combination of loosely constrained weekly/biweekly solutions submitted by each of the seven official ILRS Analysis Centers. Both, the individual and combined solutions have followed strict standards agreed upon within the ILRS Analysis Standing Committee (ASC) to provide ITRS products of the highest possible quality.

Individual solutions

The individual solutions are computed by the official ILRS ACs (ASI, BKG, DGFI, ESA, GFZ, JCET and NSGF) using the SLR data acquired from the global tracking network that observed the satellites LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2. From 1983 to 1992 the dataset is made up of LAGEOS data only (historical data). This dataset is complemented with the LAGEOS-2 and ETALON satellites starting from 1993. The main difference in the data amount is due to the LAGEOS-2 data; the amount of the Etalon data is roughly one tenth the data of the two LAGEOS, and have practically a negligible impact on the results.

AC code	Analysis Center	SW	Time span
ASI	Agenzia Spaziale Italiana	Geodyn/SOLVE	1983.0-2021.0
BKG	Bundesamt für Kartographie und Geodäsie	Bernese	1993.0 -2021.0
DGFI	Deutsches Geodätisches Forschungs Institut	DOGS	1983.0-2021.0
ESA	European Space Operation Center	Napeos	1983.0-2021.0
GFZ	GeoForschungsZentrum Potsdam	EPOSOC	1983.0-2021.0
JCET	Joint Center for Earth Systems Technology – NASA Goddard & UMBC	Geodyn/SOLVE	1983.0-2021.0
NSGF	NERC Space Geodesy Facility	SATAN	1983.0-2021.0

The SLR observations are retrieved from ILRS' CDDIS and/or EDC data center archives and analyzed to generate the individual EOP and station position solutions. The measurements are processed in intervals of 7 days (15 days in 1983-1992) to generate a loosely-constrained solution for station coordinates and EOP. The EOPs (χ_p, y_p and LOD) are all computed as daily averages since 1993 and as 3-day averages when only LAGEOS data are available. 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.

The ITRF2020 ILRS contribution was developed following an innovative approach to handling systematic errors in the network, that was never before utilized. Based on a several years pilot project of the ILRS ASC, documented in Luceri et al., (2019, <https://doi.org/10.1007/s00190-019-01319-w>): the **Station Systematic Error Monitoring** PP (SSEM) delivered a series of estimates of long-term mean biases for each station, along with the time intervals of applicability and their statistics. These were derived from freely adjusted station position and EOP solutions for the period

1993.0 to 2020.5. The use of the latest satellite CoG model and the simultaneous estimation of the station heights and measurement biases resulted in a self-consistent set of weekly bias estimates for each site. These were subsequently analyzed for breaks and “jumps” which when identified, triggered the calculation of the mean of these estimates in each period, along with its standard deviation. Once the mean bias was pre-applied in the re-analysis, the remaining jitter due to the variability of the bias was mostly white noise and had no visible effect on the results. This approach strengthened the estimation process while it did not compromise the accuracy of the final results. All results of the SSEM PP were entered in a special edition of the Data Handling File (release 2021/01/27) which was distributed privately and only to the AC teams supporting the development of the ITRF2020. This was done to avoid confusing general users of the DH file with a very tailored version that necessitates the *a priori* application of the SSEM model and the use of a specific CoG model.

An additional benefit of the new approach is the fact that these estimated long-term mean biases can be examined by the system engineers and in some cases, they may identify the root cause and perhaps a correction process. In that case, in a future re-analysis these can be removed from the model as long as the “corrected SLR data” are used. On the other hand, upon adopting this approach with the SSEM model products we now face the problem of maintaining and keeping current this model. This will require the development of a new product that will extend the estimation of the mean biases beyond the end of the SSEM period of applicability and up until this approach is revised or changed. The ILRS ASC is thus implementing such a process to seamlessly extend the SSEM up to present and then maintain the estimation process into the future. The new “product” will be the SSEM-X model that will be used for present day analyses and also as a means to examining the quality of the delivered data from all stations.

