

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

IERS Technical Note No. 40

Description and evaluation of DTRF2014, JTRF2014 and ITRF2014

Zuheir Altamimi and Wolfgang R. Dick (eds.)

**Verlag des Bundesamts für Kartographie und Geodäsie
Frankfurt am Main 2020**

Description and evaluation of DTRF2014, JTRF2014 and ITRF2014

Zuheir Altamimi and Wolfgang R. Dick (eds.)

(IERS Technical Note ; No. 40)

Technical support: Sonja Geist, Sandra-Schneider-Leck

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

ISSN: 1019-4568 (print version)
ISBN: 978-3-86482-137-0 (print version)

An online version of this document is available at:
<http://www.iers.org/TN40>

Druckerei: Bonifatius GmbH, Paderborn

© Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, 2020

Table of Contents

Foreword	4
<i>Zuheir Altamimi</i>	
DTRF2014: DGFI-TUM realization of the International Terrestrial Reference System (ITRS)	5
<i>Mathis Bloßfeld, Manuela Seitz, Detlef Angermann, and Florian Seitz</i>	
JTRF2014: Analysis, Results and Comparisons to ITRF2014 and DTRF2014	17
<i>Claudio Abbondanza, Toshio Michael Chin, Richard S. Gross, Michael B. Heflin, Jay W. Parker, Benedikt S. Soja, Tonie M. van Dam, and Xiaoping Wu</i>	
ITRS Center evaluation of DTRF2014 and JTRF2014 with respect to ITRF2014	71
<i>Zuheir Altamimi, Paul Rebischung, Xavier Collilieux, and Laurent Métivier</i>	
Comparison of latest ITRS realizations: ITRF2014, JTRF2014 and DTRF2014	79
<i>Detlef Angermann, Mathis Bloßfeld, Manuela Seitz, and Sergei Rudenko</i>	
A comparison of the DTRF2014, ITRF2014, and JTRF2014 solutions using DORIS	95
<i>Guilhem Moreaux, Hugues Capdeville, Claudio Abbondanza, Mathis Bloßfeld, Jean-Michel Lemoine, and Pascale Ferrage</i>	
Assessment of DTRF2014 and ITRF2014 by Satellite Laser Ranging	135
<i>José Rodríguez</i>	
ITRS realizations and their impact on VLBI combined EOP and Scale	151
<i>Sabine Bachmann and Daniela Thaller</i>	
Index of authors	167

Foreword

Following the IERS Terms of Reference (<https://www.iers.org/ToR>), the ITRS Center is responsible for the maintenance of the ITRS/ITRF, to provide the ITRS Combination Centers with specifications, and to evaluate their respective results.

The purpose of this IERS Technical Note is to, primarily, acknowledge the activities of the ITRS Combination Centers at DGFI and JPL, beside the ITRS Combination Center at IGN which is part of the ITRS Center. It includes the description of both DTRF2014 and JTRF2014, as well as their inter-comparisons with respect to the official IERS solution, the ITRF2014.

The Technical Note was also intended to include evaluations of the three solutions by the IERS Technique Centers (IDS, IGS, ILRS and IVS) who constantly provide input solutions to the ITRF. In addition to DGFI, JPL and ITRS Center contributions, the Technical Note includes contributions from IDS, ILRS and IVS.

The ITRS Center is therefore thankful to the ITRS Combination Centers at DGFI and JPL for the generation of their solutions: DTRF2014 and JTRF2014, as well as to the IAG Technique Services (IDS, ILRS, IGS and IVS) and their Analysis and Combination Centers for their contribution by providing reprocessed solutions to the ITRF2014.

The IERS ITRS Center is particularly grateful to all the institutions that provide the necessary investment for the space geodetic observatories which constitute the main ITRF foundation.

The great efforts by the IERS Central Bureau at BKG in providing the technical assistance for the edition and publication of the IERS Technical Notes are to be acknowledged. In particular, the ITRS Center is grateful to Wolfgang R. Dick, Sonja Geist and Sandra Schneider-Leck, who created the LaTeX template and provided technical support.

*Zuheir Altamimi,
Head, IERS ITRS Center*

DTRF2014: DGFI-TUM realization of the International Terrestrial Reference System (ITRS)

Mathis Bloßfeld¹, Manuela Seitz¹, Detlef Angermann¹, and Florian Seitz¹

¹ *Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Munich, Germany*

Abstract. This article gives a brief overview over the DTRF2014, the DGFI-TUM realization of the International Terrestrial Reference System (ITRS). The solution is based on input data provided by the Services of the International Association of Geodesy (IAG), namely the International GNSS Service (IGS), the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS), and the International DORIS Service (IDS). The paper presents the combination strategy applied at DGFI-TUM and discusses some results such as the impact of non-tidal loading corrections (reduction of the annual signal in the origin as well as the scale time series) and transformation parameters of the DTRF2014 solution on the single-technique solutions.

Introduction

The DTRF2014 is a realization of the International Terrestrial Reference System (ITRS) computed by DGFI-TUM (Seitz et al., 2016). It is computed on the basis of the same input data as the realizations ITRF2014 (IGN, Paris; Altamimi et al., 2016) and JTRF2014 (JPL, USA; Abbondanza et al., 2017). These ITRS realizations are based on the combination of the observation data of four space geodetic techniques: VLBI, SLR, GNSS, and DORIS. Observations are included from the respective start of the techniques until the end of 2014. The three ITRS realizations differ conceptually. While DTRF2014 and ITRF2014 are based on station positions at a reference epoch and velocities, the JTRF2014 is based on time series of station positions. DTRF2014 and ITRF2014 result from different combination strategies: the ITRF2014 is based on the combination of solutions, the DTRF2014 is computed by the combination of normal equations.

The DTRF2014 contains station positions and velocities as well as consistently estimated Earth orientation parameters (EOPs). Additionally, for the first time, non-tidal atmospheric and hydrological loading is considered. This new realization includes six more years of data as the previous realization, the DTRF2008 (Seitz et al., 2012), and new observing stations as well as improved models are considered. The DTRF2014 comprises 3D coordinates and velocities of 1347 GNSS, 113 VLBI, 99 SLR and 153 DORIS stations. The EOP time series cover the period from 1979.7 to 2015.0. The DTRF2014 data can be assessed via the website of DGFI-TUM at <http://www.dgfi.tum.de/en/science-data-products/dtrf2014/>. Additionally, the time series of the station position residuals as well as the SLR origin translations and the values of the applied non-tidal loading models are provided. These

data sets allow for the reconstruction of the real station positions at all observation epochs.

This paper gives, incipiently, an overview of the input data that were used for the computation of the latest ITRS realizations: ITRF2014, JTRF2014 and DTRF2014. The combination strategy of the ITRS Combination Centre at DGFI-TUM is described, divided into the accumulation of the time series per technique (intra-technique combination) and the combination of the different space-techniques (inter-technique combination). Afterwards, some major results of the DTRF2014 are summarized. Finally, a description of the DTRF2014 data files and the available time series results is given (i.e., translation time series of the origin, loading time series, station position residuals) that can be used to apply epoch-wise corrections to the conventional DTRF2014 solution in the form of station positions and linear station velocities.

Input data sets and included parameters

The input data for the three ITRS realizations are time series of station positions and EOPs which were provided by the techniques centers of the IAG Services, namely the International GNSS Service (IGS, Dow et al., 2009), the International Laser Ranging Service (ILRS, Pearlman et al., 2002), the International VLBI Service for Geodesy and Astrometry (IVS, Nothnagel et al., 2016) and the International DORIS Service (IDS, Willis et al., 2010). For the ITRF2014, the services did a complete reprocessing of the observations using the most recent models to account for geophysical and technical effects. The input data provided by the four technique-specific combination centers (TCs) are described by Rebischung et al. (2016) for the IGS contributions, Luceri and Pavlis (2016) for the ILRS, Bachmann et al. (2015) for the IVS and Moreaux et al. (2016) for the IDS. Tab. 1 gives an overview of the submitted input data that were delivered in the SINEX format as normal equations (NEQs) or solutions. In addition to these input data, local tie information provided by the ITRS Centre is used as input as well as non-tidal atmospheric and hydrological loading data released by the Global Geophysical Fluids Centre (GGFC) of the IERS.

The contributing space techniques VLBI, SLR, GNSS and DORIS are sensitive to different parameter types. Tab. 2 shows the parameters which are included in the input data provided by the TCs of the IAG Services for the generation of the ITRS realizations. This table also shows the parameters of the DTRF2014 solution.

Table 1: *Input data for the DTRF2014. The ITRF2014 and JTRF2014 are based on the same data set.*

VLBI	IVS	free NEQ	session-wise	04/80 – 12/14	35 years
SLR	ILRS	loosely constrained solution	before 1993.0: 15 days, afterwards: 7-days	12/82 – 01/15	32 years
GNSS	IGS	minimum constrained solution	daily	01/94 – 02/15	21 years
DORIS	IDS	minimum constrained solution	weekly	01/93 – 01/15	22 years

Table 2: *Input parameters and parameters included in the DTRF2014.*

	station positions	station velocities	geocenter coordinates	daily EOP at noon epochs		
				terrestrial pole	UT1	celestial pole
VLBI	✓			offsets & rates	UT1 & LOD	offsets
SLR	✓			offsets before 1993.0: 1/3d, after: daily	LOD before 1993.0: 1/3d, after: daily	
GNSS	✓		✓	offsets & rates	LOD	
DORIS	✓			offsets		
DTRF2014	✓	✓	reduced	offsets & rates	UT1 & LOD	offsets

Combination strategy of the DTRF2014

The strategy of the DTRF2014 computation is based on the combination at the normal equation level. Thus, in a preparatory step normal equations (NEQs) were reconstructed for the input SINEX solution files provided by the TCs of the IGS, ILRS, and IDS. In case of VLBI the input data were delivered in the form of normal equations so that they could be directly used for the combinations. The combination is performed with the software DOGS-CS, the combination part of the software package DOGS (DGFI Orbit and Geodetic Parameter Estimation Software) (Gerstl et al., 2000; Bloßfeld et al., 2015). The procedure can be divided into two main steps: the intra-technique combination including the pre-processing of the individual NEQs and the inter-technique combination. A detailed description of the combination strategy can be found in Seitz et al. (2012). Fig. 1 gives a schematic overview of the refined strategy for the DTRF2014 computation which considers, for the first

time, non-tidal signals in station positions induced by atmospheric and hydrological loading.

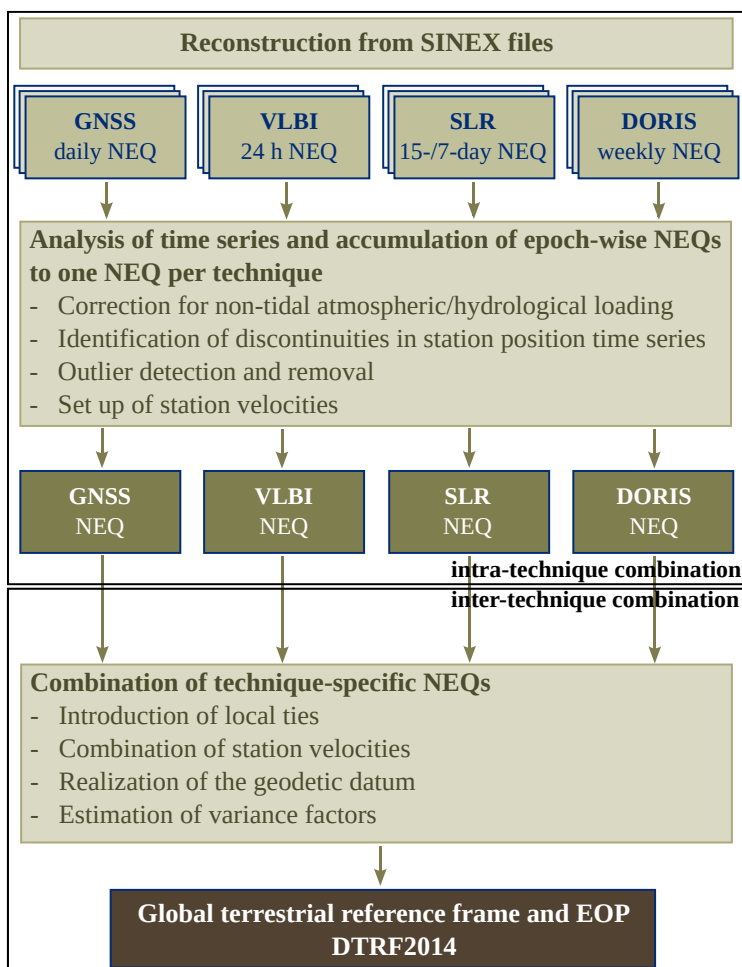


Fig. 1: Refined processing strategy for the computation of the DTRF2014 solution at DGFI-TUM.

Pre-processing and intra-technique combination

The pre-processing of the individual technique submissions comprises the analysis of the time series of station positions and datum parameters which includes the identification of discontinuities in station positions and the detection of outliers, the correction for non-tidal site displacements and finally the set up of station velocities. After the pre-processing, the edited NEQs are accumulated to one multi-year NEQ per technique.

The identification of discontinuities in the station position time series is one of the most crucial steps in the ITRF2014 computation procedure. Since not all technique services provide frequently updated discontinuity lists, this step has been performed at DGFI-TUM and the two other ITRS Combination Centres independently. Fig. 2 summarizes some statistics on the DTRF2014 solution. It is clearly visible that GNSS has by far the largest number of sites compared to the three other space techniques. This also holds for the number of discontinuities in station

positions. Reasons for such discontinuities are geophysically induced station displacements (e.g., by earthquakes) but also displacements caused by instrumental changes (e.g., antenna/receiver changes or firmware updates).

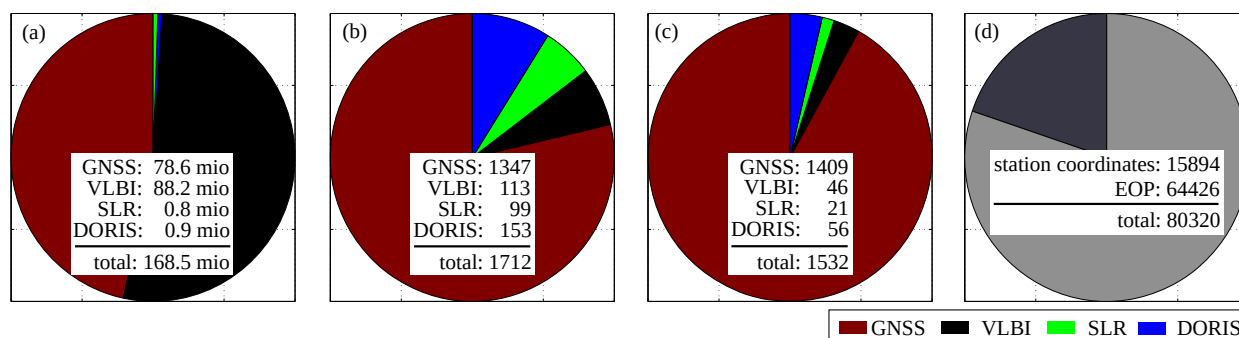


Fig. 2: Statistics of the DTRF2014 solution, including the number of GNSS, VLBI, SLR and DORIS observations (a), number of sites (b), number of discontinuities in station positions (c), number of unknowns (d).

The time series analysis also includes the investigation of the datum parameters. In particular, those parameters used for the datum realization of the DTRF2014 solution (SLR origin, SLR and VLBI scale) are important. The analyses of the datum parameter time series show that they are not affected by significant systematic effects. Therefore, the complete input data series of SLR and VLBI are used for the DTRF2014 datum realization.

As mentioned above, the DTRF2014 is corrected for site displacements caused by atmosphere and hydrology in the computation process. The corrections were provided by Tonie van Dam, and were derived from the NCEP model for the atmosphere and from the GLDAS model for hydrological loading. At DGFI-TUM, the corrections due to non-tidal loading were applied at the NEQ level.

In order to study the impact of the non-tidal corrections on the DTRF2014 computations, two solutions (with and without non-tidal loading corrections) were computed and compared. Fig. 3 shows a comparison of the translation parameters derived from SLR for both solution set ups. It is clearly visible that the annual signal obtained in the conventional solution (without loading) is significantly reduced, if non-tidal loading corrections are applied at the NEQ level. The same holds for the time series of the scale obtained from VLBI and SLR (see Fig. 4).

Inter-technique combination

The inter-technique combination is the second combination step in the DTRF2014 combination procedure. It comprises the combination of the technique-specific multi-year NEQs, the stacking of common parameters such as the EOP, the selection and introduction of local ties

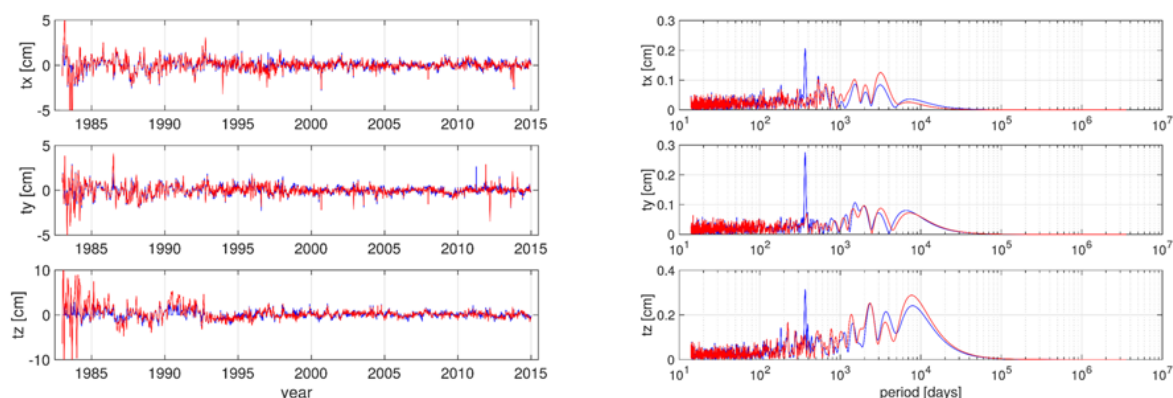


Fig. 3: Time series (left) and respective amplitude spectra (right) of the translation parameters derived from SLR (blue: conventional approach, red: non-tidal corrections applied).

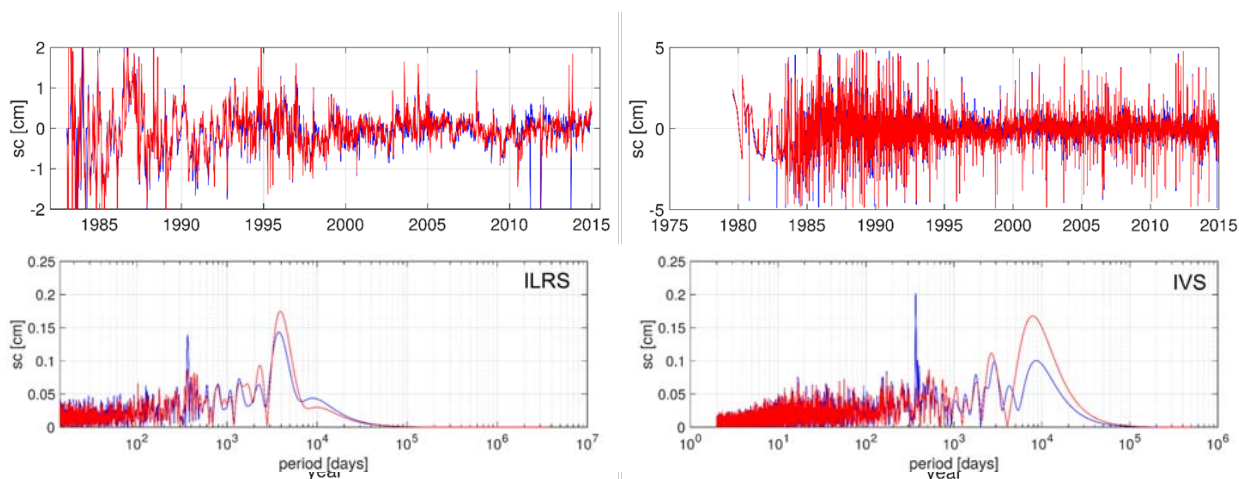


Fig. 4: Time series (left) and spectra (right) of the scale derived from SLR and VLBI (blue: conventional approach, red: non-tidal corrections applied).

and combination of station velocities at co-location sites, the realization of the geodetic datum of the combined network and the estimation of variance factors for the relative weighting of the technique-specific NEQs. At the end of this step, the combined NEQ is inverted and the DTRF2014 station coordinates and EOP are obtained.

A critical issue for the combination of the different space techniques is the selection and handling of local ties at co-location sites. The available local ties were introduced as pseudo observations and for each local tie it was tested, whether it fitted well to the space geodetic technique solutions or whether it showed significant discrepancies. The procedure for the selection and handling of the local ties is described in detail in Seitz et al. (2012). Within the combination of the station velocities, the velocities of co-located stations were tested for significant discrepancies. For all stations with insignificant differences, the velocities were combined. Concerning the datum definition of the DTRF2014, the origin of the DTRF2014 was realized from the complete SLR input

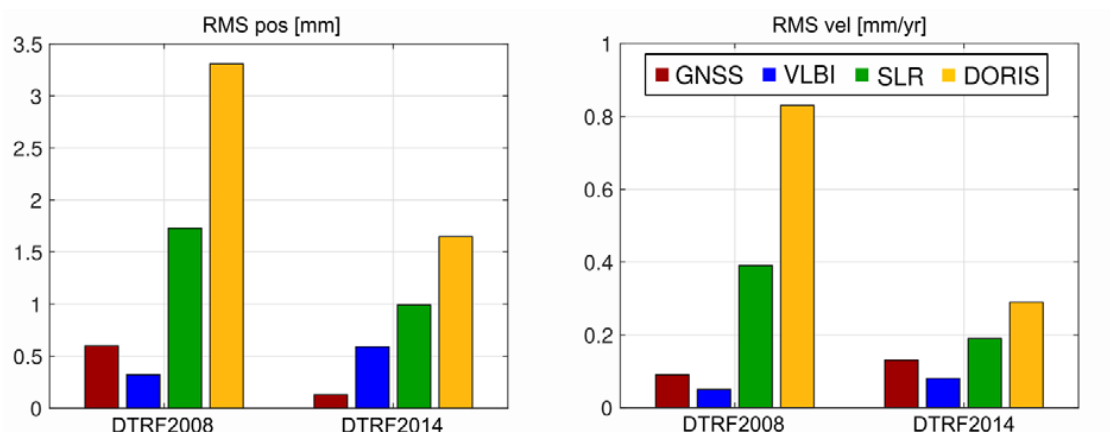


Fig. 5: RMS of station positions and velocities derived from comparisons of the single technique solutions and the combined DTRF2014 and DTRF2008 solutions by 14-parameter Helmert transformations.

data series. The scale was determined as a weighted mean of the SLR and the VLBI scale. The orientation of the DTRF2014 was realized by applying no-net-rotation conditions w.r.t. DTRF2008 using a set of well determined and homogeneously distributed GNSS stations.

To validate the inter-technique combination, 14-parameter similarity transformations between the single-technique solutions and the combined DTRF2014 solution have been performed. Furthermore, the DTRF2014 results were compared with the previous DGFI-TUM realization DTRF2008 (Seitz et al., 2012). These transformations were carried out separately for each technique by using globally distributed core stations. As a result, two quality estimates are obtained for each technique-specific network: (i) the transformation parameters between the single-technique solutions and the DTRF2014 as a measure for the accuracy of the datum definition (see Tab. 3), and (ii) the RMS for station positions and velocities as a measure for the accuracy of the network geometries (see Fig. 5). The results displayed in Tab. 3 proof that the origin of the DTRF2014 is well defined by SLR and that the scale of VLBI and SLR are in a very good agreement. Fig. 5 clearly indicates the accuracy improvement of the DTRF2014 compared to the previous DTRF2008 realization. For the DTRF2014 the RMS residuals for all four techniques are below 2 mm for positions and below 0.4 mm/yr for station velocities, respectively.

Table 3: *Results of 14-parameter Helmert transformations between SLR and VLBI single-technique solutions and DTRF2014. Only the parameters relevant for DTF2014 datum realization are shown.*

Technique		Tx	Ty	Tz	Sc
SLR	offset [mm]	0.1 ± 0.21	0.6 ± 0.21	0.9 ± 0.21	0.2 ± 0.21
	rate [mm/yr]	0.0 ± 0.04	0.0 ± 0.04	-0.1 ± 0.04	0.0 ± 0.04
VLBI	offset [mm]				0.4 ± 0.09
	rate [mm/yr]				0.1 ± 0.01

DTRF2014 results

The DTRF2014 comprises 3D coordinates and velocities of 1347 GNSS, 113 VLBI, 99 SLR and 153 DORIS stations. The reference epoch is 1.1.2005, 0h UTC. The EOP - the coordinates of the terrestrial and the celestial pole, UT1-UTC and the Length of Day (LOD) - were simultaneously estimated with the station coordinates. The EOP time series cover the period from 1979.7 to 2015.0. The horizontal station velocities of the DTRF2014 solution are shown in Fig. 6.

The velocity vectors of the DTRF2014 solution can be used to study geophysical phenomena. The left panel of Fig. 7 shows the plate tectonic motions of Greenland and the Scandinavian region. Iceland which is located directly at the mid-Atlantic ridge shows different horizontal velocities for the east and the west coast. The right panel of Fig. 7 shows the vertical land motion of Greenland and the Scandinavian region. Both regions are significantly affected by post-glacial rebound motions of up to 14 mm per year.

Fig. 8 shows differences of the global horizontal station velocity field between the DTRF2008 and the DTRF2014 solution. For most of the stations the differences of the station velocities between both realizations are almost zero. However, in some regions of the Earth there are large discrepancies due to the effect of large earthquakes (e.g., Maule earthquake in Chile on February 27, 2010 and the Tohoku-Oki earthquake in Japan on March 11, 2011). In these regions the velocities are strongly affected by post-seismic deformations which has a large impact on the observations used for the latest DTRF2014, but the data used for the DTRF2008 are not affected by these two earthquakes.

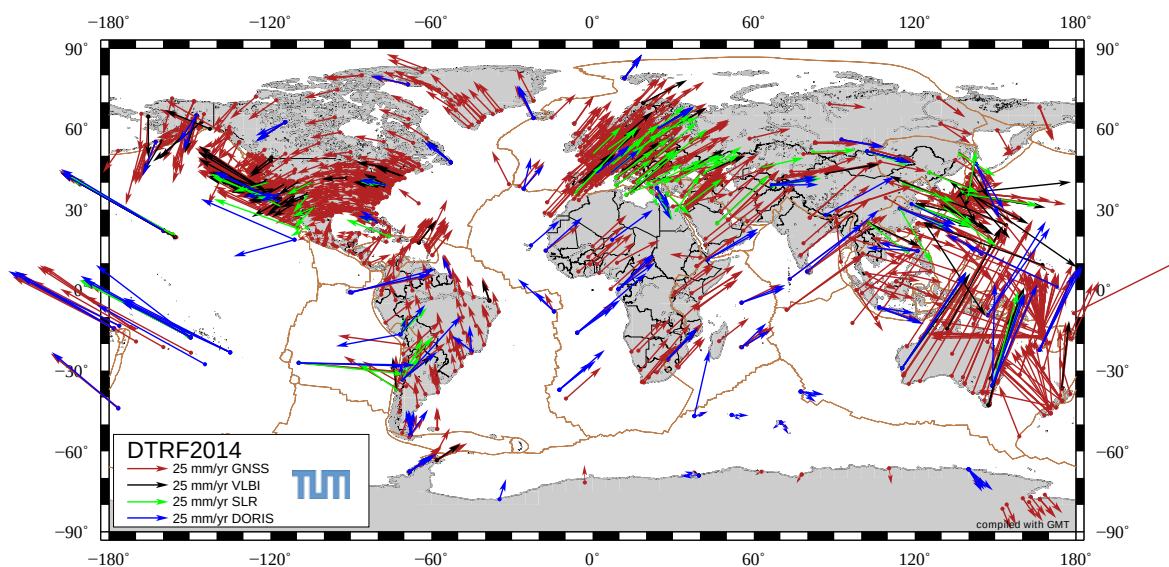


Fig. 6: The horizontal velocity field of the DTRF2014 solution.

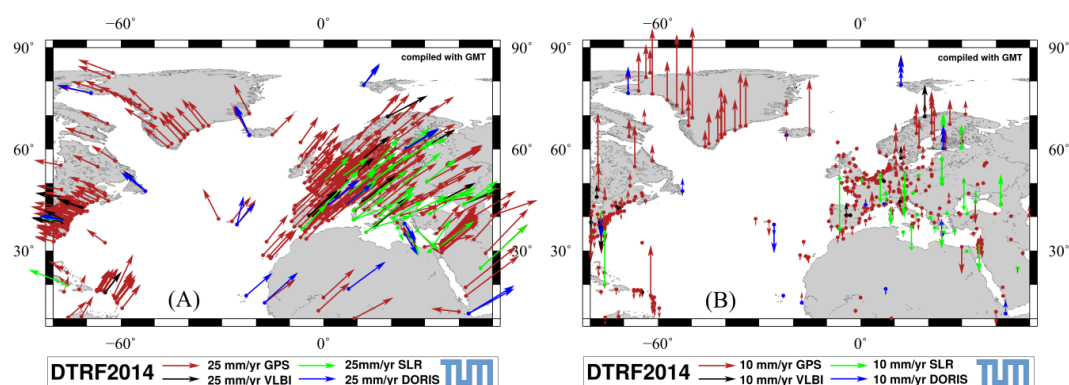


Fig. 7: Horizontal (left) and vertical station velocities (left) in Greenland and Scandinavia of the DTRF2014 solution.

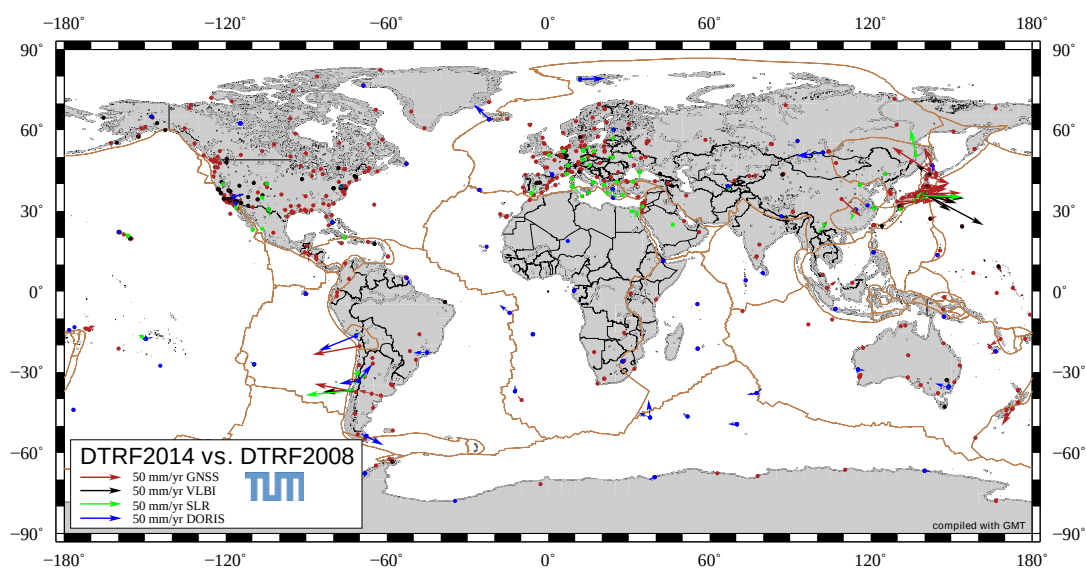


Fig. 8: Differences of horizontal velocities between the DTRF2014 and DTRF2008 solution.

DTRF2014 data files and guidelines

The data files of the DTRF2014 solution are available at the website of DGFI-TUM at <http://www.dgfi.tum.de/en/science-data-products/dtrf2014>.

The DTRF2014 solution is available in one comprehensive SINEX file and four technique-specific SINEX files (reference epoch 2005.0), as shown below:

DTRF2014.snx	Estimated station positions and velocities of the space geodetic techniques GNSS, VLBI, SLR and DORIS and the full variance-covariance matrix (12 GB).
DTRF2014.GNSS.snx	Estimated station positions and velocities of the GNSS network and the related full variance-covariance matrix.
DTRF2014.VLBI.snx	Estimated station positions and velocities of the VLBI network and the related full variance-covariance matrix.
DTRF2014.SLR.snx	Estimated station positions and velocities of the SLR network and the related full variance-covariance matrix.
DTRF2014.DORIS.snx	Estimated station positions and velocities of the DORIS network and the related full variance-covariance matrix.

In addition, the DTRF2014 solution comprises the following time series files, necessary for the computation of the quasi-instantaneous station positions based on epoch-wise corrections (see description at https://www.dgfi.tum.de/fileadmin/w00btu/www/DTRF2014_readme.pdf):

DTRF2014_SLRorigin.txt	Translation time series of the origin derived from similarity transformations of SLR-only 15-day/weekly network solutions w.r.t. the DTRF2014.
Loading time series	Weekly averaged atmospheric and hydrological non-tidal loading corrections applied in DTRF2014 computation for the correction of the respective signals. The data are provided by Tonie van Dam (GGFC, personal communication) and are based on the atmosphere model NCEP and the hydrology model GLDAS.
Station position residuals	Transformation residual time series obtained from similarity transformations of the technique-specific epoch-wise solutions w.r.t. the DTRF2014.

References

- Abbondanza C., Chin T., Gross R., Heflin M., Parker J., Soja B., van Dam T., Wu X.: JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System, *J Geophys Res Solid Earth*, doi: 10.1002/2017JB014360, 2017.
- Altamimi Z., Rebischung P., Métivier L., Collilieux X.: ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, *J Geophys Res Solid Earth*, vol. 121, doi: 10.1002/2016JB013098, 2016.
- Angermann D., Drewes H., Krügel M., Meisel B., Gerstl M., Kelm R., Müller H., Seemüller W., Tesmer V.: ITRS Combination Centre at DGFI – A terrestrial reference frame realization 2003. Deutsche Geodätische Kommission, Reihe B, Nr. 313, Munich, 2004.
- Angermann D., Bloßfeld M., Rudenko S., Seitz M.: Comparison of the latest ITRS realizations: ITRF2014, JTRF2014 and DTRF2014, this issue.
- Bachmann S., Messerschmitt L., Thaller D.: IVS Contribution to ITRF2014. In: IAG Commission 1 Symposium 2014: Reference Frames for Applications in Geosciences (REFAG 2104), pp. 1–6, Springer, 2015.
- Bloßfeld M.: The key role of Satellite Laser Ranging towards the integrated estimation of geometry, rotation and gravitational field of the Earth. Dissertation, Technische Universität München und Reihe C der Deutschen Geodätischen Kommission (ISBN: 978-3-7696-5157-7), 2015 (http://www.dgk.badw.de/fileadmin/user_upload/Files/DGK/docs/c-745.pdf).
- Dow J., Neilan R., Rizos C.: The International GNSS Service in a changing landscape of Global Navigation Satellite Systems, *J Geodesy*, vol. 83(3–4), pp. 191–198, doi: 10.1007/s00190-008-0300-3, 2009.
- Gerstl M., Kelm R., Müller H., Ehrnsperger W.: DOGS-CS Kombination und Lösung großer Gleichungssysteme. Interner Bericht, DGFI, Munich, 2000.
- Luceri C., Pavlis E.: The ILRS contribution to ITRF2014, 2016 (http://itrf.ign.fr/ITRF_solution/doc/ILRS-ITRF2014-description.pdf).
- Moreaux G., Lemoine F. G., Capdeville H., Kuzin S., Otten M., Stepanek P., Willis P., Ferrage P.: Contribution of the International DORIS Service to the 2014 realization of the International Terrestrial Reference Frame, *Adv Space Res*, doi: 10.1016/j.asr.2015.12.021, 2016.
- Nothnagel A., Artz T., Behrend D., Malkin Z.: International VLBI Service for Geodesy and Astrometry – Delivering high-quality products and embarking on observations of the next generation, *J Geodesy*, vol. 91(7), doi: 10.1007/s00190-016-0950-5, 2017.
- Pearlman M., Degnan J., Bosworth J.: The International Laser Ranging Service, *Adv Space Res.*, vol. 30(2), pp. 135–143, 2002.

- Reischung P., Altamimi Z., Ray J., Garayt B.: The IGS contribution to ITRF2014, *J Geodesy*, vol. 90(7), pp. 611–630, doi: 10.1007/s00190-016-0897-6, 2016.
- Seitz M., Angermann D., Bloßfeld M., Drewes H., Gerstl M.: The 2008 DGFI realization of the ITRS: DTRF2008. *J Geodesy*, vol. 86(12), pp. 1097–1123, doi: 10.1007/s00190-012-0567-2, 2012 (<https://mediatum.ub.tum.de/doc/1300855/1300855.pdf>).
- Seitz M., Angermann D., Gerstl M., Bloßfeld M., Sánchez L., Seitz F.: Geometrical Reference Systems. In: Freedon W., Nashed M.Z., Sonar T. (Eds.) *Handbook of Geomathematics (Second Edition)*, Springer, pp. 2995-3034, doi: 10.1007/978-3-642-54551-1_79, 2015.
- Seitz M., Bloßfeld M., Angermann D., Schmid R., Gerstl M., Seitz F.: The new DGFI-TUM realization of the ITRS: DTRF2014 (data). Deutsches Geodätisches Forschungsinstitut, Munich, doi: 10.1594/PANGAEA.864046, 2016.
- Willis P. et al.: The International DORIS Service: Toward maturity. *Adv Space Res*, vol. 45(12), pp. 1408–1420, doi: 10.1016/j.asr.2009.11.018, 2010.

JTRF2014: Analysis, Results and Comparisons to ITRF2014 and DTRF2014

Claudio Abbondanza¹, Toshio Michael Chin¹, Richard S. Gross¹, Michael B. Heflin¹, Jay W. Parker¹, Benedikt S. Soja¹, Tonie M. van Dam², Xiaoping Wu¹

¹ *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA*

² *Faculté des Sciences, de la Technologie et de la Communication, Université du Luxembourg, L-1359 Luxembourg*

Abstract. We review the main steps that led to the construction of JTRF2014, the frame solution the Jet Propulsion Laboratory (JPL) submitted for the realization of ITRF2014. In the first part of this technical note, we recall the main concepts underlying the determination of terrestrial reference frames through Kalman Filtering and Rauch-Tung-Striebel smoothing, currently adopted at JPL to compute sub-secular frame products, and we discuss the main results associated with JTRF2014. In the second part, we adopt a comparative approach and, elaborating on metrics associated with Earth Orientation and Helmert transformation parameters, we analyze JTRF2014 in relation to ITRF2014, the official combined frame computed at the Laboratoire de Recherche en Géodésie of the Institut National de l'Information Géographique et Forestière (IGN) and DTRF2014, produced at the Deutsches Geodätisches Forschungsinstitut of the Technische Universität München.

Introduction

We present and discuss JTRF2014, the Terrestrial Reference Frame (TRF) the Jet Propulsion Laboratory constructed by combining space-geodetic inputs from Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) submitted for the realization of ITRF2014. Determined through a Kalman filter and RTS smoother assimilating position observations, Earth Orientation Parameters (EOPs), and local ties, JTRF2014 is a sub-secular, time series-based TRF whose origin is at the quasi instantaneous Center of Mass (CM) as sensed by SLR and whose scale is determined by the quasi instantaneous VLBI and SLR scales. JTRF2014 is rotationally aligned to ITRF2008 through the implementation of a No-Net-Rotation (NNR) condition applied at each step of the filter.

The kinematic evolution of the station positions is described by superimposing a secular motion, annual, and semi-annual periodic modes. Site-dependent variances based on the analysis of loading displacements induced by mass redistributions of terrestrial fluids have been used to control the extent of random walk adopted in the combination. This technical note is conceptually articulated in two parts: The first recalls the main concepts underlying the JPL approach to TRF combination and illustrates the main products associated with JTRF2014;

the second dwells upon the comparative analyses of JTRF2014 in relation to ITRF2014, the official combined frame computed at the Laboratoire des Recherche en Géodésie (LAREG) of the Institut National de l'Information Géographique et Forestière (IGN) and to DTRF2014 produced at the Deutsches Geodätisches Forschungsinstitut (DGFI) of the Technische Universität München (TUM).

JTRF2014 Input Data

Between July 2015 and June 2016 entirely reprocessed global solutions from IVS, ILRS, IGS, and IDS roughly spanning the time window 1980–2015 were submitted to the IERS combination centres for the creation of ITRF2014.

Complying with the IERS-ITRF specifications, the SG global solutions are time series of Solution INdependent EXchange Format (SINEX) files containing integrated station positions at different temporal resolutions as well as daily EOP observations with full covariance matrices.

Table 1 reports the main features of the newly reprocessed SG inputs and lists recently published references wherein a thorough discussion on the nature of the solutions can be found. Prior to the combination with KALREF, the SG inputs were pre-processed, edited and pre-analysed.

Pre-processing

Since KALREF assimilates input data in the form of minimally constrained SG solutions [34], the pre-processing entails transforming the solutions into KALREF-compliant inputs.

Session-wise VLBI Normal Equations (NEQs) were inverted by applying No-Net-Translation (NNT) and No-Net-Rotation (NNR) conditions to the a-priori station coordinates supplied in the input SINEX files.

SLR inputs being loosely constrained solutions, their covariance matrices were orthogonally projected over rotations as shown in [7]. To allow for a faster data assimilation, repro2 (GNSS) daily solutions were averaged to weekly inputs. In so doing, each aggregated SINEX file contains weekly integrated station positions and seven daily EOPs, i.e. polar motion (x_p, y_p) , polar motion rates $(\dot{x}_p, \dot{y}_p)$, and the calibrated excess length-of-day.

Data Editing

Data editing is mainly concerned with the identification and removal of position outliers. Outlier detection is based upon single-technique intrinsic stacks of pre-processed input SINEX files. Adopting the approach outlined by [1], secular frames were estimated from each individual SG time series of input SINEX files and residuals were computed with respect to the model

$$X^S(t) = X_0^C + V^C \cdot (t - t_0) + T(t) + \lambda(t) \cdot X_0^C + \mathbf{R}(t) \cdot X_0^C \quad (1)$$

where $X^S(t)$ is the vector defining the technique-specific position observations at the epoch t , the pair (X_0^C, V^C) represents the secular frame, i.e. the position vector at the reference epoch t_0 and the velocity vector; $\lambda(t)$, $T(t)$, and $\mathbf{R}(t)$ are the radial scale, the 3D translation vector and the anti-symmetric matrix of the 3D infinitesimal rotations about the coordinate axes at the epoch t , respectively.

Any observation having normalized and non-normalized residuals larger than the specified thresholds (cf Table 2) in any of three North, East and Height components has been flagged and removed from the input SINEX files. The stack and subsequent outlier removal have been iterated thrice for each technique. After each iteration, VLBI and SLR edited SINEX files have been screened for regional sessions. A SINEX file is regarded as regional when the area of the observing SG network covers an extremely limited portion of the globe. SG sessions having spherical area smaller than $2 \cdot 10^{12} \text{ m}^2$ (Europe has an area of approximately 10^{13} m^2) are classified as regional. Regional SG sessions are not able to convey reliably global Helmert transformation parameters which are pivotal in the definition of combined TRFs. Particularly affected in this regard appears to be the VLBI radial scale related to regional sessions. Whenever a regional sessions is detected, its corresponding SINEX file gets removed. Table 2 features the edited SG inputs adopted in JTRF2014.

The JTRF2014 Global Network

The JTRF2014 SG network consists of 972 stations, 671 of which are GNSS, VLBI and SLR count 71 stations each, whereas DORIS 159 (cf Table 2).

The color-coded map in Figure 1 represents the spatial distributions of the SG stations. With 453 sites in the Northern hemisphere against 137 site in the Southern, the uneven site distribution is markedly evident. JTRF2014 adopts the smallest global network when compared to ITRF2014 (1499 stations) and DTRF2014 (1712 stations) both of which take advantage of the remarkably larger number of GNSS stations available in IGS repro2 [27].

Intrinsic Quality of the single-technique contributions to JTRF2014

Station position coordinates can be used to define a proxy for the frame internal precision so as to provide an indication of the intrinsic quality of the SG solutions contributing to JTRF2014. The post-fit residuals from the intrinsic stack of Equation 1 can be used to define across-stations, per-session weighted mean squared errors (WRMS). Details on the implementation of such metric can be found in [27]. The WRMS analyses conducted on the edited SG inputs to JTRF2014 proved substantially consistent with the most recent investigations reported in the literature [see e.g. 17, 27].

Table 1: SG inputs submitted for the ITRF2014 combination. *T* in the first column designates the SG techniques, whose acronyms derived from the IERS Conventions (cf Chapter 4 of [19]) are extensively used throughout the manuscript: *P* identifies GNSS, *R* VLBI, *L* SLR whereas *D* is DORIS. *TC* in the second column identifies the Technique Center. *TS* in the third column designates the time span for each technique. *SOL* in the fourth column specifies the kind of SINEX format released by the 4 TCs: *VC* stands for Variance-Covariance, *NE* for Normal Equations. *TR* in the fifth column relates to the temporal resolution, *SF* in the sixth is the number of SINEX files for each solution. *ST* in the seventh column reports the number of stations. The last column *Source* provides references.

T	TC	TS	SOL	TR	SF	ST	Source
P	IGS	1994.0 – 2015.1	VC	Daily	7714	1845	[27]
R	IVS	1979.5 – 2015.0	NE	Session-Wise	5796	158	[5]
L	ILRS	1983.0 – 1993.0	VC	Fortnightly	244	138	[16]
L	ILRS	1993.0 – 2015.1	VC	Weekly	1148	138	[16]
D	IDS	1993.0 – 2015.0	VC	Weekly	1139	160	[17]

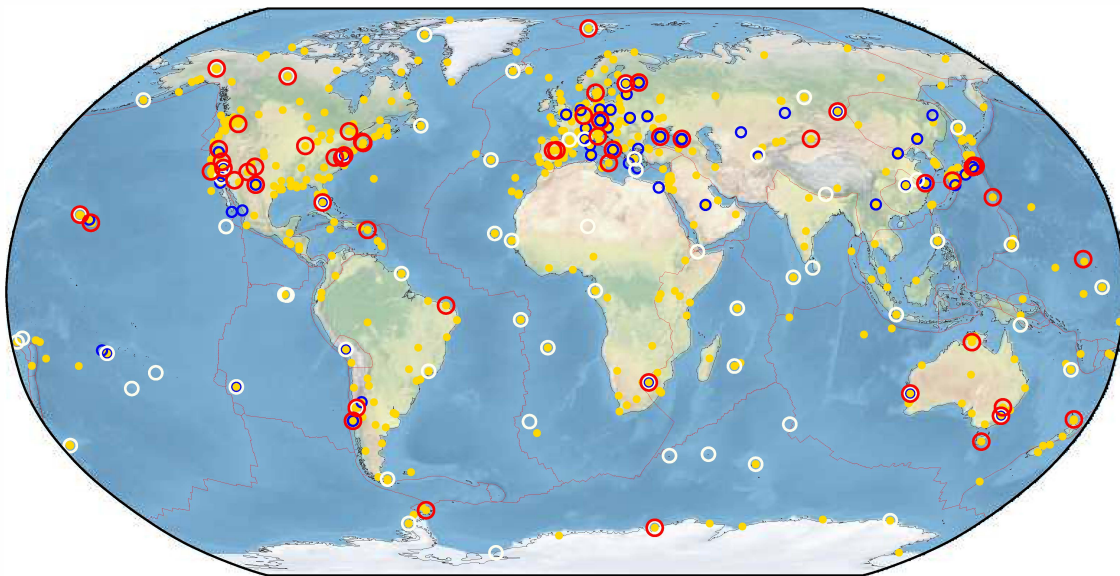


Fig. 1: Global SG network adopted in the JTRF2014 combination. Gold dots identify the GNSS sites, red circles represent VLBI, the blue ones are SLR, whereas the white ones are DORIS. The global network comprises 671 GNSS stations, 71 VLBI and SLR stations, and 159 DORIS stations. The global network is characterized by 590 sites, 453 of which are located in the Northern hemisphere. Only 137 are positioned in the Southern hemisphere. Polygons drawn in red represent tectonic plate boundaries.

Table 2: *Technique-specific thresholds adopted during the data editing of the input SINEX files. T in the first column identifies the SG technique, TC in the second one denotes the Technique Center, TR in the third one is the Temporal Resolution, the asterisk in the fourth column identifies the SG techniques subject to removal of regional sessions, OTS in the fifth column denotes the Observing Time Span threshold in yr applied to the stations, NR in the sixth column reports the Normalized Residual while AR defines the non-normalized Residual expressed in cm, STAT in the eighth designates the number of stations included in JTRF2014 and SNX in the last column denotes the number of SINEX files utilized in JTRF2014. Parenthesized in sixth column is the number of SINEX files removed over the entire time span of the combination as a result of the data editing illustrated in Section Data Editing.*

T	TC	TR	Regional	OTS	NR	AR	STAT	SNX
P	IGS	Weekly	–	2.5	5	5	671	1102 (-)
R	IVS	Session-Wise	*	2.5	7	5	71	4681 (1115)
L	ILRS	Fortnightly/Weekly	*	2.5	7	5	71	1293 (99)
D	IDS	Weekly	–	2.5	7	5	159	1139 (-)

As shown in Table 3, with median WRMS smaller than 4.4 mm on any of the three components, the weekly averaged GNSS solutions are by far the most precise, followed by VLBI, SLR and DORIS. When comparing median WRMS of SG inputs computed with consistent data editing procedures for the ITRF2008 data sets, we found a remarkable improvement for DORIS, whose station position repeatability decreases by ≈ 3 mm on each component and for SLR as well.

JTRF2014 Multi-technique Combination

KALman filter for terrestrial REference Frame (KALREF) combines minimally constrained SG inputs along with local tie observations through the adoption of a Kalman Filter and Rauch-Tung-Striebel (RTS) Smoother algorithm. While running forward in time, the filter produces optimal estimates of the state parameters of a certain epoch based on the observations assimilated up to that epoch. The fixed-interval RTS smoother is executed backward in time thus ensuring optimal state estimate based on all the measurements acquired over the entire data assimilation span.

Kinematic Model and Time Update

During the time and measurement update in the forward filtering stage, KALREF updates the set of variables describing the state of the dynamical system according to what is observed and what the physics of the dynamical model predicts. The dynamical model describes the temporal evolution of the prognostic parameters constituting the state vector. In KALREF, the state vector X_k consists of station-related parameters, such as the trend and seasonal variables describing the Earth surface deformation and network-related parameters, such as the EOPs and the Helmert transformation parameters. For the station-position related parameters, the dynamical model formulated adopting the state-space notation is

Table 3: 2nd-order statistics relevant to station positions and EOPs of the SG edited inputs. Station positions WRMS are across-station weighted root mean squared residuals computed through the linear model of Equation 1. Second, third and fourth columns report median values of the WRMS time series in mm for the North, East, and Height component, respectively. EOP WRMS reported in the following columns are weighted root mean squared residuals computed as a result of the intrinsic stack of the of the SG inputs. The fifth and sixth column report WRMS of the x and y components of the polar motion expressed in μas , respectively. Column 7 reports UT expressed in μsec . Column 8, 9 and 10 relate to the polar motion rates $\dot{x}_p$, $\dot{y}_p$ and LOD expressed in $\mu\text{as/day}$ and $\mu\text{sec/day}$, respectively. The last column reports the square root of the reduced chi-square obtained as a result of the stacking of the edited input data sets. Parenthesized are the 2nd-order statistics computed for the input data sets adopted for the KALREF analysis of ITRF2008 [cf 38].

T	Station Position			EOPs						s_0
	N	E	H	x_p	y_p	UT	$\dot{x}_p$	$\dot{y}_p$	LOD	
P	1.5 (1.6)	1.4 (1.4)	4.4 (4.2)	6.6 (1.3)	7.4 (1.3)	–	8.4 (9.3)	9.2 (12.0)	–	5.7 (0.9)
R	3.1 (3.3)	3.0 (2.9)	7.5 (7.2)	118.5 (160.5)	136.6 (179.8)	5.5 (6.3)	130.8 (132.2)	109.9 (133.6)	6.5 (5.2)	5.9 (5.5)
L	8.2 (10.1)	7.4 (9.2)	6.5 (7.8)	120.3 (168.2)	119.1 (168.5)	–	–	–	–	5.2 (4.4)
D	9.2 (10.8)	11.3 (13.6)	10.2 (13.3)	71.1 (58.8)	65.3 (68.5)	–	–	–	–	2.7 (3.2)

$$\begin{aligned}
 & \left[\begin{array}{c} x_k^{ij} \\ v_k^{ij} \\ s_k^{ij} \\ s_{k-1}^{ij} \\ q_k^{ij} \\ q_{k-1}^{ij} \end{array} \right] = \\
 & \left[\begin{array}{c} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} \right] \Delta t \left[\begin{array}{c} 0 \\ 0 \\ 2e^{-\frac{\Delta t}{\tau}} \cos\left(\frac{2\pi\Delta t}{T_s}\right) \\ 1 \\ 0 \\ 0 \end{array} \right] - e^{-\frac{2\Delta t}{\tau}} \left[\begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} \right] + \\
 & \left[\begin{array}{c} x_{k-1}^{ij} \\ v_{k-1}^{ij} \\ s_{k-1}^{ij} \\ s_{k-2}^{ij} \\ q_{k-1}^{ij} \\ q_{k-2}^{ij} \end{array} \right] + \\
 & \left[\begin{array}{c} \varepsilon_{x_k}^{ij} \\ \varepsilon_{v_k}^{ij} \\ \varepsilon_{s_k}^{ij} \\ 0 \\ \varepsilon_{q_k}^{ij} \\ 0 \end{array} \right] \mathcal{W}_k \\
 & \left[\begin{array}{c} x_k^{ij} \\ v_k^{ij} \\ s_k^{ij} \\ s_{k-1}^{ij} \\ q_k^{ij} \\ q_{k-1}^{ij} \end{array} \right] = \left[\begin{array}{c} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} \right] \Delta t \left[\begin{array}{c} 0 \\ 0 \\ 2e^{-\frac{\Delta t}{\tau}} \cos\left(\frac{2\pi\Delta t}{T_s}\right) \\ 1 \\ 0 \\ 0 \end{array} \right] - e^{-\frac{2\Delta t}{\tau}} \left[\begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} \right] + \\
 & \left[\begin{array}{c} x_{k-1}^{ij} \\ v_{k-1}^{ij} \\ s_{k-1}^{ij} \\ s_{k-2}^{ij} \\ q_{k-1}^{ij} \\ q_{k-2}^{ij} \end{array} \right] + \left[\begin{array}{c} \varepsilon_{x_k}^{ij} \\ \varepsilon_{v_k}^{ij} \\ \varepsilon_{s_k}^{ij} \\ 0 \\ \varepsilon_{q_k}^{ij} \\ 0 \end{array} \right] \mathcal{W}_k
 \end{aligned}
 \tag{2}$$

where

- the index $j = 1, 2, 3$ denotes the generic Cartesian component in the XYZ space,
- the index k identifies the epoch,
- Δt is the fixed time step set to 1 week,
- x_k^{ij} represents the non-periodic position of the station i at the epoch k ,
- v_k^{ij} is the instantaneous velocity (trend variable),
- the triplets $(s_k^{ij}, s_{k-1}^{ij}, s_{k-2}^{ij})$ and $(q_k^{ij}, q_{k-1}^{ij}, q_{k-2}^{ij})$ are the elements of a second-order regression model discretizing the differential equation of a stochastic damped oscillator [10]: the former relates to the annual periodic mode, the latter to the semi-annual periodic mode;
- T_s and T_q designate the annual and semi-annual periods, respectively.

By setting the e-folding time τ to a large value, no damping is allowed in the harmonic oscillators. The state vector X_k is completed by 42 daily EOP parameters describing the Earth rotation (namely x_p, y_p, UT and their time derivatives $\dot{x}_p, \dot{y}_p, LOD$) for each day within the weekly interval and by Helmert transformation parameters grouped in sets each of which to be individually applied to the technique-specific global SG networks. Φ_k designates the state-transition matrix allowing the state vector to be propagated from the epoch $k-1$ to k . In KALREF the state-transition matrix is time-invariant but the process- and measurement-noise covariance matrices are not. SG observing systems are uniquely able to sense the *total* station motion $\tilde{x}_k^{ij}$ defined through the following additive model:

$$\tilde{x}_k^{ij} = x_{k-1}^{ij} + v_{k-1}^{ij} \cdot \Delta t + s_k^{ij} + q_k^{ij} \quad (3)$$

Equation 3 accounts for all of elements into which the station motion has been decomposed and will be utilized during the measurement update described in the following section. Earth Orientation and Helmert transformation parameters are modeled as a pure random walk $h_k = h_{k-1} + \varepsilon_{h_k}$ where $\varepsilon_{h_k} \sim \mathcal{N}(0, \sigma^2)$ is a Gaussian process whose associated standard deviation σ is set to a value sufficiently large to accommodate the week-to-week variations observed in the Earth orientation and the Helmert parameters as well (cf Table 4).

The elements of the vector $\mathcal{W}_k$ relate to the stochastic nature of the state vector parameters, whose associated process noise is modeled as white-noise driven random walk. KALREF enables process noise

to be activated on each of the state vector parameters, although in current TRF reductions process noise is solely turned on for station positions, EOPs and Helmert transformation parameters. By setting the variances of the Gaussian processes $\varepsilon_{v_k}^i$, $\varepsilon_{s_k}^i$ and $\varepsilon_{q_k}^i$ of Equation 2 to non-zero values, velocities and seasonal terms are allowed to stochastically vary in time, thus accommodating time-variable trends and amplitudes/phases of the seasonal oscillators [10]. The filter is initialized by utilizing the a priori values specified in Table 4, along with the uncertainties adopted to fill the diagonal terms of the covariance matrix at the first step of the assimilation.

Table 4: Set-up adopted for the filter initialization: initial values of the state parameters as well as of the uncertainties adopted in the first step of the filter are reported in Column 3 (a priori state values) and Column 4 (a priori state uncertainties). Process noise for the state parameters is selected to be random walk driven by white noise, whose variance square roots are reported in Column 5. Column 6 defines the units adopted in the computational code (KALREF).

Parameter	Description	a priori Value	Uncertainty	Process Noise σ	Units
x_k	Non-periodic Coordinates	(a)	2	(b)	m
v_k	Station Velocities	0	2	0	m/yr
s_k	Periodic Displacements	0	5	0	cm
x_p, y_p	Polar Motions	0	400	100	mas
$\dot{x}_p, \dot{y}_p$	Polar Motion Rates	0	400	100	mas/day
UT	Universal Time	0	400	100	ms
LOD	Excess Length-of-Day	0	400	100	ms/day
T	Translations	0	2	1	m
λ	Radial Scale	0	20	1.6	0.1·ppm
R	Rotations	0	200	3.2	0.01 · as

(a) a priori station coordinates are derived from the first observed station coordinates in the time series.

(b) Station-dependent standard deviations of the position process noise are derived from the reduction of the UniLu-GGFC loading displacements as described in Section *Loading Models*.

Measurement Update

During the measurement update the a priori state estimates obtained by forward projecting the kinematic model are adjusted by minimizing the misfits between the physical model and the station position and EOP observations. The observation equations involved in the measurement update have therefore to establish a bijective relationship between the observed entities in the measurement space and the state parameters. The linearized Euclidean similarity transformation adapted from [1]

can be used to construct the rank-deficient linear system of Equations central to KALREF measurement update:

$$\begin{cases} X_P^S = X_P^C + T_P + \lambda_P X_P^C + \mathbf{R}_P X_P^C \\ X_R^S = X_R^C + T_R + \lambda_R X_R^C + \mathbf{R}_R X_R^C \\ X_L^S = X_L^C + T_L + \lambda_L X_L^C + \mathbf{R}_L X_L^C \\ X_D^S = X_D^C + T_D + \lambda_D X_D^C + \mathbf{R}_D X_D^C \end{cases} \quad (4)$$

where

- X_t^S and X_t^C are vectors whose elements are the technique-specific total coordinates described in Equation 3. The index t represents the SG technique where P stands for GNSS, R for VLBI, L for SLR and D for DORIS;
- X_t^S relates to the weekly/daily input SINEX files station positions;
- X_t^C to the weekly combined (outputted) station positions;
- T_t denotes the vector of the translations mapping the combined frame XC to the pseudo-observed technique-specific XSt frame;
- λ_t denotes the radial scale factor between the combined and the technique-specific frames;
- $\mathbf{R}_t$ is the antisymmetric matrix representing a 3D linearized rotation between the combined and the technique-specific frames.

Note that, since small station position motions at sub-weekly time scale are being ignored, the time dependency in Equations 4 is dropped. The system of Equations 4 is complemented by EOP measurement equations relating the combined and observed Earth rotation to the Helmert rotation parameters:

$$\begin{cases} x_{t,p} = x_p^C + r_{t,2} \\ y_{t,p} = y_p^C + r_{t,1} \\ UT_t = UT^C - \frac{1}{f} r_{t,3} \\ \dot{x}_{t,p} = \dot{x}_p^C \\ \dot{y}_{t,p} = \dot{y}_p^C \\ LOD_t = LOD^C \end{cases} \quad (5)$$

where

- the subscript t denotes the Earth Orientation (Helmert rotational) parameters as observed by (determined through) the SG technique t ;
- the superscript C denotes the combined EOP parameters included in KALREF state vector;
- (x_p, y_p) denotes the daily polar motion;
- $(\dot{x}_p, \dot{y}_p)$ denotes the daily polar motion rate;
- UT denotes the difference ($UT1 - UTC$);
- LOD is the excess length of day representing discrete variations of UT over one day;
- (r_1, r_2, r_3) represent clockwise infinitesimal rotation angles about the X, Y and Z axes, respectively;
- $f = 1.002737909350795$ is the conversion factor from UT into sidereal time.

During the measurement update the technique-specific EOPs are simultaneously calibrated with the TRF rotational parameters so as to compensate for EOP-related systematic biases. In JTRF2014, polar motion observations from VLBI, SLR, GNSS and DORIS, polar motion rates from VLBI and GNSS, UT and LOD from VLBI are assimilated. The satellite-derived LOD, though available, has not been utilized in our combination in order to avoid potential corruption of VLBI-determined LOD [25].

The measurement equations are completed by the additive model of Equation 3 described in Section *Measurement Update*. The observations of position and EOPs fed into KALREF are weighted through the inverse of the measurement (full) covariance matrices reported in the input SINEX files of the four SG solutions. The adoption of full covariance matrices allows the correlations among the observed parameters to be entirely accounted for. As illustrated in Section *Data Editing*, the formal errors of the SG inputs reported in the covariance matrices of the SINEX files are overly optimistic. The optimal set of scaling factors to apply to the stated uncertainties of the SG inputs has been iteratively determined by executing KALREF-combination tests with the a posteriori variance factors obtained from the individual stacks illustrated in Table 3. Our tests led to estimates of the variance factors of $(3.07)^2$ for GNSS, $(2.98)^2$ for VLBI, $(2.61)^2$ for SLR, and $(1.36)^2$ for DORIS to be applied to the measurement covariance matrices during the data assimilation.

Frame Definition To define origin and scale, the Helmert transformation parameters T_L , λ_L , λ_R in the rank-deficient system of Equations 4 are set to zero during the measurement update.

The condition $T_L = 0$ ensures translations are not estimated for SLR at each step of the measurement update, thus entailing the origin of the SLR network is not going to be adjusted. Since translations for the remaining SG techniques are not set to zero, the origin of VLBI, GNSS and DORIS networks are conversely being adjusted to SLR's quasi instantaneous origin (CM).

The conditions $\lambda_L = 0$, $\lambda_R = 0$ ensure that the SLR and VLBI scales are not adjusted during the weekly measurement updates. Scale parameters are estimated only for GNSS and DORIS, thus implying their intrinsic scale information is removed and adjusted to the weighted average scale defined by VLBI and SLR. Such definition will realize a combined TRF whose scale is given by the quasi instantaneous average of the interferometric (VLBI) and optical (SLR) scales weighted through the inverse of the covariance measurement matrices. Such an approach to the scale definition would be optimal were there no biases between VLBI and SLR-derived scales. Systematic scale and scale rate differences between the two observing systems, if existing, would not properly be reflected by the formal covariance matrices of the SG inputs. In recognizing this potential shortcoming, ITRF2014 adopted a scale definition based upon a simple average of the two systems, after having found a scale offset of 8.7 ± 0.6 mm at the epoch 2010.0 and a scale rate of 0.1 ± 0.1 mm/yr [3].

One way to assess potential scale and scale rate biases between VLBI and SLR in KALREF is to perform combination tests in which only λ_R is set to 0 in the system of Equations 4. Such an assumption entails adjusting SLR to VLBI scale at each step of the filter/smoothing. The resulting time series of λ_L parameters therefore represents the time-varying scale offset between the two observing systems. Least squares fits of a linear regression model conducted on such scale offset time series can therefore provide an indication of the VLBI-to-SLR scale and scale rate bias. Assimilation tests executed by combining VLBI, SLR, DORIS, and GNSS inputs restricted to the IGS global network with a subset of 140 tie vectors whose covariance matrices have been scaled adopting the same set of variance factors selected for the JTRF2014 combination led to estimates of the VLBI-to-SLR scale offsets of -4.58 ± 0.10 to -4.93 ± 0.10 mm at January 1 2005, with scale rate differences of -0.22 ± 0.01 to -0.24 ± 0.01 mm/yr depending upon the station motion model chosen (simply linear or linear plus seasonal oscillators). Though suggestive of the existence of a scale bias, KALREF-derived estimates of the VLBI-to-SLR scale offsets turn out to be consistently smaller than the ones found in ITRF realizations [see e.g. 2, 3]. This evidence led

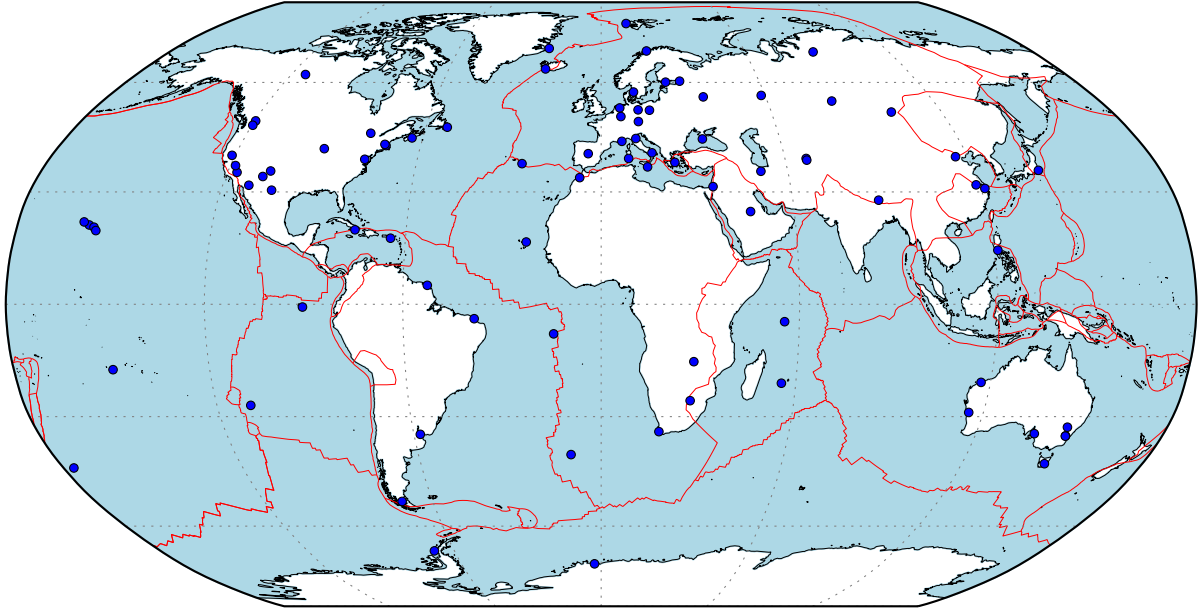


Fig. 2: Spatial distribution of the 86 SG stations adopted for the application of the NNR conditions allowing JTRF2014 to be rotationally aligned to ITRF2008. Such reference sites are all characterized by long observing histories (larger than 10 years) and affected by less than 3 station position discontinuities.

us to adopt the scale definition based upon the instantaneous weighted average of the SLR and VLBI scales. Further investigations are currently ongoing for a more in-depth analysis of the VLBI/SLR scale offsets in the context of Kalman Filter-based TRF combinations.

To define orientation, rotation parameters (R_P, R_R, R_L, R_D) featured in Equation 4 have been estimated for all of the 4 SG techniques and rotational minimal constraints to a subset of 86 stations (cf Figure 2) whose coordinates are expressed in the ITRF2008 have been applied at each step of the measurement update [cf Eq (4) in 38].

The reference sites represented in Figure 2 are characterized by long observing history (> 10 years) and affected by less than 3 station position discontinuities throughout their tracking history.

Co-motion Constraints

Adopting the state-space model illustrated in the Section *Kinematic Model and Time Update* and the coordinate the *total* displacement of the generic station i from the epoch k to $k + 1$ can be described as

$$\tilde{x}_{k+1}^{ij} - \tilde{x}_k^{ij} = v_k^{ij} \cdot \Delta t + s_{k+1}^{ij} - s_k^{ij} + q_{k+1}^{ij} - q_k^{ij} + \varepsilon_{x_k}^{ij} \quad j = 1, 2, 3 \quad (6)$$

Co-motion constraints dictate the equivalence of the displacements of Equation 6 when observed by 2 or more nearby co-located stations, and require

- The trend variable (velocity) of co-located SG stations l and m be equivalent
- The seasonal oscillator state parameters relevant to co-located stations be the same.
- The station position process noise $\varepsilon_{x_k}^{lj}$ and $\varepsilon_{x_k}^{mj}$ relevant to co-located stations l and m be characterized by a 1.0 correlation coefficient.

The equivalence of the station velocities and of the seasonal oscillators for 2 generic co-located stations l and m is formalized through soft (stochastic) constraints associated with pre-assigned uncertainty:

$$\begin{cases} v_k^{lj} - v_k^{mj} = 0, (\sigma_v) \\ s_k^{lj} - s_k^{mj} = 0, (\sigma_s) \\ q_k^{lj} - q_k^{mj} = 0, (\sigma_q) \end{cases} \quad (7)$$

The constraints of Equations 7 provide additional measurement equations to be applied during the measurement update: velocity constraints in the first line of system of Equations 7 are applied at the first ($k = 1$) step of the measurement update and, occasionally, at time steps immediately following velocity breaks; the seasonal constraints in the second (annual term) and third (semi-annual term) line are applied twice, at the first ($k = 1$) and sixth ($k = 6$) step of the measurement update.

The seasonal oscillator terms (cf Equation 2) for co-located stations are constrained to be equivalent with uncertainty value $\sigma_{s,q}$ uniformly set to $10 \mu m$, based on the assumption that, conceivably, nearby stations are subject to and detect the same seasonal displacements. As to the velocity of co-moving stations, the uncertainties σ_v associated with the equivalence constraints are, unlike what happens for the seasonal oscillators, station-dependent. The exercise of establishing the most appropriate set of σ_v is a delicate one because of the impact it may have on temporal behavior of the frame-defining Helmert transformation parameters. In JTRF2014, velocity constraint-related uncertainties have been, once again, empirically determined by analyzing the time series of station position residuals at co-located sites, based on the assumption that inaccurately constrained velocities tend to produce systematically biased (non-zero mean) residual position time series. Default values for the velocity constraints are initially set to $1.0 \mu m/yr$ for all of the co-locations with the exception of DORIS for which the uncertainties

are loosened up to the level of 1.0 mm/yr . Based on the analysis of the position residuals, σ_v can be augmented and made, in exceptional cases, as high as 1.0 cm/yr .

The constraints on the station position processes $\varepsilon_{x_k}^{lj}$ and $\varepsilon_{x_k}^{mj}$ are realized by imposing the correlation term ρ_{lm} between stations l and m to be 1.0 in the process noise covariance matrix at each step of the forward filter.

Loading Models

UniLu-GGFC loading models describe the Earth elastic response to spatio-temporal mass variations in terrestrial fluid layers. The fluid-induced elastic displacements include contributions due to variation in continental water storage, atmospheric and ocean bottom pressure (OBP) and have been determined by convolving global geophysical fluid data with mass loading Green's functions [36] and load Love numbers as determined by [14].

The displacements caused by each fluid component have been computed separately at the sampling rate of the data and expressed through appropriate choice of the degree-1 load Love numbers in a CM-centered frame. The atmospheric loading displacements, supplied at 6 hourly intervals, have been derived from National Center for Environmental Prediction (NCEP) surface pressure fields making the assumption that the oceans behave like a modified inverted barometer. The Global Land Data Assimilation System (GLDAS/Noah) [28] has been used to compute 3 hourly time series of continental water storage-induced displacements. The ocean loading displacement time series are derived at 12 hourly intervals from JPL's Estimating the Circulation and Climate of the Ocean (ECCO) [12].

Despite the growing number of loading models with ever-increasing complexity in terms of geophysical fluid modelling, their direct adoption in SG reductions still poses relevant issues as to the contamination of the error models with the geodetic observations [24]. In JTRF2014, UniLu-GGFC data have been exclusively used to determine the station-dependent variance of the position process noise which represents the non-secular and non-seasonal deviation from the model of Equation 6.

The 3 fluid components of the displacements have been separately de-trended, de-seasonalized and subsequently aggregated in weekly averages. The residuals from each separate fluid component have been added up and first differences of the weekly global displacements have been computed. The variances of the differenced time series at each JTRF2014 site characterize the site-dependent position process noise $\varepsilon_{x_k}^{ij}$ of Equation 6. Median values of the square root of the the position process noise variances are found to be 1.20, 0.97, 2.22 mm with associated standard deviations of 0.10, 0.13, 0.87 mm for the North, East and Height component, respectively. Although the loading models

do not account for either cryospheric (e.g. ice mass loss) or seismic processes, we found that the UniLu-GGFC-derived variances are large enough to allow for an adequate representation of some of the rapidly varying, non-linear and non-seasonal geophysical signals in the position time series.

JTRF2014 Main Results

By fully exploiting the sequential nature of the Kalman filter and RTS smoother algorithm, KALREF realizes time series-based TRFs at a sub-secular resolution giving access to the quasi instantaneous SLR-derived CM and to the quasi instantaneous scale realized by VLBI and SLR.

Station Position Time Series

JTRF2014 consists of a set of position time series of 972 stations at weekly intervals and daily combined EOPs along with their full covariance matrices. Station velocities may be used to produce, along with the seasonal oscillators, position predictions after 2015. To provide an indication of the internal precision of KALREF-derived station positions, an intrinsic stack of JTRF2014 SINEX files has been executed and time-dependent WRMS computed (cf Figure 3). The larger values of the WRMS in the time span 1980–1993 mostly reflect the poorer quality of the very early VLBI and SLR observations. As expected, WRMS tend to decrease as the data quality improves over time and, particularly, when GNSS observations start in the early 1990s.

An example of the station position time series outputted by KALREF is given in Figure 4 which illustrates the co-located GNSS and VLBI stations at Tsukuba (Japan). The black dots in the plots represent the observed positions of the two stations whereas the red solid lines indicate KALREF-estimated positions derived from JTRF2014. The co-seismic displacement of the two observing stations during the 9.1 Mw Tōhoku megaquake of March 11, 2011 is readily apparent, particularly in the East (see top panels of Figure 4) and Height (bottom panels) components. By resetting the variance of the station position process noise to 25.0 m^2 at the epoch of the seismic event, KALREF is able to correctly represent the sizable co-seismic dislocation. For TSKB, the GNSS station at Tsukuba, KALREF estimated a co-seismic displacement of 0.6153, 0.0341 and -0.0900 m in the East, North and Height component, respectively. In between discontinuities, the nominal value of the process noise at this site causes the KALREF-estimated station position to be a smoothed version of the observed position. The dynamical model of Equation 2 is used to interpolate across gaps in the observations and to extrapolate the station position to epochs before the station itself started observing (before 1994.0) or after it stopped observing (not shown in the plot). Since the VLBI station (7345) at Tsukuba is co-located with a GNSS station that started observing before it and

because of the co-motion constraints applied to co-located stations, the KALREF-estimated position of the GNSS station is transferred to the VLBI station at the epochs in which 7345 was not yet operating. This is most clearly seen in the Height component (right bottom panel of Figure 4) in the time window 1994-1998.

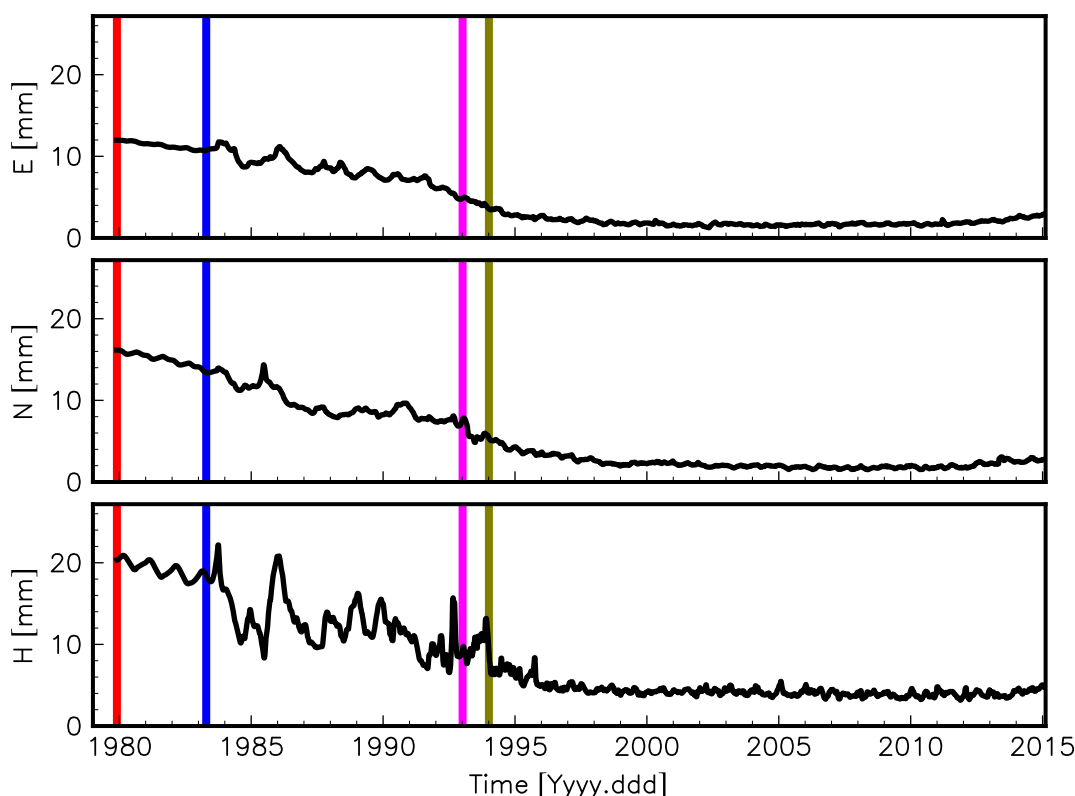


Fig. 3: Temporal variability of the WRMS in the ENU space for KALREF-determined station position time series. WRMS are functions of the post-fit residuals of an intrinsic stack of JTRF2014 SINEX files. Sites exhibiting post-seismic relaxation effects have been removed from the JTRF2014 SINEX files prior to stacking. The solid red vertical line marks the epoch at which VLBI started observing. The solid blue line marks the epoch at which SLR started observing. The solid magenta and green lines mark the epochs at which DORIS and GNSS started observing.

Local Ties and Agreement Between Ties and Space Geodesy

Local tie observations contain terrestrial estimates of SG reference points at co-location sites. During the measurement update, KALREF assimilates tie vectors providing linear constraints in the form of $X_i^C - X_j^C = \Delta\tilde{X}_{ij}$, where X_i^C and X_j^C are the station positions as determined through space-geodesy and $\Delta\tilde{X}_{ij}$ are 2017 the terrestrial tie measurements. Tie vectors are applied only once at the epoch of their measurement. Each of the tie constraints is weighted through the inverse of the measurement covariance matrices scaled by proper

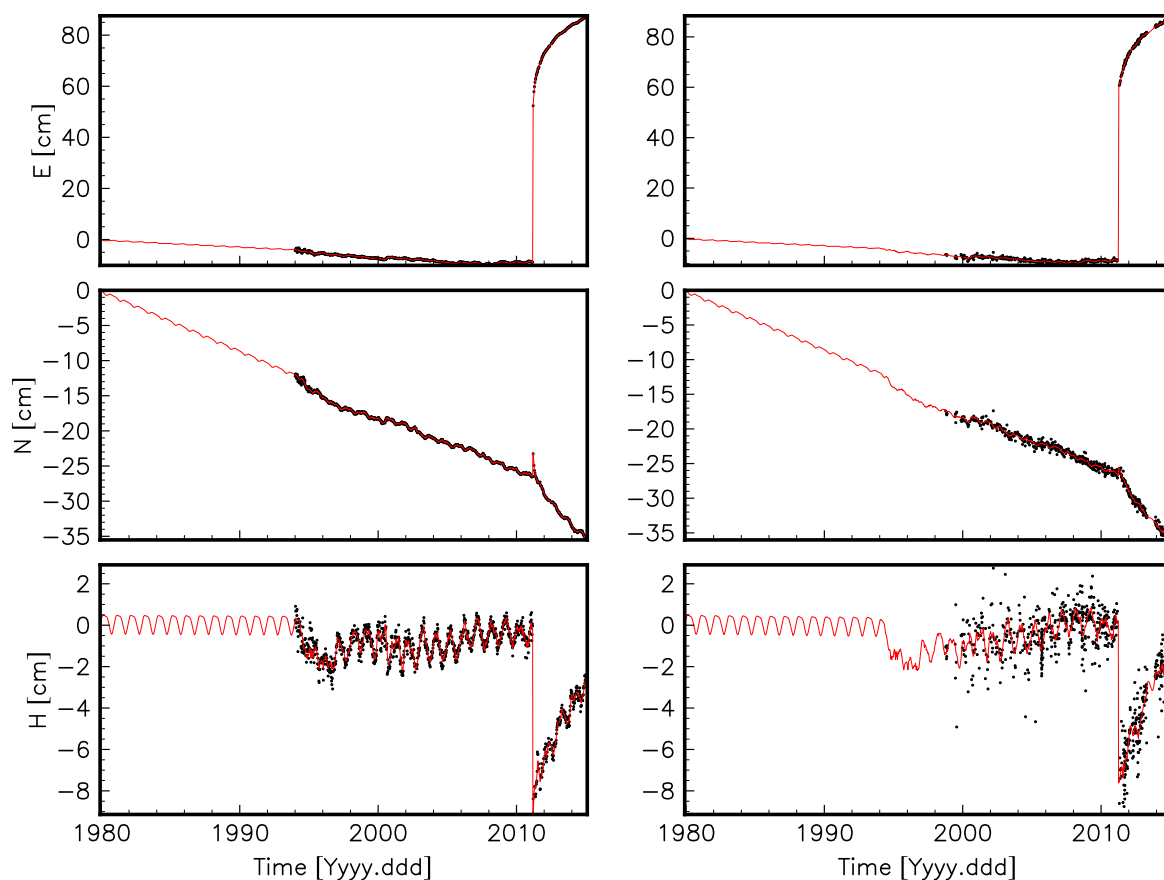


Fig. 4: *Position Time series for the co-located GNSS and VLBI stations at Tsukuba (Japan). The plots in the left panel relate to the GNSS station, whereas those on the right side to VLBI. Black dotted lines represent the station position observations assimilated by KALREF, the red solid lines are the weekly smoothed coordinates obtained as a result of the combination.*

variance factors. In JTRF2014 the optimal set of tie variance factors has been empirically determined as a function of the agreement between SG and terrestrial observations.

Post-fit tie residuals illustrate the agreement between terrestrial tie vector and SG observations. Ideally, in the absence of tie-related biases, the discrepancies between SG and terrestrial tie observations would provide a valuable proxy for assessing the internal accuracy of the SG techniques adopted in the assimilation. In reality, tie- and SG-related biases co-exist thus hindering the interpretation of tie residuals. In order to limit frame distortions in current frame reduction procedures, local ties, rather than SG observations, are down-weighted.

In JTRF2014, we adopted 234 tie vectors extracted from the total set of 142 site tie SINEX files made available by IGN-LAREG. Appendix 1, enclosed at the end of this document, lists the discrepancies for each of the tie vectors computed as differences (SG-Ties).

The results in Table 5 characterize the distribution of the tie residuals constituted by a set of 195 inter-technique terrestrial tie vectors connecting GNSS to the other SG systems. Tie residuals are classified by component in the local ENU space and by SG technique. A larger dispersion is observed in the vertical component of the residuals, with their inter-quartile variation being two to three times larger than the one of the horizontal components. The increased dispersion in the vertical component is suggestive of a poorer consistency (and therefore of a lesser accuracy) among the SG techniques in measuring the Earth radial deformations. Nonetheless tie-related biases affecting to a larger extent the vertical rather than the horizontal component cannot be ruled out. Technique-wise, it is worth observing that the IQR is consistently larger for tie vectors connecting GNSS to DORIS.

Geocenter Motion

Local tie observations and co-motion constraints have been used to connect the four SG techniques and, ultimately, to spatially and temporally transfer the SLR instantaneous CM information to the observing systems for which the geocenter is either poorly defined (such as GNSS and DORIS) or, which are, as is the case for VLBI, insensitive to GM (the product between the gravitational constant and Earth's mass). Properly tied to the SLR-derived CM-centered frame, the unified time series of KALREF-derived station positions from GNSS, DORIS and VLBI can therefore be adopted, in addition to SLR, to estimate Center of Mass to center of Network (CM-CN) offsets.

The JTRF2014-derived geocenter is based upon a selection of 80 stations extending the original ILRS network. Through the adoption of observing systems (GNSS, DORIS and VLBI) linked as a result of the combination to the SLR-derived CM, the ILRS network has been enlarged so as to include 66 stations in the Northern hemisphere and 14 in the

Table 5: *Statistical properties of the distribution of the site tie residuals computed as differences (SG-Ties) between combined space-geodetic and terrestrial tie observations. Statistics are expressed in mm in the ENU space, classified by SG techniques. Only site ties involving connections to GNSS have been considered when computing the values reported in this table. Same naming conventions for the SG techniques apply here (P is GNSS, R is VLBI, L is SLR, D is DORIS). st dev stands for standard deviation, IQR is the inter-quartile range, computed as the difference between the third and first quartile of the residual distribution.*

	N			E			H		
	R-P	L-P	D-P	R-P	L-P	D-P	R-P	L-P	D-P
min	-18.2	-25.2	-26.6	-52.5	-22.0	-35.4	-34.1	-42.4	-109.8
max	39.2	19.0	22.7	16.8	11.1	30.1	98.3	71.1	54.2
median	0.2	0.5	2.5	0.3	-0.4	-1.1	2.8	0.9	-2.2
st dev	10.2	7.2	9.2	10.4	6.6	10.0	20.6	20.7	22.2
IQR	5.0	6.8	11.0	6.0	6.2	11.4	13.8	18.7	20.2

Southern one. Although such configuration is still far from ideal for monitoring the temporal variations of (CM-CN), it is characterized by a better geographical coverage and, as a result of the spatio-temporal interpolations KALREF executes, unaffected by the large temporal turnover of the ILRS network.

The (CM-CN) offsets have been determined by applying the network shift approach [see e.g. 15] to the smoothed time series of station positions outputted by KALREF. The stacking model of Equation 1 has been adopted where the inverse of the measurement full covariance matrices has been used to weight the observations and only translations have been estimated. Internal translational constraints have been applied during the reduction in such a way that the resulting time series shown in Figure 5 are de-meaned and de-trended.

The gray-shaded area in Figure 5 identifies the time span during which only VLBI observations were being assimilated and SLR ranges were not available yet. In this time window, KALREF is backward extrapolating the geocenter information. The orange-shaded area marks the time window during which SLR stations were exclusively tracking LAGEOS 1. The first decade of SLR observations is characterized by large fluctuations of the (CM-CN) offsets which are likely to reflect the poorer data quality. When SLR ranges to LAGEOS 2, Etalon-1 and Etalon-2 were introduced starting from 1993, the quality of the geocenter (CM-CN) tends to improve and the large oscillations typical of the early years disappear. The power spectral density functions represented in the rightmost panels of Figure 5 show evidence of red-like behavior, with the power progressively decreasing as the frequency increases. With their temporal scatter (standard deviation) of 5.3, 4.9, and 10.9 mm on

the T_x , T_y and T_z component respectively, the ILRS-derived geocenter motion time series appear much noisier than the ones determined from JTRF2014. Conversely, the JTRF2014-derived (CM-CN) time series are much smoother with standard deviations of 2.3, 3.0 and 4.8 mm for the T_x , T_y and T_z component, respectively and significantly reduced uncertainties. As a result of our combination approach, the combined station position time series from VLBI, GNSS, SLR and DORIS relate CM to a much larger and stable global SG network to the extent that the KALREF-derived (CM-CN) offsets are likely to better approximate the (CM-CF) motion.

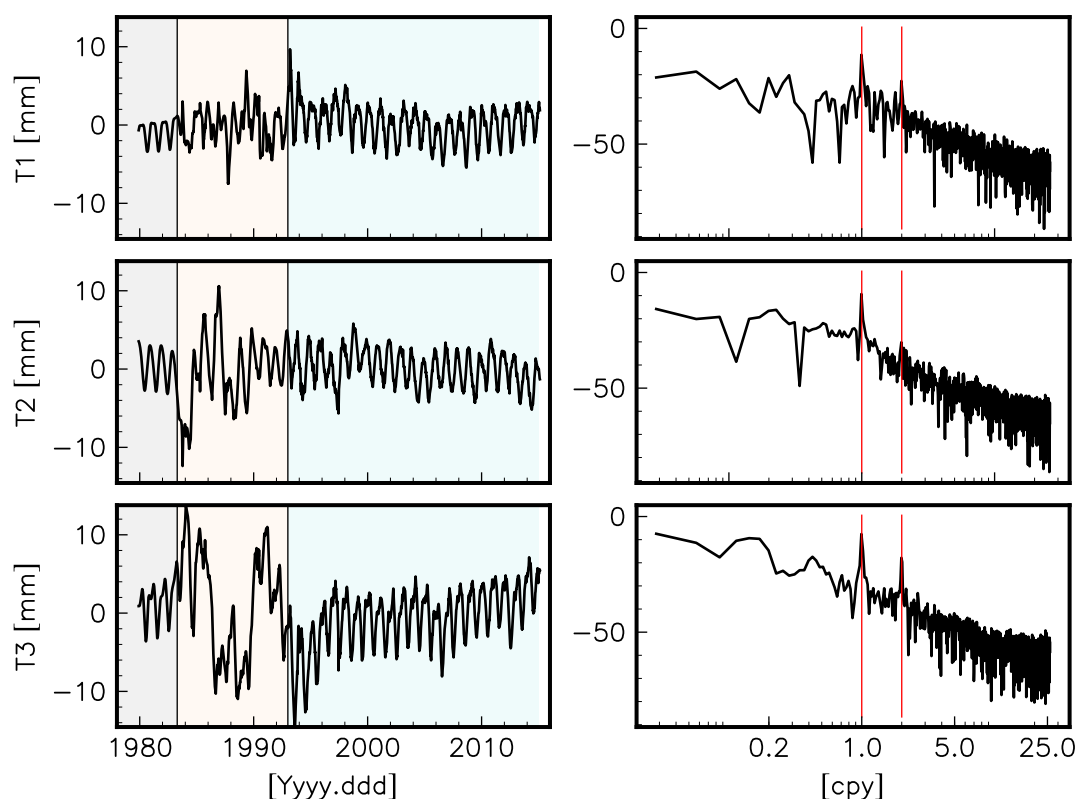


Fig. 5: JTRF2014 geocenter Motion Time Series. Plots on the left side report the time series of the (CM-CN) offsets in mm. The time series WRMS about the mean are computed over the entire time span are 2.2, 2.3 and 3.5 mm for the x (T_1), y (T_2) and z (T_3) components, respectively. The area shaded in gray identifies the time span 1979–1983 when only VLBI was observing and SLR data were not available yet. The orange-shaded area spans the time window 1983–1993 during which only LAGEOS 1 was being tracked and the ILRS solutions are based on fortnightly integrations. The area shaded in cyan spans the time window 1993–2015 during which the ILRS is a multi-satellite solution (LAGEOS 1 and 2 and Etalon 1 and 2 are being tracked) based on weekly integrations. Plots on the right side represent the time series in the spectral domain. Power spectral densities are expressed in $\text{dB mm}^2/\text{cpy}$, whereas frequencies are reported in cpy. Spectral lines at periods of 1 and 0.5 yr are marked in red.

ITRF, JTRF and DTRF

In carrying out the mandate of providing ITRS realizations to the astronomical, geodetic and geophysical communities, the IERS acknowledges contributions from three accredited combination centres hosted by IGN-LAREG, JPL-Caltech, and DGFI-TUM. For the creation of the ITRF2014, three different frame products, consistently computed from the same input SINEX files released by the four SG Technique Centres were provided to IERS for evaluation purposes. The existence of three TRFs independently computed with different input data editing, handling of site ties, and combination schemes offers the possibility to soundly analyse the degree to which the three solutions agree with one another thus shedding light on systematic effects, differences evincing the diverse frame definitions, as well as the minute discrepancies that characterise the EOP series.

Table 6 documents and compares some of the essential features of the frame products maintained by IGN, JPL, and DGFI. In examining aspects related to the frame definition, it is worth observing that the three combination centres adhere to the standard practices described in Chapter 4 of [19] wherein a “frame definition chronology” for all the ITRS realizations, constructed by IGN-LAREG, from ITRF88 through ITRF2008 has also been outlined.

As to establishing the ITRS origin, we note that there have been isolated instances in the past in which both GPS and SLR simultaneously were taken to contribute to the geocentre definition. This practice has been long since dismissed for it has become apparent over the years that GNSS, despite its inherent sensitivity to Earth's GM, has proven deficient in recovering an unbiased CM-CN due to strong correlations between geodetic estimates of satellite clock offsets, station positions, and tropospheric parameters [26]. SLR therefore remains the golden standard for CM-CN determination and origin definition in TRF reductions, as evinced by Table 6.

The frame orientation is, unlike the origin, purely conventional and lately defined by *inheritance*, i.e. by applying analytical constraints that enforce the absence of residual rotations with respect to the most recent ITRS realizations (ITRF08 in the case of TRF2014 products, ITRF05 in the case of ITRF2008, and so forth). The frame scale, intimately related to the metric structure of the 3D Euclidean space, is – and has been in general – obtained by averaging radio-interferometric (VLBI) and optical (SLR) scales. Yet there have been instances in the relatively recent past (ITRF2005) in which the ITRF scale was only defined through VLBI, thus discarding the SLR contribution. Despite its sizeable dispersion (in the order of 10 mm about its mean value), VLBI scale evinces a larger stability as opposed to SLR's which appears to be affected by conspicuous time-variable biases [4].

According to the sets of conventional definitions reported in Chapter 4 of [19], the realization of a TRS relies on the notion of *regularized coordinates* in their relation to the instantaneous position of points (i.e. geodetic stations) anchored to Earth's crust:

$$X(t) = X^R(t) + \sum_i \Delta X_i(t). \quad (8)$$

The decomposition in Equation 8 dissects the instantaneous – and therefore time-variable – station position $X(t)$ into regularized coordinates $X^R(t)$ superimposed to high-frequency (mostly) tidal-related displacements $\Delta X_i(t)$; The former are directly provided by the frame realization, the latter are accessible through conventional geophysical models which are removed at the observation level within the SG reduction procedures.

Both TRS realizations from IGN and DGFI provide the users with regularized coordinates in *parameterized* form through monolithic SINEX files containing geocentric station positions expressed at a reference epoch, velocities, and EOPs along with their full covariance matrix.

In acknowledging the role that non-linear phenomena have on the time-varying deformable Earth and their impact on the frame quality, IGN chose to enhance, for the ITRF2014, its stacking model by adjusting periodic and post-seismic displacement (PSD) terms. Station harmonic motions and PSD for seismically active sites are themselves provided in parameterized form and can be utilized to construct more accurate station motion predictions. Due to the presence of PSD terms, the ITRF2014 station motion model is by far the most comprehensive among the three TRF products.

An opposing strategy for handling non-linearities is utilized by DGFI in DTRF2014. In analogy with standard processing of GRACE data where high-frequency non-tidal mass variability is removed from the range-rate observations and can be optionally restored by the users [11], DGFI applies a remove-restore approach to its frame reduction. Rather than fitting harmonic terms to position time series, DGFI removes from the SG coordinates geophysical models of non-tidal elastic displacements whose temporal and spatial sampling has been made consistent via spatial interpolation and numerical integration with SG data, and produces after-the-fact piecewise linear estimates of station positions. DTRF users, provided with the removed models, may optionally restore the non-tidal loading (NTL) variability into the frame product [32].

JPL-Caltech adopts a different approach to determining TRFs that relies on a Kalman filter and RTS smoother algorithm: JTRF users are provided with time series of quasi instantaneous geocentric position complying with the additive model outlined in Equation 6. Such geocentric time series consistently expressed in a common and rigorously

defined frame, from long multi-technique SG records of the Earth's deformation, optimally assimilated and smoothed over the data time span of the combination (circa 1980–2015 for JTRF2014). As discussed in Section *Kinematic Model and Time update*, the station kinematic model accounts for trend terms and seasonal oscillators.

The adoption of process noise in the form of *random walk* imparts to JPL frame products a distinctive character. In allowing for deviations from the station motion model, the term ε_k in Equation 3 captures non-secular and non-seasonal components of the displacements thus enabling in principle a more realistic description of the time-variable nature of the deformable solid Earth.

To the extent that a random walk-based process noise is able to accurately represent the non-secular and non-seasonal components of the Earth deformation, JPL releases a frame product that turns out to be conceptually closer to a tide-free quasi instantaneous frame, rather than to a purely regularized product such as ITRF and DTRF (cf Equation 8). Moreover, JTRF being a sub-secular frame, its coordinates embed the quasi instantaneous variability due to smoothed SLR-sensed geo-center motion as well as the fluctuations of the quasi instantaneous VLBI/SLR scale. Users are therefore warned that a larger degree of variability is inherently present in JTRF, when compared to regularized and parameterized products such as ITRF and DTRF.

As mentioned in passing, when SG observations are no longer assimilable, KALREF may be run in predictive mode by adopting the propagator Φ_k in Equation 2 to project the state vector into the future without executing the measurement update. Unconstrained by SG data, KALREF forward filtering yields frame predictions that can be as usual outputted and delivered in form of SINEX files. Predictions are all of the more crucial in time series-based products such as JTRF in that they provide the only way to access the frame beyond its assimilation time span.

KALREF supports production of prediction SINEX files; However, these were not released for JTRF2014. Predictions are considered to be, at the current stage of development, experimental products still exhibiting deficiencies, particularly in relation to SG sites affected by post-seismic relaxation. Unlike ITRF, KALREF does not implement yet PSD terms in the state-space model of Equation 2. As a result, predictions for seismic sites are largely inaccurate and not adoptable in current SG reduction procedures. A further aspect, currently under investigation, relates to the selection of the most appropriate process noise capable of producing as accurate predictions as possible without degrading the temporal frame stability [35].

Unlike JTRF, ITRF and DTRF, both adopting a least square-based framework, do not allow for process noise in their frame reductions. In both products the stochastic component is rigorously accounted for only

through the measurement covariance matrices (as reported in the input SINEX files) and propagated into the least square estimates and their uncertainties by means of standard covariance transformation laws.

ITRF products are computed with the software package CATREF built upon the framework of the *minimal constraint theory* [see e.g. 34]. CATREF, like KALREF, makes extensive use of the notion of similarity transformation whose constitutive elements are the Helmert transformation parameters. From the conceptual standpoint, similarities act on and between 3D Euclidean spaces by preserving their inherent geometrical structures (i.e. the “*shape*”). From the empirical standpoint, the Helmert transformation parameters can be conveniently adopted as metrics helping assess the degree to which two frames are reciprocally biased.

Unlike ITRF and JTRF, the DTRF approach to TRF analysis avoids the direct adoption of the similarity transformations and relies on the accumulation and combination of datum-free, rank-deficient Normal Equations constructed from the SG inputs [31]. Though not explicitly dependent upon the formulation of Helmert transformation parameters, DOGS also makes somewhat implicit use of a minimal constraint framework whenever *datum constraints* are either removed from or applied to the SG data [31].