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 and adherence to IERS Standards and Conventions:

- The computational models follow the prevalent IERS Conventions 2010 as closely as possible (with documentation of any exceptions).
- Mean Pole: Based on the UAW2017 IERS decision, the new Secular Pole was used via a fixed polynomial and associated adopted rates.
- The Desai-Sibois (2019) High Frequency EOP model was used, following its adoption by the IERS DB into the interim IERS Conventions.
- As requested by the ITRS, the non-tidal atmospheric loading effects on station positions were not modeled.
- The stations are included in the weekly analysis if the total number of observed LAGEOS plus LAGEOS 2 ranges is greater than 10. Data weighting is applied according to the analyst's preference. However, the ASC has agreed to down-weight “non-core” sites significantly.
- The target signature model (CoG, formerly known as the “center-of-mass correction”) for each satellite is applied following the site- and time-specific tables provided by José Rodríguez/NERC (Rodríguez, J. et al., (2019), <https://doi.org/10.1007/s00190-019-01315-0>) that take into account the various laser station technologies and the mode of operation recorded in their site-logs over the years (release 2021-05-11).
- Range corrections were modeled or estimated for a number of sites based either on engineering reports from these sites or the SSEM results. All of the applied corrections are documented in a special release of the ILRS Data Handling file that will be made available at CDDIS and EDC, along with the official set of SINEX files delivered to ITRS.

- 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.
- Following the UAW2017 discussions on information to be included in the ILRS SINEX files for ITRF2020, three **new** SINEX Blocks were designed and implemented by each AC and CC:

1. The “MODEL/RANGE_BIAS” Block:

```
+MODEL/RANGE_BIAS
*CODE PT SOLN T START_DATE__ END_DATE_____ M __E-VALUE___ STD_DEV _E-RATE___ UNIT CMNTS
1874 51 501 A 14:019:00000 20:138:00000 R -17.8 0.8 mm
1879 51 501 A 13:188:00000 18:322:00000 R 17.9 1.3 mm
1887 51 501 A 11:303:00000 15:256:00000 R 21.5 1.8 mm
1887 51 501 A 16:101:00000 18:343:00000 R -21.6 1.5 mm
1890 51 501 A 12:001:00000 21:001:00000 R 12.9 1.1 mm
1893 51 501 A 05:212:00000 21:001:00000 R -33.4 1.6 mm
7080 51 501 A 96:133:00000 01:140:00000 R -8.4 0.5 mm
-MODEL/RANGE_BIAS
```

2. The “MODEL/TIME_BIAS” Block:

```
+MODEL/TIME_BIAS
*CODE PT SOLN T START_DATE__ END_DATE_____ M __E-VALUE___ STD_DEV _E-RATE___ UNIT CMNTS
7090 -- ---- A 09:344:31560 09:345:70200 T 0.90920 ms
7105 -- ---- A 12:296:55000 12:297:02400 T 7.0470 ms
7110 -- ---- A 10:173:00000 10:208:27000 T 0.00640 ms
7110 -- ---- A 11:115:00000 11:316:00000 T 0.00780 ms
7110 -- ---- A 13:164:00000 13:173:00000 T 0.89990 ms
7124 -- ---- A 19:295:00000 19:324:00000 T -1.00 ms
7237 -- ---- A 17:038:04000 17:038:60600 U +1.0000 ms ETO
7237 -- ---- A 17:037:43200 17:037:86400 U +1.0000 ms ETO
7501 -- ---- A 00:183:00000 04:279:86399 T -0.00605 ms
-MODEL/TIME_BIAS
```

```
+MODEL/TIME_BIAS
*CODE PT SOLN T START_DATE__ END_DATE_____ M __E-VALUE___ STD_DEV _E-RATE___ UNIT
1824 -- 501 A 10:126:00000 10:127:00000 T -17.750 1.000 0.0000 us
1824 -- 501 A 10:132:00000 10:133:00000 T -5.750 1.000 0.0000 us
1824 -- 501 A 12:084:68460 12:085:00000 T -24.400 5.000 0.0000 us
1873 -- 501 A 09:059:00000 09:110:00000 T -21.750 50.000 -0.2600 us
1873 -- 501 A 09:111:00000 09:160:00000 T -3.300 50.000 -0.1000 us
1873 -- 501 A 09:324:00000 10:095:00000 T 2.000 50.000 0.0750 us
-MODEL/TIME_BIAS
```