Although the three combined products stem from identical input data sets, mutual discrepancies are expected for a variety of reasons involving, on the one hand, the different computational approaches and, on the other, the way in which systematic effects inherent in the observations are treated within the frame reductions. Both SG and local tie observations are known to be affected, to a various degree, by systematic effects not properly reflected in the measurement covariance matrices. Furthermore, relative weighting of the SG solutions and local tie observations, detection of position offsets, modelling of non-linear components of station motions, constitute additional factors potentially contributing to discrepancies in the three frame products.

The following Sections are entirely devoted to constructing metrics of frame consistency. To assess the extent to which the three frame solutions differ to one another, we performed inter-comparisons between JTRF2014, ITRF2014 and DTRF2014 based on (i) the determination of the time-variable offsets in terms of Helmert transformation parameters between the three frames determined in pairs with respect to ITRF2014 chosen as a reference and (ii) the analyses of the three different Earth Orientation series.

Helmert Transformation Parameters

The analysis of the time-variable offsets of the Helmert transformation parameters offers insights as to the way in which the three combined products have been constructed and lends itself particularly well to the

definition of long-term consistency metrics (cf Table 7). The Helmert parameters described in this section provide least squares estimates of the linearized similarity transformation

$$X_i = X_{j,d} + T + \lambda X_{j,d} + \mathbf{R}X_{j,d} \quad (9)$$

where $X_{j,d}$ denotes either the JTRF2014 weekly position vector or the DTRF2014 station positions projected at the epoch t_k , X_i is the ITRF2014 station positions projected at the epoch t_k , T , λ and $\mathbf{R}$ are the translation vector, the scale factor and the antisymmetric rotation matrix mapping J(D)TRF2014 to ITRF2014 at the epoch t_k , respectively. The inverse of the covariance matrices reported in the TRF SINEX files has been adopted to weight the station position pseudo-observations from the three frames. Only ITRF2014 and DTRF2014 segments active at the epoch t_k have been considered in the least squares estimation problem. Active seismic sites have been removed from the frame products because, although ITRF2014 parameterizes post-seismic displacements and JTRF2014 tracks them thanks to station position process noise, DTRF2014 adopts piece-wise linear representation for stations characterised by post-seismic relaxation. In this analysis, time-dependent NTL corrections provided by DTRF2014 are not applied, because a rigorous covariance propagation of the models into the long-term frame is not feasible.

The time series shown in Figures 6 and 7 represent time-varying Helmerts mapping JTRF2014 to the projected ITRF2014 (right panels) and DTRF2014 (left panels). The first three plots from top of Figure 6 relate to the translations and point out the time-variable offset existing between the secular I(D)TRF2014 origins and the quasi instantaneous origin adopted by construction by JTRF2014. With the exception of Tx in the early years, the offsets to ITRF2014 and DTRF2014 evidence akin patterns and comparable temporal structures. The translation offsets in the X, Y and Z components exhibit, as expected, a seasonal signature mostly related to the sub-secular variation of the geocenter motion, unaccounted for in the I(D)TRF2014 combination process. If we were to restore time-dependent NTL corrections into DTRF2014, the translation offsets of Figure 6 would then represent discrepancies between JTRF2014 sub-secular geocenter motion and that implied by the non-tidal loading models adopted in the DTRF analyses. To the extent that such models provide a geophysically accurate representation of the degree-1 surface deformation signature, we expect translation offsets to diminish considerably when transforming JTRF2014 to DTRF2014+NTL.

Larger offset variations are observed in T_z and, to a lesser degree in T_x and T_y as well, during the time period 1984-1990, corresponding to the early years of the SLR observations, when only LAGEOS 1 was being tracked and, as a result of that, the (CM-CN) geocenter motion sensed by SLR was much noisier. After 1990, the origin differences appear much stabler over time.

The scale transformations to ITRF and DTRF also exhibit akin temporal variations with larger fluctuations in the early years which tend to subside after the introduction of LAGEOS-2 SLR observations in 1993. Afterwards, the λ 's to both ITRF and DTRF exhibit a seasonal signature modulated with a quasi-decadal oscillation. It is worth observing, in this instance, that the estimates of the scale parameters through Equation 9 and their accurate interpretation are complicated by the existence of non-negligible mutual correlations among $(T, \lambda, \mathbf{R})$, possibly enhanced by the inhomogeneous distribution of the global SG networks.

Besides, Equation 9 is also prone to aliasing phenomena, mostly due to unwanted leakage of non-linear vertical station motion into the scale. This is particularly true when, as is the case with the transformation between the non-linear JTRF to the linear I(D)TRF, the assumption of similarity upon which Equation 9 is based is inherently violated. The polyhedrons X_i and X_d evolve linearly in time and are, in fact, not isomorphic to the non-linear X_j which, by virtue of the process noise, absorbs non-secular and non-seasonal motions. These two factors might partly explain the periodic signals present in the scale transformation, thus suggesting their artificial nature.

With WRMS about the linear trend smaller than 1 mm, the rotational Helmert parameters reported in Figure 7 exhibit the least fluctuations. The estimates of offsets and drifts for each of the Helmert parameters gathered in Table 7 characterize the secular differences among the three frames and quantify their long-term agreement in terms of origin, scale, and rotational alignment. With the exception of T_z and λ , the offsets are well within the 1 mm-level. We speculate the differences in T_z may be due to a different handling of local tie weighting within the JTRF–ITRF combinations.

More subtle to interpret is the scale parameter's behaviour. Since both JTRF and DTRF opted not to adjust VLBI's and SLR's scales in their combination schemes, their long-term scales appear to be, as evidenced by the values reported in Table 7, in larger agreement. Conversely, because ITRF2014 adjusted the SLR scale to an offset VLBI scale so as to account for the systematic difference between the two systems, the 1.7 mm offset at Jan 1 2005 in Table 7 mostly reflects the different scale definition adopted in ITRF2014 and JTRF2014.

Also, we observe that the time derivatives of the Helmert's mapping JTRF2014 to ITRF2014 are in the order of 0.18 mm/yr and even smaller

for DTRF2014 (with the exception of $\dot{T}_z$ and $\dot{R}_y$). These results therefore indicate the level of long-term consistency between the three products is in the order of 0.18 mm/yr.

Table 6: *Synoptic outline of the combined products released by the official IERS ITRS Combination centres hosted at LAREG-IGN (ITRF), JPL-Caltech (JTRF), DGFI-TUM (DTRF). Additional pieces of information on the TRS-related activities promoted under the aegis of the IERS can be found on <https://www.iers.org/iers/en/organization/itrscmbinationcentres/itrsc.html>.*

	JTRF	ITRF	DTRF
Combination Center	JPL-Caltech	LAREG-IGN	DGFI-TUM
Computational Code	KALREF	CATREF	DOGS
Frame Type	Time Series	Parametric	Parametric
Estimator	Kalman Filter	Least-square	Least-square ^(a)
Process Noise	Random Walk	None	None
Origin	Instantaneous SLR CM	Long-term SLR CM	Long-term SLR CM
Scale	Instantaneous VLBI/SLR	VLBI/SLR ^(b)	VLBI/SLR ^(c)
Orientation	NNR ^(d) to ITRF2008	NNR to ITRF2008	NNR to ITRF2008
Station Motion Model	Trend, Annual, Semi-Annual	Trend, Periodic, PSD ^(e)	Trend, Non-Tidal Corrections

^(a) Based on the inversion of accumulated Normal Equations

^(b) Simple Average of VLBI and SLR Scales

^(c) Weighted Average of VLBI and SLR Scales

^(d) NNR stands for No-Net-Rotation

^(e) PSD stands for Post-Seismic-Displacements

Earth Orientation Parameters

In all of three combined products, EOPs are adjusted conjointly with the global TRFs. Polar motion and polar motion rates therefore provide strong constraints ideally acting as inter-technique space-ties [see e.g. 22,23].

Considering the duality between frame rotational parameters and (x_p, y_p, UT) evidenced in Equation 5, the comparative analyses of the Earth Orientation series can be used to assess the degree of mutual consistency of ITRF, JTRF, and DTRF and to shed some light into the subtle differences characterizing the three products.

To verify the existence of systematisms affecting the three EOP series, in a first stage we form pair-wise differences to ITRF2014 restricting the analysis to the time span 1998–2015. In this exercise and in all the following analyses, prior to determining the differences, EOP interpolated values, purely based on a random walk model and unconstrained by actual measurements of the Earth rotational state, have been removed from the JPL series.

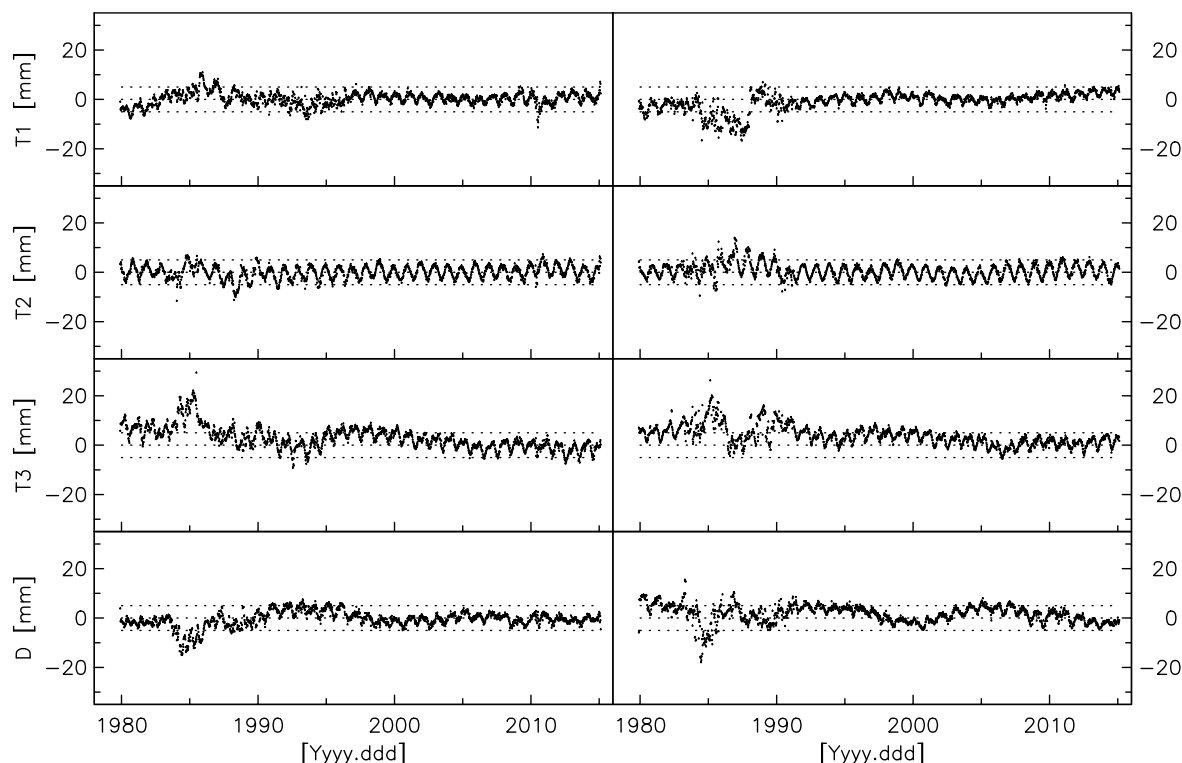


Fig. 6: Time series of the Helmert Transformation parameters (translations and scale) from JTRF to ITRF/DTRF. Left panels illustrate Helmert offsets between JTRF and DTRF, whereas panels on the right are offsets between JTRF and ITRF. The dotted lines in all the panels represent the bounded region $[-10, 10]$. Units are mm.

As evidenced by the plots in Figure 8, the time series of the polar motion differences to ITRF2014 are both characterized by conspicuous residual signals in the form of linear trends and periodic signals at seasonal frequencies, whereas polar motion rates, UT and LOD differences are substantially flat.

We observe that, as can be seen from the least squares fits of Table 8, the linear trends of the pole coordinate differences are in the order of a few micro-arcseconds. With a value of $5.35 \mu\text{as}/\text{day}$ on YPO, the largest rate is found for the JTRF-to-ITRF differences. Likewise, the seasonal amplitudes of the XPO and YPO JTRF-to-ITRF differences are the highest.

To isolate the source of such perturbations, an independent Earth orientation series with signal-to-noise ratio comparable to the combined products would be needed. For this purpose, we adopt COMB2016,

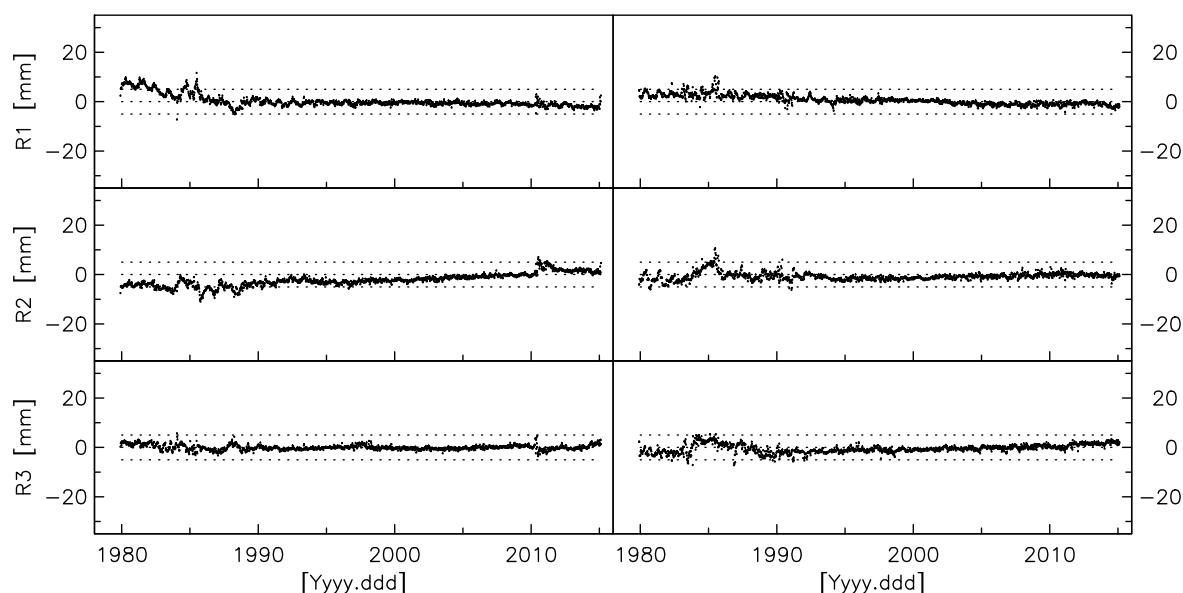


Fig. 7: Time series of the Helmert Transformation parameters (rotations) from JTRF to ITRF/DTRF. Left panels illustrate Helmert offsets between JTRF and DTRF, whereas panels on the right are offsets between JTRF and ITRF. The dotted lines in all the panels represent the bounded region $[-10, 10]$. Units are mm.

the EOP series that JPL constructs with a Kalman filter approach by combining an ensemble of optical astrometry and SG observations based on LLR, SLR, VLBI, and GPS spanning the time window 1976–2017. EOP data are calibrated in isolation, i.e. inter-technique biases and rate biases are determined by disassociating the observations from their underlying TRFs [21].

Though not entirely independent of the inputs employed in TRF reductions, COMB makes additional use of astrometric and LLR data unaccounted for in IERS TRF combinations and suffers less from the adverse effects of multiple reference frame changes plaguing products such as the operational IGS polar motion series.

Moreover, COMB2016 series is rotationally consistent with ITRF2014 and is sampled and provided at daily intervals available at, unlike analogous products such as IERSC04 [6], either noon or midnight. This last feature is particularly appealing when comparisons to TRF-related

products are needed since combined TRF EOPs are, unlike IERS04, traditionally outputted at noon.

That COMB2016 is rotationally consistent with ITRF2014 can be deduced from the estimates of biases and rates to ITRF reported in Table 9, which are the least found. When compared to COMB2016, all of the three pole time series bear indication of corruption to a varying degree at seasonal frequencies (particularly at the annual). As far as XPO, the level of agreement of the annual signal of the three series to COMB is within the range 6–9 μas . At semi-annual periods, DTRF2014 differences appear to be characterised by larger amplitudes in the order of 9 μas . We found the differences JTRF2014 to COMB2016 polar motions are characterised by annual amplitudes markedly larger for YPO (cf Table 9). We speculate the residual seasonal signals in the JTRF2014 polar motion may result from the inconsistency between the daily resolution of the EOPs and the linear site motion approximation of the ITRF2008 adopted to define the orientation of the non-linear JTRF2014.

Likewise, it cannot be ruled out at this stage of the analysis that unwanted systematic perturbations to the EOP time series have been introduced both by IGN, when fitting seasonal terms during the single-technique stacks, and DGFI, during the removal of NTL corrections.

Incidentally, we observe that, when all of the systematic effects are removed, the dispersions of the residuals as quantified by the RMS are consistently smaller for JTRF. Yet the RMS differences are minute, often in the order of a few micro-arcseconds and therefore likely to be below noise level.

If we circle back to the plots of Figure 8, we notice that the UT dispersion is visibly larger for the DTRF differences to ITRF (cf also RMS in the Table 8). Likewise, the dispersion of polar motion rates and LOD residuals are found to be the largest for the DTRF differences to ITRF, with RMS values one order of magnitude larger than JTRF. We speculate the larger dispersions of UT and LOD from DTRF2014 may be due to a different handling of the input EOP data within the DTRF processing scheme: DGFI is the only combination center combining LOD observations from GNSS and SLR (see comparative Table 10). Indeed, the adoption of satellite-derived LOD in EOP combinations is still rather controversial: GNSS-derived LOD appears to be affected by time-varying biases which are only partially mitigated in the IGS reprocessing [27]. Likewise, ILRS-derived LOD, far from being constrained by a robust multi-satellite geometry as described in [8], may still suffer from sizeable correlations with orbital parameters such as the nodal precession rate.

To assess the uncertainty of the combined polar motion, UT and their rates, a three-corner hat (TCH) approach has been applied to the Earth

Orientation series from JPL, IGN, and DGFI. Only simultaneous measurements of the Earth rotational state common to the three series in the time window 1998–2015 have been used in this analysis. TCH has been applied by following the implementation outlined in [20] where the authors, in addition to computing the unknown process noise variance of each of the three time series, also solve for their mutual correlations. Additional constraints enforcing the positive definiteness of the covariance matrix of the unknowns have also been implemented.

TCH operates by forming pair-wise differences between time-based measurements of the same physical processes from three (or more) observing systems. Implicit in TCH is the idea that, when forming the processes of the differences, common-mode signals/errors are eliminated in such a way that the TCH-derived uncertainties allegedly represent the variance of the process noise associated with each of the series.

As evidenced by the results in Table 8, the time series of the EOP differences to ITRF2014 are both characterized by significant residual signals (trends and seasonals), none of which has been removed prior to forming differences. Hence the TCH results reported in Table 11 may be affected to some degree by the different character of the seasonal and linear trend terms described in Table 8.

With UT- and LOD-related uncertainties being much larger for DTRF than the other centres, the results of Table 11 corroborate the inferences about the adverse effects that the adoption of satellite-derived LOD observations has on UT in the DGFI combination. DTRF-derived polar motion rates are also characterized by uncertainties one order of magnitude larger than ITRF's and JTRF's.

With the only exception of UT, ITRF2014's EOPs, followed by JTRF2014's, turn out to be characterised by the smallest uncertainties. The YPO uncertainty for JTRF2014 is the highest found, and this is not surprising considering the fact that TCH is most likely to absorb part of the anomalously large seasonal variability affecting JPL's YPO (cf Table 8). Incidentally we observe that YPO from DTRF2014 appears to be the preciseest in the TCH sense.

Though highly appealing for its straightforward analytical formulation, TCH relies on a set of assumptions which appear to be too restrictive when applied to potentially correlated sets of precise observations of the Earth rotational state.

The assumption of absence of correlation between the three classes of observations and their underlying process noise is barely acceptable, considering the fact that the three solutions stem from the same input data. The modified TCH approach here implemented tries to overcome such limitation by introducing mutual correlations as additional unknowns in the estimation problems. [20].

Even more critical is the presence of temporally correlated noise processes affecting to a various extent the EOP series which TCH is not able by design to account for. Tests have been conducted on simulated data sets in order to assess the impact of time-correlated noise, such as random walk, on TCH results. Our simulations show that as the random walk levels injected in the time series increase, TCH tends to overestimate the uncertainties and appears unable to correctly recover the true uncertainties.

A more sophisticated approach to assessing the intrinsic noise level associated with each of the three EOP products blends standard time- and frequency-domain techniques allowing for a more accurate representation of the frequency-dependent nature of the EOP process noise. By recognizing that low-order autoregressive (AR) processes are fit to approximate the background noise in EOP series, we estimate the AR-related parameters in the frequency domain and we adopt the AR-related white noise to quantify the noise level in each series. In the following, we show how such an approach can be easily applied to polar motion data.

That standard Fourier analyses of EOP parameters bear uncontrollable evidence of processes wherein power is enhanced at lowest frequencies and monotonically decays as the frequency increase can be easily seen in Figure 10, where the retrograde/prograde amplitude spectrum (black solid line) of JTRF2014 polar motion is represented.

We observe that, although x_p and y_p have been both detrended before being Fourier transformed, the polar motion spectrum exhibits a considerably high dynamical range in the order of 10^3 . To minimize spectral leakage and aliasing, the polar motion observations have been tapered with discrete prolate spherical sequences characterized by maximal energy concentration and the final amplitude spectrum has been determined through an adaptively weighted average of Slepian-tapered “eigenspectra” as described in [18]. We made sure the time product bandwidth selected for the multi-tapering would not cause excessive spectral smoothing and, at the same time, allow for an adequate representation of the high dynamic range of the process.

To suppress peaks across all of the spectral frequencies, a median filter with moving window of semi-width of 0.004 cpd has been run on the spectrum (thick gray line in Figure 10). Once the peaks largely corresponding to signal of geophysical nature are removed, the median spectrum can be taken to represent the frequency-dependent background noise level associated with polar motion data.

The simplest description in the time domain of a discrete finite series

characterized by red noise is a causal first-order autoregressive process – termed as AR(1) in the following:

$$x_n = \phi x_{n-1} + w_n \quad \phi \in]0, 1[\quad (10)$$

where the integer $n = 1, \dots, N$ denotes the discrete time increments in units of the sampling interval Δt (day, in this case), the coefficient ϕ quantifies the degree of persistence between consecutive terms in the series, $w_n \sim \mathcal{N}(0, \sigma^2)$ is the n -th realization of a Gaussian process with zero-mean and variance σ^2 . Positive values of ϕ are indicative of a spectrum wherein the power of low frequency components is enhanced, as is the case for polar motion and most geophysical processes. Negative values of ϕ conversely describe non-causal and explosive processes whose power spectrum is monotonically increasing with f and therefore enhanced at higher frequencies (the so-called blue noise). The power spectral density of an AR(1) process can be described as follows [see e.g. 33]:

$$S(f) = \frac{\sigma^2}{1 - 2\phi \cos(\frac{\pi f}{f_n}) + \phi^2} \quad (11)$$

where f and f_n denote the frequency and the Nyquist frequency, respectively. We observe that, when ϕ is positive and smaller than one, Equation 11 is representative of a power spectral density decaying to zero for increasing frequencies. When $\phi = 1$, the AR(1) degenerates to a random-walk and the power spectrum, theoretically undefined for non-stationary processes, is discontinuous at $f = 0$. When ϕ approaches zero, Equation 11 degenerates to a pure white noise spectrum.

The spectrum of Equation 11 is a non-linear function in the parameters (σ, ϕ) , which can be estimated via Bayesian regression from a realization of the empirical spectrum (i.e. the thick gray line in Figure 10).

Uninformative (i.e. uniform) priors have been adopted on (σ, ϕ) with additional constraints enforcing the positivity of the variance factor and restricting ϕ to $]0, 1[$.

To the extent that the estimate of the AR(1) parameters leads to an accurate representation of the polar motion background noise level, then Equation 11 can be effectively used to define a frequency-dependent signal-to-noise ratio for polar motion. By inspecting Figure 10, we note that the AR(1) representation (red line) might underfit the high-frequency portion of the empirical spectrum (gray line).

Table 12 collects median values of the parameters drawn from the posterior distribution. With estimates of ϕ close to unity in all cases, the background noise process in EOP series appears to be consistent with random walk. Since σ quantifies the amount of white noise in the EOP series, it conveys an informative content analogous to the TCH

uncertainties reported in Table 11, with the only difference that TCH has been run separately on the two equatorial components XPO and YPO, whereas the estimates of Table 12 are indicative of the complex polar motion signal $p(t) = x_p(t) - iy_p(t)$. The direct comparison of the results reported in Table 11 with those of Table 12 points out that AR(1)-related white noise estimates are on the whole smaller than TCH's, thus corroborating the hypothesis that TCH may overestimate the polar motion uncertainties. The spectral estimates of the white noise levels for the three EOP series are much closer to one another than TCH's. The largest differences being in the order of $\approx 3 \mu\text{as}$, they are likely to be well below the noise level. Therefore the AR(1)-related estimates appear to suggest that the polar motion series are of comparable quality. Incidentally, we note that DTRF polar motion is, in the AR(1) sense, characterized by the lowest white noise level whereas COMB polar motion has the highest.

Some Final Considerations

JTRF2014 is a sub-secular TRF based on a Kalman filter and RTS smoother and obtained by combining SG inputs from VLBI, SLR, GNSS, and DORIS. The multi-technique position time series associated with JTRF2014 are accurately linked to the SLR CM frame through the usage of local ties and the implementation of co-motion constraints.

Though still far from representing a standard operational TRF product, JTRF offers to the geodetic and geophysical community tantalizing features. With its time series representation, JTRF gives access to a quasi-instantaneous CM as sensed by SLR as well as to a quasi-instantaneous scale as realized by VLBI and SLR which, if accurately realized by data, can be used by geodetic systems with inaccurate scale information for monitoring time-variable station coordinates.

The time-variable geocentric station coordinates appear to describe the Earth deformation reasonably well during tracking periods and short data gaps. The JTRF2014 unified time series have been used to infer temporal variations of (CM-CN) offsets which appear to be in good agreement with the quasi-independent geocenter motion estimated via spectral inversion of GNSS, GRACE and ECCO-derived OBP variations [37].

In an effort to modernize the computational code, improvements to KALREF are currently being tested. These relate to e.g. strategies for providing accurate predictions of the station motions, data-editing pipelines, break detection, the transition to a more flexible and numerically stabler square-root information filter with a time-variable step, the adoption of a dynamical model for daily EOPs.

As efforts to improve KALREF and to research time-series based TRFs continue, positive feedback on JTRF2014 has been received. When adopted in precise orbit determination of high and low Earth orbiters

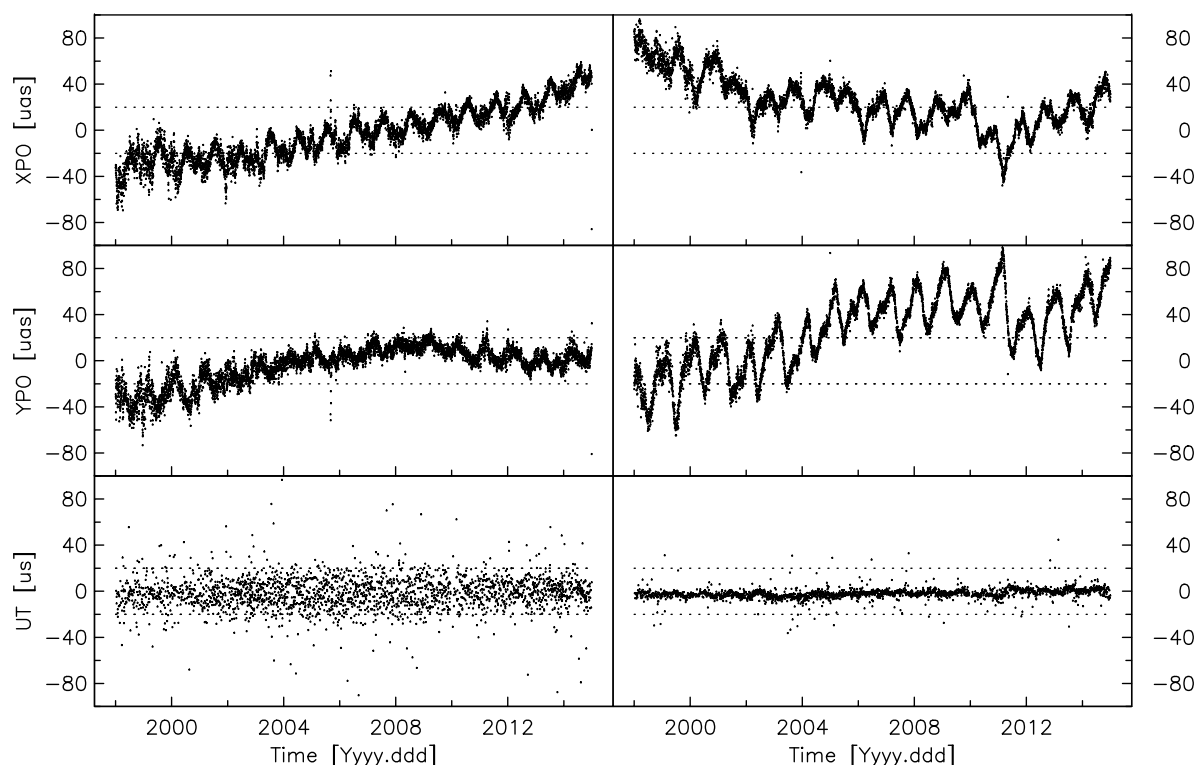


Fig. 8: Time series of the polar motion differences to ITRF. Left panels illustrate differences (DTRF–ITRF), whereas panels on the right are differences (JTRF–ITRF). Dotted black lines in the plots mark the range $[-20.0, 20.0]$. Values of the EOP differences larger than $|100.0|$ have been filtered out. Units are μas for the pole coordinates (x_p, y_p), and $\mu\text{sec/d}$ for UT.

JTRF2014-derived time series are reported to make valuable contributions in terms of reduction of post-fit residuals and an improved geocenter determination [see e.g. 39, 29]

The inter-comparisons among ITRF, JTRF, and DTRF suggest a high level of long-term consistency of the three products: the offsets at January 1, 2005 of the Helmert transformation parameters relating JTRF2014 and DTRF2014 to ITRF2014 are in the order of 1 mm with the exception of the JTRF-to-ITRF scale, whose larger offset (1.70 mm) is attributable to the different strategy adopted in averaging the VLBI/SLR scale information. The scale offset mapping JTRF to DTRF is close to zero with no significant drift found.

In this regard, we wish to warn the readers not to misinterpret such a finding: The absence of scale offset and drift between the JPL and DGFI solution merely suggests that the two TRFs adopted a somewhat

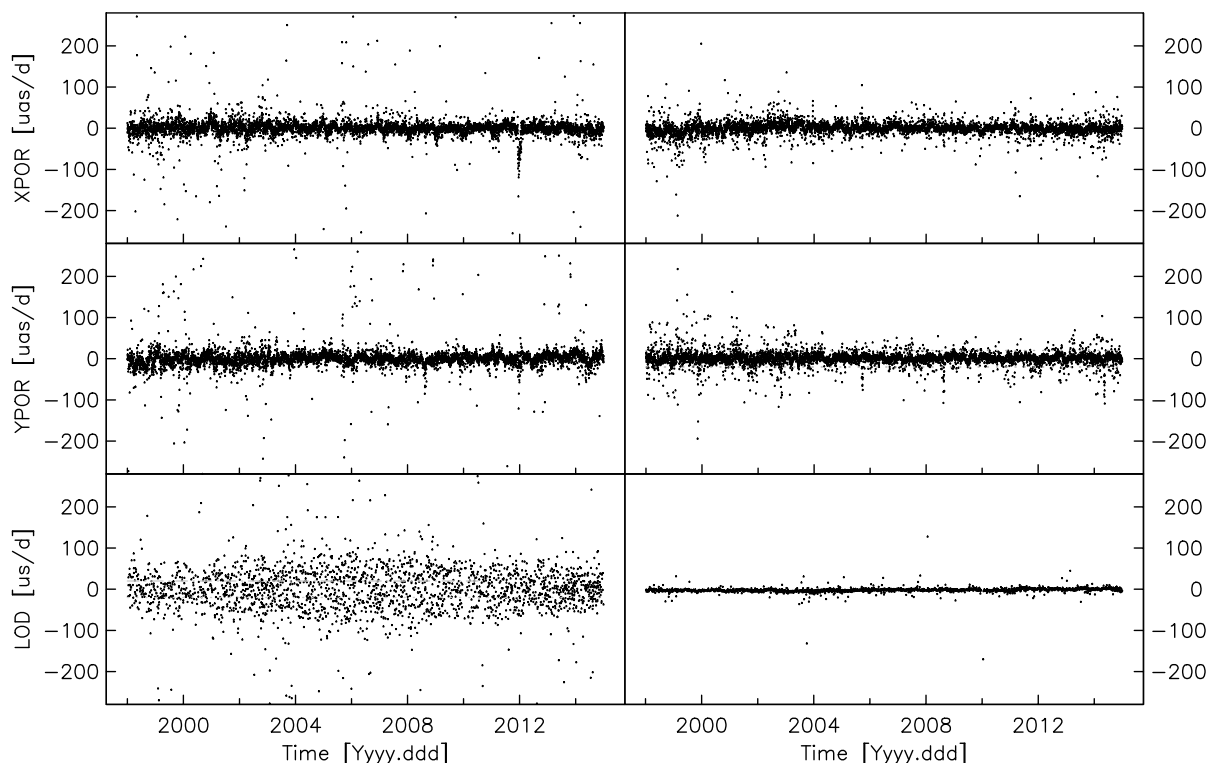


Fig. 9: Time series of the polar motion rates differences to ITRF. Left panels illustrate differences ($DTRF-ITRF$), whereas panels on the right are differences ($JTRF-ITRF$). Units are $\mu as/d$ for the pole coordinates ($\dot{x}_p, \dot{y}_p$), and $\mu s/d$ for LOD .

akin scale definition, i.e. neither VLBI's nor SLR's scale have been adjusted during the combination. No inference can be made from the results presented in Table 7 as to the existence of a VLBI/SLR scale bias. The determination of the time variable nature of the VLBI/SLR scale bias requires special analyses of the IVS and ILRS input data sets tied through local ties, whose results were not reported in this note. Drifts of the Helmert transformation parameters between ITRF and JTRF are found to be smaller than 0.18 mm/yr. The drifts between DTRF and JTRF are even smaller, with the exception of a large trend (-0.42 mm/yr) found on T_z .

It is important to stress that the results presented in Section *ITRF*, *JTRF*, and *DTRF* uniquely address reciprocal consistency of the three frame products. No inference can be made at this stage of the analysis regarding TRF accuracy (i.e. degree of closeness to some external "truth").

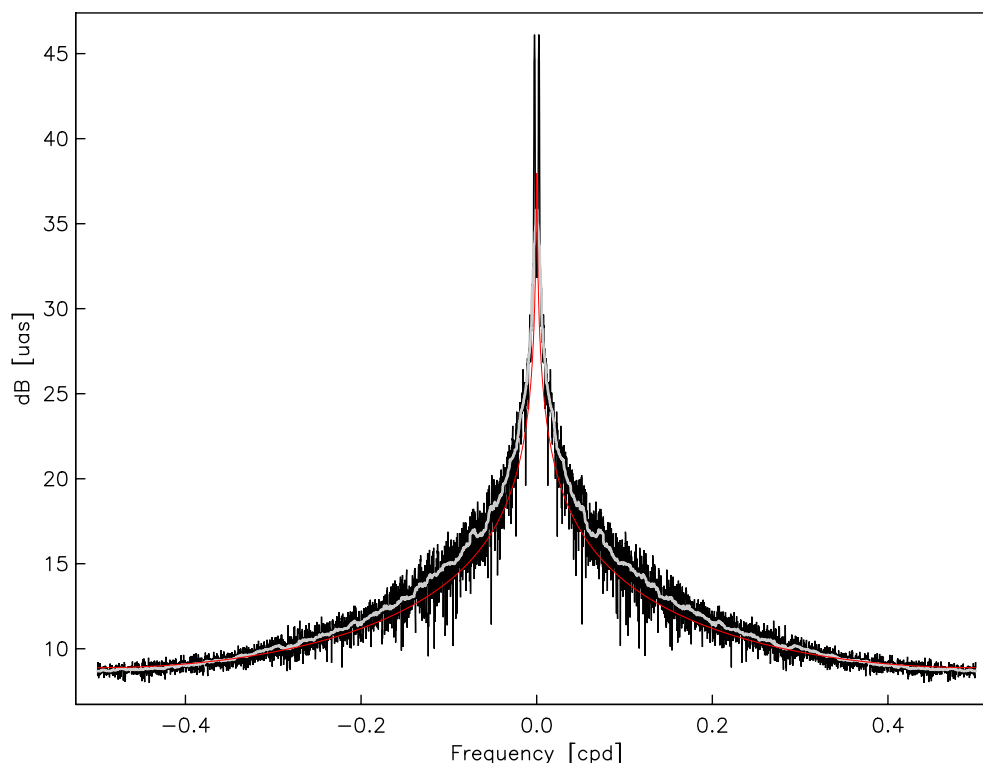


Fig. 10: *Amplitude Spectrum of the polar motion signal ($x_p - iy_p$) from JTRF2014. The black solid curve represents the adaptively weighted amplitude spectrum determined via multitaper approach. The time-bandwidth product NW has been set to 3, and the corresponding $(2NW-1)$ Slepian functions were used as tapers. The solid gray curve reports the median spectrum determined from the black line with a window of semi-width w set to 0.004 cpd.*

Users should be aware of the fact that JTRF station positions are characterized by much a larger variability than standard parameterized products because (i) KALREF adopts a station motion model based on trend and seasonal terms, (ii) JTRF coordinates reflect, unlike ITRF and DTRF, week-to-week geocentre as well as scale variability.

In future JTRF realizations, the quasi instantaneous scale representation can be improved by accounting for potential systematic effects between VLBI's and SLR's scales. Yet the adoption of such a scale may prove challenging: JTRF2014 pointed out larger oscillations of the scale parameters in the early years of the observations (before 1993.0). The nature of such oscillations (geophysical signal versus inherent noise of the observing systems) should be ascertained. If such oscillations prove unphysical because mostly due to larger noise of the two systems, then such noise may get directly transferred to the height component

of the station motion. One way to alleviate this effect might come from adopting the scale information derived from independently calibrated GNSS observations [13]: KALREF could be made flexible enough to allow for a scale definition based on a VLBI/SLR secular scale superimposed with the day-to-day variability provided by the “dynamic” GNSS’s scale.

As efforts to improve IERS-ITRF products are being made, it is mandatory that the Technique Centres pursue and foster in-depth analyses aimed at assessing technique-specific systematic effects.

ILRS is, as of this writing, testing the effect of the introduction in the data reduction of time-variable range biases at all SLR stations on the scale definition. Such an approach proved instrumental in partially reconciling SLR’s to VLBI’s scale [see e.g. 4].

IVS should consider assessing the effects of structural deformations in VLBI radiotelescope with particular regard to the scale parameter [30].

The scale remains the major source of inconsistencies in TRF products. From KALREF’s standpoint, further investigations are required to assess (and to understand) the scale differences between VLBI and SLR under the various possible configurations offered by the computational code (e.g. the activation of process noise while determining the scale difference between VLBI and SLR appears to exacerbate the time-variable biases).

JTRF is a sub-secular and inherently non-linear frame, whereas DTRF and ITRF are primarily secular frames. The representation of non-linear phenomena in ITRF and DTRF is possible through the introduction of correction terms. ITRF2014 provides seasonal and PSD terms in parameterized form to account for non-linear behaviour. DTRF2014, which was computed by removing NTL displacements from the input SINEX files, supplies the NTL corrections for users interested in restoring the non tidal loading variability.

The analyses of EOP consistency pointed out that all of the three Earth rotation time series are affected to a varying degree by systematics. We found evidence of statistically significant trend and seasonal terms in the EOP differences from ITRF, JTRF, and DTRF to COMB2016. This is particularly evident for polar motion observations. JTRF YPO is affected by an anomalously large annual component.

ITRF and DTRF also bear indication of significant EOP contaminations at the seasonal frequencies. When systematic effects are removed from the combined polar motion, the RMS of the differences (JTRF–ITRF) and (DTRF–ITRF) are in the order of $10 \mu\text{as}$.

TCH results applied to polar motion time series in the time interval 1998–2015 suggest the uncertainties are well within the range $[15,30] \mu\text{as}$. Polar motion rates from DTRF are affected by larger dispersion, when

compared to ITRF and DTRF. TCH applied to the three time series confirm a clear degradation of LOD and UT for DTRF. Yet there are indications that TCH results may be affected by time-correlated errors inherent to the EOP series.

Time- and spectral-domain approaches applied to the polar motion series suggests that TCH may overestimate the square root of the process noise variance up to a factor two. Estimation of the noise content based on a simple AR(1) model seems to suggest that the σ associated with white noise in polar motion series ranges within [12,16] μas , thus testifying the excellent level of consistency between the three products.

Acknowledgements

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). We gratefully acknowledge funding support from NASA's Space Geodesy Program.

B Soja's research was supported by an appointment to the NASA Post-doctoral Program at the NASA Jet Propulsion Laboratory, administered by Universities Space Research Association under contract with NASA. The valuable contributions from the Space-Geodetic Technique Services (IVS, ILRS, IGS and IDS) continuously providing data for the IERS-ITRF combination projects are acknowledged.

JTRF2014 SINEX files as well as associated files such as station position time series, Earth Orientation series, geocenter motion (CM-CN) time series are available upon request (claudio.abbondanza@jpl.nasa.gov).

Maps in this manuscript have been produced with CartoPy, freely available under the terms of the GNU License.

© 2018 California Institute of Technology.

All rights reserved.

U.S. Government sponsorship acknowledged.

Table 7: Linear regression of the time series of the Helmert transformation parameters mapping JTRF2014 to ITRF2014 and DTRF2014 represented in Figures 6 and 7. Values in the Table are determined via least-square estimation of the model $h(t) = a + b \cdot (t - t_0)$ applied to the time series of Figures 6 and 7 restricted to the time span 1995–2015. The row (a) reports the offset estimates whereas (b) the time derivatives of the transformation parameters. Offsets and trends are converted into surface equivalent displacements and rates of surface equivalent displacements and suitably expressed in mm at the reference epoch t_0 Jan 1 2005 and in mm/yr , respectively. Parenthesized are $(1 \cdot \sigma)$ formal errors.

		T_1	T_2	T_3	λ	R_1	R_2	R_3
JTRF to ITRF	(a)	0.40 (0.04)	-0.21 (0.04)	1.45 (0.05)	1.70 (0.08)	-0.69 (0.02)	-0.81 (0.02)	-0.22 (0.02)
	(b)	0.17 (0.01)	0.12 (0.01)	-0.18 (0.01)	-0.18 (0.01)	-0.11 (0.01)	0.10 (0.00)	0.16 (0.01)
JTRF to DTRF	(a)	0.37 (0.04)	0.11 (0.03)	1.10 (0.04)	-0.27 (0.04)	-0.76 (0.02)	-1.03 (0.02)	-0.23 (0.02)
	(b)	-0.05 (0.01)	0.02 (0.01)	-0.42 (0.01)	-0.02 (0.01)	-0.07 (0.01)	0.29 (0.01)	-0.01 (0.01)

Table 8: *Least-square fits of the EOP differences to ITRF to the model $h(t) = a + b \cdot (t - t_0) + c \cdot \sin[\omega(t - t_0) - \varphi]$, where h is the generic Earth Orientation parameter, a is the bias, b is the rate, c is the amplitude of a periodic signal with angular frequency $\omega = 2\pi f$. Frequencies considered in this analysis are annual ($f = 1$ cpy) and semi-annual ($f = 2$ cpy). The reference epoch t_0 is set to January 1 2005. Units are μas for polar motion components and $\mu\text{as}/\text{d}$ for polar motion rate. UT and LOD are expressed in $\mu\text{s}/\text{day}$. The RMS's reported in the last column are computed after the removal of linear trends and seasonal terms and expressed in μas and $\mu\text{as}/\text{day}$.*

			<i>Bias</i>	<i>Rate</i>	<i>Annual</i>	<i>Semi – Annual</i>	<i>RMS</i>
x_p	JTRF		26.30 (0.27)	-3.21 (0.07)	9.85 (0.21)	2.59 (0.21)	14.94
	DTRF		-7.51 (5.24)	3.81 (0.99)	9.30 (0.30)	2.23 (0.28)	17.00
y_p	JTRF		23.05 (0.26)	5.35 (0.07)	17.86 (0.27)	8.00 (0.27)	16.31
	DTRF		-9.40 (5.11)	2.99 (0.96)	5.39 (0.24)	1.70 (0.23)	12.10
UT	JTRF		-2.73 (0.11)	0.31 (0.02)	1.18 (0.06)	0.11 (0.07)	8.94
	DTRF		-2.18 (4.40)	0.28 (0.85)	1.28 (0.40)	1.46 (0.40)	15.90
$\dot{x}_p$	JTRF		0.30 (0.73)	-0.22 (0.15)	2.12 (0.31)	0.99 (0.30)	17.53
	DTRF		-0.69 (3.95)	-0.91 (0.79)	5.37 (2.04)	3.88 (2.05)	117.14
$\dot{y}_p$	JTRF		0.43 (0.72)	-0.07 (0.14)	1.67 (0.31)	0.60 (0.30)	18.62
	DTRF		1.20 (3.87)	0.88 (0.78)	2.48 (2.11)	4.36 (2.10)	117.21
LOD	JTRF		-0.05 (0.22)	0.02 (0.04)	0.13 (0.10)	0.08 (0.10)	13.72
	DTRF		6.13 (3.58)	-0.58 (0.71)	3.17 (4.15)	4.08 (4.26)	142.49

Table 9: *Least-square fits of the EOP differences to COMB2016 [21]. Same conventions as those of Table 8 are applied here.*

			<i>Bias</i>	<i>Rate</i>	<i>Annual</i>	<i>Semi – Annual</i>	<i>RMS</i>
x_p	ITRF		3.86 (0.68)	-0.85 (0.14)	9.27 (0.82)	1.06 (0.81)	51.13
	JTRF		32.89 (0.73)	-4.11 (0.16)	8.02 (0.79)	4.50 (0.77)	48.67
	DTRF		-17.16 (5.52)	5.90 (1.06)	6.62 (1.09)	8.83 (1.04)	52.46
y_p	ITRF		2.40 (0.58)	-1.44 (0.12)	1.17 (0.72)	4.95 (0.71)	44.83
	JTRF		25.96 (0.64)	2.79 (0.14)	18.36 (0.69)	6.74 (0.67)	43.54
	DTRF		-3.89 (5.31)	1.34 (1.01)	8.29 (1.05)	9.12 (1.01)	43.89

Table 10: *Observational contributions to combined (multi-technique) Earth Orientation Parameters for each of three TRF products. Bulleted cells in the double-entry table indicate which of the EOP parameters observed by which of the four SG techniques were used in ITRF, JTRF, and DTRF. For instance, the bullet in the row UT-JTRF, column R specifies that UT from VLBI (R) was used when constructing JTRF2014.*

			P	R	L	D
(x_p, y_p)	ITRF		•	•	•	•
	JTRF		•	•	•	•
	DTRF		•	•	•	•
UT	ITRF			•		
	JTRF			•		
	DTRF			•		
$(\dot{x}_p, \dot{y}_p)$	ITRF		•	•		
	JTRF		•	•		
	DTRF		•	•		
LOD	ITRF			•		
	JTRF			•		
	DTRF		•	•	•	

Table 11: *TCH-based estimates of the uncertainty (i.e. square root of the variance associated with the process noise) characterizing the 3 Earth Orientation time series from ITRF, DTRF and JTRF. The first row reports the number of common observations per EOP used in the estimation process. Values reported in the Table are standard deviations whose units are μas for the pole coordinates, $\mu s/d$ for UT and LOD and $\mu as/d$ for polar motion rates. TCH estimates shown here are based on Earth orientation time series spanning the time window 1998.0-2015.0.*

	x_p	y_p	UT	$\dot{x}_p$	$\dot{y}_p$	LOD
OBS	6212	6212	2323	6208	6208	2323
ITRF	18.66	19.93	7.21	11.87	12.13	9.32
JTRF	26.74	23.15	5.50	12.98	14.21	10.06
DTRF	30.23	14.15	14.30	116.74	116.80	142.26

Table 12: *Estimates of the parameters (σ, ϕ) of the AR(1) process of Equation 10, based on a Bayesian fit of Equation 11, adopted to describe the empirical power spectral density of polar motion observations from COMB2016 [21], ITRF2014-, JTRF2014-, DTRF2014-derived EOPs. The estimates reported are median values sampled from the posterior distribution. Parenthesized are 15.73-th and 84-th percentiles, respectively. Units for σ are $\mu\text{a.s.}$ ϕ is dimensionless.*

	σ	ϕ	χ^2/dof
COMB	17.1586 (-0.0014,0.0009)	0.9977 (-0.0129,0.0103)	1.0002
ITRF	16.1254 (-0.0014,0.0010)	0.9975 (-0.0151,0.0138)	0.9998
JTRF	15.4620 (-0.0015,0.0010)	0.9975 (-0.0157,0.0143)	0.9998
DTRF	12.7757 (-0.0022,0.0014)	0.9974 (-0.0255,0.0244)	1.0000

References

- [1] Altamimi, Z., Collilieux, X., Legrand, J., Garayt, B., and Boucher, C. (2007). ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters. *J Geophys Res-Sol Ea*, 112, B09401.
- [2] Altamimi, Z., Collilieux, X., and Métivier, L. (2011). ITRF2008: an improved solution of the International Terrestrial Reference Frame. *J Geodesy*, (8), 457–473.
- [3] Altamimi, Z., Rebischung, P., Métivier, L., and Collilieux, I. (2016). ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. *J Geophys Res-Sol Ea*, 121(8), 6109–6131.
- [4] Appleby, G., Rodríguez, J., and Altamimi, Z. (2016). Assessment of the accuracy of global geodetic satellite laser ranging observations and estimated impact on ITRF scale: estimation of systematic errors in LAGEOS observations 1993–2014. *J Geodesy*, 90(12), 1371–1388.
- [5] Bachmann, S., Thaller, D., Roggenbuck, O., Lösler, M., and Messerschmitt, L. (2016). IVS contribution to ITRF2014. *J Geodesy*, 90(7), 631–654.
- [6] Bizouard, C., Lambert, S., Becker, O., and Richard, I. Y. (2017). Combined solution C04 for Earth Rotation Parameters consistent with International Terrestrial Reference Frame 2014. Available on-line at the following URL <https://hpiers.obspm.fr/iers/eop/eopc04/C04.guide.pdf> On-line Accessed 4 August 2017.
- [7] Blewitt, G., Heflin, M. B., Webb, F. H., Lindqwister, U. J., and Malla, R. P. (1992). Global coordinates with centimeter accuracy in the International Terrestrial Reference Frame using GPS. *Geophys Res Lett*, 19(9), 853–856.
- [8] Bloßfeld, M., Müller, H., Gerstl, M., Štefka, V., Bouman, J., Göttl, F., and Horwath, M. (2015). Second-degree Stokes coefficients from multi-satellite SLR. *J Geodesy*, 89(9), 857–871.
- [9] Chin, T. M., Gross, R. S., and Dickey, J. O. (2004). Modeling and forecast of the polar motion excitation functions for short-term polar motion prediction. *J Geodesy*, 78(6), 343–353.
- [10] Davis, J. L., Wernicke, B. P., and Tamisiea, M. E. (2012). On seasonal signals in geodetic time series. *J Geophys Res-Sol Ea*, 117.
- [11] Dobslaw, H., Flechtner, F., Bergmann-Wolf, I., Dahle, C., Dill, R., Esselborn, S., Sasgen, I., and Thomas, M. (2013). Simulating high-frequency atmosphere-ocean mass variability for dealiasing of satellite gravity observations: AOD1B RL05. *J Geophys Res-Sol Ea*, 118(7), 3704–3711.

- [12] Fukumori, I., Raghunath, R., Fu, L. L., and Chao, Y. (1999). Assimilation of TOPEX/Poseidon altimeter data into a global ocean circulation model: How good are the results? *J Geophys Res-Oceans*, 104(C11), 25647–25665.
- [13] Haines, B. J., Bar-Sever, Y. E., Bertiger, W. I., Desai, S. D., Harvey, N., Sibois, A. E., and Weiss, J. P. (2015). Realizing a terrestrial reference frame using the Global Positioning System. *J Geophys Res-Sol Ea*, 120(8), 5911–5939. 2015JB012225.
- [14] Han, D. and Wahr, J. (1995). The viscoelastic relaxation of a realistically stratified earth, and a further analysis of postglacial rebound. *Geophys J Int*, 120(2), 287–311.
- [15] Lavallée, D. A., van Dam, T., Blewitt, G., and Clarke, P. J. (2006). Geocenter motions from GPS: A unified observation model. *J Geophys Res-Sol Ea*, 111(B5). B05405.
- [16] Luceri, V. and Pavlis, E. (2016). The ILRS contribution to ITRF2014. Int Laser Rang Serv, Greenbelt, MD, http://itrf.ign.fr/ITRF_solutions/2014/doc/ILRS-ITRF2014-description.pdf. On-line Accessed 4 August 2017.
- [17] Moreaux, G., Lemoine, F. G., Capdeville, H., Kuzin, S., Otten, M., Štefánek, P., Willis, P., and Ferrage, P. (2016). The International DORIS Service contribution to the 2014 realization of the International Terrestrial Reference Frame. *Adv Space Res*, 58(12), 2479–2504.
- [18] Percival, D. B. and Walden, A. T. (1993). *Spectral Analysis for Physical Applications: Multitaper and Conventional Univariate Techniques*. Cambridge University Press.
- [19] Petit, G. and Luzum, B. (2010). IERS Conventions (2010), pages 1–179. International Earth Rotation and Reference Systems Service, Central Bureau, Bundesamt für Kartographie und Geodäsie, Richard-Strauss-Allee 11, 60598 Frankfurt am Main, Germany. IERS Technical Note, No. 36.
- [20] Premoli, A. and Tavella, P. (1993). A Revisited Three-Cornered Hat Method For Estimating Frequency Standard Instability. *IEEE Trans Instrum Meas*, 42(1), 7–13.
- [21] Ratcliff, J. T. and Gross, R. S. (2017). Combinations of Earth Orientation Measurements: SPACE2016, COMB2016 and POLE2016. JPL Publication 17-8.
- [22] Ray, J. and Altamimi, Z. (2005). Evaluation of co-locations ties relating the VLBI and GPS reference frames. *J Geodesy*, 79(4-5), 189–195.
- [23] Ray, J., Kouba, J., and Altamimi, Z. (2005). Is there utility in rigorous combination of VLBI and GPS Earth orientation parameters? *J Geodesy*, 79, 505–511.

- [24] Ray, J., Altamimi, Z., van Dam, T., and Herring, T. (2007). Principles for conventional contributions to modeled station displacements. IERS Conventions Workshop 2007.
- [25] Ray, J. R. (1996). Measurements of length of day using the global positioning system. *J Geophys Res-Sol Ea*, 101(B9), 20141–20149.
- [26] Rebischung, P., Altamimi, Z., and Springer, T. (2014). A collinearity diagnosis of the GNSS geocenter determination. *J Geodesy*, 88(1), 65–85.
- [27] Rebischung, P., Altamimi, Z., Ray, J., and Garayt, B. (2016). The IGS contribution to ITRF2014. *J Geodesy*, pages 1–20.
- [28] Rodell, M., Houser, P. R., Jambor, U., Gottschalk, J., Mitchell, K., Meng, C. J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D., and Toll, D. (2004). The Global Land Data Assimilation System. *B Am Meteorol Soc*, 85(3), 381–394.
- [29] Rudenko, S., Bloßfeld, M., Müller, H., Dettmering, D., Angermann, D., and Seitz, M. (2018). Evaluation of DFTR2014, ITRF2014 and JTRF2014 by Precise Orbit Determination of SLR Satellites. *IEEE Transactions on Geoscience and Remote Sensing*, 56(6), 3148–3158, 10.1109/TGRS.2018.2793358.
- [30] Sarti, P., Abbondanza, C., Petrov, L., and Negusini, M. (2011). Height bias and scale effect induced by antenna gravitational deformations in geodetic VLBI data analysis. *J Geodesy*, 85(1), 1–8.
- [31] Seitz, M., Angermann, D., Bloßfeld, M., Drewes, H., and Gerstl, M. (2012). The 2008 DGFI realization of the ITRS: DTRF2008. *J Geodesy*, 86(12), 1097–1123.
- [32] Seitz, M. and Bloßfeld, M. and Angermann, D. and Schmid, R. and Gerstl, M. and Seitz, F. (2016). The new DGFI-TUM realization of the ITRS: DTRF2014 (data).
- [33] Shumway, R.H. and Stoffer, D.S. (2017). *Time Series Analysis and Its Applications*. Springer Text in Statistics. Springer. Fourth Edition.
- [34] Sillard, P. and Boucher, C. (2001). A review of algebraic constraints in terrestrial reference frame datum definition. *J Geodesy*, 75, 63–73.
- [35] Soja, Benedikt and Gross, R. S. and Abbondanza, C. and Chin, T. M. and Heflin, M. B. and Parker, J. W. and Wu, X. and Nilsson, T. and Glaser, S. and Balidakis, K. and Heinkelmann, R. and Schuh, H. (2018). On the long-term stability of terrestrial reference frame solutions based on Kalman filtering. *J Geod*, 92(9), 1063–1077.
- [36] van Dam, T. M., Wahr, J., Chao, Y., and Leuliette, E. (1997). Predictions of crustal deformation and of geoid and sea-level variability caused by oceanic and atmospheric loading. *Geophys J Int*, 129(3), 507–517.

- [37] Wu, X. and Heflin, M. B. (2015). A global assessment of accelerations in surface mass transport. *Geophys Res Lett*, 42(16), 6716–6723, 2015GL064941.
- [38] Wu, X., Abbondanza, C., Altamimi, Z., Chin, T. M., Collilieux, X., Gross, R. S., Heflin, M. B., Jiang, Y., and Parker, J. W. (2015). KALREF – A Kalman Filter and Time Series Approach to the International Terrestrial Reference Frame Realization. *J Geophys Res-Sol Ea*, 120(5), 3775–3802.
- [39] Zelensky, N. P., Lemoine, F. G., Beckley, D. B., Chinn, D. S., and Pavlis, D. (2017). Impact of ITRS 2014 Realizations on Altimeter Satellite Precise Orbit Determination. *Adv Space Res*, 61(1), 45–73.

Appendix 1

JTRF2014 Terrestrial Tie and Space Geodesy Discrepancies

JTRF2014 discrepancies between Space Geodesy and Local ties expressed in mm in the local geodetic frame (ENU). The code outputs differences (Space Geodesy – Local Ties). Also values are in the order ENU, expressed in millimeters. Column 10 and 12 report the SG techniques involved in the tie vectors, with the usual code conventions adopted throughout the manuscript (P is GNSS, R is VLBI, L is SLR, D is DORIS). The asterisks in the last column mark discrepancies larger than 5.0 mm whereas the dashes indicate residuals smaller than 5.0 mm (for instance, the combination ‘*-’ indicates discrepancies larger than 5.0 mm on the East and Height components, and smaller than 5.0 mm on the North one.)

From		To								
ID	DOMES	SOLN	ID	DOMES	SOLN	East [mm]	North [mm]	Height [mm]	SG Tec	Epoch
QUIN	40433M004	1	7109	40433M002	1	-12.6	19.0	34.2	P -> L	1985.6753 ***
VNDP	40420M007	1	7223	40420M002	1	0.3	-1.1	-1.1	P -> R	1991.9247 ---
SANT	41705M003	1	1404	41705S006	1	-7.3	6.6	13.9	P -> R	1992.5178 ***
GRAZ	11001M002	1	7839	11001S002	1	3.1	-2.1	-6.8	P -> L	1992.8620 --*
PIE1	40456M001	1	7234	40456S001	1	-1.0	-4.8	-3.2	P -> R	1992.9194 ---
7295	40499M002	1	7219	40499S001	1	0.4	-35.9	-12.4	L -> R	1993.0151 --**
7295	40499M002	1	RIDA	40499S016	1	1.7	-6.2	33.5	L -> D	1993.0151 --**
NLIB	40465M001	1	7612	40465S001	1	-1.1	-1.5	0.2	P -> R	1993.1685 ---
MD01	40442M012	1	7080	40442M006	1	1.7	1.0	31.4	P -> L	1993.2068 --*
MD01	40442M012	1	7216	40442S003	1	-7.6	-18.2	20.6	P -> R	1993.2068 ***
MD01	40442M012	1	7613	40442S017	1	5.2	-8.4	23.5	P -> R	1993.2068 ***
KOSG	13504M003	1	8833	13504M002	1	11.1	-25.2	9.9	P -> L	1993.2836 ***
FORT	41602M001	1	7297	41602S001	1	-2.1	-1.7	1.1	P -> R	1993.7247 ---

GUAM	50501M002	1	GUAB	50501S001	1	12.8	2.6	15.5	P -> D	1993.9548	**
BOR1	12205M002	1	7811	12205S001	1	0.2	2.1	-12.0	P -> L	1994.0315	---
CRO1	43201M001	1	7615	43201S001	1	0.8	1.4	3.9	P -> R	1994.0507	---
POTS	14106M003	1	7836	14106S009	1	6.5	-1.1	28.4	P -> L	1994.6068	**
POTS	14106M003	1	7841	14106S011	1	-15.7	-2.1	10.3	P -> L	1994.6068	**
AREQ	42202M005	1	7403	42202M003	1	-4.4	6.3	11.1	P -> L	1995.0096	---
AREQ	42202M005	1	AREA	42202S005	1	-16.5	-8.7	44.4	P -> D	1995.0096	***
CAGL	12725M003	1	7545	12725M002	1	8.8	18.7	20.6	P -> L	1995.4315	***
CAGL	12725M003	1	CAGZ	12725M004	1	2.3	-3.9	8.9	P -> P	1995.4315	---
TIDB	50103M108	1	7843	50103S007	1	-10.9	4.2	-42.4	P -> L	1995.7192	**
TIDB	50103M108	1	1545	50103S010	1	1.8	4.3	1.4	P -> R	1995.7192	---
TIDB	50103M108	1	ORRA	50103S201	1	-35.4	-26.6	-47.0	P -> D	1995.7192	***
TIDB	50103M108	1	ORRB	50103S202	1	-20.9	-15.2	-58.1	P -> D	1995.7192	***
ZIMM	14001M004	2	7810	14001S001	1	2.8	-3.7	0.4	P -> L	1996.2555	---
MKEA	40477M001	1	7617	40477S001	1	-2.0	0.8	1.7	P -> R	1996.5997	---
GOMA	40405S005	1	GOMB	40405S037	1	4.4	5.8	0.3	D -> D	1996.6571	-*
WES2	40440S020	2	7205	40440S002	1	9.8	2.1	0.8	P -> R	1996.7527	**
WES2	40440S020	2	7209	40440S003	1	2.0	-1.8	13.5	P -> R	1996.7527	---
SANT	41705M003	2	SANA	41705S007	1	2.8	14.3	-16.7	P -> D	1996.9249	---
SANT	41705M003	2	SAOB	41705S008	1	6.9	-1.1	9.7	P -> D	1996.9249	**
SANT	41705M003	2	SANB	41705S009	1	-22.6	0.9	16.8	P -> D	1996.9249	**
MADR	13407S012	7	1565	13407S010	1	-52.5	17.5	-1.3	P -> R	1998.9959	**
ALGO	40104M002	1	7282	40104S001	1	-1.7	-2.3	13.4	P -> R	1998.9959	---
NKLG	32809M002	1	LIBA	32809S002	1	13.7	-4.7	0.3	P -> D	1999.0918	**
NKLG	32809M002	1	LIBB	32809S003	1	5.0	5.7	-0.8	P -> D	1999.0918	**
CHAT	50207M001	1	CHAB	50207S001	1	-3.7	1.9	6.7	P -> D	1999.1493	---
STJO	40101M001	3	STJB	40101S002	1	3.1	-0.7	7.7	P -> D	1999.7438	---
MONP	40497M004	1	7110	40497M001	3	3.2	1.7	1.4	P -> L	1999.7630	---
KGNI	21704S005	1	7308	21704S002	1	-5.4	3.0	71.1	P -> L	1999.7822	**
KGNI	21704S005	1	7328	21704M001	1	-4.6	-0.6	57.2	P -> L	1999.7822	---
GRAS	10002M006	1	7835	10002S001	1	2.2	0.0	-3.6	P -> L	1999.7822	---
GRAS	10002M006	1	7845	10002S002	1	-0.6	0.6	7.3	P -> L	1999.7822	---
KSMV	21701S007	1	1856	21701S001	1	1.8	15.1	98.3	P -> R	1999.8014	---
KSMV	21701S007	1	1857	21701S004	1	-0.5	15.2	75.5	P -> R	1999.8014	---
YEBE	13420M001	1	7333	13420S001	1	2.0	1.4	-34.1	P -> R	1999.8781	---
SYOG	66006S002	2	SYOB	66006S001	1	-5.4	0.2	-41.7	P -> D	1999.9932	**
SYOG	66006S002	2	SYPB	66006S003	1	9.5	11.0	-16.3	P -> D	1999.9932	***
SYOG	66006S002	2	7342	66006S004	1	-6.8	13.0	43.7	P -> R	1999.9932	***
AJAC	10077M005	1	7848	10077M002	1	-9.9	-6.0	17.2	P -> L	1999.9932	***
KSTU	12349M002	1	KRAB	12349S001	1	-4.0	15.5	3.7	P -> D	1999.9932	-*
LHAS	21613M001	1	LHAZ	21613M002	1	3.3	1.6	-13.8	P -> P	2000.1462	---
DJIA	39901S002	1	DJIB	39901S003	1	0.0	0.1	-0.2	D -> D	2000.4904	---
DJIA	39901S002	1	DJIB	39901S003	1	0.0	0.1	-0.2	D -> D	2000.4904	---
METS	10503S011	1	META	10503S013	1	-1.0	-0.8	-17.7	P -> D	2000.8156	---
METS	10503S011	1	METB	10503S015	1	0.1	3.8	-10.0	P -> D	2000.8156	---

METS	10503S011	1	7806	10503S014	1	-2.0	-6.0	-10.3	P -> L	2000.8156	***
METS	10503S011	1	METZ	10503M005	1	-0.5	-0.3	-3.9	P -> P	2000.8156	---
BAKO	23101M002	3	CIBB	23101S001	1	-2.8	6.4	54.2	P -> D	2000.9495	***
BAKO	23101M002	3	CICB	23101S002	1	-15.5	4.9	43.5	P -> D	2000.9495	*--
RIOG	41507M004	2	RIOA	41507S003	1	7.6	1.3	2.4	P -> D	2001.0452	*--
RIOG	41507M004	2	RIOB	41507S004	1	-3.7	10.8	-13.3	P -> D	2001.0452	***
RIOG	41507M004	2	RIPB	41507S005	1	-1.9	-1.8	-6.7	P -> D	2001.0452	--*
EISL	41703M003	1	EASB	41703S009	1	9.1	8.2	-5.2	P -> D	2001.1219	***
EISL	41703M003	1	EASA	41703S008	1	-6.5	12.8	-25.5	P -> D	2001.1219	***
EISL	41703M003	1	7097	41703M002	1	-17.6	5.5	14.5	P -> L	2001.1219	***
PDEL	31906M004	1	PDLB	31906S001	1	8.0	9.7	4.8	P -> D	2001.2178	**--
PDEL	31906M004	1	PDMB	31906S002	1	16.5	3.4	-2.2	P -> D	2001.2178	*--
KIT3	12334M001	1	KITA	12334S004	1	-25.5	10.2	-9.6	P -> D	2001.3137	***
KIT3	12334M001	1	KITB	12334S005	1	-10.4	14.0	-2.3	P -> D	2001.3137	**--
KIT3	12334M001	1	KIUB	12334S006	1	10.3	7.7	-3.4	P -> D	2001.3137	**--
SEY1	39801M001	2	MAHB	39801S005	1	-0.3	-1.7	-109.8	P -> D	2001.4096	--*
STR2	50119M001	1	STR1	50119M002	1	-1.6	-1.2	11.5	P -> P	2001.5630	--*
STR2	50119M001	1	MSOB	50119S002	1	-6.0	11.6	16.0	P -> D	2001.5630	***
STR2	50119M001	1	MSPB	50119S004	1	-10.3	2.1	-7.1	P -> D	2001.5630	*--
STR2	50119M001	1	7849	50119S001	1	-4.4	0.8	6.3	P -> L	2001.5630	--*
STR2	50119M001	1	7825	50119S003	1	-4.6	-4.5	-8.1	P -> L	2001.5630	--*
FAIR	40408M001	3	FAIA	40408S004	1	-7.3	-8.2	-29.8	P -> D	2001.7548	***
FAIR	40408M001	3	FAIB	40408S005	1	14.8	-2.5	-17.7	P -> D	2001.7548	*--
FAIR	40408M001	3	7225	40408S002	1	-1.3	-6.7	4.2	P -> R	2001.7548	*--
YELL	40127M003	2	YELB	40127S008	1	5.1	-4.3	-9.3	P -> D	2001.7740	*--
YELL	40127M003	2	YEMB	40127S009	1	2.4	0.4	-9.7	P -> D	2001.7740	--*
YELL	40127M003	2	7296	40127M004	1	-2.6	-4.9	-7.7	P -> R	2001.7740	--*
TRIA	30604S001	1	TRIB	30604S002	1	4.3	-5.1	-17.9	D -> D	2002.0616	***
OHI2	66008M005	1	7245	66008S001	1	-0.8	3.7	2.1	P -> R	2002.1192	---
HOB2	50116M004	1	7242	50116S002	1	6.1	-1.2	-0.3	P -> R	2002.2151	*--
MORA	51001S001	1	MORB	51001S002	1	-15.2	9.9	3.8	D -> D	2002.2151	**--
ADEA	91501S001	1	ADEB	91501S002	1	-8.6	-5.4	22.9	D -> D	2002.2918	***
ONSA	10402M004	3	7213	10402S002	1	7.6	0.2	-3.2	P -> R	2002.5219	*--
THU2	43001M002	1	THUB	43001S005	1	28.8	8.6	4.8	P -> D	2002.6945	**--
KOKB	40424M004	3	KOLB	40424S009	1	1.4	12.1	-24.9	P -> D	2002.8671	***
KOKB	40424M004	3	KOKA	40424S008	1	10.7	10.9	-17.1	P -> D	2002.8671	***
KOKB	40424M004	3	1311	40424S001	1	15.6	39.2	4.3	P -> R	2002.8671	**--
KOKB	40424M004	3	7298	40424S007	1	16.8	38.6	-4.8	P -> R	2002.8671	**--
MANA	22006S001	1	MANB	22006S002	1	3.6	-20.2	8.0	D -> D	2003.1548	***
HELA	30606S002	1	HELB	30606S003	1	17.1	3.5	-16.2	D -> D	2003.2123	*--
HELA	30606S002	1	HEMB	30606S004	1	15.4	1.2	-10.7	D -> D	2003.2123	*--
CONZ	41719M002	1	7405	41719M001	1	3.5	-4.7	21.4	P -> L	2003.2123	--*
CONZ	41719M002	1	7640	41719S001	1	3.3	-3.4	29.5	P -> R	2003.2123	--*
BJFS	21601M001	2	7249	21601S004	1	-1.5	9.1	-4.2	P -> L	2003.4616	*--
HRAO	30302M004	1	7232	30302S001	1	3.9	0.3	1.7	P -> R	2003.5767	---

HRAO	30302M004	1	7501	30302M003	1	-0.1	6.8	1.9	P -> L	2003.5767	--*
HRAO	30302M004	1	HARB	30302M009	1	2.6	2.3	0.6	P -> P	2003.5767	---
HRAO	30302M004	1	HBKB	30302S006	1	4.9	6.6	-2.6	P -> D	2003.5767	--*
HRAO	30302M004	1	HBKA	30302S202	1	-1.6	-5.0	-16.9	P -> D	2003.5767	---
HRAO	30302M004	1	HBLA	30302S005	1	0.4	2.7	-20.2	P -> D	2003.5767	---
NYA1	10317M003	2	SPIA	10317S002	1	-2.0	-1.7	-13.5	P -> D	2003.6151	--*
NYA1	10317M003	2	SPIB	10317S004	1	-2.9	1.3	-1.1	P -> D	2003.6151	---
NYA1	10317M003	2	SPJB	10317S005	1	0.1	-3.6	-12.8	P -> D	2003.6151	--*
NYA1	10317M003	2	7331	10317S003	1	4.2	-1.8	1.4	P -> R	2003.6151	---
YAR1	50107M004	2	YARR	50107M006	1	-0.6	1.9	0.8	P -> P	2003.8260	---
YAR1	50107M004	2	7090	50107M001	1	-4.2	4.6	14.2	P -> L	2003.8260	--*
YAR1	50107M004	2	YARB	50107S010	1	1.2	21.7	19.4	P -> D	2003.8260	---
YAR1	50107M004	2	YASB	50107S011	1	-7.2	13.6	21.6	P -> D	2003.8260	***
AMSA	91401S001	1	AMTB	91401S003	1	1.9	2.6	2.2	D -> D	2003.8836	---
SHAO	21605M002	1	7837	21605S001	1	0.0	0.4	-15.7	P -> L	2003.9027	--*
SHAO	21605M002	1	7227	21605S009	1	3.7	-6.3	1.3	P -> R	2003.9027	--*
REUN	97401M003	2	REUA	97401S001	1	-7.6	7.7	0.9	P -> D	2003.9219	---
REUN	97401M003	2	REUB	97401S002	1	-3.9	9.9	2.1	P -> D	2003.9219	--*
WUHN	21602M001	5	JIUB	21602S005	1	-7.1	-12.6	-12.5	P -> D	2003.9411	***
ASC1	30602M001	1	ASDB	30602S004	1	30.1	6.9	-15.0	P -> D	2003.9603	***
TLSE	10003M009	1	TLHA	10003S003	1	4.3	-4.0	-13.6	P -> D	2004.0943	--*
TLSE	10003M009	1	TLSA	10003S001	1	-3.3	8.4	-4.7	P -> D	2004.0943	--*
CHPI	41609M003	1	CACB	41609S001	1	-18.9	10.0	-11.8	P -> D	2004.2281	***
CHPI	41609M003	1	CADB	41609S002	1	4.1	4.0	-95.5	P -> D	2004.2281	--*
BADA	12338S001	1	BADB	12338S002	1	-0.7	-0.4	0.1	D -> D	2004.6107	---
YSSK	12329M003	3	SAKA	12329S001	2	-16.6	2.0	-7.5	P -> D	2004.6298	--*
YSSK	12329M003	3	SAKB	12329S002	1	-1.2	2.5	1.1	P -> D	2004.6298	---
MARA	30313S001	1	MARB	30313S002	1	-13.3	26.0	3.5	D -> D	2004.6489	---
MARA	30313S001	1	MATB	30313S003	1	0.3	-24.4	-4.9	D -> D	2004.6489	--*
REYK	10202M001	6	REYA	10202S001	1	-7.7	-18.3	-43.2	P -> D	2004.6680	***
REYK	10202M001	6	REYB	10202S002	1	-4.3	-4.4	-5.0	P -> D	2004.6680	---
REYK	10202M001	6	REZB	10202S003	1	8.5	-7.7	-1.4	P -> D	2004.6680	--*
MATE	12734M008	3	7243	12734S005	1	-0.3	-4.1	-1.2	P -> R	2004.8210	---
MATE	12734M008	3	7941	12734S008	1	0.5	-0.3	-5.8	P -> L	2004.8210	--*
SVTL	12350M001	2	7380	12350S001	1	-3.6	-9.3	-12.6	P -> R	2004.9932	---
ZECK	12351M001	1	7381	12351S001	1	-19.9	0.6	24.5	P -> R	2004.9932	--*
MALD	22901S001	3	MALB	22901S002	1	-3.8	-9.1	-0.5	P -> D	2005.0315	--*
AOML	49914S001	2	MIAB	49914S003	1	6.7	1.6	-3.0	P -> D	2005.0890	---
ROTA	66007S001	1	ROTB	66007S002	1	0.1	-0.1	-1.0	D -> D	2005.1466	---
GLPS	42005M002	1	SCRB	42005S001	1	0.1	3.4	5.5	P -> D	2005.2425	--*
NOUM	92701M003	3	NOUB	92701S002	1	-0.6	12.5	13.3	P -> D	2005.6452	---
NOUM	92701M003	3	NOWB	92701S003	1	-2.3	21.4	19.1	P -> D	2005.6452	---
NOUM	92701M003	3	NOUA	92701S001	1	-5.6	6.5	-9.5	P -> D	2005.6452	***
NOT1	12717M004	2	7547	12717S001	1	-0.5	-1.5	8.2	P -> R	2005.7219	--*
MONP	40497M004	3	MONB	40497S008	1	6.2	-0.7	2.5	P -> D	2005.9137	--*

MONP 40497M004	3	MOOB 40497S009	1	-0.7	-1.4	-0.7	P -> D	2005.9137	---
BRFT 41602M002	1	7297 41602S001	1	1.1	-4.3	8.4	P -> R	2006.2205	--*
DIOB 12602S012	1	DIOA 12602S011	1	-2.4	-9.3	0.3	D -> D	2006.3740	*--
MAUI 40445S008	2	7119 40445M004	1	1.3	4.6	-15.7	P -> L	2006.7192	--*
MAUI 40445S008	2	7210 40445M001	3	3.4	1.6	-18.9	P -> L	2006.7192	--*
CROB 91301S001	1	CRPB 91301S002	1	-1.2	0.2	-1.6	D -> D	2007.2562	---
KERG 91201M002	3	KERB 91201S003	1	-1.6	6.7	1.3	P -> D	2007.2753	*--
KERG 91201M002	3	KESB 91201S004	1	8.7	10.0	15.2	P -> D	2007.2753	***
KERG 91201M002	3	KETB 91201S005	1	4.9	18.5	5.1	P -> D	2007.2753	--*
AMTB 91401S003	1	AMUB 91401S004	1	-2.5	0.5	-2.1	D -> D	2007.2945	---
MEDI 12711M003	4	7230 12711S001	1	5.1	-0.2	2.8	P -> R	2007.6589	*--
THTI 92201M009	1	7124 92201M007	1	-2.8	-2.9	-1.8	P -> L	2007.7548	---
THTI 92201M009	1	PAPB 92201S007	1	6.3	-16.1	17.9	P -> D	2007.7548	***
THTI 92201M009	1	PAQB 92201S008	1	-4.3	-2.3	12.6	P -> D	2007.7548	--*
THTI 92201M009	1	PATB 92201S010	1	-5.0	-1.8	11.8	P -> D	2007.7548	*--
GODE 40451M123	2	7105 40451M105	2	0.8	5.0	-5.6	P -> L	2008.0041	--*
GODE 40451M123	2	GREB 40451S176	1	8.1	-4.9	-13.8	P -> D	2008.0041	*--
TSKB 21730S005	6	7345 21730S007	1	-2.1	0.9	8.3	P -> R	2008.0423	--*
DUM1 91501M001	3	ADEA 91501S001	1	0.2	3.0	-13.7	P -> D	2008.0997	--*
DUM1 91501M001	3	ADFB 91501S003	1	-6.7	0.2	7.2	P -> D	2008.0997	*--
HERS 13212M007	4	HERT 13212M010	2	0.2	-2.9	-6.1	P -> P	2008.4822	--*
HERS 13212M007	4	7840 13212S001	1	-0.3	-1.9	-8.1	P -> L	2008.4822	--*
GRAS 10002M006	2	7845 10002S002	1	-4.0	-2.5	-4.9	P -> L	2009.6507	---
GRAS 10002M006	2	GR3B 10002S018	1	6.6	-8.9	4.3	P -> D	2009.6507	*--
STR1 50119M002	2	MSPB 50119S004	1	-8.7	8.8	-9.5	P -> D	2009.8616	***
STR1 50119M002	2	7825 50119S003	1	-6.0	-1.5	-18.5	P -> L	2009.8616	*--
HOB2 50116M004	2	7242 50116S002	1	2.0	-1.4	-1.7	P -> R	2009.9000	---
HOB2 50116M004	2	7374 50116S007	1	5.2	1.9	3.0	P -> R	2009.9000	*--
NKLG 32809M002	3	LICB 32809S004	1	-9.8	-8.1	25.6	P -> D	2010.3411	***
ASDB 30602S004	1	ASEB 30602S005	1	32.3	-15.8	0.2	D -> D	2010.4562	*--
YAR1 50107M004	2	YARR 50107M006	1	-0.5	1.0	-1.1	P -> P	2010.5521	---
YAR1 50107M004	2	7090 50107M001	2	-7.5	1.3	6.6	P -> L	2010.5521	*--
YAR1 50107M004	2	YASB 50107S011	1	-6.7	11.8	21.4	P -> D	2010.5521	***
YAR1 50107M004	2	YAR3 50107M008	2	-0.8	1.3	21.4	P -> P	2010.5521	--*
YAR1 50107M004	2	7376 50107S012	1	-7.6	0.0	-12.5	P -> R	2010.5521	*--
ROTH 66007M003	1	ROTB 66007S002	1	11.1	0.7	-16.8	P -> D	2011.0890	*--
ROTH 66007M003	1	ROUB 66007S003	1	6.2	3.7	-18.2	P -> D	2011.0890	*--
ROTH 66007M003	1	ROVB 66007S004	1	0.8	4.6	-9.2	P -> D	2011.0890	--*
KOUG 97301M402	1	KRWB 97301S006	1	0.1	-15.6	23.2	P -> D	2011.1466	--*
KOUG 97301M402	1	KRUB 97301S004	1	-2.5	-21.0	16.4	P -> D	2011.1466	--*
KOUG 97301M402	1	KOUR 97301M210	3	-1.3	-1.9	4.1	P -> P	2011.1466	---
DYNG 12602M006	1	DIOB 12602S012	1	-4.7	-7.1	-4.7	P -> D	2011.3575	*--
THTI 92201M009	1	PATB 92201S010	1	-4.9	-1.7	11.9	P -> D	2011.3575	--*
KAT1 59968M001	2	7375 59968S001	1	-2.3	0.7	12.0	P -> R	2011.4151	--*
BREW 40473M001	1	7614 40473S001	1	0.3	0.7	5.5	P -> R	2011.5685	--*

RILB	92301S003	1	RIMB	92301S004	1	-0.5	0.8	-0.5	D -> D	2011.5877	---
SOLA	20101M001	1	7832	20101S001	1	-1.5	-2.3	-29.8	P -> L	2012.0861	--*
FTNA	92902S002	3	FUUB	92902S003	1	-8.0	15.8	3.2	P -> D	2012.3730	**-
FTNA	92902S002	3	FUTB	92902S001	1	-17.7	22.7	10.4	P -> D	2012.3730	***
WTZA	14201M013	1	7224	14201S004	1	-5.3	-4.2	-3.9	P -> R	2012.4112	---
WTZA	14201M013	1	8834	14201S018	1	-8.2	-3.6	4.9	P -> L	2012.4112	---
WTZA	14201M013	1	WTZJ	14201M012	1	-6.6	-5.5	-1.2	P -> P	2012.4112	**-
WTZA	14201M013	1	WTZR	14201M010	3	-3.5	-0.4	-15.2	P -> P	2012.4112	--*
WTZA	14201M013	1	WTZS	14201M015	3	-4.8	-3.3	-10.4	P -> P	2012.4112	--*
WTZA	14201M013	1	WTZZ	14201M014	2	-2.3	-0.2	-7.5	P -> P	2012.4112	--*
TRIB	30604S002	2	TRJB	30604S003	1	0.0	0.0	0.7	D -> D	2012.4495	---
SEY1	39801M001	4	MAHB	39801S005	1	-11.6	-1.0	20.7	P -> D	2012.4495	**-
SEY1	39801M001	4	MAIB	39801S006	1	-4.1	3.6	11.7	P -> D	2012.4495	--*
METS	10503S011	6	MEUB	10503S016	1	5.8	-4.7	-1.8	P -> D	2012.5068	---
METS	10503S011	6	METB	10503S015	1	0.9	-3.3	2.5	P -> D	2012.5068	---
GODE	40451M123	2	7105	40451M105	2	2.8	1.3	-6.5	P -> L	2012.5260	--*
GODE	40451M123	2	7918	40451M120	1	0.6	-2.9	-4.6	P -> L	2012.5260	---
GODE	40451M123	2	GODN	40451M127	1	1.6	1.0	-4.2	P -> P	2012.5260	---
GODE	40451M123	2	GODS	40451M128	1	2.2	1.5	-5.1	P -> P	2012.5260	--*
GODE	40451M123	2	GRFB	40451S178	1	13.2	-2.3	-18.3	P -> D	2012.5260	**-
WUHN	21602M001	7	JIUB	21602S005	1	-11.6	-6.3	-20.3	P -> D	2012.7746	***
WUHN	21602M001	7	JIVB	21602S006	1	-8.6	4.7	-15.6	P -> D	2012.7746	**-
AREQ	42202M005	14	ARFB	42202S007	1	16.3	18.9	34.2	P -> D	2013.0233	***
AREQ	42202M005	14	7403	42202M003	5	0.1	0.1	2.1	P -> L	2013.0233	---
OHI2	66008M005	3	OHI3	66008M006	3	1.1	0.5	-4.2	P -> P	2013.1192	---
MDO1	40442M012	5	7080	40442M006	2	-0.3	17.7	-20.8	P -> L	2013.1384	--*
MDO1	40442M012	5	7613	40442S017	1	8.6	18.6	-0.5	P -> R	2013.1384	**-
STJO	40101M001	5	STJB	40101S002	1	4.1	4.7	0.6	P -> D	2013.5219	---
STJO	40101M001	5	STKB	40101S003	1	-12.3	15.4	-7.5	P -> D	2013.5219	***
YELL	40127M003	4	YEMB	40127S009	1	-1.1	4.9	-5.6	P -> D	2013.5411	--*
TLSE	10003M009	2	TLSE	10003S005	1	4.3	-9.6	-12.4	P -> D	2014.1164	**-
HARB	30302M009	2	HBMB	30302S008	1	1.4	8.0	-1.9	P -> D	2014.1548	**-
HRAO	30302M004	4	7501	30302M003	1	-22.0	8.1	6.6	P -> L	2014.1548	***
HRAO	30302M004	4	7378	30302S009	1	-21.0	4.2	19.5	P -> R	2014.1548	**-
HRAO	30302M004	4	7232	30302S001	1	-16.7	0.3	15.5	P -> R	2014.1548	**-
KOKB	40424M004	5	KOLB	40424S009	1	-1.6	-0.6	0.1	P -> D	2014.2123	---
KOKB	40424M004	5	7298	40424S007	1	2.8	3.8	12.6	P -> R	2014.2123	--*
RIO2	41507M006	2	RIRB	41507S007	1	1.0	14.6	-8.5	P -> D	2014.3849	**-
ONSA	10402M004	3	7213	10402S002	1	4.5	0.0	9.1	P -> R	2014.4808	**-
PDEL	31906M004	5	PDMB	31906S002	1	11.4	-12.4	-4.6	P -> D	2014.7301	**-
PTAG	22006M005	1	MANB	22006S002	1	-15.7	6.4	22.2	P -> D	2014.9219	***

ITRS Center evaluation of DTRF2014 and JTRF2014 with respect to ITRF2014

Zuheir Altamimi¹, Paul Rebischung¹, Xavier Collilieux^{2,1}, and Laurent Métivier¹

¹ *Institut National de l'Information Géographique et Forestière (IGN), Paris, France*

² *Ecole Nationale des Sciences Géographiques, Champs sur Marne, France*

Abstract. We evaluate the two solutions DTRF2014 and JTRF2014 provided by the two ITRS Combination Centers DGFI and JPL, with respect to the ITRF2014. We first summarize briefly the three reference frame solutions in terms of combination strategy and their main features. We then compare the two solutions DTRF2014 and JTRF2014 with the ITRF2014, focusing more specifically on the scale and scale rate, as the scale issue had generated many discussions in the past 20 years. We found in particular that SLR and VLBI intrinsic scales are actually coexisting together in both DTRF2014 and JTRF2014 solutions, and that the results of these comparisons confirm the finding of the ITRF2014 analysis.

Summary The three reference frame solutions used the same input data submitted by the IERS Technique Centers (IDS, IGS, ILRS and IVS) for the ITRF2014 computation, provided in the form of time series of station positions and Earth Orientation Parameters (EOPs). The reader may refer to the following publications for more details regarding the technique solutions: IDS: Moreaux et al., 2016, IGS: Rebischung et al., 2016, ILRS: Luceri and Pavlis, 2016, IVS: Bachmann et al., 2015 and Nothnagel et al., 2015.

ITRF2014 Detailed description of ITRF2014 can be found in Altamimi et al. (2016a, 2017) from which we extract here a brief summary of ITRF2014.

The ITRF2014 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 124 sites that were subject to major earthquakes. It is achieved through a two-step procedure: (1) stacking the time series of station positions and Earth Orientation Parameters provided by the four IERS Technique Centers (TC); (2) combining the long-term solutions as obtained in step 1, together with local ties in co-location sites. The two-step procedure makes use of full variance-covariance information provided in SINEX format. The TC solutions incorporated in the ITRF2014 combination are free from any external constraints, thus preserving the actual space geodesy estimates of station positions and EOPs. The ITRF2014 origin is defined in such a way that it has zero translations and translation rates with

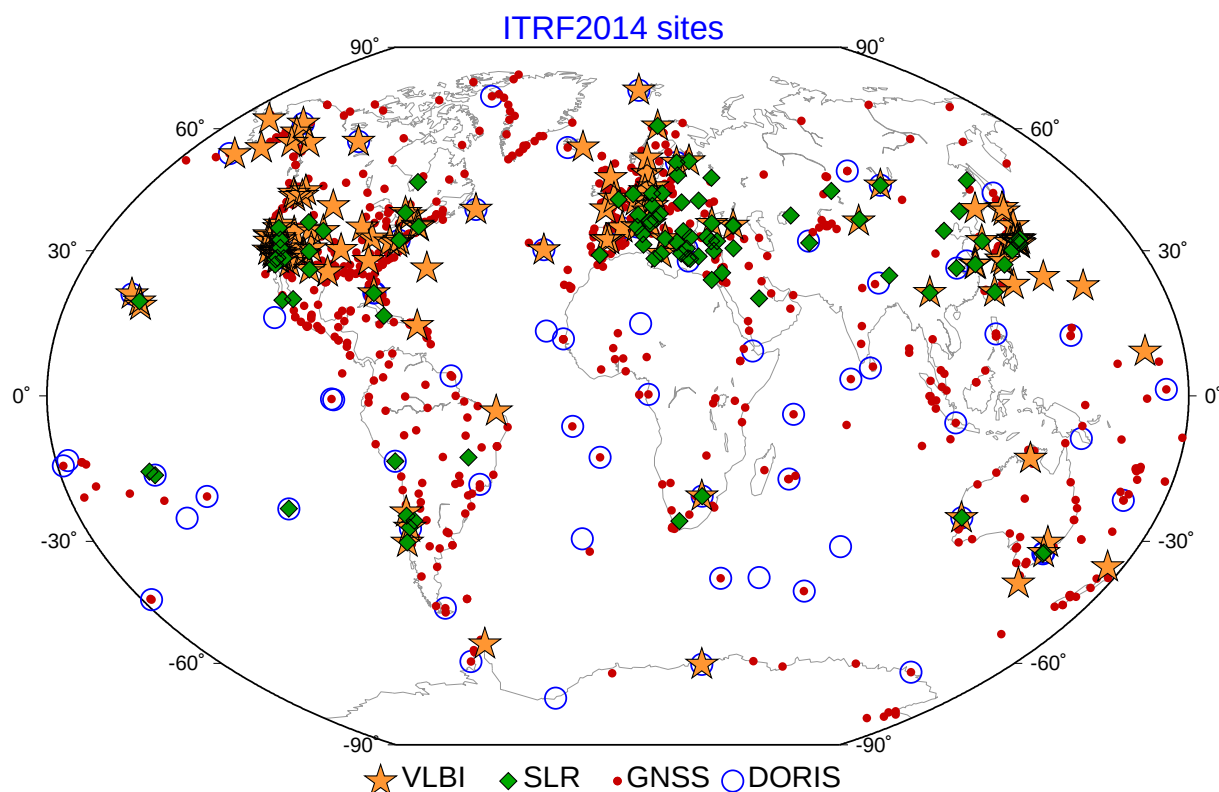


Fig. 1: ITRF2014 network highlighting VLBI, SLR and DORIS sites co-located with GNSS

respect to the mean Earth center of mass, as defined by the SLR station positions time series. Its scale is defined by zero scale factor and zero scale rate with respect to the mean of VLBI and SLR long-term solutions as obtained by stacking their respective time series. The ITRF2014 orientation (at epoch 2010.0) and its rate are aligned to the ITRF2008 using 127 stations of high geodetic quality.

The ITRF2014 includes the positions and velocities of 1499 stations located at 975 sites. Figure 1 shows the coverage of these sites, underlying the co-located space geodesy techniques.

DTRF2014 The DGFI combination strategy is largely described in Seitz et al. (2016). The main feature of the DTRF combination is the accumulation of normal equations of the technique solutions and inverting for station positions at a reference epoch, linear velocities and Earth Orientation Parameters. The DTRF combination model does not (1) include an unknown and explicit scale factor between SLR and VLBI TRF solutions and (2) equate velocities before and after discontinuities in the time series of single technique solutions. The consequence of not explicitly including a scale factor as unknown, is that the two SLR and VLBI intrinsic scales

will co-exist in the DTRF combined frame. Therefore the resulting DTRF frame will have two different scales in cohabitation. Note also that a nontidal atmospheric and hydrological loading model was applied to the station coordinate time series during the computation of the DTRF2014 solution (Bloßfeld et al., this issue). However, applying a nontidal loading model has negligible impact on station velocities with time-span longer than 2.5 year (Collilieux et al., 2010).

JTRF2014 The JTRF2014 combination strategy is largely described in Abbondanza et al. (2017). It is based on a Kalman filter and smoother algorithm. The JTRF2014 is provided in the form of time series of weekly solutions comprising station positions and EOPs. The JTRF2014 origin is defined to follow the instantaneous origin of the SLR weekly solutions. Analogous to the DTRF strategy, the scale factor between SLR and VLBI is eliminated from the normal equation, by setting to zero the two corresponding scales in the combination model, see Subsection 4.3 of Abbondanza et al. (2017).

Evaluation of DTRF2014 and JTRF2014

We choose here to evaluate the scale parameters of both DTRF and JTRF 2014 solutions with respect to ITRF2014, as the scale issue had generated many discussions so far within the geodetic community. In order to guide the evaluation of the DTRF and JTRF 2014 scales with respect to ITRF2014, we reproduce in Figure 2 here the Figure 9 of Altamimi et al. (2016a). We recall that the ITRF2014 scale is defined by the arithmetic average of the implicit scales of SLR and VLBI solutions as obtained by the stacking of their respective time series. The resulting scale and scale rate differences between the SLR and VLBI solutions are respectively $1.37 (\pm 0.10)$ ppb at epoch 2010.0 and $0.02 (\pm 0.02)$ ppb/yr. Note that the scale offset is determined via the appropriate usage and weighting of local ties while the scale drift reflects the level of agreement in vertical velocities between technique solutions. We reiterate here that there is a persistent scale offset of the order of, or larger than 1 ppb (at epoch 2010.0) between SLR and VLBI solutions submitted to the ITRF, since the ITRF2005 (Altamimi et al., 2007). We have in particular conducted thorough investigations to validate these scale offset estimates using different weighting and selection of local ties at co-location sites, see for instance discussion and Table 3 of Altamimi et al. (2011). For example, using ITRF2014 input data we combined SLR and VLBI solutions alone, involving 13 local tie vectors located at 9 well distributed co-located sites of both techniques. The results of this specific test combination indicate a scale offset of $1.14 (\pm 0.29)$ ppb at epoch 2010.0 and a scale rate of $0.02 (\pm 0.02)$ ppb/yr (Altamimi et al., 2016b).

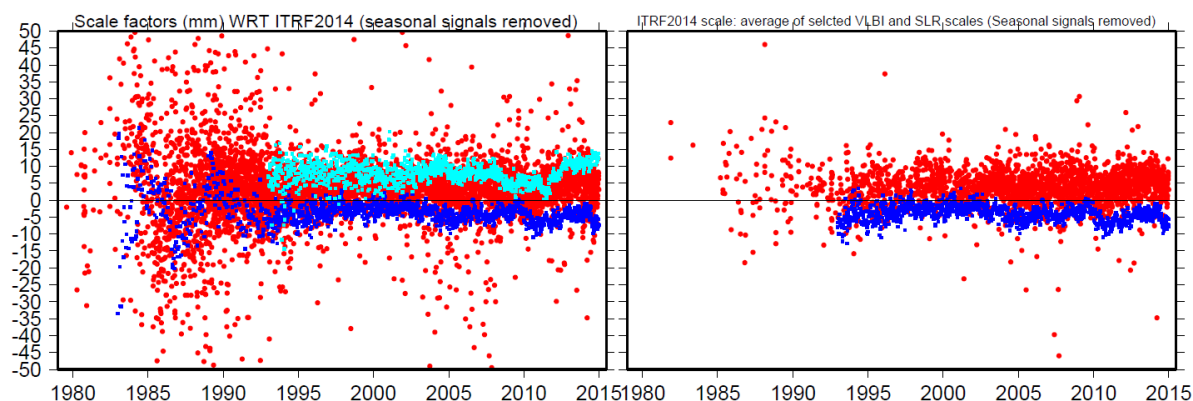


Fig. 2: Figure 9 of Altamimi et al. (2016): Full time series of (left) scale factors with respect to ITRF2014 and (right) selected SLR and VLBI scale factors whose average defines the ITRF2014 scale, in mm, annual and semiannual signals removed: daily VLBI (red) and weekly SLR and DORIS (blue and light blue), respectively.

Evaluation of the DTRF2014 scale

In order to evaluate the scale behavior of the DTRF2014, we extracted from the full DTRF2014 SINEX files four subsets of station positions and velocities corresponding to DORIS, GNSS, SLR and VLBI networks. We then compared these four subset DTRF2014 solutions to the ITRF2014, by estimating a 14-parameter similarity transformation, including the scale and scale rate. Figure 3 illustrates the DTRF2014 scale behavior of the four subset solutions, with respect to ITRF2014. From that figure we can easily see that the DTRF2014 solution has four different scales coexisting together, one per technique, assuming that the ITRF2014 provides a homogeneous scale for all four techniques. The numerical values obtained from these comparisons are summarized in Table 1. The scale factors listed in Table 1 are consistent with those obtained in the ITRF2014 combination, see Figure 2, which demonstrates that the inherent SLR and VLBI scales are conserved in the DTRF2014 solution.