3. The “MODEL/TARGET_SIGNATURE_GEOMETRY” Block:

```
+MODEL/TARGET_SIGNATURE_GEOMETRY
*CODE PT SOLN T START_DATE__ END_DATE_____ M __E-VALUE___ STD_DEV _____ UNIT CMNTS
1873 51 501 L 08:288:00000 08:295:00000 C 0.1234 0.002 m 2020-06-08
1879 52 501 L 08:288:00000 08:295:00000 C 0.1234 0.002 m 2020-06-08
7810 53 501 L 08:288:00000 08:295:00000 C 0.9373 0.005 m 2020-06-08
7810 60 501 L 08:288:00000 08:295:00000 C 0.0163 0.002 m 2020-06-08
-MODEL/TARGET_SIGNATURE_GEOMETRY
```

Additional details on the individual AC analysis strategy can be found on the ILRS web page <https://ilrs.gsfc.nasa.gov/science/analysisCenters/index.html>.

ILRSA Combined time series

The official ILRS combined solution is produced by the Primary Combination Center, ASI/CGS, and labeled ILRSA; a backup combined solution (ILRSB) is computed at JCET/UMBC, the backup CC.

The ILRSA solution has been obtained by a direct combination of the loosely constrained solutions, taking advantage of the fact that loosely constrained solutions, although they possess an ill-defined datum, they still preserve the relative geometry of the station polyhedron figure.

$$R_1^T(\sigma_1 \Sigma_1)^{-1} R_1 = \dots = R_i^T(\sigma_i \Sigma_i)^{-1} R_i \dots = R_N^T(\sigma_N \Sigma_N)^{-1} R_N \quad \text{and}$$

$$\chi^2 = R_1^T \Sigma_1^{-1} R_1 + \dots + R_N^T \Sigma_N^{-1} R_N = 1$$
[illegible]

A rigorous editing (Brockmann, 1996) has been introduced to eliminate outliers with respect to the combined solution following a 5σ criterion for:

1. sites with less than 10 observations, erroneously present in the contributing solutions,
2. sites with too large uncertainties ($> 1\text{m}$) and
3. sites with large coordinate residuals with respect to the *a priori* SLRF2014 ($>0.5\text{m}$).

The internal precision of the ILRSA solution is checked through the computation of the weighted root mean square (WRMS) over the time series of the coordinate residuals of each input solution with respect to the combination. The coordinate residuals are computed after a rototranslation of each loose AC solution with respect to the combined solution using a set of core sites. The list of core sites has been officially defined, within the Analysis Standing Committee, considering the quality and stability of the entire set of network sites over several decades (Fig. 1).

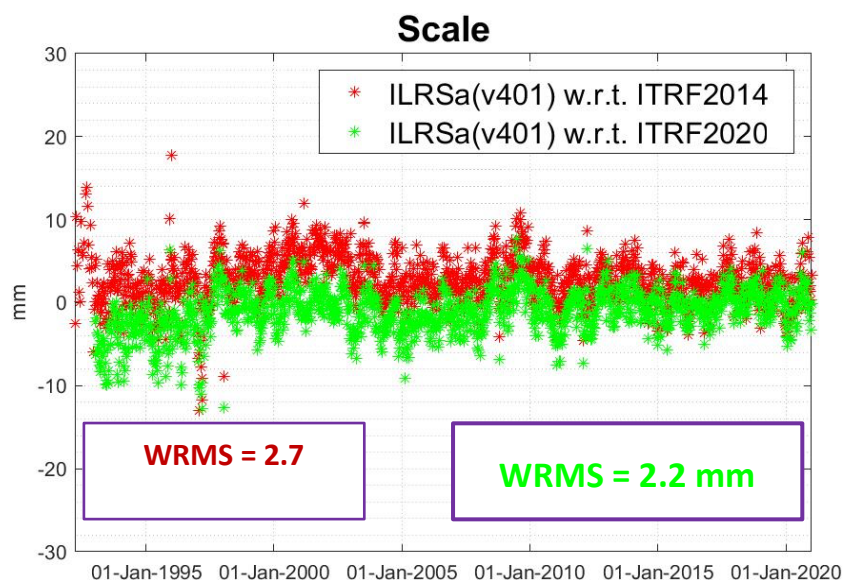
The ILRSA solution has been compared to ITRF2014 in terms of the 3D WRMS of the site coordinates residuals. The 3D WRMS computed using the full network is not so representative since it involves a lot of new sites and sites with lower than average performance. The subset of “core sites” which are well-defined is by far a more representative figure of merit.