Table 1: Summary of the scales at epoch 2010.0 and scale rates of DTRF2014 DORIS, GNSS, SLR and VLBI with respect to ITRF2014

	Scale (ppb)	scale rate (ppb/yr)
DTRF2014 DORIS	0.43 ($\pm$ 0.53)	0.01 ($\pm$ 0.10)
DTRF2014 GNSS	0.10 ($\pm$ 0.17)	0.00 ($\pm$ 0.03)
DTRF2014 SLR	-0.67 ($\pm$ 0.24)	-0.02 ($\pm$ 0.05)
DTRF2014 VLBI	0.65 ($\pm$ 0.10)	0.02 ($\pm$ 0.02)

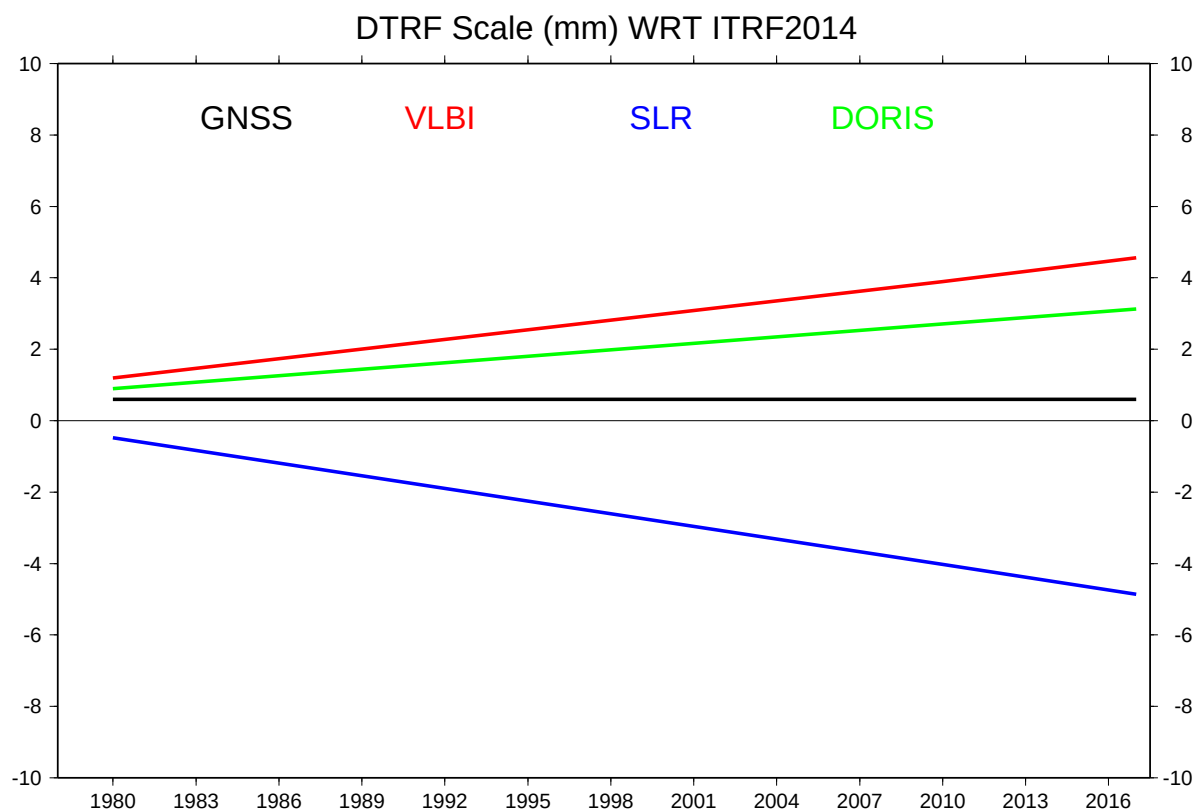


Fig. 3: *DTRF2014 scale with respect to ITRF2014*

Evaluation of the JTRF2014 scale

In order to evaluate the scale behavior of the JTRF2014 with respect to ITRF2014, we stacked (accumulated) the JTRF2014 time series to estimate a long-term solution of station positions at a reference epoch (2010.0) and velocities, expressed in the ITRF2014 using minimum constraints (MC) approach. We repeated the stacking four times, and for each run we selected the ITRF2014 reference frame stations used in the MC to match the best performing stations of each technique. As a result of the four runs, Figure 4 illustrates the time series of the JTRF2014 scales of the four techniques with respect to ITRF2014. Similar to DTRF2014, we can see that the JTRF2014 has actually four different scales coexisting together, one per technique, with respect to ITRF2014 assumed homogeneous scale. Fitting regression lines to the four scale time series presented at Figure 4, estimating an offset at epoch 2010.0 and a drift, yields the numerical results summarized in Table 2. From that table we can draw similar comments as for DTRF2014. We also notice that the DORIS scale in the JTRF2014 solution has a very large unexplained drift of $0.12 (\pm 0.03)$ ppb/yr, corresponding to approximately 0.7 mm/yr at the equator, comforting the result of Abbondanza et al. (2017) of 0.63 mm/yr. We suspect that drift to be caused by too strong

co-motion constraints between DORIS stations and the three other techniques.

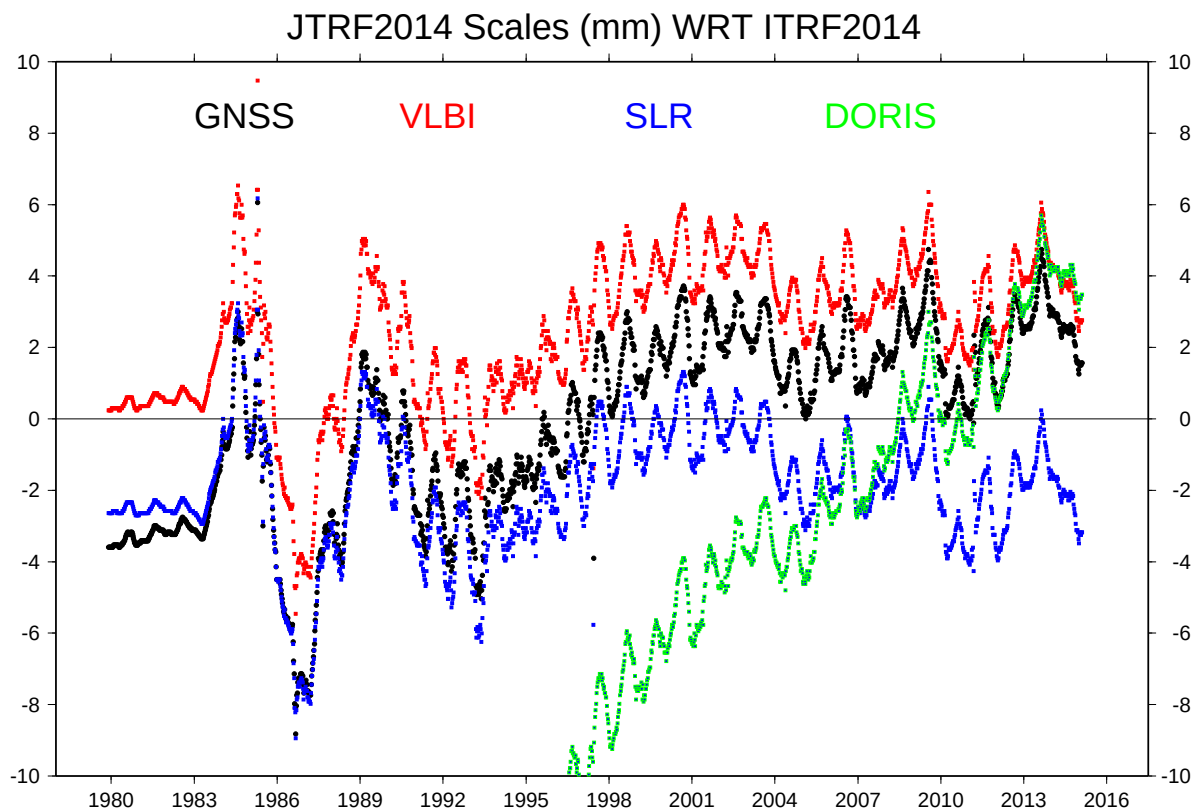


Fig. 4: *JTRF2014 scale with respect to ITRF2014*

Conclusion We evaluated DTRF2014 and JTRF2014 with respect to ITRF2014 and focussed more specifically on the scale parameter. The main key results of our comparative analysis are twofold: (1) SLR and VLBI intrinsic and discrepant scales coexist in the DTRF and JTRF 2014 solutions, and (2) with respect to ITRF2014 and assuming that its scale is homogeneous, the scale offsets and rates between SLR and VLBI solutions embedded in DTRF2014 and JTRF2014 are respectively 1.32 and 1.21 ppb at epoch 2010.0 and 0.04 and 0.01 ppb/yr. These results are in almost perfect agreement with the results of ITRF2014 analysis (Altamimi et al., 2016).

References Abbondanza C., T. M. Chin, R. S. Gross, M. B. Heflin, J. Parker, B. S. Soja, T. van Dam, and X. Wu (2017), JTRF2014, the JPL Kalman filter, and smoother realization of the International Terrestrial Reference System, *J. Geophys. Res. Solid Earth*, 122, 8474–8510, doi:10.1002/2017JB014360.

Table 2: *Summary of the scales at epoch 2010.0 and scale rates of JTRF2014 DORIS, GNSS, SLR and VLBI with respect to ITRF2014*

	Scale (ppb)	scale rate (ppb/yr)
JTRF2014 DORIS	-0.03 ($\pm$ 0.03)	0.12 ($\pm$ 0.03)
JTRF2014 GNSS	0.39 ($\pm$ 0.03)	0.06 ($\pm$ 0.03)
JTRF2014 SLR	-0.53 ($\pm$ 0.06)	0.00 ($\pm$ 0.06)
JTRF2014 VLBI	0.68 ($\pm$ 0.04)	-0.01 ($\pm$ 0.04)

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

Altamimi, Z., X. Collilieux, and L. Métivier (2011), ITRF2008: An improved solution of the International Terrestrial Reference Frame, *J. Geod.*, 85(8), 457–473, doi:10.1007/s00190-011-0444-4.

Altamimi, Z., P. Rebischung, L. Métivier, and X. Collilieux (2016a), ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, *J. Geophys. Res. Solid Earth*, 121, doi:10.1002/2016JB013098.

Altamimi, Z., P. Rebischung, L. Métivier, and X. Collilieux (2016b), ITRS Center Report: Minutes of IERS Directing Board Meeting No. 63, December 10, 2016, San Francisco. (Summary in IERS Annual Report 2016)

Altamimi, Z., Rebischung, P., Métivier, L., Collilieux, X. (2017): Analysis and results of ITRF2014. International Earth Rotation and Reference Systems Service (IERS), Technical Note 38. Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt a.M.

Bachmann, S., L. Messerschmitt, and D. Thaller (2015), IVS contribution to ITRF2014, in IAG Commission 1 Symposium 2014: Reference Frames for Applications in Geosciences (REFAG2014), pp. 1–6, Springer, Berlin.

Bloßfeld, M., M. Seitz, D. Angermann and F. Seitz, this issue, DTRF2014: DGFI-TUM realization of the International Terrestrial Reference System (ITRS).

Collilieux, X., Z. Altamimi, D. Coulot, T.M. van Dam and J. Ray (2010) Impact of loading effects on determination of the International Terrestrial Reference Frame, *Advances in Space Research*, vol. 45, pp. 144–154, doi:10.1016/j.asr.2009.08.024

- Luceri, V., and E. Pavlis (2016), The ILRS contribution to ITRF2014. Available at http://itrf.ign.fr/ITRF_solutions/2014/doc/ILRS-ITRF2014-description.pdf.
- Moreaux, G., F. G. Lemoine, H. Capdeville, S. Kuzin, M. Otten, P. Stepanek, P. Willis, and P. Ferrage (2016), Contribution of the International DORIS Service to the 2014 realization of the International Terrestrial Reference Frame, *Adv. Space Res.*, doi:10.1016/j.asr.2015.12.021
- Nothnagel, A., et al. (2015), The IVS Data Input to ITRF2014. International VLBI Service for Geodesy and Astrometry, GFZ Data Services, Helmholtz Centre, Potsdam, Germany.
- Seitz, M., D. Angermann, M. Bloßfeld, H. Drewes, and M. Gerstl (2012), The 2008 DGFI realization of the ITRS: DTRF2008, *J. Geod.*, 86, 1097–1123.

Comparison of latest ITRS realizations: ITRF2014, DTRF2014 and JTRF2014

Detlef Angermann¹, Mathis Bloßfeld¹, Manuela Seitz¹, and Sergei Rudenko¹

¹ *Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Munich, Germany*

Abstract. This article compares the three realizations of the International Terrestrial Reference System (ITRS) computed in 2015, namely the ITRF2014 (IGN, Paris, France), the DTRF2014 (DGFI-TUM, Munich, Germany), and the JTRF2014 (JPL, Pasadena, USA). After comparing the different combination strategies applied by the three official IERS ITRS Combination Centres, the reference frames are inter-compared based on precise orbit determination of near-Earth satellites and Helmert transformations. A special focus is put on the investigation of the scale differences between the ITRF2014 and the DTRF2014 solution where also external studies performed by the technique-specific Combination Centres of the ILRS and the IVS are presented.

Introduction

The three Combination Centres of the International Earth Rotation and Reference Systems Service (IERS) are in charge of computing a realization of the International Terrestrial Reference System (ITRS). The most recent realizations are the ITRF2014 (IGN, France; Altamimi et al., 2016), DTRF2014 (DGFI-TUM, Germany; Seitz et al., 2016) and JTRF2014 (JPL; USA; Abbondanza et al., 2017). These three realizations are based on identical input data of the contributing space techniques VLBI, SLR, GNSS and DORIS but different software and combination approaches were used. The input data in the form of time series of station positions and Earth Orientation Parameters (EOPs) were combined per technique by the four technique-specific combination centers, i.e. Rebischung et al. (2016) for the IGS contributions, Luceri and Pavlis (2016) for the ILRS, Bachmann et al. (2015) for the IVS and Moreaux et al. (2016) for the IDS. The advantage of multiple ITRS realizations based on identical input data is that errors or systematics caused by the combination approaches, the analysts, or the softwares can be identified. Thus, the IERS structure with three ITRS Combination Centres is of high importance to allow for a decisive validation and quality control of the ITRF.

This paper gives an overview of the combination strategies of the three ITRS Combination Centres and it summarizes the results of the comparisons which have been performed at DGFI-TUM. Based on these comparisons the current accuracy of the terrestrial reference frame can be assessed, systematic differences as, for example, the SLR and VLBI scale issue can be identified. Finally, some conclusions of the comparisons and studies are provided.

Comparison of the ITRS combination strategies of IGN, JPL and DGFI-TUM

Although the same input data were used by the three ITRS Combination Centres, their combination strategies differ conceptually. While ITRF2014 and DTRF2014 provide station positions at a reference epoch and station velocities according to the conventional ITRS definition, the JTRF2014 consists of weekly time series of station positions. Thus, the two conventional multi-year solutions computed at IGN and DGFI-TUM are not directly comparable with the JTRF2014 time series of weekly station position and EOP solutions (see Abbondanza et al., 2017).

The two multi-year solutions of IGN and DGFI-TUM are based on a two-step procedure: (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) combination of the resulting long-term solutions (IGN) or normal equations (DGFI-TUM) of the four techniques together with the local ties at co-location sites. However, the combination strategies and software packages used at IGN and DGFI-TUM are different as outlined below.

The strategy followed by the ITRS Combination Centre at IGN is based on the combination of technique-specific solutions (combination on parameter/solution level). The ITRF2014 has been generated with an enhanced modeling of non-linear station motions, including seasonal (annual and semi-annual) signals of station positions and post-seismic deformation (PSD) for sites that were subject to major earthquakes (Altamimi et al., 2016). This time series analysis was performed before the least-squares adjustment process.

The general concept of the combination strategy used at DGFI-TUM is based on the combination of constraint-free normal equation systems resulting from the observation analysis of the space geodetic techniques GNSS, VLBI, SLR and DORIS (combination on normal equation level). Another difference is that within the DTRF2014 computation, atmospheric and hydrological non-tidal loading was applied, while in the ITRF2014 seasonal signals were estimated. Also the modeling of non-linear station motions differs from the IGN approach. Thus, for the sites affected by major earthquakes, the DTRF2014 uses a piece-wise linear representation of station motions in contrast to the PSD models applied at IGN. A detailed description of the combination methodology at DGFI-TUM including the mathematical background is given in (Seitz et al., 2012). The combination is performed with the software DOGS-CS, the combination part of the software package DOGS (DGFI Orbit and Geodetic Parameter Estimation Software; Gerstl et al., 2000; Bloßfeld et al., 2015).

The combination strategies of the three ITRS Combination Centres applied for the generation of the ITRF2014, DTRF2014 and JTRF2014 along with the parameterization of station positions and EOPs are summarized in Tab. 1.

Table 1: *Summary of combination strategies for the ITRF2014, DTRF2014 and JTRF2014.*

Solution	ITRF2014	DTRF2014	JTRF2014
Institute	IGN (Paris, France)	DGFI-TUM (Munich, Germany)	JPL (Pasadena, USA)
Software	CATREF	DOGS-CS	CATREF+KALMAN
Combination approach	Solution (parameter) level	Normal equation level	Solution (parameter) level
Station position	Position $\mathbf{X}_{\text{ITRF}}(t_0)$ + velocity $\dot{\mathbf{X}}_{\text{ITRF}}(t_0)$ + PSD models (selected stations) + periodic signals (on request)	Position $\mathbf{X}_{\text{DTRF}}(t_0)$ + velocity $\dot{\mathbf{X}}_{\text{DTRF}}(t_0)$ + NT-L models + SLR origin + residual station motions	Weekly positions $\tilde{\mathbf{X}}_{\text{ITRF}}(t_i)$
Earth orientation parameters	<u>Combined:</u> - Terrestrial pole (PM), - PM rates from GNSS + VLBI <u>Separate VLBI-only:</u> - dUT1, - LOD, - Celestial pole	<u>Combined:</u> - Terrestrial pole (PM), - PM rates from GNSS + VLBI, - LOD from GNSS + SLR + VLBI <u>Separate VLBI-only:</u> - dUT1, - Celestial pole	<u>Combined:</u> - Terrestrial pole (PM), - PM rates from GNSS + VLBI <u>Separate VLBI-only:</u> - dUT1, - Celestial pole

More background on the combination at different levels of the least squares adjustment (i.e., observation, normal equation and solution level) can be found in the literature (e.g., Angermann et al., 2004; Bloßfeld et al., 2015; Seitz et al., 2012 and 2015). As outlined in Seitz et al. (2012), there are the following main differences between the combination at the normal equation level and at the solution level:

- When combining normal equation systems, corrections of the original observations are estimated. In case of combining solutions, the parameters of the input solutions are corrected.
- If normal equation systems are used as input data, in principle, no a priori datum conditions in form of pseudo-observations are

added to the individual input normal equations. In case of combination of solutions, the input solutions have to be generated applying datum conditions. In order to ensure undeformed input data sets, the so called minimum conditions are necessary.

- In order to be free to select the geodetic datum of the reference frame, in case of combination of solutions, it is necessary to estimate parameters of a similarity transformation between the final and the input solutions. The estimated transformation parameters, which should represent the datum differences, might absorb non-modelled station movements. This can lead to biases in the estimated station coordinates and can affect the realization of such geodetic datum parameters as origin and scale. A further aspect to be kept in mind is that the results depend on the selection of stations used for the transformation.

In summary, the combination approach at the normal equation level is a very good approximation of the combination of the original space geodetic observations, if the reduction models and parameterizations used for the analysis of the observation data are homogenized.

Comparison of ITRF2014, DTRF2014 and JTRF2014

At DGFI-TUM various comparisons were performed to evaluate the three latest ITRS realizations. Concerning these comparisons, it shall be noted that the two conventional multi-year reference frames computed by IGN and DGFI are conceptionally different from the epoch reference frames computed at JPL. The ITRF2014, DTRF2014 and JTRF2014 were compared by Precise Orbit Determination (POD) of high and low Earth orbiting ten geodetic satellites (altitudes between 680 and 19130 km) using SLR observations over a total time span of 24 years (see following subsection). The results of a direct comparison of the two multi-year solutions ITRF2014 and DTRF2014 by performing similarity transformations between both realizations are provided afterwards. It was found that both realizations show a significant difference with respect to the SLR and VLBI scale. Thus, this topic was investigated in more detail. Moreover, the IVS and the ILRS compared their combined VLBI and SLR solutions with the ITRF2014, DTRF2014 and JTRF2014, respectively. Finally, some results of the EOP comparisons between the ITRF2014 and DTRF2014 are provided.

Evaluation by Precise Orbit Determination (POD) of SLR satellites

The three new ITRS realizations ITRF2014, DTRF2014 and JTRF2014 have been evaluated by using their station positions as a priori values within Precise Orbit Determination (POD) for SLR satellites. This study was based on POD of ten geodetic satellites at high (with an altitude more than 2000 km) and low (with an altitude below this value) Earth

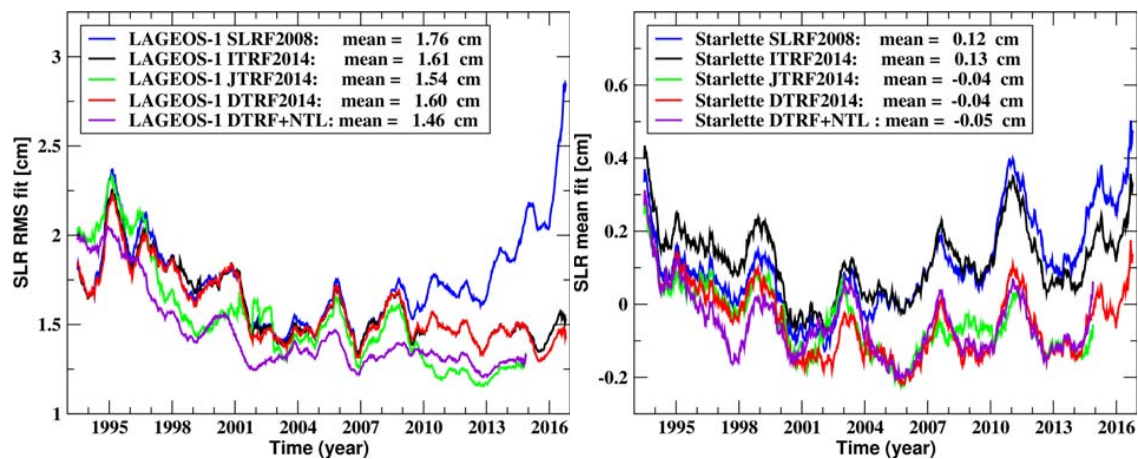


Fig. 1: (Left) 50-week running averages of the RMS fits of SLR observations (in cm) for LAGEOS-1 orbits derived using SLRF2008, ITRF2014, DTRF2014 linear, DTRF2014+NTL and JTRF2014. (Right) 50-week running averages of the mean fits of SLR observations (in cm) for Starlette orbits derived using SLRF2008, ITRF2014, DTRF2014 linear, DTRF2014+NTL and JTRF2014 (taken from Rudenko et al., 2018).

orbiting geodetic satellites in total over 24 years from 1993.0 to 2017.0 using SLR-only orbit determination (see Rudenko et al., 2018).

As an example of this POD study, we provide in this paper some results for the SLR satellites Lageos-1 and Starlette. It was found that all new ITRS realizations perform better than the previous reference frame realization for SLR, the SLRF2008 (Pavlis, 2009). In this time span, the mean values of the SLR orbit fits are on average reduced (improved) by 3 %, 3.6 %, 8.1 %, and 7.7 % for ITRF2014, DTRF2014, DTRF2014 with non-tidal loading (NTL), and JTRF2014, respectively. The improvement of the RMS fits is even larger at 2015.0 – 2017.0: 14 % for ITRF2014 and 15.5 % for DTRF2014. Using SLRF2008 causes increasing with time (after 2009) RMS fits of observations (Fig. 1, left), since this realization was derived using data until 2009.0 only, while the latest ITRS realizations were derived using the data until 2015.0 and, therefore, more precisely provide station motions after 2009.0 than their predecessors. The ITRF2014 and SLRF2008 show a trend of 0.16 and 0.28 mm/y in the mean fits of observations for LAGEOS-1 (not shown here) and Starlette (Fig. 1, right), respectively, at the time span 2001.0 – 2017.0. More results are given in Rudenko et al., 2018.

From our analysis, we conclude that DTRF2014 with NTL corrections and JTRF2014 (with the editing for SLR stations Concepcion and Zimmerwald as described in the cited article) show the best performance among the ITRS realizations for the satellites tested.

Comparison of ITRF2014 and DTRF2014

The two long-term ITRS realizations, the ITRF2014 and DTRF2014, have been directly compared by similarity transformations. These 14-parameter Helmert transformations have been performed individually for the four space-techniques GNSS, VLBI, SLR and DORIS by using

stable reference stations (core stations) for each technique-specific network. The results of these similarity transformations are shown in Fig. 2.

From these comparisons, two quality estimates are obtained for each technique-specific network:

- the transformation parameters (origin, scale, orientation) and their time derivatives as a measure for the accuracy of the datum definition.
- the RMS for station positions and velocities as a measure for the agreement of the network geometries.

With respect to the datum parameters (origin, scale and orientation), the two realizations show an overall agreement within 5–6 mm (positions at epoch 2000.0) and below 1 mm/yr for their rates. For DORIS, the differences between the ITRF2014 and DTRF2014 are slightly larger than for the three other techniques. A major difference between both ITRS realizations is visible for the scale of VLBI and SLR. The observed scale bias is in the order of about 8 mm ($= 1.2$ ppb), which is almost identical with the scale offset between SLR and VLBI of 1.37 ppb as reported in the ITRF2014 results (Altamimi et al., 2016). As shown in the next section, this scale bias is not visible in the DGFI computations. The network geometry of DTRF2014 and ITRF2014 shows the best agreement for the GNSS and VLBI sub-networks. For these two techniques, the RMS differences of station coordinates between both ITRS realizations are below 0.5 mm for the positions and about 0.2 mm/yr for the velocities. For SLR the discrepancies are larger by a factor of about 2 and for DORIS the RMS differences are in the order of 4 mm for station positions and 0.5 mm/yr for velocities.

VLBI and SLR scale investigations based on ITRF2014 and DTRF2014 performed at DGFI-TUM

In this section, the results of the scale investigations performed by the DGFI-TUM group are summarized which were presented at the IAG-IASPEI Scientific Assembly in Kobe, Japan and published in the corresponding Symposia Proceedings (see Bloßfeld et al., 2018).

As recommended by the IERS Directing Board, in a first step, the long-term single-technique SLR and VLBI solutions provided by DGFI-TUM and IGN are compared directly. The advantage of such a comparison is that the intra-technique solutions based on identical input data are not yet affected by the inter-technique combination. The solutions are obtained after the epoch-wise input data was accumulated and the geodetic datum was realized. These steps had been performed by the institutes themselves. This study allows to test, if either SLR or VLBI might solely responsible for the scale bias found by IGN. The transformations are applied at two different reference epochs to enhance

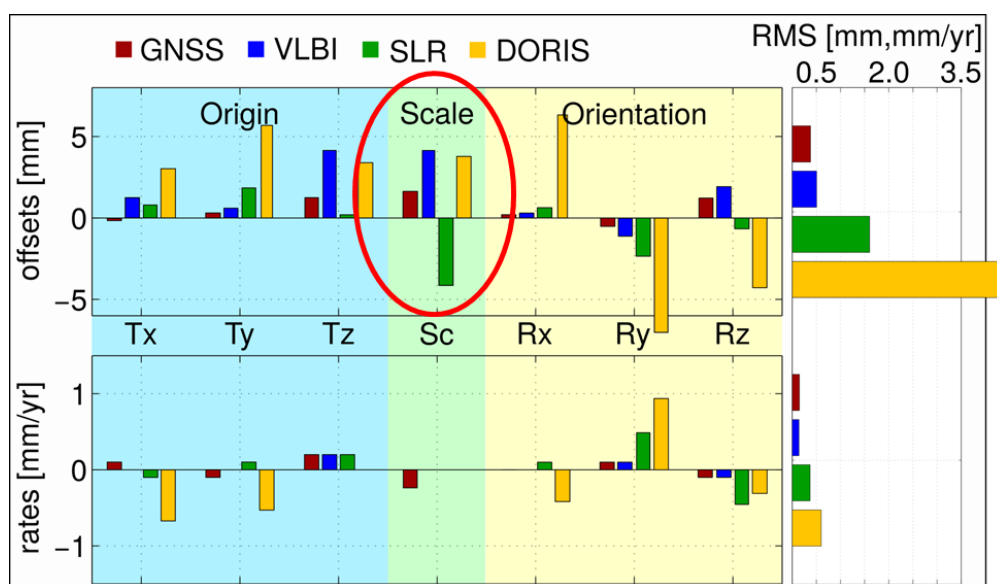


Fig. 2: Results of technique-specific Helmert transformation between ITRF2014 and DTRF2014.

the significance of the outcome. The results of the transformations applied each by a set of globally well-distributed datum stations are shown in Tab. 2.

Table 2: Scale offsets and rates obtained from 14-parameter Helmert transformations of VLBI and SLR single-technique solutions of DGFI-TUM and IGN (transformation epochs are 2000.0 and 2010.0).

Technique (IGN w.r.t. DGFI-TUM)	Epoch	Scale offset [mm]	Scale rate [mm/yr]	Number of stations (used for transformation)
VLBI	2000.0	0.2 ± 0.2	0.1 ± 0.04	22
	2010.0	1.5 ± 0.5	0.0 ± 0.05	22
SLR	2000.0	2.2 ± 1.0	0.1 ± 0.11	19
	2010.0	0.7 ± 0.9	0.0 ± 0.07	19

We found that there is neither a significant scale offset nor rate between the DGFI-TUM and IGN single-technique solutions for SLR and VLBI. If the transformation epoch is changed from 2000.0 to 2010.0, the scale offset between the VLBI solutions increases from 0.2 mm to 1.5 mm (0.2 ppb) but still not explains the large bias of 1.37 ppb seen by IGN. The vice-versa is obtained in the case of the SLR transformation. Here, the scale bias decreases from 2.2 mm at 2000.0 to 0.7 mm (0.1 ppb) at 2010.0. As an intermediate conclusion, we can state that the scale bias seen by IGN is not present in the SLR and VLBI input data.

This indicates that the effects might be caused by the inter-technique combination.

In a second test, we compared the single-technique VLBI and SLR solutions of DGFI-TUM directly by applying the local ties at co-located observation sites. Since the VLBI and SLR observations refer to different reference points, we used the local tie vectors to compute a “VLBI reference point” at an SLR marker and performed a direct 14-parameter Helmert transformation with the SLR-only solution. A deficiency of this direct transformation between SLR and VLBI is that there are only 19 co-location sites between both techniques and that half of them have a common observation time span below 5 years. Fig. 3 shows the global distribution and the common observation time span of the available co-location sites between SLR and VLBI.

The results of this direct transformation between the SLR and VLBI intra-technique solutions computed at DGFI-TUM are shown in Tab. 3. The transformation parameters of three different station networks (test cases A, B and C) at three different epochs (2000.0, 2005.0 and 2010.0) are compared in order to evaluate the stability of these transformations. For test case A the scale offset is between 3 and 4 mm for all epochs. If we add Yarragadee (Australia) to the transformation network (test case B), we see a significant impact of this station on the obtained offsets (as well as on the rates) with a good fit at the epoch 2010.0. This is mainly caused by the fact that only 2 years of VLBI data (the VLBI telescope starts operation around 2012) are not sufficient for a reliable velocity estimation. Thus, the propagation of the VLBI station coordinates certainly affects the results at the epochs 2000.0 and 2005.0. If the old VLBI and SLR data of Quincy (USA) from the early 90's are used, the comparisons are obviously affected by extrapolation errors causing an (arbitrary) scale bias between SLR and VLBI (see test case C). These results indicate that a direct comparison (transformation) between SLR and VLBI suffers from the rather limited number of co-location sites between both techniques and that individual stations can have quite a large impact on the transformations.

Thus, we also did a third comparison by performing an indirect transformation between SLR and VLBI by using co-locations to GNSS. In this case we get up to 31 co-locations between SLR and GNSS and up to 36 between VLBI and GNSS, respectively. The obtained scale differences between SLR and VLBI using the indirect approach via the GNSS co-locations are summarized in Tab. 3. To test the robustness of this comparison, we use four different local tie thresholds for the discrepancy between the single-technique coordinates of the reference points and the measured local tie vectors. It was found that a restrictive local tie selection (e.g., 7 mm threshold) results in the smallest number of transformation stations (20 for VLBI, 15 for SLR) and a scale bias of

0.1 ppb (0.7 mm at the Earth's crust). If the threshold is increased to 25 mm, also the number of transformation stations is increased to up to 36 stations, but a scale bias of -0.5 ppb (-3.3 mm) is obtained. This threshold seems to be too large for SLR due to the high dependency on single stations. For the other two test scenarios, the VLBI and SLR scale differences are below 0.15 ppb (1.0 mm). These test computations confirm that the DGFI-TUM solution do not show a significant bias between the SLR and VLBI scale. This indirect comparison via GNSS provides much more co-locations with a better spatial distribution, but on the other hand the large number of GNSS discontinuities is critical and needs to be taken into account.

Scale comparisons performed by the IVS and the ILRS

To further investigate the scale bias between VLBI and SLR, the three ITRS realizations were compared with the combined VLBI and SLR solutions obtained by the Combination Centres (CC) of the IVS and ILRS, respectively.

The IVS CC located at BKG (Germany) provided Fig. 4, which shows epoch-wise estimated scale parameters of the IVS combined solutions (VLBI-only) w.r.t. several different TRF realizations. It is clearly visible that the DTRF2008, the DTRF2014, the JTRF2014, and the quarterly VLBI-only TRF solution VTRF2015q2 agree quite well with the IVS combined solutions showing a mean value close to zero. The ITRF2008 as well as the ITRF2014 show a mean bias of about -0.5 ppb.

Similar investigations have been performed for SLR. The primary ILRS CC located at ASI (Italy), named ILRSA in the following, provided epoch-wise estimated scale parameters of combined ILRSA solutions w.r.t. the most recent ITRS realizations (Fig. 5). Again, the DTRF2014 as well as the JTRF2014 do not show a long-term mean offset w.r.t. the SLR-only solutions, whereas the ITRF2014 shows a mean offset of about 0.7 ppb. This means that the DTRF2014 and the JTRF2014 do not distort the scale of the SLR subnet.

Table 3: Scale offsets [mm] obtained from 14-parameter Helmert transformations of SLR and VLBI single-technique solutions of DGFI-TUM. The transformations are computed directly for three different epochs using local ties.

Test	Transformation setup	2000.0	2005.0	2010.0
A	11 good co-locations	3.2	3.6	4.0
B	11 + Yarragadee	6.8	-3.2	0.3
C	11 + Yarragadee + Quincy	-9.8	-8.0	-6.1

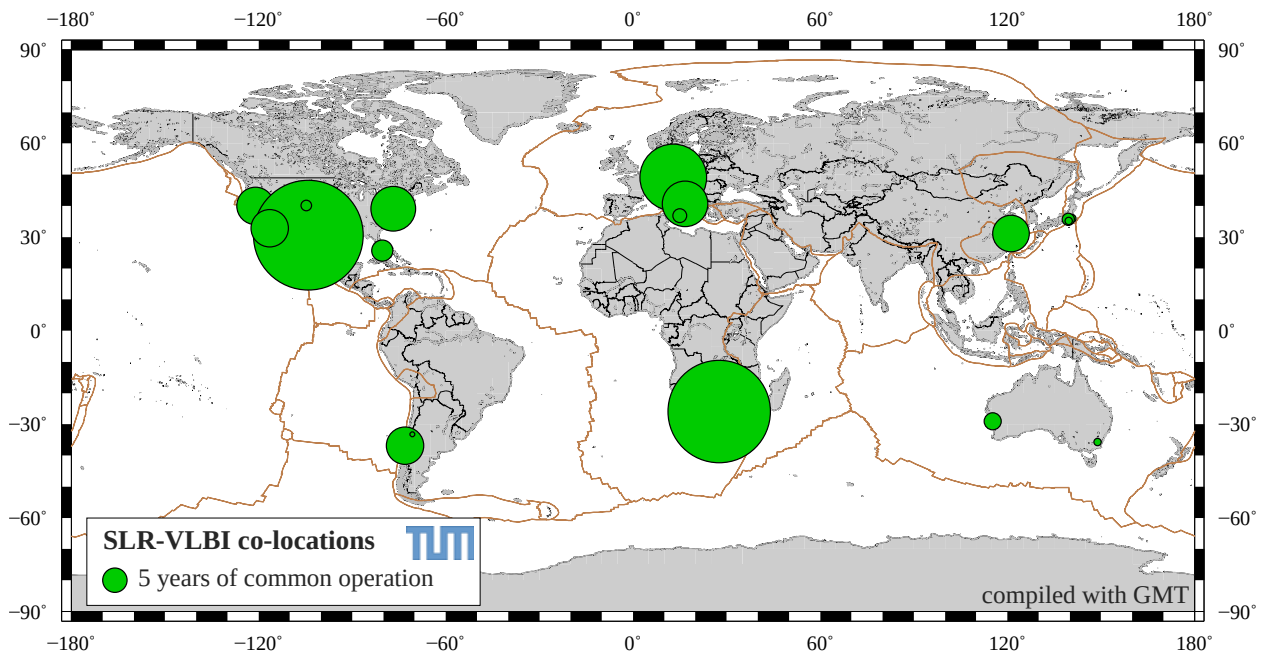


Fig. 3: Global distribution of VLBI and SLR co-location sites. The radius of the circles indicate the common observation time span of VLBI and SLR.

Table 4: Scale offsets [mm] obtained from 14-parameter Helmert transformations of GNSS markers computed using local ties (LTs) from SLR and VLBI reference points at the epoch 2000.0. For the LTs, different thresholds are applied.

LT threshold	VLBI w.r.t. GNSS [mm]	number of stations	SLR w.r.t. GNSS [mm]	number of stations	Δ scale (VLBI w.r.t. SLR) [mm]
7 mm	0.3 ± 0.08	20	-0.4 ± 0.07	15	0.7
10 mm	0.9 ± 0.07	26	0.3 ± 0.06	19	0.6
15 mm	1.4 ± 0.06	34	1.3 ± 0.07	23	0.1
25 mm	1.2 ± 0.07	36	4.5 ± 0.09	31	-3.3

Comparison of Earth Orientation Parameters (EOP)

As shown in Tab. 1, the three ITRS realizations also contain daily Earth orientation parameters (EOP). The terrestrial pole estimates result from a combination of the different space techniques, their rates are combined from VLBI and SLR. Length of Day (LOD) is derived from VLBI-only for the ITRF2014 and JTRF2014, whereas the DTRF2014 values are estimated from a combination of GNSS, SLR and VLBI. For all three ITRS realizations the celestial pole and dUT1 are derived from VLBI-only. At DGFI-TUM investigations were performed to study the impact of different station parameterizations on the terrestrial pole estimations. We compared the EOP results of the ITRF2014 with the DTRF2014 including non-tidal loading corrections (see Bloßfeld et al., this issue). The major difference between both multi-year reference

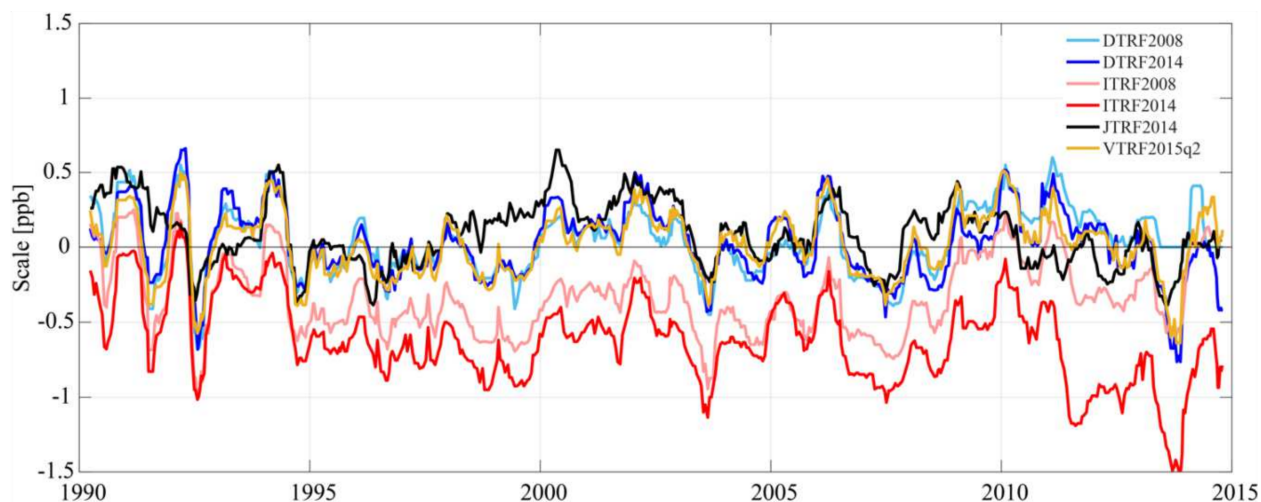


Fig. 4: Scale of combined IVS solutions w.r.t. different TRF realizations. This plot has been kindly provided by S. Bachmann (IVS CC at BKG, Germany).

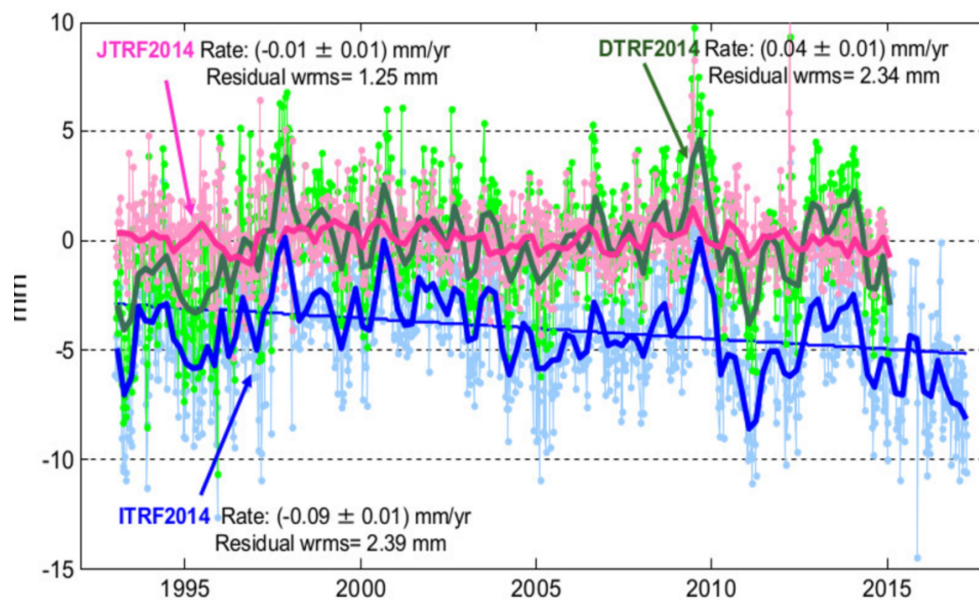


Fig. 5: Scale of combined ILRSA solutions w.r.t. different TRF realizations. This plot has been kindly provided by C. Luceri (ILRS CC at ASI, Italy).

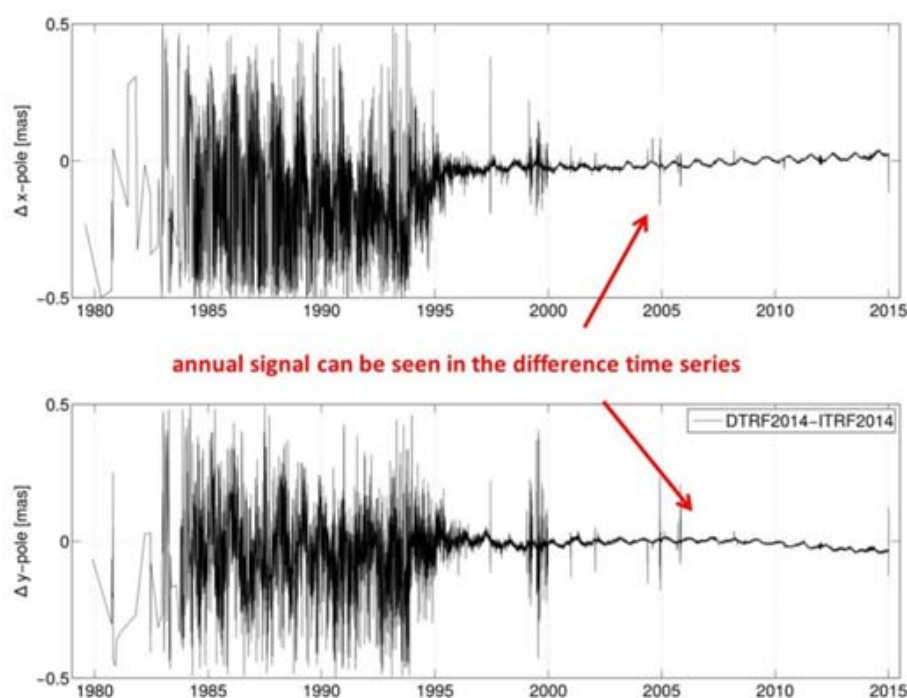


Fig. 6: Differences in the x- and y-pole obtained from ITRF2014 vs. DTRF2014+NTL.

frames (w.r.t. the estimated EOP) is that non-tidal loading corrections are applied at DGFI-TUM while ITRF2014 is computed by a simultaneous estimation of annual and semi-annual signals of the station positions. The differences between the terrestrial pole coordinates of the DTRF2014-NTL and the ITRF2014 are shown in Fig. 6. After 1994 when the GNSS were included in the combination, the scatter of the difference signals decrease significantly and a clear annual signal is visible in the time series. Details on the investigation of the impact of different station motion parameterization on the EOP estimation are provided in Bloßfeld et al. (2014). As shown in Fig. 7, the amplitude of the annual signal is about 0.01 mas for the x- and y-pole, which is in the order of only 0.3 mm.

Conclusions

This paper focuses on a comparison of the three latest realizations of the ITRS, namely the ITRF2014, the DTRF2014 and the JTRF2014 computed by the ITRS Combination Centers at IGN (France), DGFI-TUM (Germany) and JPL (USA), respectively. The fact that three different ITRF solutions are available within the IERS provides a valuable basis for a validation of the ITRF results and to assess the present accuracy of the terrestrial reference frame.

We performed an evaluation and comparison of the three latest realizations by Precise Orbit Determination (POD) for ten (high and low Earth orbiting) geodetic satellites using 24 years of SLR data. The results

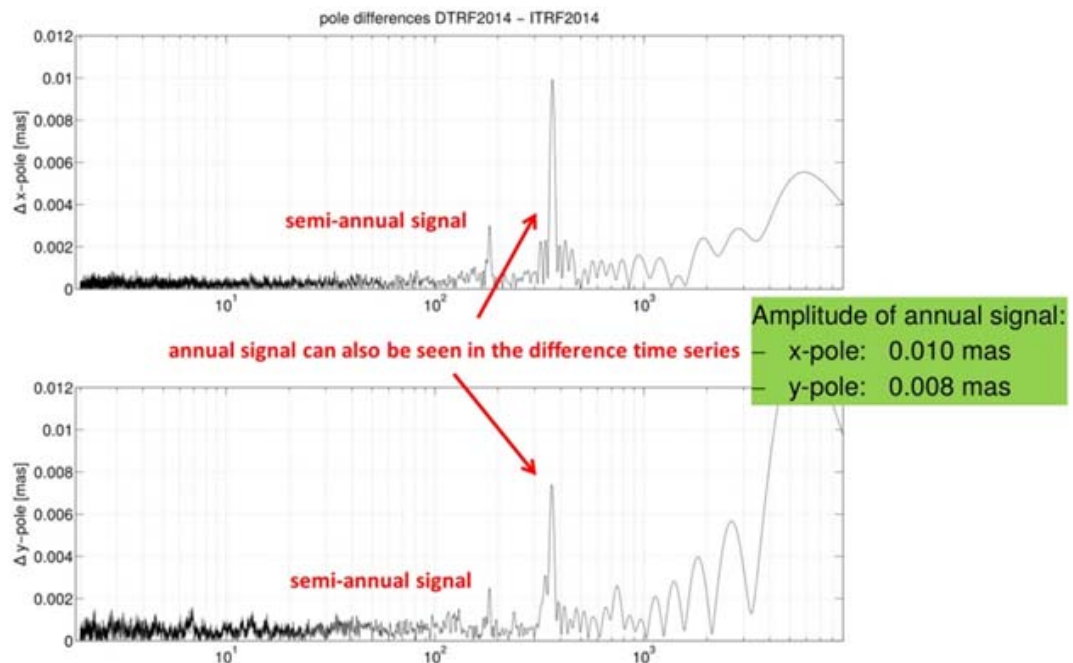


Fig. 7: Spectra of x - and y -pole differences obtained from ITRF2014 vs. DTRF2014+NTL.

revealed almost the same accuracy level for the ITRF2014, DTRF2014 and JTRF2014, and all of them performed better than the previous realization for SLR, the SLRF2008. The best results were obtained from the JTRF2014 and the DTRF2014+NTL which provide also non-linear variations in all station positions.

The direct comparison between the two long-term realizations, the ITRF2014 and DTRF2014, by applying 14-parameter Helmert transformations individually for the four different space techniques can be used to assess the present accuracy of the terrestrial reference frame. The realization of the geodetic datum (origin, scale and orientation) agrees within 5–6 mm and the agreement for station positions is better than 1 mm for VLBI and GNSS, about 2 mm for SLR and 4 mm for DORIS. The rates of the datum parameters and the station velocities agree (mostly) within 0.5 mm/yr.

Concerning the VLBI and SLR scale issue different comparisons have been performed (a) comparison of the SLR and VLBI single-technique solutions of IGN and DGFI-TUM, (b) direct comparison of the DGFI-TUM SLR and VLBI solutions using co-locations between both techniques, (c) indirect comparison between SLR and VLBI via GNSS co-locations, (d) scale comparisons performed by the IVS and ILRS Combination Centres at BKG (Germany) and ASI (Italy), respectively.

In summary, we can state that the DTRF2014 results do not confirm the scale bias between SLR and VLBI which was found in the ITRF2014 in the order of 1.37 ppb (= 9 mm). However, the results clearly indicate that the direct comparison of the SLR and VLBI scale is problematic, since

there are only about 10 good co-locations between both techniques. Thus, it would be essential to further improve the global core network and in particular the co-locations between SLR and VLBI to get a more stable integration of both techniques. The SLR and VLBI scale issue remains a key topic that needs to be further addressed by the ITRS Combination Centers and the technique-specific services. It would also be essential to develop advanced combination strategies to enable a refined analysis of technique-specific effects.