3D WRMS of the ILRSA coordinate residuals with respect to ITRF2014 & ITRF2020

Units in millimeters (mm)	1993-2020
ITRF2014 Core sites (average)	5.48 ± 1.80
ITRF2020 Core sites (average)	3.66 ± 1.58

In addition to the official ILRSA combination series from the re-analysis products, the back-up Combination Center at JCET/UMBC delivered a back-up series designated ILRSB. The ILRSB series are developed in a slightly different formalism, using the de-constrained normal equations derived from the individual AC solutions and relative weighting of the input AC series determined through Variance Component Estimation.

As a result of the improved reanalysis and the new approach in handling systematic errors, the SLR scale with respect to the new ITRF2020 is by more than a full 1 ppb closer to the ITRF2020 overall scale than in previous TRFs.



Scale	Wmean (mm)	σ - WMean (mm)	Slope (mm/yr)	σ - Slope (mm/yr)
vs ITRF2014	2,654	0,069	-0,028	0,009
vs ITRF2020	-0,743	0,063	0,084	0,008

ILRS Contributed time series

The ILRS official contribution to ITRF2020 is publicly available at the ILRS Data Centers. It is a combined effort of several entities and individuals, we therefore ask that when you make use of it or any portion of it, please acknowledge their work by referencing this document and the DOI associated with these products:

doi: 10.5067/SLR/slr_itrf20200_repro2020_001

The ILRS REPRO2020 combined SINEX products follow the standard ILRS filename convention. Details and other information can be found on the associated CDDIS reference page:

https://cddis.nasa.gov/Data_and_Derived_Products/SLR/slr_itrf20200_repro2020_001.html

Data access at CDDIS is through:

The SLR products Contributed to ITRF2020 Station Positions and Earth Orientation Parameters Time Series (REPRO2020):

https://cddis.nasa.gov/archive/slr/products/REPRO_SERIES/REPRO2020/

organized in subdirectories for each weekly/biweekly case, using the date of the last day of solution period (Saturday) as follows:

yymmdd/ilrsa.pos+eop. yymmdd.v40x.snx.gz

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Appendix 6 IVS contribution

The IVS contribution to ITRF2020

The IVS contribution to ITRF2020 is provided by the *IVS Combination Centre* located at the *Federal Agency for Cartography and Geodesy* (BKG, Germany) and the *Deutsches Geodätisches Forschungsinstitut* at TUM (DGFI-TUM, Germany). It is achieved by an intra-technique combination of the individual contributions of 11 different Analysis Centres (ACs). Thereby sessions containing 24h VLBI observations from 1979 until the end of 2020 were re-processed and submitted. As a result, datum-free normal equations – including station coordinates, source positions and full sets of *Earth Orientation Parameters* (EOP) – are delivered. Table 1 shows the participating ACs and the utilized software packages.

Table 1: Software packages used by the different IVS ACs.

AC	Name	Software
ASI	Italian Space Agency	CALC/SOLVE
BKG	Federal Agency for Cartography and Geodesy	CALC/SOLVE
DGFI-TUM	Deutsches Geodätisches Forschungsinstitut	DOGS-RI
GFZ	German Research Centre for Geosciences	PORT
GSFC	Goddard Space Flight Center	CALC/SOLVE
IAA	Institute of Applied Astronomy	QUASAR
NMA	Norwegian Mapping Authority	Where
OPA	Observatoire de Paris	CALC/SOLVE
OSO	Onsala Space Observatory, Sweden	ivg::ascot
USNO	United States Naval Observatory	CALC/SOLVE
VIE	Vienna University of Technology	VieVS

The variety of applied software tools is thereby increased since ITRF2014. Via the required SINEX format, a number of almost 6,600 sessions have been contributed from the different ACs. Due to formal or numerical errors within the data, almost 350 sessions had to be excluded from the contribution to ITRF, however 94.5% could be successfully combined. In addition, sessions based on observations of the VLBI Global Observing System (VGOS) became available in the most recent years and are part of the ITRF for the first time. Figure 1 shows the global distribution of the IVS station network and the corresponding VLBI sites.

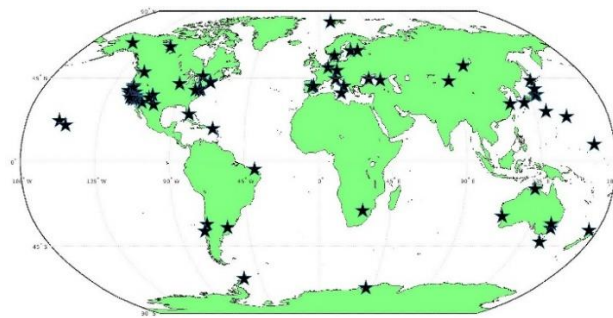


Figure 1: Global distribution of VLBI station network

New models for ITRF2020

New and improved models for IVS analysis have been applied which cause the necessity of a regular update of the ITRF. Thereby in comparison to ITRF2014, the contribution includes the following new models:

Galactic Aberration

The secular aberration drift is caused mainly by the rotation of the Solar System barycentre around the Galactic centre. The predicted secular aberration amplitude amounts to 4-6 $\mu\text{as}/\text{year}$, which impact cannot be neglected in the long-time span and produces the dipole systematic error of 100 μas after 20 years. Therefore, the IVS Working group recommends the applied constant drift of 5.8 $\mu\text{as}/\text{year}$ on Galactic aberration. The secular drift affects the source positions with the reference point of the source catalogue or J2000 by default.

Pole tide model

Changes in the direction of the Earth's rotation axis w.r.t. the Earth's surface cause local deformations resulting in station coordinate variations of up to a few centimetres (Desai, 2002). The corresponding site displacement models for *pole tides* and *ocean pole tides* contain a conventional representation of the low-frequency motion of the Earth's rotation axis w.r.t. the terrestrial reference system. At the Unified Analysis Workshop in 2017 (UAW 2017), it was decided to change the function for the *Conventional Mean Pole* (CMP) to a purely linear one. This *secular pole* is derived by a fit utilizing polar motion observations from 1900 through 2017 (Ries, 2017).

Gravitational Deformation

The effect of the gravitational antenna deformation impacts the reference geometry of the VLBI antenna. The elevation dependent structural deformation affects the signal propagation path. Besides, the antenna deformation effect depends on the system type of the dish and increases with the size. As follows, the elevation depended corrections are available for a few largest antennas only: EFLSBERG, GILCREEK, MEDICINA, NOTO, ONSALA60 and YEBES40M.

High-frequency EOP model

The high-frequency variations of the Earth rotation axis are described mainly by the gravitational lunar-solar interactions based on the equilibrium theory. The high-frequency Earth Rotation Parameter (ERP) variations are observed in the terrestrial reference frame as diurnal and semidiurnal tides. In contrast, the long-term variations are referred to as nutation with respect to the IERS Convention definition. The coefficients of the diurnal and semidiurnal tidal variations in polar motion and dUT1 derived in the paper by Desai & Sibois (2016) represent the recommended high-frequency EOP model. The distributed set of coefficients contains 159 tidal terms. The appropriate libration terms are provided by the IVS Coordinator, John Gipson, as well.