References

- Abbondanza C., Chin T., Gross R., Heflin M., Parker J., Soja B., van Dam T., Wu X.: JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System. *J Geophys Res Solid Earth*, doi: 10.1002/2017JB014360, 2017.
- Altamimi, Z., Rebischung P., Métivier L., Collileux X.: ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. *J Geophys Res Solid Earth*, vol. 121, doi: 10.1002/2016JB013098, 2016.
- Angermann D., Drewes H., Krügel M., Meisel B., Gerstl M., Kelm R., Müller H., Seemüller W., Tesmer V.: ITRS Combination Centre at DGFI – A terrestrial reference frame realization 2003. Deutsche Geodätische Kommission, Reihe B, Nr. 313, Munich, 2004.
- Bachmann S., Messerschmitt L., Thaller D.: IVS Contribution to ITRF2014. In: IAG Commission 1 Symposium 2014: Reference Frames for Applications in Geosciences (REFAG 2104), pp. 1–6, Springer, 2015.
- Bloßfeld M., Seitz M., Angermann D.: Non-linear station motions in epoch and multi-year reference frames. *J Geodesy*, vol. 88(1), pp. 45–63, doi: 10.1007/s00190-013-0668-6, 2014.
- Bloßfeld M.: The key role of Satellite Laser Ranging towards the integrated estimation of geometry, rotation and gravitational field of the Earth. Dissertation, Technische Universität München und Reihe C der Deutschen Geodätischen Kommission (ISBN: 978-3-7696-5157-7), 2015 (http://www.dgk.badw.de/fileadmin/user_upload/Files/DGK/docs/c-745.pdf).
- Bloßfeld M., Angermann D., Seitz M.: DGFI-TUM analysis and scale investigations of the latest terrestrial reference frame realizations, IAG-IASPEI Symposia Proceedings, Springer, 2018.
- Bloßfeld M., Seitz M., Angermann D., Seitz F.: DTRF2014: DGFI-TUM realization of the International Terrestrial Reference System (ITRS), this issue.
- Gerstl M., Kelm R., Müller H., Ehrnsperger W.: DOGS-CS Kombination und Lösung großer Gleichungssysteme. Interner Bericht, DGFI, Munich, 2000.

- Luceri C., Pavlis E.: The ILRS contribution to ITRF2014. 2016 (http://itrf.ign.fr/ITRF_solution/doc/ILRS-ITRF2014-description.pdf).
- Moreaux G., Lemoine F. G., Capdeville H., Kuzin S., Otten M., Stepanek P., Willis P., Ferrage P.: Contribution of the International DORIS Service to the 2014 realization of the International Terrestrial Reference Frame, *Adv Space Res*, doi:10.1016/j.asr.2015.12.021, 2016.
- Pavlis E.: SLRF2008: The ILRS reference frame for SLR POD contributed to ITRF2008, Ocean Surface Topography Science Team 2009 meeting. Seattle, WA, June 22–24, 2009 (http://www.avisioceanobs.com/fileadmin/documents/OSTST/2009/poster/Pavlis_2.pdf).
- Rebischung P., Altamimi Z., Ray J., Garayt B.: The IGS contribution to ITRF2014, *J Geodesy*, vol. 90(7), pp. 611–630, doi: 10.1007/s00190-016-0897-6, 2016.
- Rudenko S., Bloßfeld M., Müller H., Dettmering D., Angermann D., Seitz M.: Evaluation of DTRF2014, ITRF2014 and JTRF2014 by Precise Orbit Determination of SLR Satellites. *IEEE Transactions on Geoscience and Remote Sensing*, vol. 56(6), pp. 3148–3158, doi: 10.1109/TGRS.2018.2793358, 2018.
- Seitz M., Angermann D., Bloßfeld M., Drewes H., Gerstl M.: The 2008 DGFI realization of the ITRS: DTRF2008. *J Geodesy*, vol. 86(12), pp. 1097–1123, doi: 10.1007/s00190-012-0567-2, 2012 (<https://mediatum.ub.tum.de/doc/1300855/1300855.pdf>).
- Seitz M., Angermann D., Gerstl M., Bloßfeld M., Sánchez L., Seitz F.: Geometrical Reference Systems. In: Freedon W., Nashed M.Z., Sonar T. (Eds.) *Handbook of Geomathematics (Second Edition)*, Springer, pp. 2995–3034, doi: 10.1007/978-3-642-54551-1_79, 2015.
- Seitz M., Bloßfeld M., Angermann D., Schmid R., Gerstl M., Seitz F.: The new DGFI-TUM realization of the ITRS: DTRF2014 (data). Deutsches Geodätisches Forschungsinstitut, Munich, doi: 10.1594/PANGAEA.864046, 2016.

A comparison of the DTRF2014, ITRF2014, and JTRF2014 solutions using DORIS

Guilhem Moreaux¹, Hugues Capdeville¹, Claudio Abbondanza², Mathis Bloßfeld³, Jean-Michel Lemoine⁴, and Pascale Ferrage⁴

¹ *Collecte Localisation Satellites, Ramonville Saint-Agne, France*

² *Jet Propulsion Laboratory – California Institute of Technology, Pasadena, USA*

³ *Deutsches Geodätisches Forschungsinstitut at the Technische Universität München (DGFI-TUM), Munich, Germany*

⁴ *Centre National d'Etudes Spatiales (CNES), Toulouse, France*

Abstract. In the context of the 2014 realization of the International Terrestrial Reference Frame (ITRF2014), the International DORIS Service (IDS) submitted to the International Earth Rotation and Reference Systems Service (IERS) a set of 1140 weekly solution files including station coordinates and Earth orientation parameters, covering the time period from 1993.0 to 2015.0. Then, in combination with the three other space geodetic contributions (GNSS, SLR and VLBI) to ITRF2014, the DGFI-TUM, the IGN, and the JPL IERS Combination Centres (CCs) computed their own TRF realizations denoted as DTRF2014 [Seitz *et al.*, 2016], ITRF2014 [Altamimi *et al.*, 2016], and JTRF2014 [Abbondanza *et al.*, 2017]. In this paper, we shortly present the computation procedures of the three TRF realizations to be able to interpret the obtained comparison results. However, the main objective of this study is to compare these three TRF realizations in terms of geocenter, scale, station positioning, and precise orbit determination (POD) performances based on the IDS contribution to ITRF2014 (IDS 09) and DORIS satellite localization from the IDS CNES-CLS analysis center. In case of the geocenter and scale realization, we found significant differences between the TRF solutions. The DTRF2014 shows the smallest total offset w.r.t. IDS 09 whereas the ITRF2014 shows the best overall performance. In terms of station position residuals, JTRF2014 performs best since this TRF includes non-linear station variations. For the DORIS POD, we found only differences at a very low level. As a summary, we can state that all TRF solutions agree very well with each other and that the obtained differences are very small. Nevertheless, the ITRF2014 solution shows the slightly best overall performance of all solutions.

Introduction

DORIS (Doppler Orbitography Radiopositioning Integrated by Satellite) is one of the four fundamental geodetic techniques contributing to the realization of the ITRS (International Terrestrial Reference System). Thus, early 2015, in the framework of the 2014 realization of the International Terrestrial Reference Frame (ITRF), the IDS [International DORIS Service; Willis *et al.*, 2010] delivered a set of 1140 files including weekly minimum constrained solutions of station coordinates and daily Earth orientation parameters, covering the time period from January 1993 to December 2015 [Moreaux *et al.*, 2016a] to the International Earth Rotation and Reference Systems Service (IERS). In addition to the DORIS data span, the IDS contributions to ITRF2008 and ITRF2014 differ by the number of multi-satellite weekly IDS analysis center solutions they are based on (7 for ITRF2008, 6 for ITRF2014), the DORIS observations (even over the common time period), and the DORIS measurement

modeling. Benefiting from the development of new models to correct the Jason-1 [Lemoine & Capdeville, 2006] and SPOT5 [Capdeville *et al.*, 2016] data for the South Atlantic Anomaly (SAA) effects, the new series includes Jason-1 data between the end of the TOPEX/Poseidon mission and the beginning of the Jason-2 mission and uses the SPOT5 SAA-corrected data starting on SPOT5 cycle 138 (2005/12/27). The IDS contribution to ITRF2014 also includes tracking data from the DORIS satellites launched after mid-2008: Jason-2, Cryosat-2, HY-2A and Saral. Note that all these new satellites carry on-board the latest generation of the DORIS receivers, the so-called DGXX receivers, which can track up to seven beacons simultaneously, resulting in a significant increase in the number of available measurements especially at lower elevations [Bloßfeld *et al.*, 2016b]. As a consequence of their low orbital altitudes (700–1340 km), the DORIS satellites are more sensitive to the time-variable geopotential [e.g. EIGEN-6S2, Rudenko *et al.*, 2014]. Then, the IDS analysis centers adopted geopotential models that included more detailed time-variable gravity modeling. Furthermore, the new IDS solution includes the implementation of beacon frequency offset estimations (i.e. difference between actual frequency and the nominal value) as well as DORIS ground antenna phase center variations [Tourain *et al.*, 2016]. As a result, compared to the IDS contribution to ITRF2008 [Altamimi *et al.*, 2011], the IDS contribution to ITRF2014 exhibits more accurate translation and scale parameters and vertical positioning performances are improved. For more details on the IDS contribution to ITRF2014, see Bloßfeld *et al.* [2016b]; Moreaux *et al.* [2016a]. From the IDS, the IGS (International GNSS Service), the ILRS (International Laser Ranging Service) and the IVS (International VLBI Service) submissions for the ITRF2014, the three IERS Combination Centres (CCs: DGFI-TUM, IGN and JPL) computed combined TRF solutions individually. The three CCs combine technique-specific products provided by the above mentioned services of the International Association of Geodesy (IAG). Thereby, the IGS and the IDS provide minimum constrained daily and weekly solutions whereas the ILRS provides loosely constrained weekly solutions. The only service which provides session-wise datum-free normal equations is the IVS. Since all of the four fundamental geodetic space techniques, namely GNSS, VLBI, SLR, and DORIS, have technique-specific strengths, highest accuracy of derived geodetic parameters can only be achieved in a rigorous combination of them as long as an appropriate weighting of the observations is adopted, local ties are provided and introduced, and velocity equality constraints are properly selected. Thus, to link the different techniques, one needs co-located sites: sites where two or more space geodesy instruments are operating and where the differential coordinates between the geodetic instruments are known (so called local ties). In addition to the availability of co-located sites, the TRF computation strongly depends on the segmentation of station

position time series into time intervals with constant velocity and without any coordinate jumps. While DGFI-TUM and IGN use the conventional least-squares approach to estimate mean positions and velocities at a reference epoch, JPL implemented the Kalman filtering approach [Wu *et al.*, 2015] to estimate weekly positions. Other examples of epoch-wise (sub-secular) estimated frames are given in Bloßfeld *et al.* [2014, 2016a]. In the JPL solution, the station position is modeled as a random walk driven by white noise whose variance is characterized by analyzing station displacements induced by temporal changes of planetary fluid masses (atmosphere, oceans and continental surface water). The main objective of this investigation is to show and analyze the impact of using one of the three ITRF2014 realizations while estimating precise positions of either DORIS stations or DORIS satellites. After a brief presentation of the three combination approaches and solutions, we evaluate geocenter and scale offsets between IDS 09 to the 3 TRF realizations. Then, we show the station position differences between the three 2014 TRF realizations and we evaluate these three solutions in terms of tie residuals w.r.t. surveyed ties. Afterwards, we analyze the impact of estimating the DORIS station positions from the three different TRF solutions on the precise orbit determination (POD) of three DORIS satellites: Topex/Poseidon, SPOT5 and Jason-2. Within the DORIS POD, the station coordinates are fixed to the different TRF realizations. A similar study for a POD of SLR satellites was done by Rudenko *et al.* [2017]. Moreover, for altimetry satellites, Zelensky *et al.* [2017] did some investigations. Finally, we provide recommendations in the use of the DTRF2014, ITRF2014, and JTRF2014 for those who are interested in the estimation of precise positions of either DORIS stations or DORIS satellites.

Characteristics of the DTRF2014, ITRF2014, and JTRF2014 solutions

This section briefly discusses the characteristics of each of the three evaluated ITRF realizations used in this paper. For further details, the reader is referred to Seitz *et al.* [2012] and Seitz *et al.* [2016] for the DGFI-TUM solution DTRF2014, to Altamimi *et al.* [2016] for the IGN solution ITRF2014, and to Abbondanza *et al.* [2017] for the JPL solution JTRF2014. The main characteristics are summarized in Table 1.

DTRF2014 from DGFI-TUM

The DTRF2014 solution was computed in a procedure originally developed for the computation of the DTRF2008 solution. A detailed description of the DGFI-TUM combination approach at the normal equation level of the least-squares adjustment process can be found in Seitz *et al.* [2012]. More details on the DORIS-specific solution of TRFs and EOPs which was incorporated into the DTRF2014 can be found at Bloßfeld *et al.* [2016b]. The IDS contribution to the DTRF2014 is a time series of weekly minimum constrained solutions with full

variance-covariance information reported in SINEX files. In a first step, datum-free normal equations (NEQs) are reconstructed by inverting the variance-covariance matrix and introducing similarity transformation parameters w.r.t. the origin, the orientation and the scale (7 parameter in total each week). The epoch-wise TRF solutions are screened for outliers and discontinuities which are introduced afterwards into the weekly NEQ system. In the so called intra-technique combination step, the datum-free NEQs are accumulated using equal weights each week. The parametrization of the epoch-wise available station coordinates is changed to one offset and one velocity estimated at a reference epoch. At the end of this step, the IDS contribution to the DTRF2014 comprise one multi-year NEQ containing station coordinates, velocities and epoch-wise given EOPs. The NEQs of the other geodetic space techniques are derived in a similar way with slight changes due to technique-specific aspects. In the inter-technique combination step, the technique-specific NEQs of the four geodetic space techniques DORIS, VLBI, SLR, and GNSS are combined. Equal parameters such as EOP at a common epoch are stacked. The relative weighting of the NEQs is based on the a posteriori variance factors of the single-technique solutions. The station coordinates and velocities are combined by introducing external constraints between the station coordinates (local ties) and between the velocities at one station (more than one technique operated at a station). The relative weighting of the local ties is done according to the residuals between the local tie and the 3D-difference between the technique-specific reference points in the single-technique solutions. The datum of the combined solution is realized as follows. The origin is implicitly realized within the SLR NEQ. This means, no translation constraints have to be introduced. The origin information is transferred via the local ties from the SLR station network to the other techniques. In a similar way, the scale of the combined NEQ is realized. The SLR- and VLBI-NEQ contain implicit information of the scale. Before combination, the SLR- and VLBI-only scales are compared. Since DGFI-TUM founds that they are equal, it is valid to treat the scales as one common scale in the combination which means that this information is transferred via the local ties to the DORIS and GNSS station network. The orientation is realized by a no-net-rotation (NNR) condition applied to a selected subnet of GNSS stations (stable time series and long observation time span). Again, this information is distributed to the other technique-specific networks via the local ties. From the datum realization described above it is obvious that the quality of the estimated solution strongly depends on the quality and the global distribution of the introduced local ties. Therefore, it is often stated in the literature that currently, the main limiting factor of the global TRF accuracy are the local ties.

ITRF2014 from IGN

Globally, the IGN procedure to compute the ITRF2014 [Altamimi *et al.*, 2016] is very similar to the one used for the previous ITRF realizations such as ITRF2005 [Altamimi *et al.*, 2007] and ITRF2008 [Altamimi *et al.*, 2011]. Therefore, the ITRF2014 realization can be seen as a two step process: 1) stacking of individual time series to get a long-term solution per technique including station positions and velocities at a reference epoch as well as daily EOPs; and 2) combining the four space geodesy technique long-term solutions with local ties at the co-located sites. Similar to the past ITRF solutions, the ITRF2014 long-term (mean) origin coincides with the Earth system center of mass as observed by the SLR technique over the full ITRF2014 time span (i.e. 1993.0–2015.0) whereas the ITRF2014 scale is defined as the weighted mean of the SLR and VLBI intrinsic scales. Moreover, IGN still makes use of velocity constraints to force nearby stations or multiple segments of the same station to have the same velocity. The station position time series discontinuities were identified by the visual inspection of the time series. In addition, to ensure the consistency between all the techniques, while an earthquake happened at one site, the same discontinuity epoch was used for all the techniques present at that site. However, this new IGN solution differs to the previous ITRF realizations by the addition in the time series analysis of both annual and semi-annual signals as well as post-seismic deformation (PSD) for sites affected by major earthquakes. The modelization of the periodic signals is limited to the sites with sufficient time-span (longer than 2 years) and is realized by the addition to the stacking of sinusoidal functions. While the estimation of the periodic seasonal signals is done per technique, the PSD parameters are fitted to the GNSS station position time series only. In overall, 13 DORIS stations from 7 sites are associated to PSD corrections. Due to the lack of a co-located GNSS receiver at the epoch of the earthquake, some DORIS sites (ex: Cibinong – Indonesia, Colombo – Philippines) which faced some Earthquakes do not take benefit of a logarithmic and/or exponential motion modeling. If the motion of a station was modeled with a PSD correction then, not computing the corrections to be added to the linear model would introduce position errors at the decimeter level. As the periodic signals are deduced from the coordinate time series, they must contain not only geophysical phenomena (such as atmospheric and hydrological non-tidal one) but also technique systematic errors. Altamimi *et al.* [2016] reported that estimating the annual and semi-annual signals allows to reduce the velocity formal errors by about 10 %.

JTRF2014 from JPL

The Kalman filter and smoother for reference frame combination (KALREF) developed at the Jet Propulsion Laboratory combines observations of station positions as determined from VLBI, SLR, GNSS

and DORIS and EOP measurements along with the data measurement covariance matrices. Local tie observations at ITRF co-located sites are also assimilated during the combination and adopted as constraints to tie the technique-specific TRF. KALREF allows TRFs to be realized at a sub-secular time scale. The filter assimilates observations at a fixed weekly time step and includes options for constraining the station positions to move linearly or to move linearly and seasonally. Through the use of stochastic models for the process noise of the state vector parameters consisting of station positions, velocities, EOPs and the frame defining parameters (the Helmert transformation parameters), the station positions can be constrained to follow the linear or linear plus seasonal models (by setting the process noise variance to zero), to recover temporally unconstrained state parameters close to the observed station positions (by setting the process noise variance to a large value) or to follow a smoothed path (by setting the process noise variance to an intermediate value).

JTRF2014, in particular, adopts a dynamical model describing the evolution of the station positions based upon trend, annual, and semi-annual oscillatory modes. Unlike ITRF and DTRF realizations, JTRF makes use of position process noise to describe the non-secular and non-seasonal component of the Earth deformation. White-noise driven random walk is chosen to represent the station position process noise. Site-dependent variances were determined by analyzing the non-seasonal and non-secular component of the Earth elastic response to terrestrial fluid redistributions. EOPs and Helmert transformation parameters instantly mapping the combined frame to the space-geodetic inputs are also modeled as random walk driven by white noise, with variances sufficiently large to accommodate the week-to-week fluctuations of the Earth rotation and the Helmert parameters variations.

JTRF2014 frame definition is accomplished by setting to zero the SLR translational parameters and by sequentially estimating translational parameters from GNSS, DORIS and VLBI to SLR during the measurement update. This entails the SLR origin is not being adjusted during the assimilation. Likewise, scale Helmert parameters of VLBI and SLR are set to zero whereas the scale of GNSS and DORIS inputs is being adjusted to the weighted (through the inverse of the covariance matrices of the observations) average of VLBI and SLR scale. As a result of that, JTRF2014 provides a sub-secular (weekly) frame whose origin is the quasi-instantaneous CM (as detected by SLR) and whose scale is the quasi-instantaneous scale from VLBI and SLR.

Tie vectors are applied at the epoch of their measurement and each of the tie constraints is weighted through the inverse of the measured covariance matrices scaled by properly selected variance factors. The optimal set of tie variance factors has been empirically determined as

Table 1: *Main features of the DTRF2014, ITRF2014 and JTRF2014 DORIS solutions.*

Solution	DTRF2014	ITRF2014	JTRF2014
Producer	DGFI-TUM	IGN	JPL
Post-seismic deformation	No	Yes	No
Technique-specific velocity constraints	No	Yes	Yes
Nb of files	1	1	1838
Nb of sites	71	71	71
Nb of stations	153	160	159
Nb of discontinuities	56	62	13
Nb of velocities	148	127	-
Nb of vertical velocities with $\sigma \leq 1$ mm/yr	123	196	-
Nb of horizontal velocities with $\sigma \leq 1$ mm/yr	106	160	-

a function of the agreement between space-geodetic and terrestrial observations.

Co-motion constraints have also been applied during the JTRF2014 assimilations. Such constraints dictate the equivalence of the displacements observed by nearby stations at co-located sites and they require (i) the trend variable (i.e. the velocity) of co-located stations be equivalent, (ii) the seasonal oscillator parameters relevant to co-located instruments be the same, (iii) the station position process noise of co-located stations be characterised by a 1.0 correlation coefficient.

Table 2: Main statistics of the transformation parameters of the IDS 09 series wrt DTRF2014, DTRF2014ntc, ITRF2014, ITRF2014asc and JTRF2014. Units are mm and mm/yr.

Time span	Datum	Scale			T_x			T_y			T_z		
		mean	trend	std	mean	trend	std	mean	trend	std	mean	trend	std
	DTRF2014	1.51	0.59	4.00	2.35	-1.33	5.76	5.73	-1.78	5.76	1.45	1.92	20.64
	DTRF2014ntc	1.99	0.58	4.01	2.64	-1.37	5.89	5.71	-1.76	5.71	2.77	1.80	20.41
	1993.0 ITRF2014	7.52	0.25	3.94	-1.28	-0.08	5.75	-2.47	-0.59	5.85	-3.83	3.26	20.70
2002.4	ITRF2014asc	7.56	0.25	3.87	-1.30	-0.08	5.20	-2.57	-0.59	5.28	-3.84	3.29	20.49
	JTRF2014	16.19	-1.38	4.23	-0.31	-0.54	5.94	2.36	-1.86	5.99	-3.26	3.80	20.32
	DTRF2014	5.37	-0.20	2.11	-0.98	-0.02	3.85	-0.33	-0.27	4.00	-18.59	-3.05	12.11
2002.4	DTRF2014ntc	5.22	-0.19	2.16	-1.10	0.06	4.07	-0.54	-0.24	3.56	-19.14	-3.12	12.01
	ITRF2014	8.78	-0.15	2.06	-1.01	0.01	3.90	1.50	0.06	3.99	-17.68	-2.93	12.11
	2008.5 ITRF2014asc	8.80	-0.14	1.97	-0.94	0.07	3.03	1.48	-0.06	3.38	-17.68	-2.94	12.04
2008.5	JTRF2014	10.36	-0.09	2.30	-1.36	-0.08	3.99	-0.13	0.25	3.52	-17.41	-3.30	12.33
	DTRF2014	2.86	1.13	2.04	-0.43	0.93	3.32	-1.48	0.34	3.71	-7.76	1.72	9.39
	DTRF2014ntc	2.79	1.07	1.91	-0.60	0.90	3.48	-1.29	0.28	3.07	-8.14	1.50	9.51
2008.5	ITRF2014	7.62	1.48	2.15	-2.50	0.33	3.40	-0.70	-0.23	3.67	-8.40	1.04	9.37
	ITRF2014asc	7.64	1.49	2.04	-2.53	0.38	3.36	-0.55	-0.25	2.83	-8.37	1.01	9.43
	JTRF2014	7.59	1.11	2.07	-2.96	0.02	3.44	-4.85	-0.87	2.94	-8.74	0.65	9.64

Table 3: Station position WRMS of IDS 09 w.r.t. DTRF2014, DTRF2014ntc, ITRF2014, ITRF2014asc, and JTRF2014. Unit is mm.

Time span	Datum	East		North		Up	
		mean	std	mean	std	mean	std
1993.0-2002.4	DTRF2014	16.97	2.24	12.13	2.04	14.79	2.15
	DTRF2014ntc	16.97	2.24	12.11	2.04	14.81	2.15
	ITRF2014	17.10	2.21	12.29	2.05	14.95	2.16
	ITRF2014asc	17.04	2.21	12.12	2.03	14.72	2.13
	JTRF2014	16.60	2.18	11.34	1.93	13.60	2.04
2002.4-2008.5	DTRF2014	10.26	1.85	7.53	1.26	8.61	1.59
	DTRF2014ntc	10.34	1.84	7.54	1.24	8.62	1.58
	ITRF2014	10.68	1.89	7.86	1.32	9.05	1.61
	ITRF2014asc	10.44	1.87	7.60	1.34	8.75	1.63
	JTRF2014	10.30	1.82	7.15	1.20	8.09	1.54
2008.5-2015.0	DTRF2014	8.03	1.17	6.36	1.10	7.25	1.10
	DTRF2014ntc	8.05	1.17	6.32	1.10	7.14	1.08
	ITRF2014	8.37	1.15	6.61	1.06	7.60	1.15
	ITRF2014asc	8.27	1.11	6.26	1.00	7.14	1.06
	JTRF2014	7.97	1.11	5.90	1.06	6.59	1.00

Comparisons between DTRF2014, ITRF2014 and JTRF2014

From the previous sections on the presentation of the three solutions, we first note that while DGFI-TUM and IGN estimate mean positions and velocities at a mean reference epoch by the least-squares technique (see Fig. 1 and 2), JPL combines the four space geodetic time series using a Kalman filter to produce weekly positions. Furthermore, the three IERS CCs differ in the handling of constraints in their inversion processes. For example, DGFI-TUM handles velocity equality constraints to force the same value over multiple segments unless a velocity discontinuity was observed (e.g. due to an earthquake) very carefully. Therefore, in the DTRF2014 solution, at any station and any time span corresponds one velocity vector while, in the ITRF2014 solution, for one station several time intervals can rigorously have an identical velocity. That explains why the DTRF2014 solution comprises more velocity vectors than the ITRF2014 (see Fig. 1 and 2) and presents larger formal errors for their velocities (which might be more realistic). For each DORIS station and each time period from the DTRF2014 solution, we identified the corresponding ITRF2014 velocity and computed both the horizontal and vertical velocity differences as depicted in Fig. 3. For the sites with ITRF2014 post-seismic corrections, the time periods corresponding to the post-seismic corrections were removed as they do not correspond

Table 4: Amplitude of annual, semi-annual, 118-120, and 58-59 days signal in geocenter of IDS 09 wrt DTRF2014, DTRF2014ntc, ITRF2014, ITRF2014asc and JTRF2014. Unit is mm.

Time span	Datum	T_x				T_y				T_z			
		365	183	118	59	365	183	118	59	365	183	118	59
1993.0 2002.4	DTRF2014	2.98	1.15	-	1.36	3.59	-	-	-	-	-	5.16	-
	DTRF2014ntc	-	1.28	-	1.39	3.54	-	-	-	-	-	5.21	-
	ITRF2014	-	1.24	-	1.33	3.58	-	-	-	-	-	5.15	-
	ITRF2014asc	-	1.19	-	1.17	1.44	-	-	-	-	-	5.19	-
	JTRF2014	3.69	0.96	-	1.35	3.62	-	-	-	-	-	5.18	-
2002.4 2008.5	DTRF2014	3.22	0.97	0.83	-	3.44	1.20	-	-	-	-	3.62	3.17
	DTRF2014ntc	3.39	-	-	-	2.10	1.31	-	-	-	-	3.63	3.05
	ITRF2014	3.11	0.96	0.79	-	3.35	1.28	-	-	-	-	3.49	3.13
	ITRF2014asc	-	-	0.84	-	-	-	-	-	-	-	3.56	3.10
	JTRF2014	3.45	-	-	-	1.97	1.39	-	-	-	-	3.56	3.14
2008.5 2015.0	DTRF2014	1.59	1.27	2.50	0.86	3.53	-	1.31	1.67	-	-	5.65	-
	DTRF2014ntc	2.02	1.28	-	0.85	2.02	-	1.37	1.65	-	-	5.56	-
	ITRF2014	-	1.30	2.49	-	3.43	-	1.29	1.60	-	-	5.65	-
	ITRF2014asc	-	1.03	2.54	0.82	0.97	-	1.38	1.59	-	-	5.72	-
	JTRF2014	2.22	0.63	2.49	0.85	1.69	-	1.35	1.61	-	2.09	5.79	-

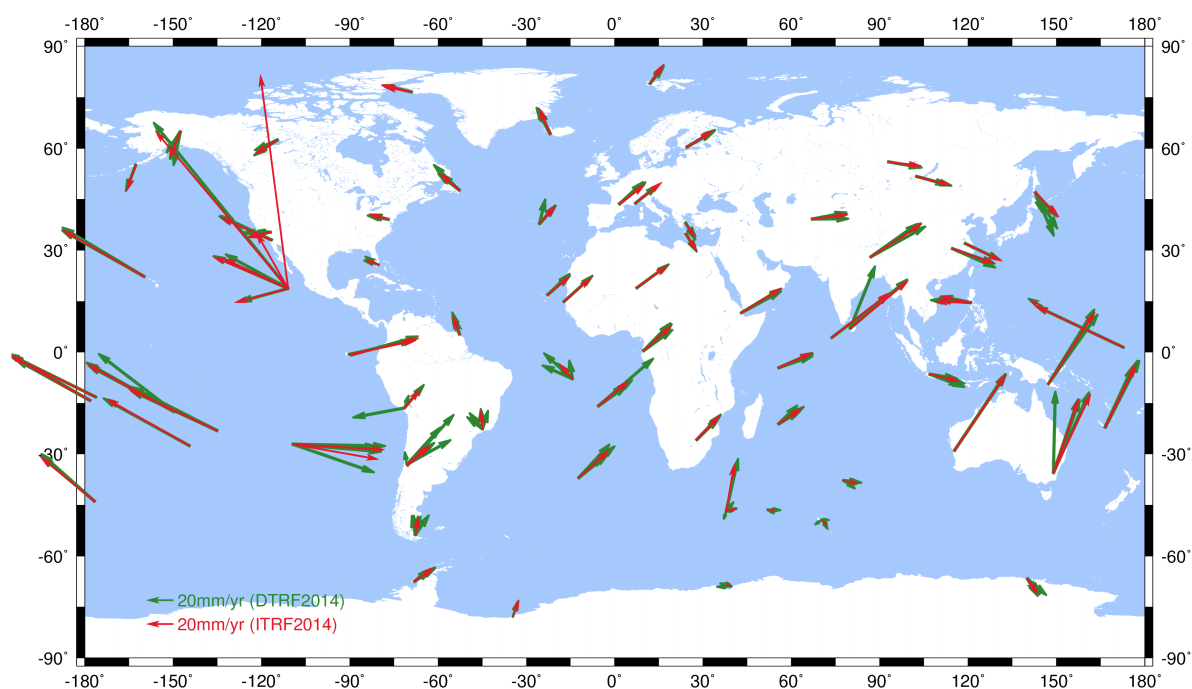


Fig. 1: Horizontal DORIS velocities from DTRF2014 and ITRF2014.

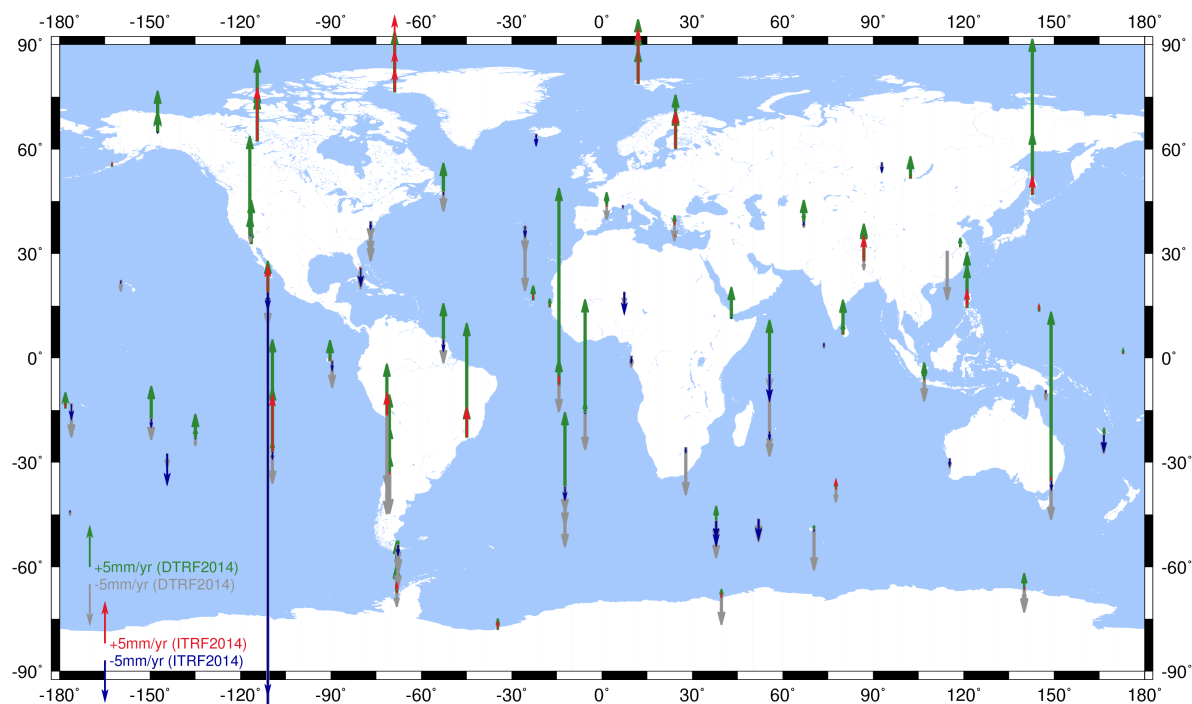


Fig. 2: Vertical DORIS velocities from DTRF2014 and ITRF2014.

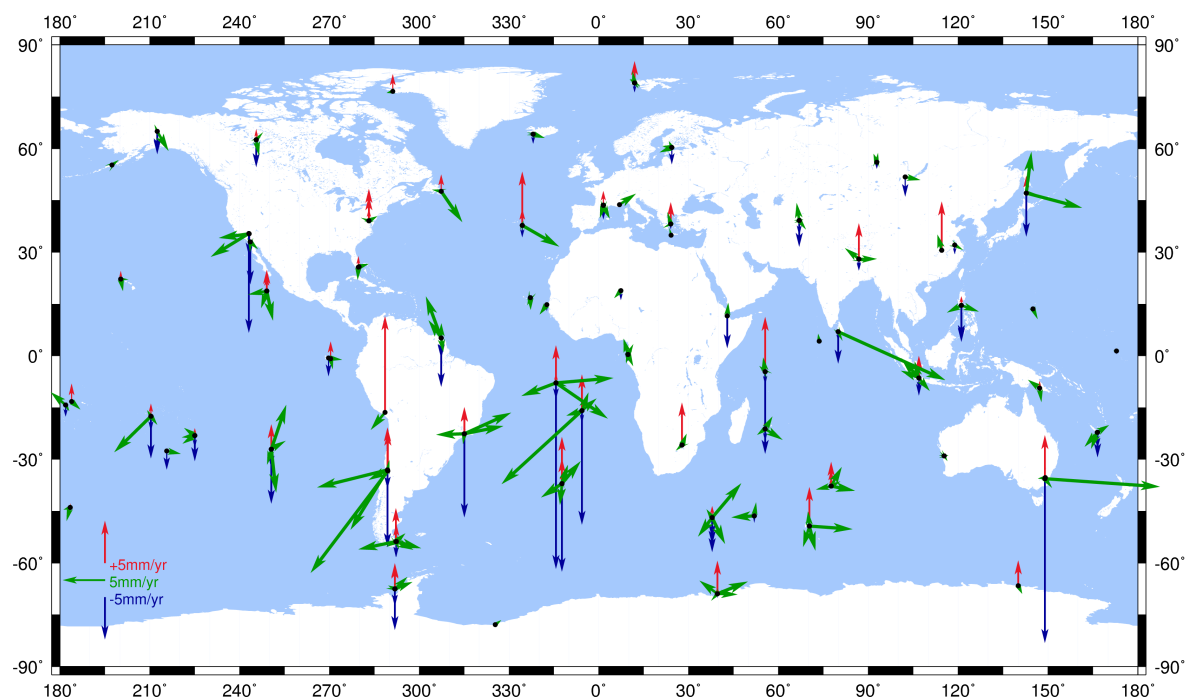


Fig. 3: Velocity differences between DTRF2014 and ITRF2014.

Table 5: Tie residuals of DTRF2014, ITRF2014 and JTRF2014 wrt IGN DORIS ground ties. Unit is mm.

Datum	Nb of ties	mean	std	rms
DTRF2014	50	17	20	26
ITRF2014	50	13	13	18
JTRF2014	50	18	19	26
DTRF2014	76	20	19	28
ITRF2014	76	15	18	23

Table 6: RMS and maxim of station position differences between DTRF2014, ITRF2014 and JTRF2014. Unit is mm.

Datum	Time span	East		North		Up	
		rms	max	rms	max	rms	max
DTRF2014 - ITRF2014	1993.0-2002.4	7.95	46.00	7.50	55.80	9.82	46.20
DTRF2014 - ITRF2014	2002.4-2008.5	4.01	38.00	3.24	59.90	4.97	52.40
DTRF2014 - ITRF2014	2008.5-2015.0	3.21	19.70	3.39	22.10	5.85	52.50
JTRF2014 - ITRF2014	1993.0-2002.4	7.13	32.60	6.01	42.10	13.19	47.50
JTRF2014 - ITRF2014	2002.4-2008.5	4.29	25.30	4.23	23.20	6.15	31.60
JTRF2014 - ITRF2014	2008.5-2015.0	4.82	21.00	4.16	18.80	6.60	36.20
JTRF2014 - DTRF2014	1993.0-2002.4	7.10	46.20	8.18	64.40	17.82	59.70
JTRF2014 - DTRF2014	2002.4-2008.5	4.29	23.10	4.65	21.80	7.57	23.10
JTRF2014 - DTRF2014	2008.5-2015.0	5.23	24.50	4.85	20.40	8.08	46.10

to a linear motion model as it is for DTRF2014. As a consequence, such velocity comparisons between these two solutions will have no meaning. From Fig. 3, we observe that for most of the sites with a significant velocity difference (i.e. larger than 5 mm/yr; such as Ponta-Delgada, Canberra, Santiago, St-Helena, Tristan Da Cunha), both the horizontal and vertical velocities disagree. The analysis of the velocity differences showed that they are associated with short periods of observations (smaller than 3 years) in the DTRF2014. Over the 56 position discontinuities introduced by DGFI-TUM, 31 discontinuities differ from some IGN ones by either less than seven days (frequency of the DORIS solution) or by a data gap (e.g. the DGFI-TUM discontinuity is at the start of the DORIS data gap while the IGN one is at the end), so these 31 discontinuities can be considered as in common. The JPL defined 13 DORIS position discontinuities at 10 sites; 6 discontinuities can be assimilated to ITRF2014 ones.

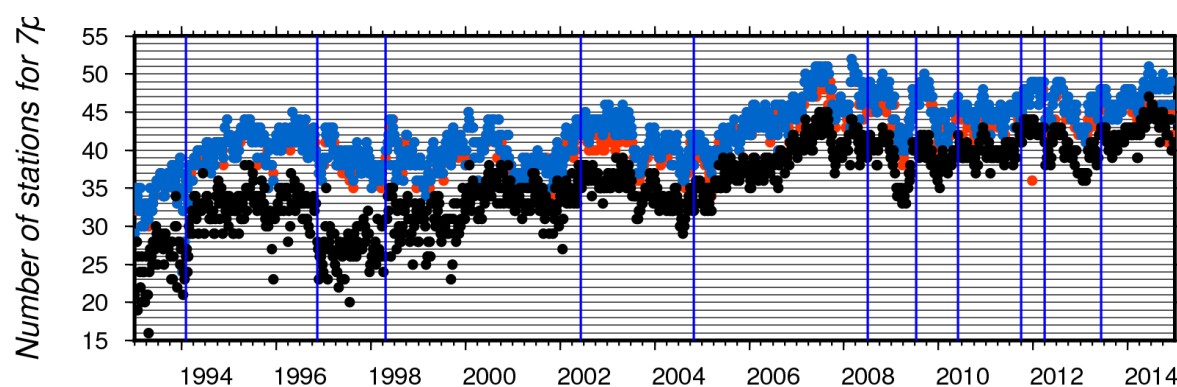


Fig. 4: DTRF2014 (red), ITRF2014 (blue) and JTRF2014 (black) weekly DORIS network. Vertical lines correspond to DORIS satellite constellation changes.

IDS 09 evaluation w.r.t. DTRF2014, ITRF2014, and JTRF2014

That section presents and discusses the differences in terms of Helmert parameters and station position performances while using the DTRF2014, ITRF2014, and JTRF2014 solutions as reference frame when evaluating the IDS 09 series. The software package used for the evaluation is the IGN CATREF (Combination and Analysis of Terrestrial Reference Frames) package [Altamimi *et al.*, 2002a] which was also used for the computation of the ITRF2014 solution. Each week, according to the so-called SOLUTION/EPOCHS of the SINEX files, we extracted the list of the active DORIS stations. Whereas in the case of JTRF2014 the positions of the active stations were simply extracted from the weekly JPL files, in the case of the DTRF2014 and ITRF2014, the weekly positions were computed from the positions and velocities given at the reference epoch. Furthermore, in the case of ITRF2014, the post-seismic corrections were taken into considerations while estimating the weekly station positions. Hereafter, by DTRF2014ntc, we denote the DTRF2014 with the atmospheric and hydrological non-tidal loading corrections and, by ITRF2014asc, the ITRF2014 within annual and semi-annual signals.

Weekly DORIS ground network

While doing the evaluation of the IDS 09 series w.r.t. the three TRF realizations (DTRF2014, ITRF2014, and JTRF2014), we first observed that the number of DORIS stations used to estimate the Helmert parameters w.r.t. JTRF2014 differ from the ones associated to the DTRF2014 and the ITRF2014 (see Fig. 4). The differences can be explained by a more restrictive data editing in the JPL process. From Fig. 4, we also see that the IGN networks contain more DORIS stations than the DGFI-TUM ones due to less velocity equality constraints. Using less equality constraints implies positions and velocities with larger standard deviations for stations with shorter observation time spans inducing that these stations may be rejected during the selection of the network for the Helmert parameters. To avoid any impact of the DORIS network on the Helmert parameters, in the following, we used for the evaluation the same weekly networks for the three TRFs. Each week, the network was defined as the common network between the weekly realizations of DTRF2014, ITRF2014, and JTRF2014 (see also Table 1).

Scale

As displayed in Fig. 5 and Fig. 6, the scale factors of the IDS 09 series w.r.t. DTRF2014, ITRF2014, and JTRF2014 show differences which can be associated with two time periods: before and after 2002 day-of-year (doy) 167 which corresponds to the inclusion of the DORIS missions with second generation of DORIS receivers on-board (Envisat and SPOT5). While after 2002 doy 167 the scales are very similar (in both trends and STDs – see Table 2), before that date, the scales present different trends. However, in addition to the fact that these differences

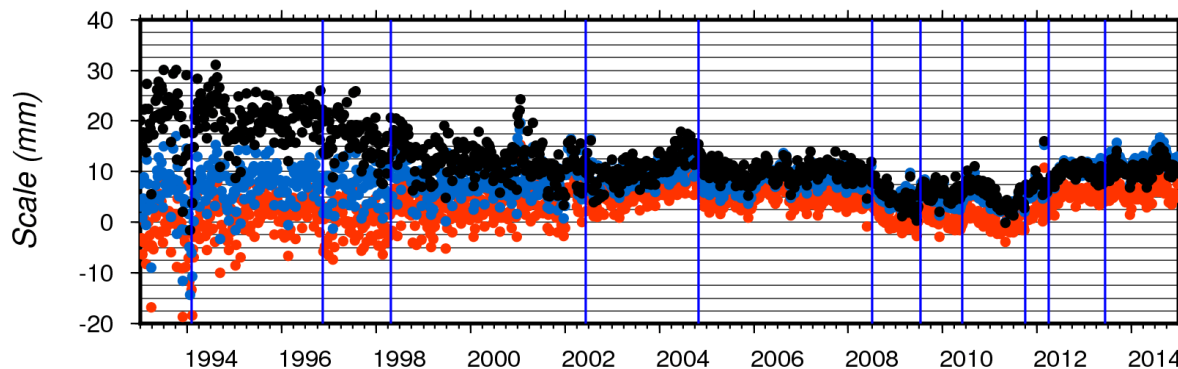


Fig. 5: Scale factors of IDS 09 time series w.r.t. DTRF2014 (red), ITRF2014 (blue), and JTRF2014 (black). The vertical lines correspond to DORIS satellite constellation changes.

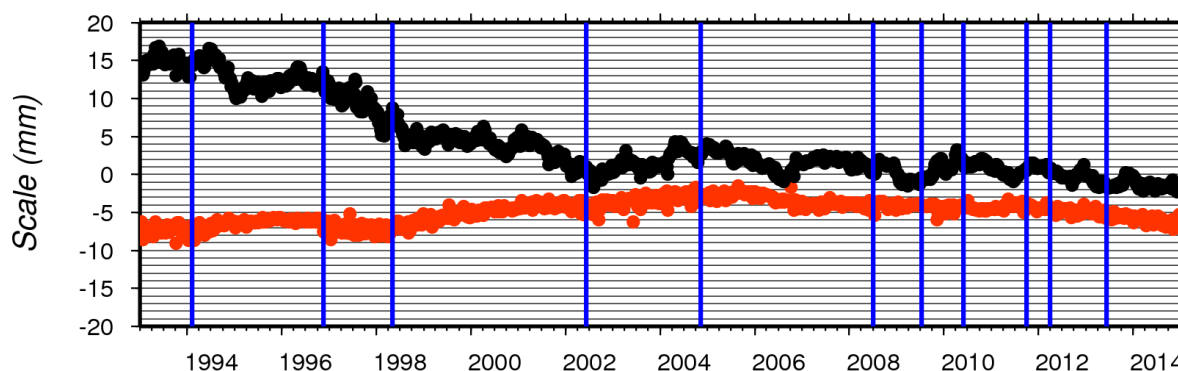


Fig. 6: Differences of scale factors between DTRF2014 (red) and JTRF2014 (black) with ITRF2014 as seen by IDS 09 series. Vertical lines correspond to DORIS satellite constellation changes.

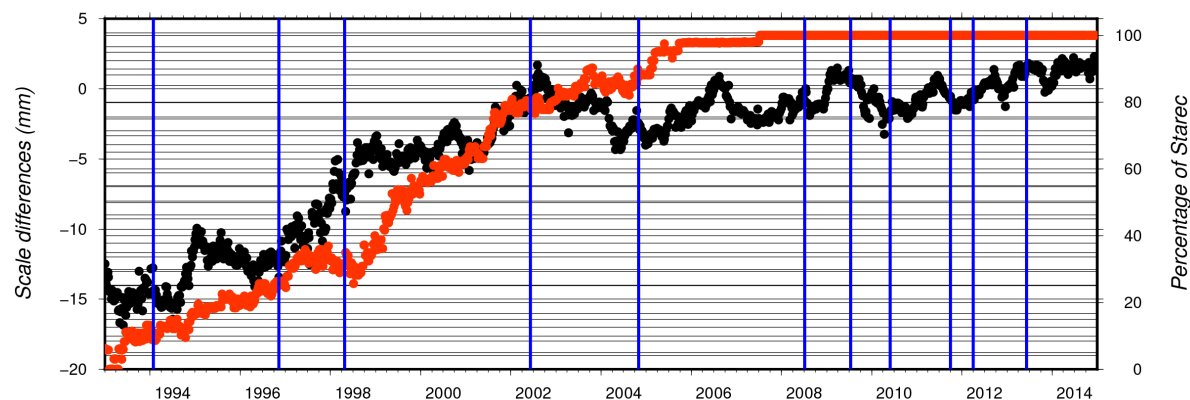


Fig. 7: Time evolution of the scale difference between ITRF2014 and JTRF2014 ($JTRF2014 - ITRF2014$; black) and of the percentage of STAREC DORIS ground antennas (red).

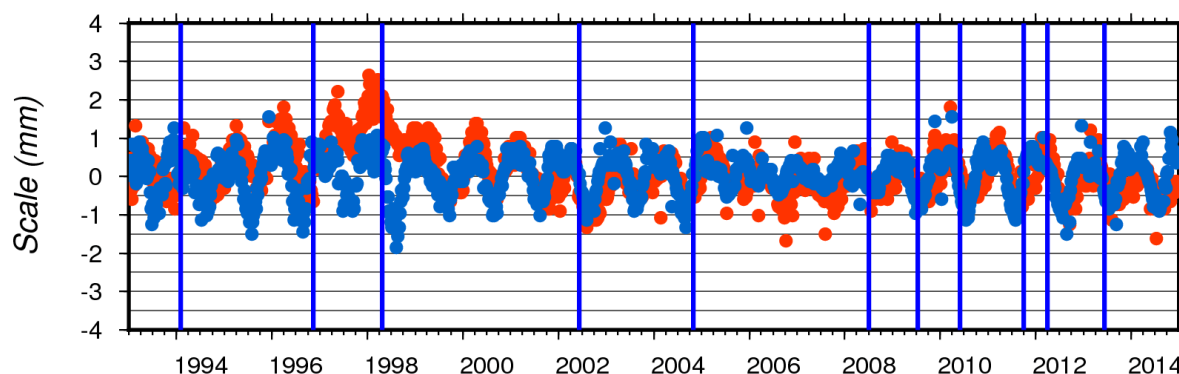


Fig. 8: IDS 09 scale differences between *DTRF2014ntc* and *DTRF2014* (red) and between *ITRF2014asc* and *ITRF2014* (blue). The vertical lines correspond to the DORIS satellite constellation changes.

occur while the DORIS constellation includes only satellite receivers of the first generation, we cannot neglect a possible correlation with the DORIS ground beacon network. As displayed in Fig. 7, until 2001, there is still a majority of ALCATEL ground antennas associated with a different phase center variation (PCV) compared to the STAREC antennas. Moreover, from that figure, we also observe a strong correlation (coefficient 0.94) between the percentage of STAREC antennas in the DORIS ground network and the scale difference between the JTRF2014 and ITRF2014 solutions. That feature must be the consequence of the different strategies the IGN and the JPL adopted to include the local ties in their processing.

From Table 2, the IGN solution gives the smallest trend whereas the JPL weekly files show the highest trend. The DTRF2014 solution provides the smallest scale offsets w.r.t. the IDS 09 solution and also shows the smallest scale trend after 2008.5. Furthermore, from Fig. 5, we also observe that the scale differences decrease after 2008 doy 195, i.e. when the missions (Jason-2, Cryosat-2, HY-2A, and Saral) with the new DGXX DORIS receiver start to be included in the IDS solution. As explained in Moreaux *et al.* [2016a], the mean scale offsets of the IDS 09 series with the three TRF solutions are the consequence of the use of the DORIS antenna PCVs in the IDS reprocessing standards for ITRF2014.