Combination strategy

The combination on the level of normal equations leads to more stable equation systems in comparison to the individual solutions. In addition, the correct correlations between the different parameters are considered. For ensuring a reliable data basis several quality checks concerning the required SINEX format, numerical stability and the quality of the estimated parameters are carried out. This includes the completeness of the parameters and models (full

set of EOPs, existence of all station IDs, applied precession and nutation models), as well as an outlier detection for rejecting contributions with low quality.

The remaining normal equations are subject to the session-wise IVS combination procedure which is sketched in Figure 2. A transformation to equal epochs and equal a priori values achieves consistency between the individual contributions. Thereby the reference epoch is the middle of the 24h observation interval and the a priori TRF is defined by the latest IVS Quarterly solution (2020/Q2) as an update of the ITRF2014. For the outlier test individual solutions are computed by applying No-Net-Rotation (NNR) and No-Net-Translation (NNT) conditions on core stations for datum definition. The positions of the radio sources are fixed to the ICRF3 and become eliminated from the equation system. For the remaining contributions a variance-component estimation (VCE) computes AC-specific weightings, so that the combined normal equation consists of the accumulated, weighted individual NEQs. Thereby, station coordinates and EOPs are stacked. The IVS contribution to the ITRF combination consists of two series: one series based on the mid-epoch of each VLBI session and one series with all parameters transformed to noon epochs (UTC). For assessing the quality of the combination, the combined EOPs and station coordinates are estimated by applying adequate datum constraints (NNR/NNT).

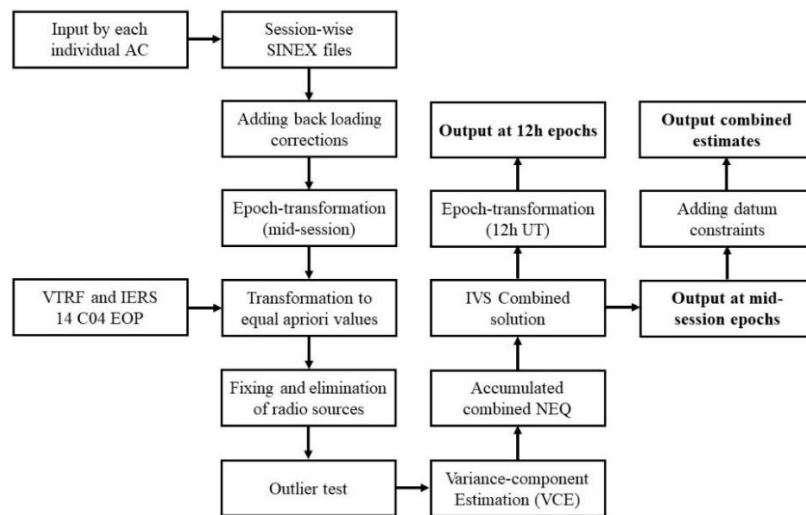


Figure 2: Combination procedure for the session-wise IVS combination.

IVS combination results

The final combination estimates are evaluated session-wise concerning station coordinates and to assess the combined product's quality. Comparisons of the combined and the individual AC solutions w.r.t. the external IERS Bulletin A timeseries are carried out, leading to Mean and Weighted-Root-Mean-Square (WRMS) values. In addition, the accuracy of the station coordinates are derived by an evaluation w.r.t. the current IVS quarterly solution.

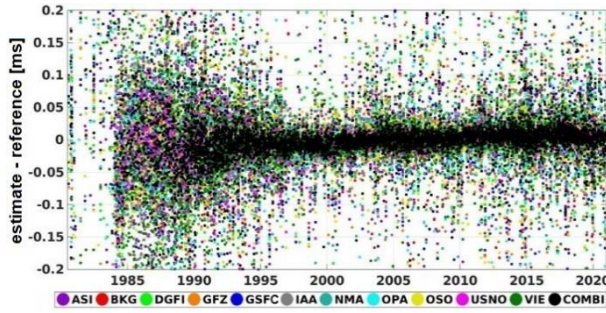


Figure 3: Difference of dUT1 w.r.t. IERS Bulletin A

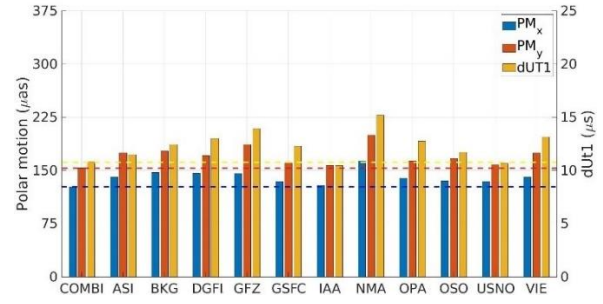


Figure 4: WRMS of EOP estimates w.r.t. Bulletin A

Figure 3 shows the “estimate minus reference” comparison of the estimated dUT1 timeseries. Based on a space-fixed reference VLBI is the only technique which observes the time depending parameter dUT1 directly, while satellite-based techniques rely on integrating the time derivative LOD. Therefore, dUT1 is characterized by VLBI for the most part consequently ideal for assessing the technique. It is evident, that a reliable estimation of dUT1 could be reached since the middle of the 1980s. While the fluctuation within the first 10 years has an amount of up to ± 0.2 ms the accuracy could be increased to ± 0.05 ms since the middle of the 1990s. It is also clear, that the combination (black dots) is characterized by fewer fluctuations than the individual AC solutions. Figure 4 shows the corresponding WRMS deviations of all ACs and the combination. Because $10 \mu\text{s}$ of dUT1 corresponds to the same angular displacement as $150 \mu\text{as}$ of Polar Motion, the axes are scaled in such a way that the angles of dUT1 and PM are commensurate. The vertical dashed lines, which represents the level of the combination are below the WRMS levels of the individual solutions, so that an accuracy enhancement through the combination is confirmed. Furthermore, the external agreement for the Polar Motion is slightly better than for dUT1.

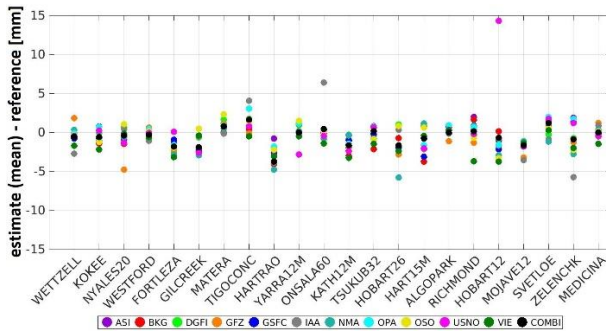


Figure 5: Accuracy of the station height components

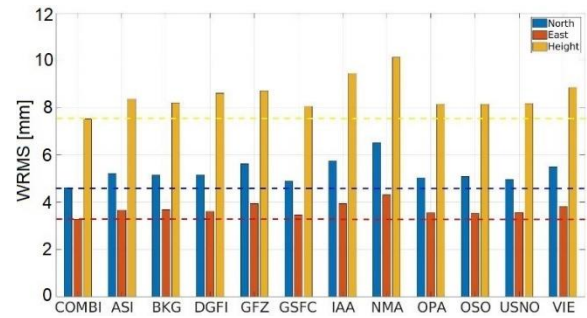


Figure 6: WRMS of the station components of Wettzell

Figure 5 shows the “estimated minus reference” comparison for the 22 best performing stations within the combination process. These are characterized by few outliers and corresponding time series with low noise levels. The reference TRF for the shown height component is given by the current IVS quarterly solution (2020/Q2) and the mean values are calculated using the station coordinate estimates from 1979 until 2020. The combined solution (black dot) for every station is well within the range spanned by the individual solutions. Due to the variance component estimation and the applied weighting factors, the combination mathematically describes a weighted mean of the AC contributions. A benefit from the diversity of software packages becomes clear. For getting more detailed information about the station coordinate repeatability, the WRMS deviations in all three components for Wettzell are shown in Figure 6. Similar to the observation of Figure 4, all individual AC solutions show higher WRMS values than the combination level. Consequently, the benefit of the combined product compared to the individual solutions is confirmed for all three components.

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