Moreover, as pointed out by Moreaux *et al.* [2016a], the linear pattern of the scales between 2003 doy 026 and 2004 doy 340 and between 2008 doy 244 and 2011 doy 100 is induced by the sawtooth pattern of the SPOT5-only scale see Fig. 9 from Moreaux *et al.* [2016a]. From Table 2, we also observe that the ITRF2014 gives the a constant (and stable) scale offset over the entire time span (1993.0–2015.0). In addition, as depicted by Fig. 8, the scale impact of the hydrological and atmospheric non-tidal loading corrections and of the annual and semi-annual corrections is in overall at the sub-millimeter level. The IDS 09

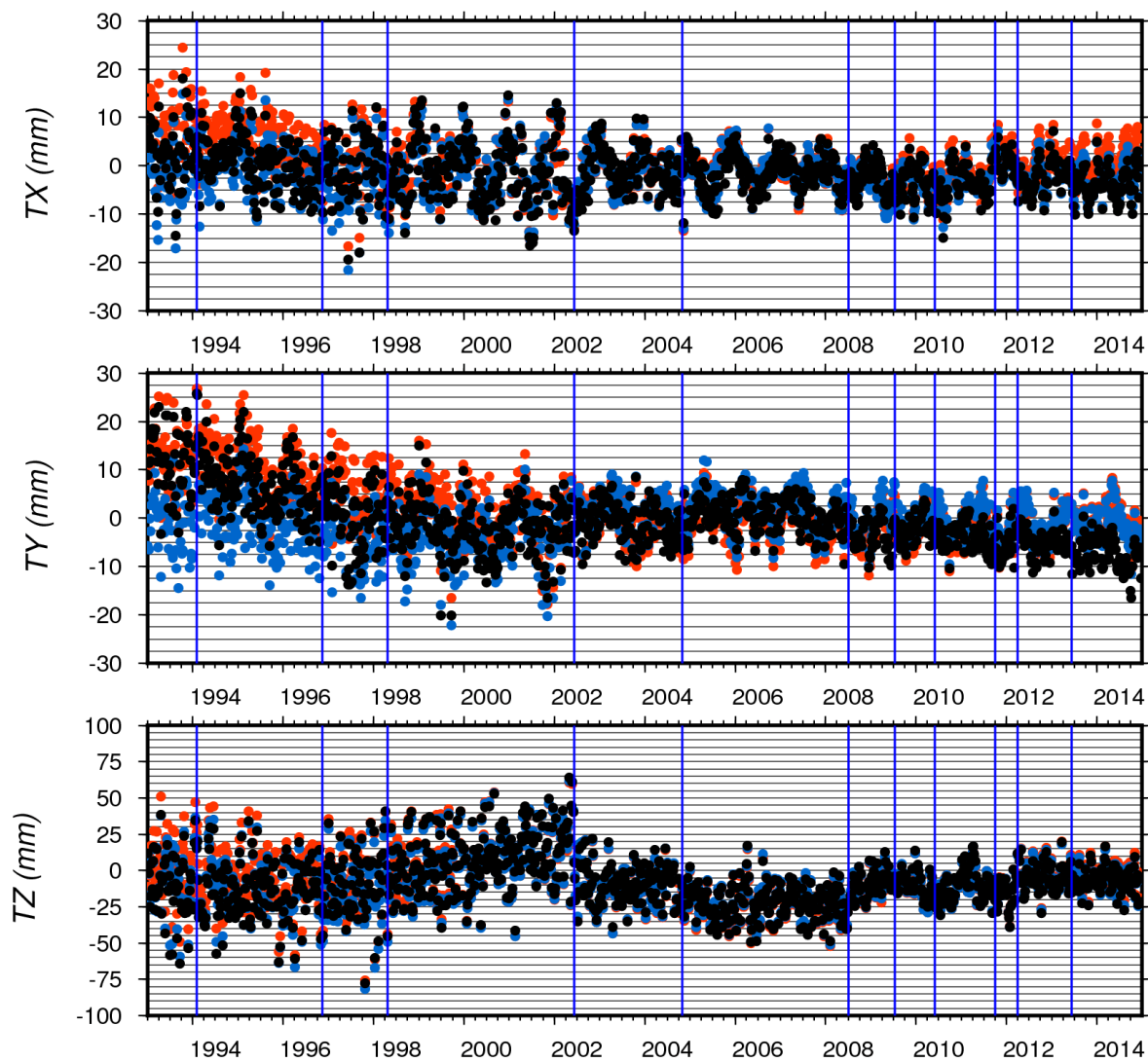


Fig. 9: Translations of IDS 09 w.r.t. DTRF2014 (red), ITRF2014 (blue), and JTRF2014 (black). The vertical lines correspond to DORIS satellite constellation changes.

scale differences represented in Fig. 6 may be attributable to a variety of factors, the most important of which relates the different scale definitions adopted by the three solutions. Also, tie vectors and velocity ties used to transfer the scale information from the VLBI and SLR systems to DORIS may play an important role in explaining the different temporal patterns of the scale offsets of Figure 6. Moreover, since JTRF2014 makes use of an instantaneous (and time-varying) VLBI/SLR scale definition, the values reported in Figure reflect the actual differences between the instantaneous IDS 09 and JTRF2014 scales. The mean scale offset between the DTRF2014 and the ITRF2014 solution as seen from the DORIS evaluation are about 4–5 mm which can also be clearly seen in Fig. 6.

Translations

From Fig. 9 which displays the translation parameter time series of the IDS contribution (IDS 09) to ITRF2014 w.r.t. DTRF2014 (red), ITRF2014 (blue), and JTRF2014 (black), we first observe annual signals of the x- and y-components as well as an 11 year signal on the z-translations. Furthermore, Fig. 9 shows that while the STDs of the x- and y-translation parameters are of the same order, the STDs of the z-component are 3 to 4 times larger. As early observed by Seitz *et al.* [2012], Bloßfeld *et al.* [2016b] and Moreaux *et al.* [2016a], the z-translation is also highly correlated with the Sunspot number indicating that the DORIS z-geocenter is still suffering from a mis-modeling of the solar radiation pressure on the DORIS satellites [Gobinddass *et al.* [2010]]. Moreover, as hypothesized by Bloßfeld *et al.* [2016b], due to the strong relation between the Sunspot numbers and the atmospheric density, the IDS series may also be impacted by a problem on the atmospheric drag modeling. In addition, the T_z peak in 1999–2002 is more likely associated with activity at the peak of the solar cycle which degrades the DORIS measurements of the 800 km SPOT satellites.

From Fig. 9 and Table 2, the best compromise between the lowest trends and standard deviations of the three translations is given by ITRF2014 solution. In agreement to the scale differences, from Fig. 10, we observe that the translation differences are larger before than after 2002 doy 167. We can also see the presence of seasonal (annual and semi-annual) signal in the differences between the JTRF and ITRF translations due to the capability of the random walk to give back the station displacements induced by temporal changes of planetary fluid masses. As depicted by Fig. 11, adding atmospheric and hydrological non-tidal loading or annual and semi-annual signals on the station coordinates induce annual variations on the translation parameters with amplitudes of ± 4 mm peak-to-peak. It is also visible that especially in the x-component, there is a clear phase offset between the geophysical loading impact on the DTRF2014 and the artificial annual and semi-annual variations in the ITRF2014. Furthermore, according to Table 2, the use of annual and semi-annual signals from the coordinate time series within ITRF2014 allows to decrease the magnitude of the standard deviations of the translation parameters. The effect of the addition of the atmospheric and hydrological non-tidal loading corrections to DTRF2014 is mitigated: it deteriorates the T_x performances whereas it improves the mean values and standard deviations of the T_y parameter. As expected and reported in Table 4, adding the annual and semi-annual corrections to the ITRF2014 station positions reduce the amplitudes of the annual and semi-annual signals of the translation parameters.

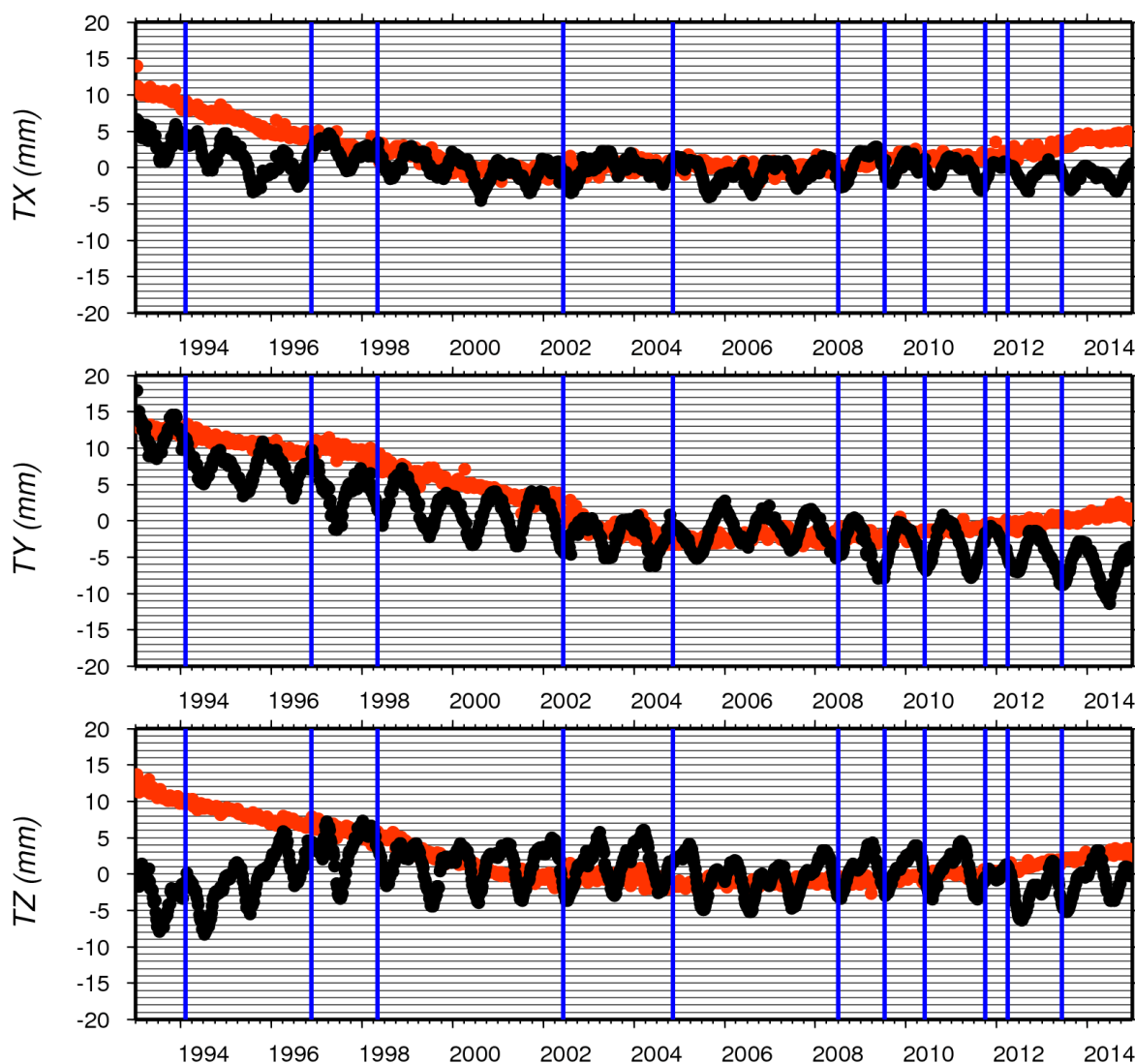


Fig. 10: Translation differences between DTRF2014, JTRF2014 (red, black), and ITRF2014 as seen by the IDS 09 time series. The vertical lines correspond to DORIS satellite constellation changes.

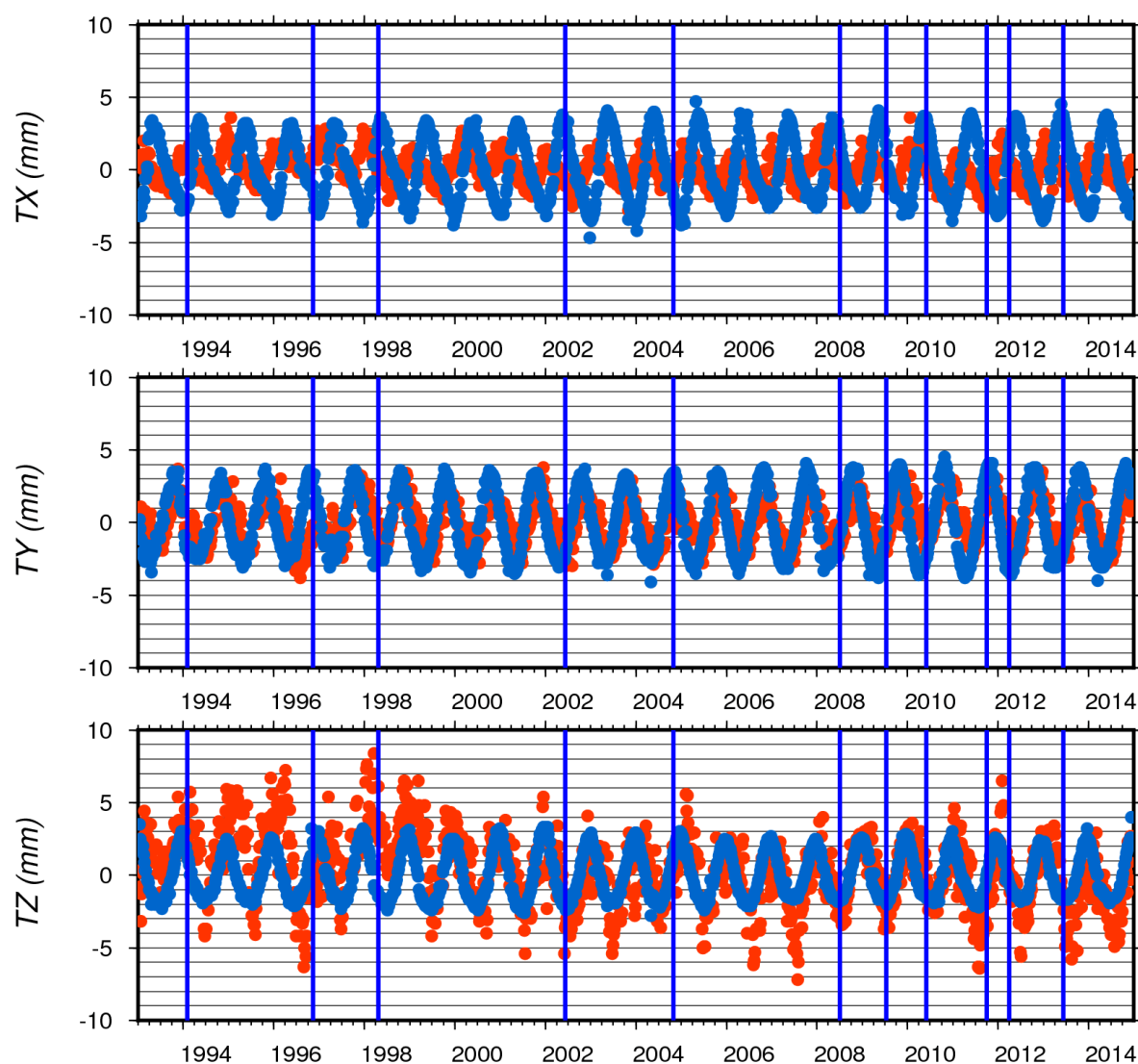


Fig. 11: Translation differences between DTRF2014_{ntc} and DTRF2014 (red) and between ITRF2014_{asc} and ITRF2014 (blue) as seen by the IDS 09 time series. The vertical lines correspond to the DORIS satellite constellation changes.

Station positioning

From the Helmert parameters, we aligned the IDS 09 series to the three TRFs and computed the WRMS (weighted RMS) of the station position residuals, i.e. differences between the aligned IDS 09 and the TRF weekly positions. From Fig. 12, we clearly see the impact of the DORIS constellation on the station positions in the local horizontal frame ENU (East, North, Up) weighted root-mean-square (WRMS) values within the three different time periods: 1993 doy 001 until 2002 doy 167, 2002 doy 188 until 2008 doy 160, and 2008 doy 188 until 2014 doy 365 which reflects the increase of the number of stations that can be tracked simultaneously on-board the DORIS satellites. The more stations being tracked, the smaller are the position WRMS expressed in the local horizontal frame. As depicted by Fig. 12, the East direction gives the worst results. This pattern is due to the fact that the Doppler technique provides observations that lack information in the direction perpendicular to the satellite track. From the three TRF solutions, even if the performances are very similar (see Table 3), we observe that slightly better results (in terms of mean and STD) are obtained using the JTRF2014 followed by the DTRF2014. This fact might be the consequence of two facts: i) the non-linear content of the JPL solution and ii) the use of the “cleaned” JPL weekly network for the Helmert parameter estimation (see Sect. Weekly DORIS ground network). However, the differences between the three TRFs expressed in NEU are less than 1.35 mm in mean and 0.15 mm in STD. Furthermore, we note no impact of the atmospheric and hydrological non-tidal loading corrections on the station position performances due to the small amplitudes of the non-tidal corrections compared to the standard-deviation of the DORIS coordinate time series. Since the non-tidal loading corrections had been computed from GNSS time series, it was assumed that DORIS beacons are affected the same way (and with the same amplitude) than GNSS antennas. Meanwhile, the including annual and semi-annual corrections in the ITRF2014 solution induces reduction of the mean WRMS in the North and Up directions by 0.15 to 0.35 mm. The impact of the annual and semi-annual corrections must be explained by larger amplitudes compared to the non-tidal ones due to the fact that these periodic signals were deduced from the coordinate time series and so, must contain not only geophysical phenomena. The RMS of the periodic corrections (resp. non-tidal corrections) are 2.92, 3.28 and 4.09 mm (resp. 0.95, 1.85, and 3.30) in ENU directions respectively. Note that [Altamimi et al. \[2016\]](#) (see Table 2) also observed that the addition of annual and semi-annual corrections gives higher improvements in the station position residuals compared to the non-tidal corrections.

Station position differences

To visualize the station coordinate differences obtained when using one of the three TRF solutions, we computed weekly DORIS station

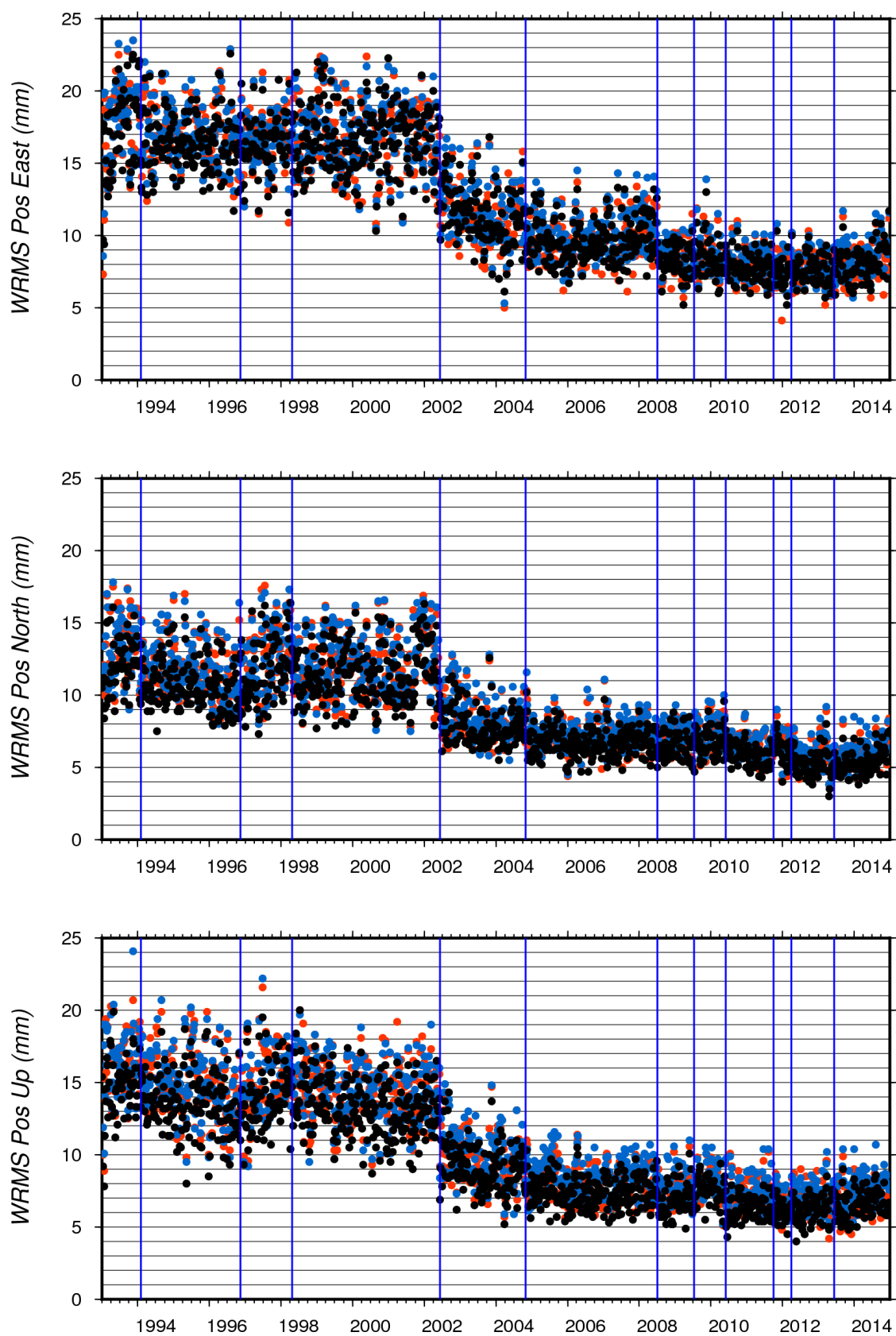


Fig. 12: Weighted root-mean-square (WRMS) values of station positions of IDS 09 w.r.t. DTRF2014 (red), ITRF2014 (blue), and JTRF2014 (black). The vertical lines correspond to DORIS satellite constellation changes.

networks using the positions and velocities given in the DTRF2014 and ITRF2014 SINEX files and using the weekly SINEX files of the JTRF2014. Afterwards we derived the differences between these weekly TRF solutions in the local horizontal frame (East, North, Up) of each station. In that study, we use the same ellipsoid as IDS does while generating the so-called STCD (time series of station coordinates differences) files from the DORIS weekly SINEX files. It is defined by: flattening factor $1/f=198.257810$ and equatorial radius $a=6378136.0$ m. Due to the link between the DORIS satellite constellation and the positioning precision of the DORIS ground beacons, as we did in the previous section, we also divide the full time span into three periods: before 2002 doy 167 (first satellite of 2nd generation of DORIS receiver), 2002 doy 167 to 2008 doy 188 (first satellite with 3rd generation of DORIS receiver) and after 2008 doy 188.

The analysis of the statistics of the differences reported in Table 6, shows that i) in terms of RMS, the most important differences are on the vertical and for all the three time periods, ii) whatever is the couple of solutions, the RMS of the differences of the second and third time periods are of the same order and smaller than the RMS of the first time period; iii) point-wise, the maximum of the differences on one component can be up to 60 mm. As expected, the maximum of differences occur at a station discontinuity from one solution and so, emphasizes the differences of the discontinuity files used by the three centers. Furthermore, these maximum values are associated with either sites in seismic active zones (ex: Arequipa, Reykjavik, Santiago) or in the SAA region (ex: Cachoeira). Nevertheless, as depicted by Fig. 13, for a majority of the DORIS sites, the RMS of the 3D position differences between the three ITRF2014 realizations is smaller than 15 mm. We can also see that overall the differences between the DTRF2014 and the ITRF2014 are the smallest ones. That may be the consequence of the fact that these two solutions make the hypothesis of a linear motion (plus PSD corrections for a few sites for the ITRF2014). From that figure, the DORIS sites showing the most important differences (Arequipa, Canberra, Cachoeira, Yuzhno-Sakhalinsk, Wallis) are either sites with short time span (Canberra, Wallis) or sites in seismic active zones (Arequipa, Yuzhno-Sakhalinsk) or sites in the SAA region (Cachoeira).

Tie vector residuals

If station B supersedes to station A at a given DORIS site, we can estimate the coordinate differences between A and B from one of the ITRS realizations (at the date when B was turned on) and then, compute the difference to the tie vector from a survey (if available). This latter difference can be seen as a tie vector residual. Even if the tie residuals may reflect how the surveyed ties were used as constraints in the

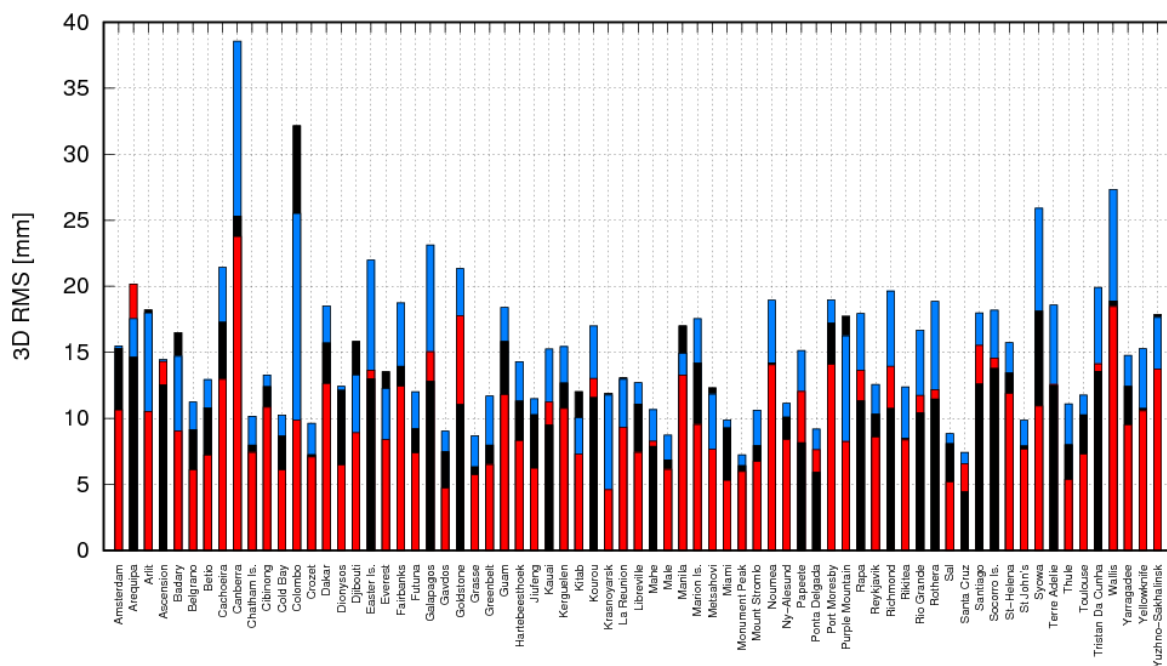


Fig. 13: 3D RMS of DORIS site coordinate time differences from 1993.0 to 2015.0 between DTRF2014, ITRF2014, and JTRF2014 (red: DTRF2014-ITRF2014, blue: JTRF2014-ITRF2014, black: JTRF2014-ITRF2014).

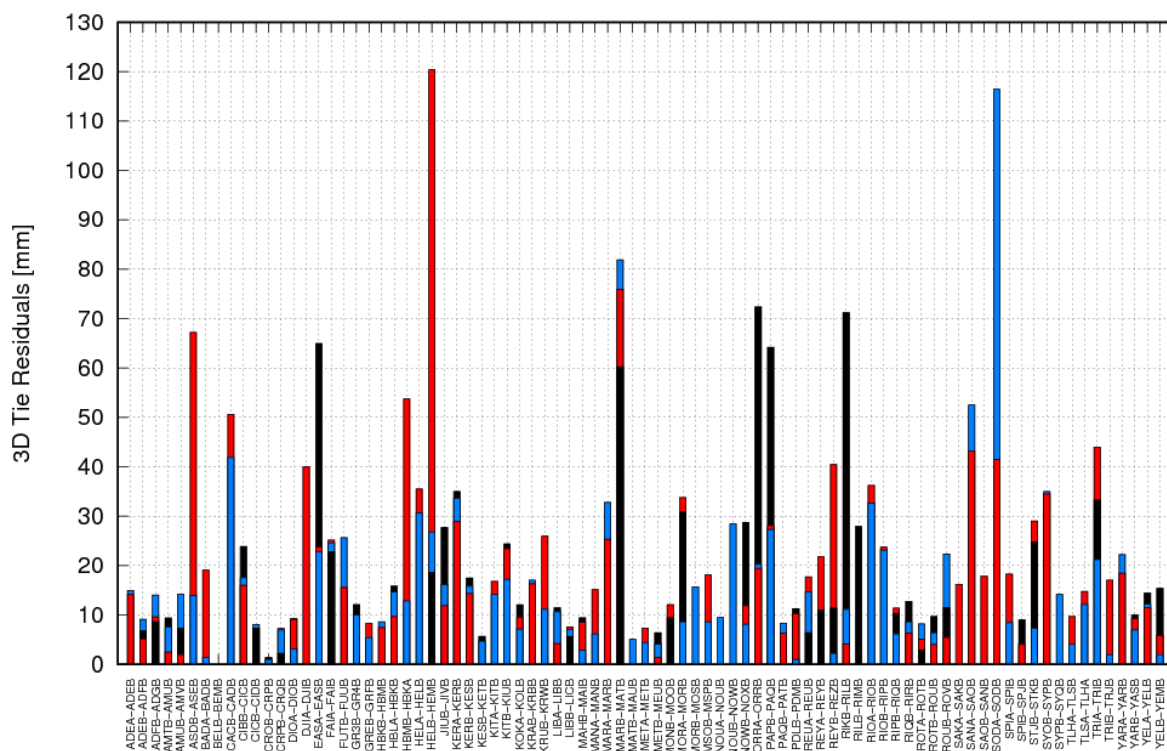


Fig. 14: DTRF2014 (red), ITRF2014 (blue), and JTRF2014 (black) DORIS tie residuals w.r.t. the surveyed ties from IGN.

construction of DTRF2014, ITRF2014 and JTRF2014, they can be considered as one benchmark of the quality of the three TRF solutions. Since the DGFI-TUM and IGN solutions contain velocities, it is straightforward to extrapolate the positions at any date whereas, this can not be achieved with the JTRF2014 because we only have weekly positions. Therefore, due to the amplitude of the horizontal and vertical velocities, for JTRF2014, we assumed that the ties could be obtained as the differences of the last and first weekly positions of, respectively stations A and B, if these two dates do not differ by more than one year. Thus, we end up with a set of 50 common pairs of stations between DTRF2014, ITRF2014 and JTRF2014. As depicted by Fig. 14 and reported in Table 5, the smallest differences with the surveyed ties are obtained with the ITRF2014 solution. We also observe that the DTRF2014 and JTRF2014 gives similar performances.

If we now only compare DTRF2014 and ITRF2014, due to the fact that some successive stations were separated by more than one year, we get a common set of 76 couples of stations. Once again, the IGN solution gives the smallest residuals. From Fig. 14 we can identify the stations with tie residuals larger than 50 mm: MARB-MATB and HELB-HEMB for DTRF2014, MARB-MATB for ITRF2014 and, EASA-EASB, MARB-MATB, ORRA-ORRB, PAPB-PAQB and RIKB-RILB for JTRF2014. First, we notice that the three solutions do not agree with the surveyed tie for the stations MARB and MATB at Marion Island in the Southern Indian ocean. According to [Moreaux *et al.* \[2016b\]](#), that discrepancy may be the consequence of the South Africa earthquake of magnitude 5.4 which happened in 2002, June 16. Second, the DTRF2014 solution shows its biggest residual (121 mm) for HELB-HEMB, two stations located on the South Atlantic island of Saint-Helena. Even if that DORIS site is localized in the SAA region, as the two other ITRF realizations do not show such tie residuals, the SAA cannot be considered at the origin of the DTRF pattern. The Saint-Helena tie residual may be explained by the DTRF velocity differences between HELB and HEMB. Note that while the HEMB DTRF2014 and ITRF2014 velocities are very similar for the first period of time, the HELB velocity from DTRF2014 strongly differs than HEMB velocities as well as to HELB ITRF2014 velocity which is equal to the first velocity of HEMB (as a consequence of IGN velocity continuity constraint). Third, the length (larger than 300 days) of the time interval between the two stations must be the cause for JTRF2014 large tie discrepancies for the two station couples (ORRA-ORRB, RIKB-RILB). In the case of the couple EASA-EASB, the JTRF2014 tie discrepancy (nearly 6 mm) is the conjunction of the length of the time interval between the two stations (231 days) and the amplitude of the horizontal velocity (nearly 70 mm/yr).

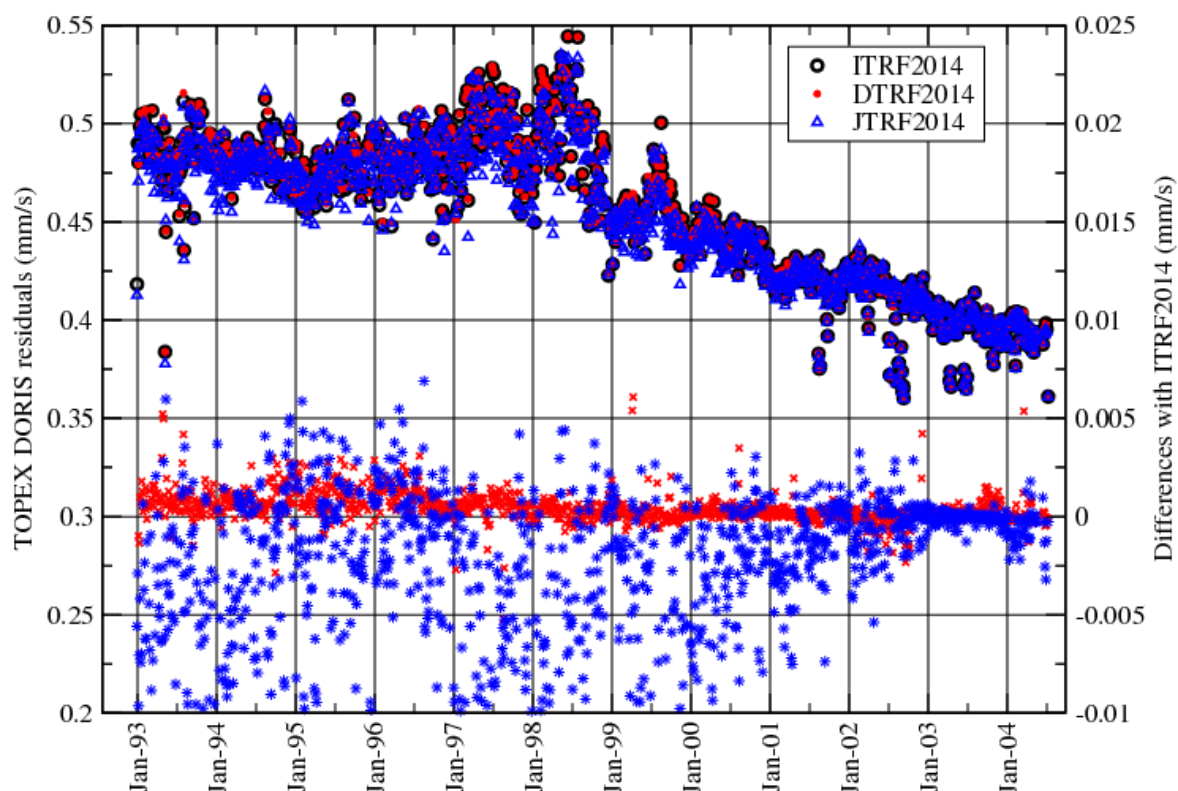


Fig. 15: *Topex DORIS RMS residuals for the DGFI-TUM, IGN, and JPL solutions and differences w.r.t. ITRF2014.*

DORIS Precise Orbit Determination Evaluation

In this section, we show the impact on selected examples of DORIS satellite orbit determination of using DTRF2014, ITRF2014 and JTRF2014 for the positioning of the DORIS ground beacons. The three realizations DTRF2014 (DGFI-TUM), ITRF2014 (IGN), and JTRF2014 (JPL) are evaluated by DORIS and SLR data processing for TOPEX, Jason-1, and Jason-2 satellites to explore the whole period of the DORIS observations. Thereby, the station coordinates of the different TRF realizations are kept fixed to see their impact on the DORIS POD. The processing of the DORIS and SLR data is performed using the GINS software [Marty *et al.*, 2011] developed by the GRGS (Groupe de Recherche de Géodésie Spatiale, i.e. the French Space Geodesy Research Group). The DORIS post-fit residuals (global and per station) and the SLR residuals on DORIS-only orbits are analyzed. We also show some orbits comparison such as the RMS of the radial differences and the mean of the z-component of the orbit differences.

POD results

This section deals with the orbit results obtained on the time span from January 03, 1993 to December 27, 2014 of Topex, Jason-1 and Jason-2 satellites for the three 2014 TRF realizations. The standards and models of the POD processing correspond to the ones used in the CNES/CLS IDS AC contribution to the IDS contribution to the ITRF2014 realization

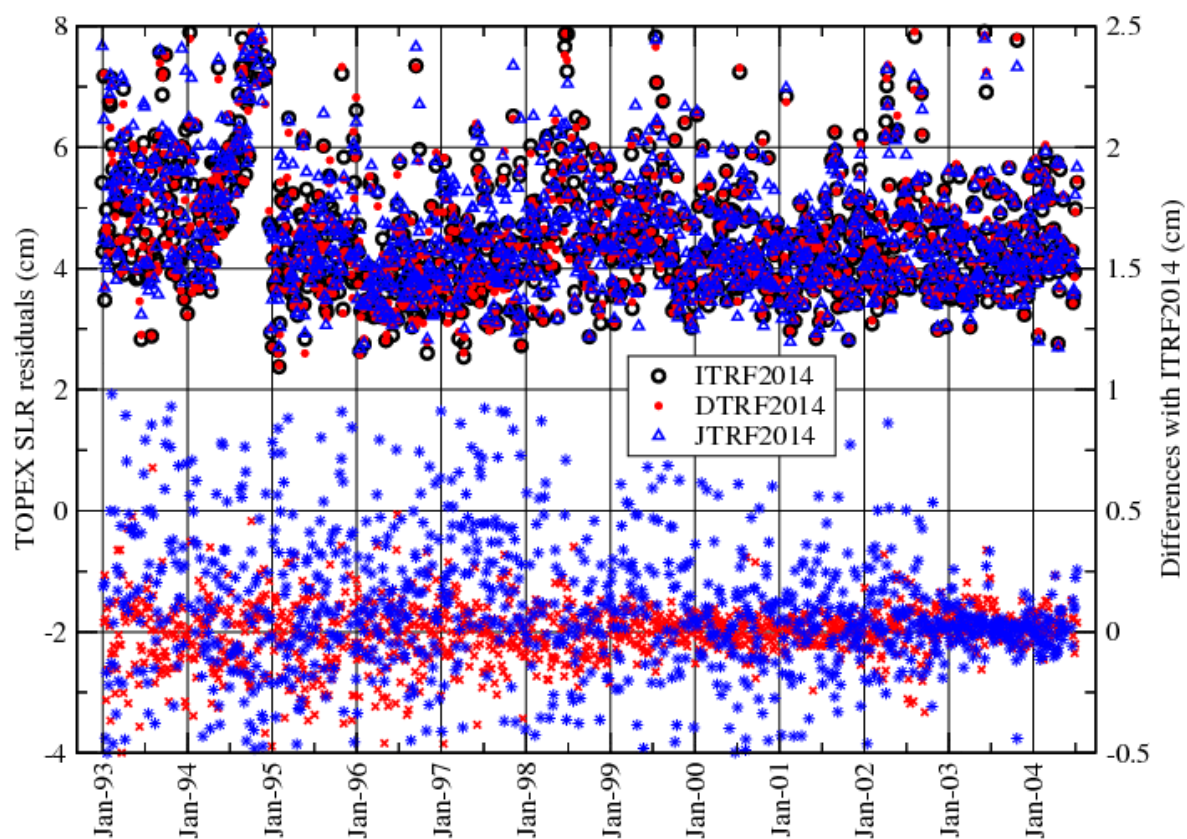


Fig. 16: *Topex* DORIS-only orbit independent SLR RMS residuals for DGFI-TUM, IGN, and JPL solutions and differences w.r.t. ITRF2014.

[Soudarin *et al.*, 2016]. Thus, Jason-1 data were corrected by the SAA corrective model from Lemoine & Capdeville [2006].

Table 7 gives the average per arc of the DORIS station number, the overall number of DORIS and SLR observations, as well as the RMS of both the DORIS and SLR residuals. For each satellite (Topex, Jason-1, Jason-2), we analyzed the differences of the DORIS RMS of fit of the orbit determination between the DTRF2014, the JTRF2014, and the ITRF2014 solution. The DORIS-only orbits were also evaluated by independent SLR data processing. Then, we focused on the differences of the RMS of the DORIS residuals per station. Due to a more aggressive data editing of the JPL solution, compared to the DTRF2014 and ITRF2014, the weekly JTRF2014 files contain less stations, particularly at the beginning of the processed time period. After the end of 2014, there are fewer stations for the ITRF2014 and DTRF2014 solutions because the new DORIS stations were not part of the IDS contribution to ITRF2014, and so not in the ITRF solutions. As a consequence, we decided to make the comparisons until the end of 2014.

To analyze the impact of the different 2014 TRF realizations on the DORIS residuals, we looked at the differences between the ITRF2014 and the two other 2014 TRF solutions. When the differences are positive, the ITRF2014 solution is better than the two others solutions. The fact that the JTRF2014 contains fewer stations at the beginning of the processed period may also explain the best performances of the JTRF2014 solution in terms of DORIS RMS residuals (see Table 7 and Fig. 15). According to Table 7 and Fig. 15, the DTRF2014 and ITRF2014 solutions give very similar DORIS RMS residuals. Nevertheless, as depicted by Fig. 15, the DTRF2014 performs slightly less well than ITRF2014 before January 1999. We also analyzed the DORIS RMS residual differences per station between the three TRF solutions. For these calculations, in order to not bias the results, we took into account exactly the same observations. The results show that the three solutions are very close. Meanwhile, the JTRF2014 gives the best results probably thanks to a reduction of the observations number and to the Kalman capability to capture more than the secular variations of the DORIS station positions. To evaluate the quality of the different 2014 TRF realizations, we also estimated the SLR residuals on the DORIS-only orbits. For Topex, even if the overall DORIS RMS residuals are lower (explained above), the JTRF2014 solution gives the worst SLR RMS residuals. That's the consequence of the lower number of SLR points associated to the JTRF2014 (see Table 7 and Fig. 16). We can see also from mid 2002, when the observations number is similar, that the JTRF2014 solution is equivalent to the two others. The DGFI and IGN solutions are very similar and give the same global RMS residuals value of 4.58 cm.

For Jason-1, as shown in Table 7 and Fig. 17, the three solutions i) are very close in terms of DORIS and SLR RMS residuals and ii) give the same global DORIS RMS residuals (0.307 mm/s). Furthermore, we observe that the DTRF2014 solution shows slight improvements (about 0.5 %) over one period of 7 months (from August 2004 to February 2005). That improvement can be directly correlated to the smaller number of observations (stations) during this time span. It also explains why the RMS residuals per station are systematically lower, except for about ten stations in the case the DTRF2014 solution compared to the ITRF2014. However, the DTRF2014 shows slight, but systematically lower, DORIS residuals for Jason-1 than the ITRF2014. Note that for Yuzhno-Sakhalinsk (SAKA) and Rapa (RAQB) stations, the results are not significant because it concerns only very few arcs. Regarding the JTRF2014 solution, there are two periods: a degradation from January to March 2006 and, an improvement from May to September 2008. These two periods are associated to a reduction of the observations number. Every time the observations number is similar, the three solutions give roughly the same DORIS RMS residuals. With regard to Jason-2, as shown in Table 7, in Fig. 19 and in Fig. 20, the three solutions are also very similar in terms of DORIS and SLR RMS residuals. However, there are two periods where the DTRF2014 solution is slightly worse than the ITRF2014 ($<0.5\%$): from February 2010 to January 2011 and after May 2014. The degradation for the first period is explained by the high RMS residuals obtained for the Santiago station (SANB). The second period corresponds to fewer observations (up to 4 stations less) for DTRF2014.

One important fact to note is that the differences between all the 2014 TRF solutions are at a very low level, in particular for the Jason-1 and Jason-2 (see Table 7). The JTRF2014 solution looks better but there are fewer observations and some missing stations. It is also a weekly solution and it cannot be usable in prediction. For these reasons, the ITRF2014 solution presents the best overall performances.

Table 7: Summary of POD results.

DORIS mission	TRF Solution	# DORIS points	# DORIS points	# SLR points	RMS residuals	
		(mean)	(mean)	(mean)	DORIS [mm/s]	SLR [cm]
TOPEX	ITRF2014	39.8	18,718	1,662	0.455	4.58
	DTRF2014	39.8	18,765	1,663	0.456	4.58
	JTRF2014	35.3	17,226	1,665	0.452	4.69
Jason-1	ITRF2014	43.9	36,270	1,463	0.307	2.52
	DTRF2014	43.8	36,106	1,463	0.307	2.51
	JTRF2014	43.2	35,913	1,464	0.307	2.53
Jason-2	ITRF2014	46.3	50,934	1,646	0.313	2.15
	DTRF2014	45.9	50,498	1,645	0.313	2.17
	JTRF2014	45.7	50,458	1,648	0.312	2.15

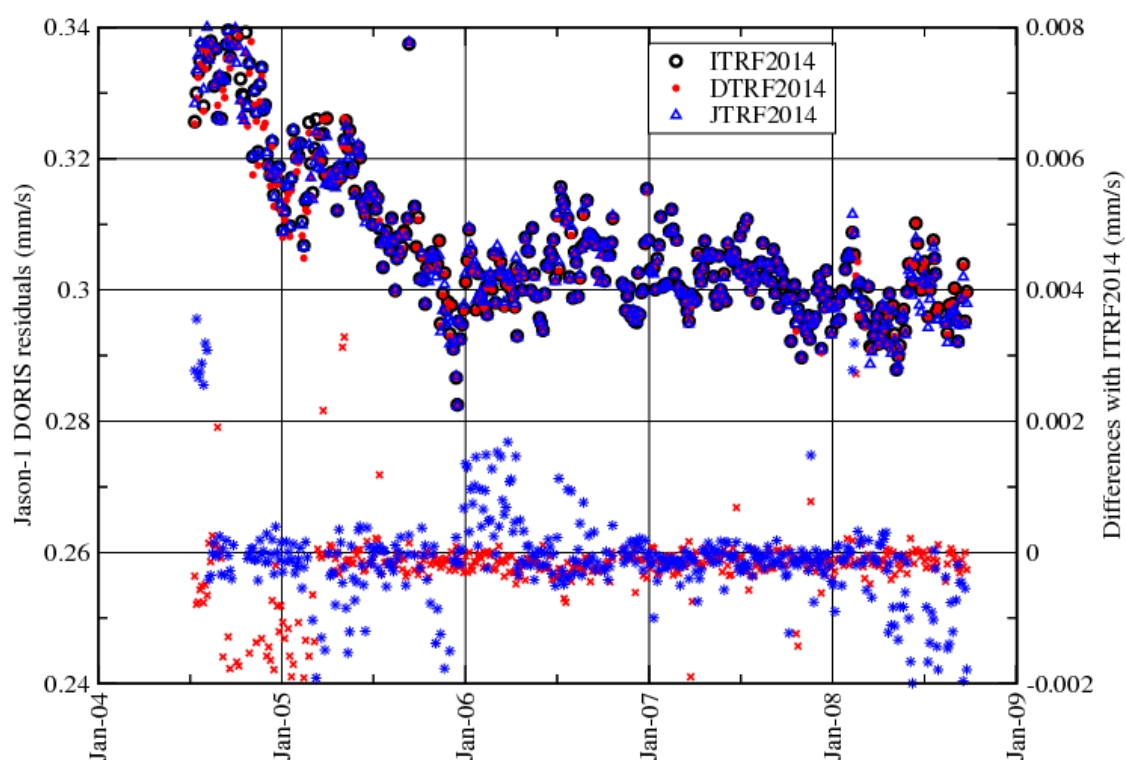


Fig. 17: Jason-1 DORIS RMS residuals for the DGFI-TUM, IGN, and JPL solutions and differences w.r.t. ITRF2014.

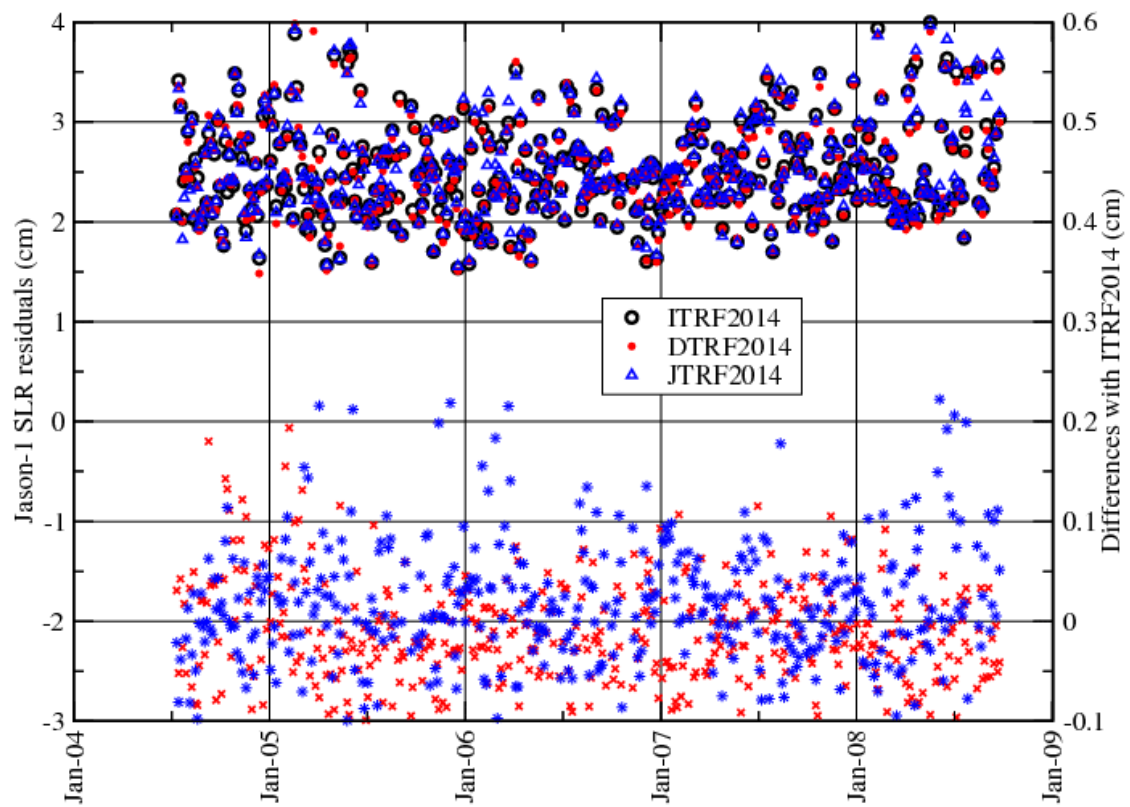


Fig. 18: Jason-1 DORIS-only orbit independent SLR RMS residuals for DGFI-TUM, IGN, and JPL solutions and differences w.r.t. ITRF2014.

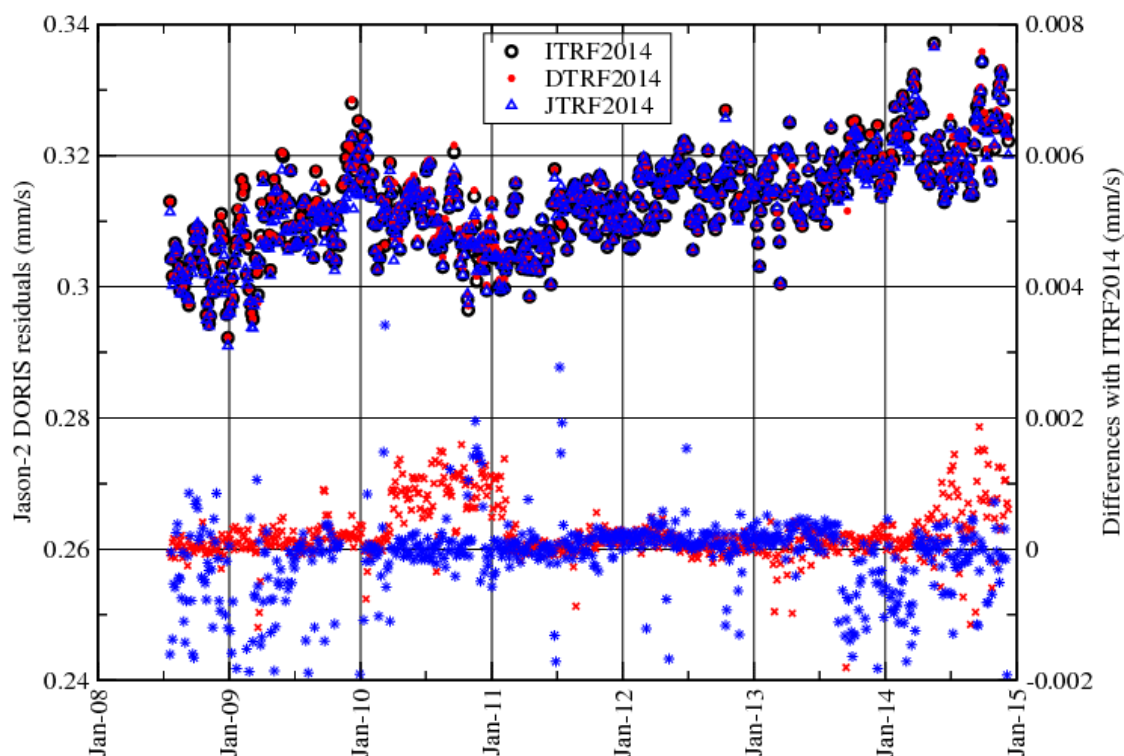


Fig. 19: *Jason-2 DORIS RMS residuals for the DGFI-TUM, IGN, and JPL solutions and differences w.r.t. ITRF2014.*

Orbital z-differences

Fig. 21 gives the orbit centering difference in the z-direction. We observe i) an important drift of DTRF2014 w.r.t. ITRF2014 from 1993 to 2001; ii) a 2 mm bias of DTRF2014 w.r.t. ITRF2014 from February 2010 to January 2011 as a consequence of a different positioning of the Santiago station; iii) an annual signal for the JTRF2014 realization. The annual signal markedly visible in the JTRF2014 solution can also be found in the time series of the translation offsets of JTRF2014 to ITRF2014 (see Fig. 9) and mostly attributable to the sub-secular nature of JTRF2014.

The drift of the DTRF2014 solution from 1993 to 2001 can also be correlated to the difference of the z-translation between the DTRF2014 and ITRF2014 solutions displayed by the Fig. 9 (around 10 mm from 1993 to 2001). Similarly to the results obtained on the mean z-differences, as depicted by Fig. 22, the RMS of the radial orbit differences between DTRF2014 (resp. JTRF2014) and ITRF2014 show an important drift from 1993 to 2001 (resp. an annual signal). The dispersion and the level of the RMS are higher (and different) between 1993 and 2002 for the TRF solutions. After 2003, the level of RMS for the three 2014 TRF realizations is more consistent. These results can be correlated to the scale factors of IDS 09 w.r.t. 2014 TRF solutions depicted by the Fig. 5.

As explained in Sect. Scale, the change after mid of 2004 (resp. mid of 2008) can be explained by the including of the DORIS missions with on-board the second (resp. third) generation of DORIS receivers starting with with Jason-1 (resp. Jason-2).

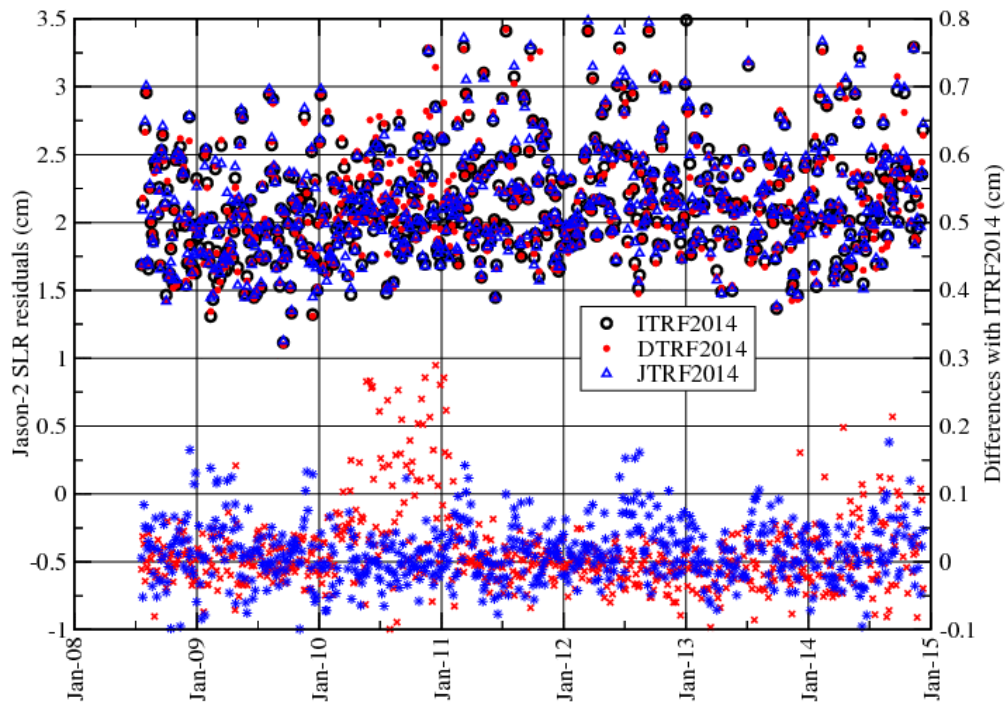


Fig. 20: Jason-2 DORIS-only orbit independent SLR RMS residuals for DGFI-TUM, IGN, and JPL solutions and differences w.r.t. ITRF2014.

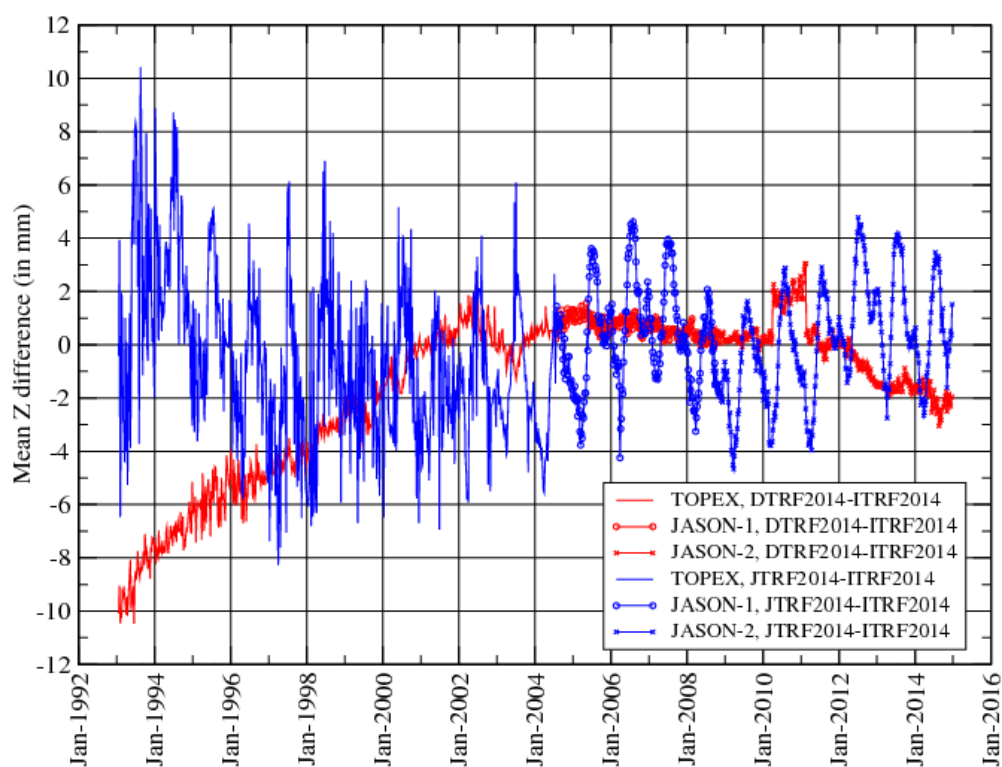


Fig. 21: Mean orbital z-differences between DGFI-TUM, IGN, and JPL solutions.

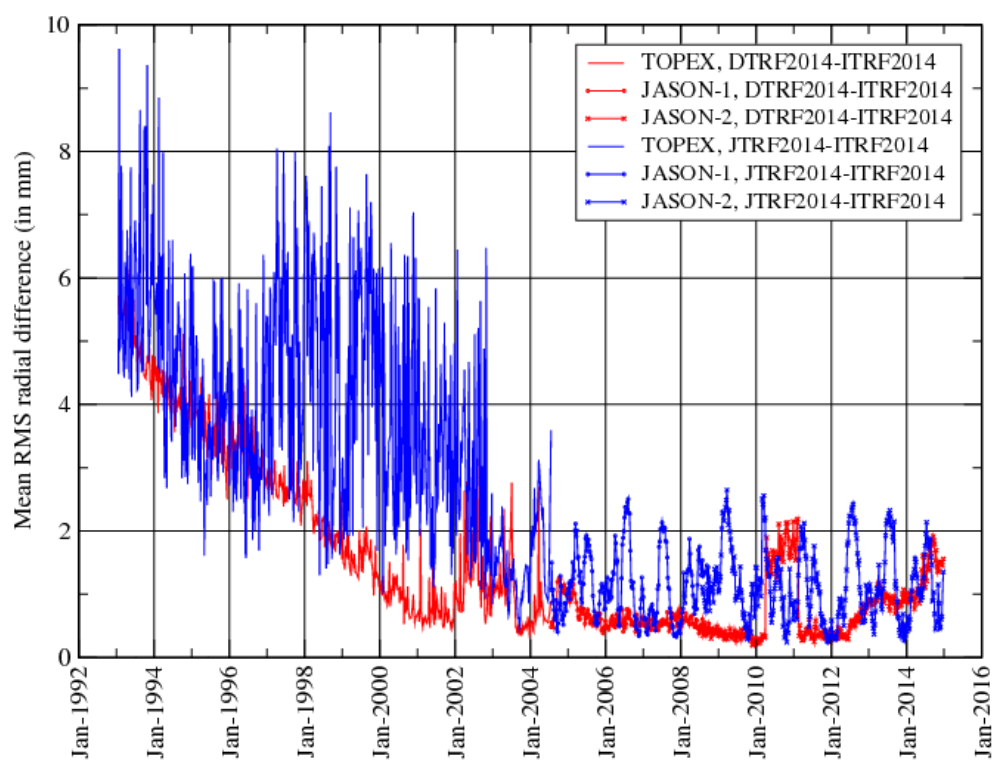


Fig. 22: RMS of orbital z-differences (radial) between DGFI-TUM, IGN, and JPL solutions.

Conclusions

This paper evaluates the DORIS component of the three 2014 TRF realizations: DTRF2014 from DGFI-TUM, ITRF2014 from IGN, and JTRF2014 from JPL. After a brief presentation of the methodology of the computation of the three solutions, the solution SINEX files are analyzed. That first analysis shows that i) due to a more intensive data editing, the weekly SINEX files from the JPL contain less DORIS stations than the two cumulative solutions from DGFI-TUM and IGN; ii) as the consequence of the use of velocity constraints to force the same value over multiple segments (unless a velocity discontinuity was observed) and iii) the DORIS stations showing large velocity differences (i.e. larger than 5 mm/yr) between DTRF2014 and ITRF2014 were stations with a short period of observations.

Then, we estimate, compare and analyze the Helmert transformation parameters of the IDS 09 series [IDS contribution to ITRF2014, [Moreaux et al., 2016a](#)] w.r.t. the three 2014 TRF realizations as well as w.r.t. the DGFI-TUM solution including atmospheric and hydrological non-tidal loading and the IGN solution including annual and semi-annual station position corrections. The scale and translation parameter time series (see Fig. 5 and Fig. 9) show a better agreement after mid of 2002 and the addition of the first missions (Envisat, SPOT5) with on-board the second generation of DORIS receiver. Furthermore, while the DGFI-TUM scale differs to the IGN scale by at most 5-10 mm (see Fig. 6), the differences between the JPL and IGN scales can reach 10-15 mm between 1993.0 and 1998.3 (the including of SPOT4). Nevertheless, the DGFI-TUM scale agrees better (in case of the overall offset) to the IDS 09 solution than the other two TRF solutions do. As depicted by Fig. 7, the correlation between the difference of the JPL and the IGN scales and the percentage of STAREC antennas in the ground network suggests that the scale difference may be the consequence of the different strategies IGN and JPL adopted while including the local ties. In terms of Helmert parameters, the impact of the including of either atmospheric and hydrological non-tidal corrections or annual and semi-annual corrections is very limited. In overall, we observe that the IGN solution gives the more stable transformation parameters over the full time span (1993.0–2015.0, see Table 2), but the DTRF2014 shows the smallest scale offsets w.r.t. the IDS 09 time series. As expected, due to the capability of the random walk to give back the station displacements by temporal changes of planetary fluid masses, the JTRF2014 gives the best performances in terms of station position residuals (see Table 3). The analysis of the station position residuals also shows a better improvement of the including of the annual and semi-annual corrections compared to addition atmospheric and hydrological non-tidal corrections thanks to larger amplitudes of the former corrections and to the fact they must contain more than the geophysical phenomena.

In addition to the translation and the scale parameter time series, we also discussed the impact of using these three 2014 TRF realizations in the positioning of the DORIS stations. That test consisted in estimating the East, North, and Up weekly positions of the DORIS stations from the three solutions over the full time span (1993.0–2015.0). As revealed by Table 6, the RMS of the horizontal position differences are smaller than 10 mm whereas the RMS of the vertical discrepancies are smaller than 20 mm. The differences in the height component are fully correlated with the scale differences. The investigation on the maximum values showed that these were point values corresponding to i) dates of discontinuities in one of the solutions and ii) to stations located in either seismic zones (ex: Arequipa, Reykjavik, Santiago) or SAA region (ex: Cachoeira). The analysis of the site-by-site 3D RMS coordinate differences (see Fig. 13) showed that the most important values were also in seismic or SAA regions as well as associated with short period of observations. In addition to the station position differences, to evaluate the DTRF2014, ITRF2014 and JTRF2014 solutions, we analyzed the discrepancies between the estimated (from the solutions) and measured (from the IGN leveling team) DORIS tie vectors. That study illuminated the best results from the ITRF2014.

An additional issue of concern is the impact of these three 2014 TRF realizations in the framework of DORIS POD. As showed in Sect. POD results, the differences between the three solutions are at a very low level, in particular for the Jason-1 and Jason-2 results. For the ITRF2014 and DTRF2014 solutions, the most significant improvements are obtained for the time periods from 1992 to 1998 and from 2010 to 2014. That may be due to the improvement of the estimation of the station velocities compared to those estimated in the DPOD2008 solution. The POD evaluation of the ITRF2014 solution including annual and semi-annual corrections and the DTRF2014 solution including atmospheric and hydrological non-tidal loading revealed no significant impact.

In summary, based on the different criteria used for evaluation, even if the three solutions gives similar results in terms of DORIS positioning and DPOD POD, we showed that it is the ITRF2014 solution from IGN which presents the best overall performances. As a consequence, we recommend it as the standard and the reference for future IDS products. It should be pointed out here again, that this investigation of the ITRF2014 solution was only possible since several solutions had been computed for the most recent ITRF realization. This study emphasizes the need for multiple solutions to inter-compare and validate results.

Acknowledgements

Part of this work was performed at CLS under contract with the Centre National d'Etudes Spatiales (CNES). Part of this work was carried out at

the Jet Propulsion Laboratory – California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).

References

- Abbondanza C., Chin T.M., Gross R., *et al.* (2017) JTRF2014, the JPL Kalman Filter and Smoother Realization of the International Terrestrial Reference System. *J Geophys Res*, DOI 10.1002/2017JB014360
- Altamimi Z., Boucher C., Sillard P. (2002a) New trends for the realization of the international terrestrial reference system. *Adv Space Res*, vol 30(2), pp 175–184, DOI 10.1016/S0273-1177(02)00282-X
- Altamimi Z., Collilieux X., Legrand J., *et al.* (2007) ITRF2005: a new release of the International Terrestrial Reference Frame based on time series of station positions and earth orientation parameters. *J Geophys Res*, vol 112(B9), B09401, DOI 10.1029/2007JB004949
- Altamimi Z., Collilieux X. & Métivier L. (2011) ITRF2008: an improved solution of the international terrestrial reference frame. *J Geod*, vol 85(8), pp 457–473, DOI 10.1007/s00190-011-0444-4
- Altamimi Z., Rebischung P., Metivier P., *et al.* (2016) ITRF2014: A new release of the International Terrestrial Reference Frame modeling non-linear station motions. *J Geophys Res*, vol 121(8), pp 6109–6131, DOI 10.1002/2016JB013098
- Bloßfeld M., Seitz M., Angermann D. (2014) Non-linear station motions in epoch and multi-year reference frames. *J Geod*, vol 88(1), pp 45–63, Springer, DOI 10.1007/s00190-013-0668-6
- Bloßfeld M., Seitz M., Angermann D. (2016a) Epoch reference frames as short-term realizations of the ITRS – datum stability versus sampling. *IAG Symposia 143*, Springer Berlin Heidelberg, pp 26–32, DOI 10.1007/1345_2015_91
- Bloßfeld M., Seitz M., Angermann D., *et al.* (2016b) Quality assessment of IDS contribution to ITRF2014 performed by DGFI-TUM. *Adv Space Res*, vol 58(12), pp 2505–2519, DOI 10.1016/j.asr.2015.12.016
- Capdeville H., Štěpánek P., Lemoine J.-M., *et al.* (2016) Update of the corrective model for Jason-1 DORIS data in relation to the South Atlantic Anomaly and a corrective model for Spot-5. *Adv Space Res*, vol 58(12), pp 2628–2650, DOI 10.1016/j.asr.2016.02.009
- Gobinddass M. L., Willis P., Menvielle M., *et al.* (2010) Refining DORIS atmospheric drag estimation in preparation of ITRF2008. *Adv Space Res*, vol 46(12), pp 1566–1577, DOI 10.1016/j.asr.2010.04.004

- Lemoine J.-M. & Capdeville H. (2006) A corrective model for Jason-1 DORIS Doppler data in relation to the South Atlantic Anomaly. *J Geod*, vol 80(8-11), pp 507–523, DOI 10.1007/s00190-006-0068-2
- Marty J. C., Loyer S., Perosanz F., *et al.* (2011) GINS: the CNES/GRGS GNSS scientific software, 3rd International Colloquium Scientific and Fundamental Aspects of the Galileo Programme, ESA Proceedings WPP326, 31 August – 2 September 2011, Copenhagen, Denmark.
- Moreaux G., Lemoine F. G., Capdeville H., *et al.* (2016a) The International DORIS Service contribution to the 2014 realization of the International Terrestrial Reference Frame. *Adv Space Res*, vol 58(12), pp 2479–2504, DOI 10.1016/j.asr.2015.12.021
- Moreaux G., Lemoine F. G., Argus D. F., *et al.* (2016b) Horizontal and vertical velocities derived from the IDS contribution to ITRF2014, and comparisons with geophysical models. *Geophys J Int*, vol 207, pp 209–227, DOI 10.1093/gji/ggw265
- Rudenko S., Dettmering D., Esselborn S., *et al.* (2014) Influence of time variable geopotential models on precise orbits of altimetry satellites, global and regional mean sea level trends. *Adv Space Res*, vol 54(1), pp 92–118, DOI 10.1016/j.jog.2014.04.008
- Rudenko S., Bloßfeld M., Müller H., Dettmering D., Angermann D., Seitz M. (2017) Evaluation of DTRF2014, ITRF2014 and JTRF2014 by Precise Orbit Determination of SLR Satellites. *IEEE T Geosci Remote*, submitted
- Saunier J. (2016) Assessment of the DORIS network monumentation. *Adv Space Res*, vol 58(12), pp 2725–2741, DOI 10.1016/j.asr.2016.02.026
- Seitz M., Angermann D., Bloßfeld M., *et al.* (2012) The 2008 DGFI realization of the ITRS: DTRF2008. *J Geod*, vol 86(12), pp 1097–1123, DOI 10.1007/s00190-012-0567-2
- Seitz M., Bloßfeld M., Angermann D., *et al.* (2016). The new DGFI-TUM realization of the ITRS: DTRF2014 (data). Deutsches Geodätisches Forschungsinstitut, Munich, DOI 10.1594/PANGAEA.864046 (Open Access)
- Soudarin L., Capdeville H., Lemoine J. M. (2016) Activity of the CNES/CLS Analysis Center for the IDS contribution to ITRF2014. *Adv Space Res*, vol 58(12), pp 2543–2560, DOI 10.1016/j.asr.2016.08.006
- Tourain C., Moreaux G., Auriol A., *et al.* (2016) Doris STAREC ground antennas characterization, impact on localization. *Adv Space Res*, vol 58(12), pp 2707–2716, DOI 10.1016/j.asr.2016.05.013

- Valette J.-J., Lemoine F. G., Ferrage P., *et al.* (2010) IDS contribution to ITRF2008. *Adv Space Res*, vol 46(12), pp 1614–1632, DOI 10.1016/j.asr.2010.05.029
- Willis P., Deleflie F., Barlier F., *et al.* (2005) Effects of thermosphere total density perturbations on LEO orbits during severe geomagnetic conditions (Oct–Nov 2003) using DORIS and SLR data. *Adv Space Res*, vol 36(3), pp 522–533, DOI 10.1016/j.asr.2005.03.029
- Willis P., Berthias J.-P., Bar-Sever Y. E. (2006) Systematic errors in the Z-geocenter derived using satellite tracking data, A case study from SPOT-4 DORIS data in 1998. *J Geod*, vol 79(10-11), pp 567–572, DOI 10.1007/s00190-005-0013-9
- Willis P., Fagard H., Ferrage P., *et al.* (2010) The International DORIS Service (IDS) toward maturity. *Adv Space Res*, vol 45(12), pp 1408–1420, DOI 10.1016/j.asr.2009.11.018
- Wu X., Abbondanza C., Altamimi Z., *et al.* (2015) KALREF-a Kalman filter and time series approach to the International Terrestrial Reference Frame realization. *J Geophys Res Solid Earth*, pp 3775–3802, DOI 10.1002/2014JB011622
- Zelensky N. P., Lemoine F. G., Beckley D. B., Chinn D. S., Pavlis D. (2017) Impact of ITRS 2014 Realizations on Altimeter Satellite Precise Orbit Determination. *Adv Space Res*, DOI 10.1016/j.asr.2017.07.044

Assessment of DTRF2014 and ITRF2014 by Satellite Laser Ranging

José Rodríguez¹

¹ *NERC Space Geodesy Facility, Herstmonceux, UK
(Current address: Yebes Observatory (IGN), Yebes, Spain)*

Abstract. Satellite laser ranging orbital solutions, using observations of satellites LAGEOS and LAGEOS-2 collected from 2000 to 2017, were used to test the performance of two reference frame realisations, ITRF2014 and DTRF2014. We compare the post-fit residuals from solutions where only initial conditions and orbit parameters were solved for, leaving apriori coordinates unchanged. We examine some differences that arise, and explore the behaviour of SLR sites affected by earthquake events. The combined ILRS-A solution, input for both reference frames, is compared to each TRF as well, and disparities discussed. The main finding of this exercise is that the scales of the SLR subnetworks of both TRF products differ by approximately 0.6 ppb, resulting from an unchanged scale of DTRF2014 relative to the input ILRS site coordinates, as opposed to the average frame scale between the VLBI and SLR networks employed in ITRF2014. Analysis of the residuals obtained here, as well as the site coordinates estimated from solutions computed outside the scope of this work, indicate that ITRF2014 is less subject on average to the effects of systematic errors present in the input solutions, although by no means exempt.

Introduction

The particular choice of terrestrial reference frame employed for the computation of routine ILRS products (daily solutions of combined LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2), has a very limited impact on their quality. Since site coordinates are estimated in this type of solutions, as long as the apriori frame is a reasonable representation (centimetres) of the secular motions of the stations, essentially the same results should be obtained following iteration. On the other hand, any differences in the apriori frame will become apparent if coordinates are left fixed. In particular, since satellites LAGEOS and LAGEOS-2 are the workhorse of the ILRS solutions ($\sim 90\%$ observations) that were used as an input for the production of both ITRF2014 and DTRF2014, a useful comparison of the performance of the two frames, in terms of post-fit residuals, can be obtained from re-computing the orbits of these two satellites. Any differences in the coordinates of SLR sites (in particular the UP component) between these two TRFs should be readily detectable in the observation residuals of the new solutions. Furthermore, as we are comparing these products on the basis of the very input data they relied on in the first place, we will be able to draw some additional conclusions as to the nature of the differences obtained.

Analysis Solution description	For both DTRF2014 and ITRF2014 we computed orbital solutions using normal point observations of satellites LAGEOS and LAGEOS-2, using our orbit dynamics analysis software SATAN. Except for some updates (e.g. ocean loading, FES2004 to FES2014), the background modelling and orbit parameterisation was identical to what the ILRS NSGF AC employed for the solutions submitted to the official ILRS combination centres in preparation for ITRF2014. Seven-day orbital arcs were computed for years 2000 through 2017, a period that extends beyond the input data employed for both DTRF2014 and ITRF2014 (up to 2015). Station coordinates were fixed to the apriori values, obtained by propagating their initial positions with the corresponding velocities. For ten SLR sites affected by earthquakes, the linearly propagated coordinates were corrected with the post-seismic functions supplied with ITRF2014 (for this frame only). Additional solutions were computed where we solved for weekly bias parameters, combined for LAGEOS and LAGEOS-2, to best follow the differences between both TRFs. Full reference frame solutions (coordinates, EOPs, biases, and orbits estimated), computed for the development of new ILRS products with systematic error estimation, were also employed to compare site heights over certain periods.
Solution statistics	At the most elementary level, no major differences between the two reference frame realisations considered are apparent, when employed to model the positions of SLR stations used to derive orbits of the LAGEOS satellites. Table 1 details the total number of stations, normal points (after initial screening and iterative rejection), average values and RMS of post-fit residuals (after outlier rejection), for the two satellites included in the analysis (2000–2017). It appears that ITRF2014 included a few more stations than DTRF2014, but these only account for a minimal proportion of the normal point data and should not have any noticeable impact on any key TRF parameters. Considering the totality of stations simultaneously, no TRF represents an advantage over the other, judging from the nearly identical post-fit residuals RMS. These values are reduced when biases are estimated, as expected, and although the RMS of residuals obtained with ITRF2014 are marginally smaller, the results in this case appear essentially identical to each other as indicated by the identical averages of the residuals obtained. We note that this is not exactly the case for the solutions where only orbits were estimated (no range bias parameters); the average value of all post-fit observation residuals obtained with ITRF2014 as a fixed frame are 2 mm higher than those obtained with DTRF2014. Since the altitude of the orbits is constrained by the timing of the observations over the course of one arc, and there are no other differences between the two solutions, this implies that the heights of the laser ranging stations as

Table 1: Number of NPs, mean post-fit residual values and RMS (mm) for the solution types computed for this comparison. Solutions where range errors were estimated are noted as RB.

solution	stations	satellite	NPs	mean res.	RMS
ITRF2014	65	LAGEOS	1,234,336	0.7	12.2
		LAGEOS-2	1,114,336	1.4	12.3
DTRF2014	57	LAGEOS	1,230,690	−1.2	12.2
		LAGEOS-2	1,109,704	−0.7	12.3
ITRF2014 (RB)	65	LAGEOS	1,213,992	−0.5	10.8
		LAGEOS-2	1,094,006	0.3	10.5
DTRF2014 (RB)	57	LAGEOS	1,207,192	−0.5	11.0
		LAGEOS-2	1,087,365	0.2	10.7

modelled in ITRF2014 are higher than in DTRF2014, on average. This is the case for most stations of the network, as it can be seen from the difference between the average values of post-fit residuals per station shown in Fig. 1. The significance of this will be further discussed in the following sections of this report.

Regarding possible differences, per station, on the RMS values of the range residuals obtained with each frame, no evident trends at any significant level can be appreciated. From inspection of Fig. 1, it can be said that the performance of both TRFs is nearly identical for the 25 most productive stations of the network over the period of analysis. RMS differences for all of these stations (except two), are within 0.1–0.2 mm. Stations on the right hand side of the plot, beyond position 25 approximately, have submitted an order of magnitude less data volumes than the most prolific tracking sites; their overall weight on both the ILRS combined solutions and, ultimately, on the terrestrial reference frame, is quite limited. The quality of the solutions derived for these stations—when not of the observations themselves—is reduced compared to the more prolific sites; the greater variability seen in the RMS values is to be expected and bears little useful information for the purposes of TRF comparison.

Earthquake sites

In ITRF2014, the positions of 123 stations affected by earthquake events were modelled using non-linear functions in addition to the standard secular velocities. Of these, ten sites are SLR stations, indicated in the previous plots of statistics of residuals. Focusing on these stations, only the average value of the post-fit residuals for station 7821 SHA2 (Shanghai, China) is notably different between the two solutions, with +6 mm higher mean residuals in ITRF2014 relative to DTRF2014. Notably, this site also presents the greatest RMS difference of all stations, with ap-

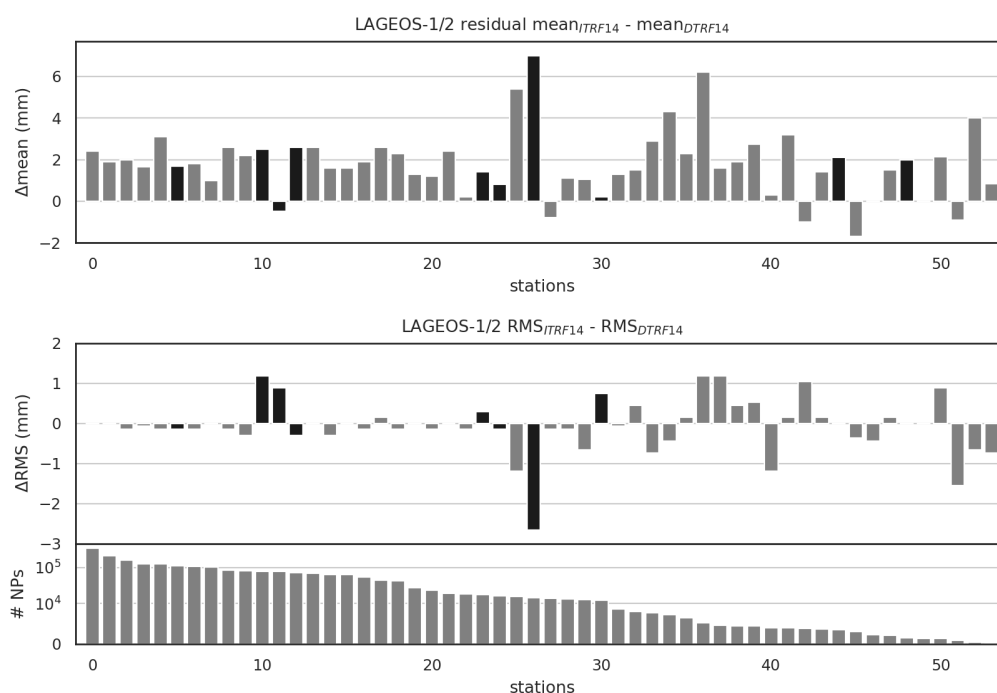


Fig. 1: Difference (ITRF2014 – DTRF2014) of mean (top) and RMS (bottom) values of post-fit range residuals obtained with these two TRF (fixed). Stations are ordered by number of observations provided (2000–2017). Darker bars indicate sites affected by earthquake events.

proximately +2.5 mm higher RMS for the range residuals obtained with DTRF2014. Inspection of the modelled station positions and velocities, as well as of the range biases obtained in the solutions where these parameters were estimated, reveals that the differences in the post-fit residuals are mainly caused by disparities in the propagated positions of this station after 2014 (see Fig. 2). After an apparent low-productivity period between 2012 and 2014, the amount of data available to obtain an accurate estimate of the position and velocities for this station towards the end of the time period included in ITRF2014 and DTRF2014 was perhaps somewhat limited.

It must be noted that the range bias estimates displayed in Fig. 2 only represent the apparent range errors caused solely by the use of different TRFs. These estimates are not genuine systematic errors at the observation or analysis level, which at this stage, if present, are already absorbed in the coordinates of the stations as modelled by each frame. The range bias time series obtained with both frames for all SLR stations affected by earthquakes can be found in Figs. 6, 7, and 8, at the end of this document. The differences arising from the use in ITRF2014 of non-linear functions to model the postseismic deformation motions, as opposed to employing only the classical linear velocities in DTRF2014, are relatively minor for the few laser ranging sites affected by earthquakes. The main exception may be 7403 AREL (Arequipa,

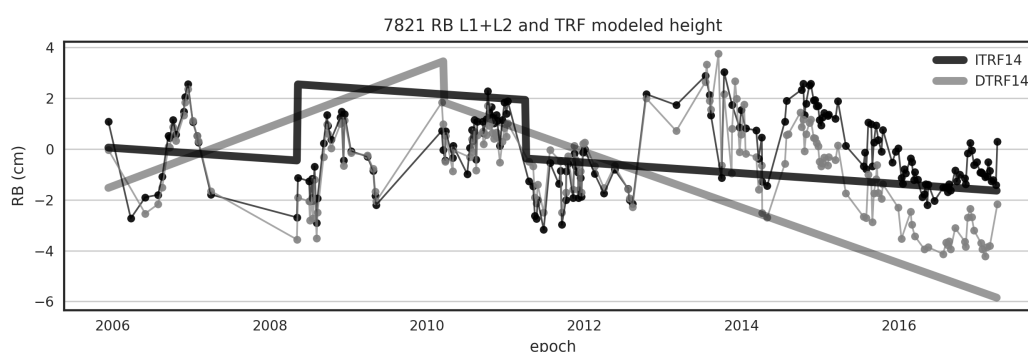


Fig. 2: Time series of estimated biases for SLR site 7821 SHA2 (Shanghai), computed using coordinates from ITRF2014 and DTRF2014. For reference, the solid lines show the heights modelled by these two frames, to which the average ITRF2014 height has been subtracted.

Peru), where centimetre-level differences in the modelled heights are seen throughout the analysis period. Disparities between the two TRFs in the break points chosen to delimit discontinuities appear in some cases to cause noticeable differences in the height/RB time series (e.g. 2008–2011 for 7237 CHAL (Changchun, China); 2001–2002 for 7403 AREL). This latter difference in the coordinates discontinuity is severe enough that observations from Arequipa station were discarded during iteration in our computations employing DTRF2014 (no weekly solutions obtained during this period).

Aside from the kind of site-specific differences pointed out above, a remarkable feature present in most of the plots shown for sites affected by earthquakes are the predominant greater station heights as modelled by ITRF2014. With very few exceptions, and normally for no more than some fraction of the entire time series, coordinates propagated with ITRF2014 result in greater SLR site heights than those from DTRF2014. This again points to a systematic difference between the scales of the whole SLR network in the two frames, which we examine next.

Comparison to ILRS-A

In order to assess the extent to which the input ILRS solution, result of the combination of eight independent solutions provided by the official ILRS Analysis Centres¹, differs from the end product result of the combination of the four space geodetic techniques contributing to the realisation of the reference system, we compared the official ILRS-A solution (ASI Combination Centre) to both ITRF2014 and DTRF2014 by means of weekly seven-parameter similarity transformations. The translation parameters, ΔX , ΔY , and ΔZ , as well as the scale Δ_s are shown in Fig. 3, where rotations were not included given the loose constraints of the SLR solutions. The direction of the computed Helmert transformations is ILRS-A→XTRF2014, that is, the parameters shown are

¹ASI, BKG, DGFI, ESA, GFZ, GRGS, JCET, and NSGF (<https://ilrs.cddis.eosdis.nasa.gov/science/analysisCenters/index.html>).

those required to map the weekly ILRS-A coordinates onto ITRF2014 and DTRF2014. For clarity, we also plot the difference between the Helmert parameters computed between the ILRS-A coordinates and each frame.

Regarding the translation components, no long-term differences of any import can be seen in the time series. Over the 15 years of analysis, the agreement between ILRS-A and both TRFs, and by implication between the reference frames themselves, exceeds the GGOS requirement of 0.1 mm/year. Perhaps only in the last three years, after 2010–2012, a slight trend can be appreciated in the X and Z components of the translations, in particular when the Helmert transformation is computed using all stations instead of only the core sites, but this was not tested for significance nor investigated any further.

As hinted to in previous sections, it is in the scale parameters where a substantial difference is evident. The scale of ITRF2014 is on average 0.6 ppb greater than the ILRS-A solution, over the period 2000–2015 (only core sites taken into account). Contrariwise, essentially no scale change is observed between ILRS-A and DTRF2014 (–0.04 ppb on average in 2000–2015). Attending to the difference between the two, the scale factor in 2010.0 after a linear fit is 0.70 ppb. This finding follows from the decision to define the scale of ITRF as the arithmetic average of the scales of the VLBI and SLR subnetworks. The scale difference between these was computed in ITRF2014 to be 1.37 ppb at epoch 2010.0, double the difference found here, as expected if one of the compared set of coordinates shows no difference to the input time series. This is a significant result that clearly must respond to different (fundamentally, even) approaches adopted for the computation of the combined reference frames.

It is not within the remit of this author to pass judgement on whatever different strategies, principles, or philosophical approaches underpin the production of the TRFs tested here. What we may examine is the goodness of the final result, restricted to the SLR subnetwork, on the basis of a few developments in the analysis and modelling of SLR data that have occurred since the publication of ITRF2014 and DTRF2014. These developments cast some light over the relative merits of these two products regarding their adopted scales.

Mitigation of SLR systematic errors

Since the definition of the ILRS standard products, a great deal of efforts have been devoted within the ILRS Analysis Standing Committee to minimise, identify, and rectify the presence of errors in the laser ranging observations. Other than constant monitoring of the data for quality control purposes (Otsubo et al., 2018), these efforts involved periodic reanalyses of the SLR solutions to detect potential problems, providing to and obtaining feedback from the tracking stations, as well as maintain-

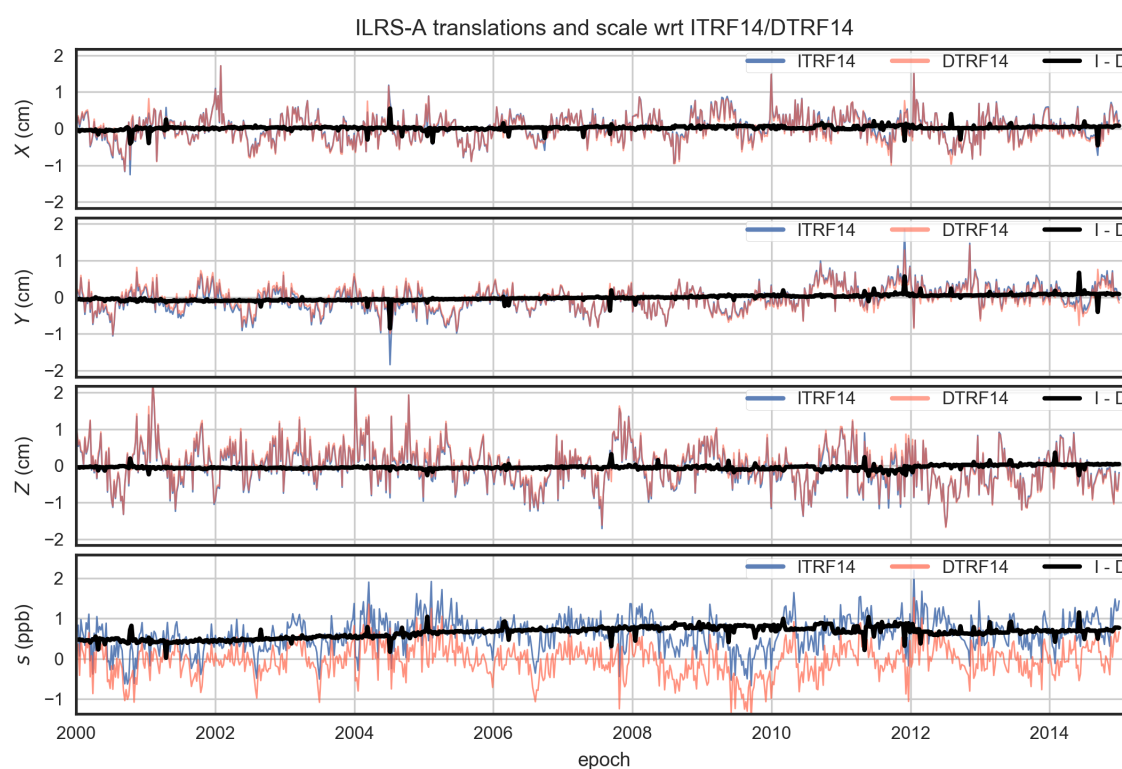


Fig. 3: Weekly translation and scale parameters between the official ILRS-A combined solution and: ITRF2014 (blue); DTRF2014 (red). In black, the differences between these two, approximately equivalent to the transformation parameters between both frames, in the direction DTRF2014 $\rightarrow$ ITRF2014.

ing a database of known issues together with instructions for analysts about how to handle them (Luceri et al., 2019). Unfortunately these practices do not guarantee the detection of all problems, especially long-term issues below the level of perhaps 3–4 cm. Thus, the ultimate accuracy of the technique is achieved with simultaneous estimation of observation errors along the rest of parameters of interest (Appleby et al., 2016). These kinds of solutions are the basis for a new ILRS product currently under development, seeking to ensure that station coordinates are as free as possible from any potential systematic errors (Luceri et al., 2019). It must be noted the diverse nature of the systematic errors that may affect the data, from actual observation errors at the station level, inaccurate survey of calibration targets, and several modelling deficiencies. For instance, recent work on the computation of centre of mass corrections for several spherical geodetic satellites shows that a significant proportion of the errors previously estimated have their cause in inaccuracies in the modelling of centre of mass corrections for spherical geodetic satellites (Rodríguez et al., 2019).

Of immediate interest for the present discussion are the several results, obtained by all the ILRS ACs that have produced solutions with simultaneous coordinates and systematic error estimation, which found an average increase of about 0.7 ppb in the scale of the SLR network relative to previous determinations. The ILRS contribution to ITRF2014/DTRF2014 included only error estimation for a very limited number of sites known to be problematic during certain periods, and therefore did contain systematic errors in the site coordinates that would eventually find their way into the final combined terrestrial reference frames. However, as seen in the previous section, the scale of ITRF2014 is on average (2000–2015) 0.6 ppb greater than the input ILRS-A solution, so it appears that this frame is a more accurate representation of the scale of the SLR network.

The better average agreement between ITRF2014 and the new solutions produced by ILRS ACs, following the latest strategy for mitigation of systematic errors, is not completely consistent at the level of individual stations. We show in Fig. 4 two examples of time series of station heights, with coordinates taken from ILRS-A, an independent NSGF AC solution with range bias estimation (simultaneous with coordinates), and the site heights modelled by ITRF2014 and DTRF2014. While the ITRF2014 height for station 7839 GRZL (Graz, Austria) is closer to the newer estimates that take into account the presence of systematic errors (such as NSGF RB in the plot), this is not true at all epochs; the first years after 2000 show a similar disagreement between ITRF2014/DTRF2014 and the heights obtained in the solution with bias estimation. The second example in Fig. 4 shows the opposite behaviour (to what is generally the norm), i.e. a better agreement between

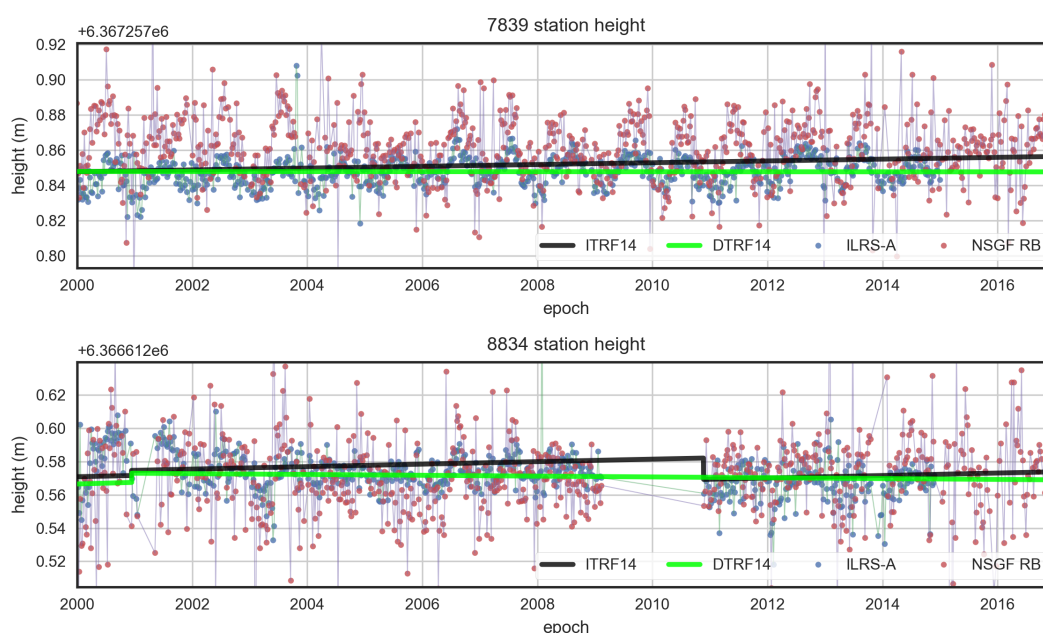


Fig. 4: Time series of weekly heights for stations 7839 GRZL (Graz, Austria) and 8834 WETL (Wetzell, Germany), from: ILRS-A solution (blue dots); NSGF solution with RB estimation (red dots); ITRF2014 (black line); DTRF2014 (green line).

DTRF2014 and the coordinates estimated taking into account range biases. Station 8834 WETL (Wetzell, Germany) is one of the few cases where negative average biases have been found during some periods of its operation. The effect of these negative biases is an overestimation of station heights in some years of the solutions submitted for the ILRS contribution to ITRF2014/DTRF2014. Since ITRF2014 heights are on average greater than those from ILRS-A, stations with negative biases will tend to show worse agreement between ITRF2014 and the latest estimates than what is the case with DTRF2014.

Residual trends

The aforementioned solutions obtained with simultaneous estimation of biases and station coordinates have been thoroughly tested (Appleby et al., 2016) and replicated by all ILRS ACs. But for the avoidance of any doubts about the conclusions drawn regarding the increase of the scale of the SLR network that these solutions indicate, we discuss here independent evidence of inaccurate modelling of station heights in ITRF2014 and DTRF2014, which shows equivalent findings.

Let us remind ourselves of what the effect of biases and incorrect site heights have on the range residuals after a least squares adjustment of the satellite orbits. If the observations of a given station have a constant, positive range bias during a given arc, the estimated site height in solutions with no range error estimation will be lower than the “true” value (station coordinates accommodate the bias in the UP component, mainly). Furthermore, the amount by which the estimated station height

will be biased towards lower values is greater than the magnitude of the constant bias. This simply arises from the observation geometry; although a 1:1 ratio between $\text{bias}/\Delta h$ obtains for zenithal observations, low elevation ones drive the estimated height in the negative direction. The point at which the sum of squared residuals is minimised is somewhere between the value of the bias and what would result if only low elevation observations were present. The exact $\text{bias}/\Delta h$ ratio depends on the specific distribution of angular elevations for each station and arc. For perfectly distributed observations between 25 and 90 degrees of elevation, the excess Δh can be computed to be approximately 33% for zenithal passes. Taking into account actual, typical elevation distributions suggest greater ratios (approaching 1.5), confirmed empirically by our geodetic solutions. The result of this effect is that the observation residuals of stations with a height that is lower than the correct value will show a pattern with zenith distance, where high elevation residuals will tend to be negative (observed ranges lower than the computed ones), and will become positive at low satellite elevations. The opposite will be true for sites with overestimated station heights (positive residuals at the zenith, negative in the horizon).

With the above considerations in mind, we show in Fig. 5 the average post-fit residuals of the same two stations displayed in Fig. 4, aggregated by zenith distance, obtained from solutions where only orbits were adjusted and employing ITRF2014 and DTRF2014 to model station coordinates. The aggregated residuals for station 7839 GRZL during the first three years of the analysis (2000–2003), where both ITRF2014 and DTRF2014 underestimated the height of this station (because of the underestimation already present in the input ILRS-A solution), show an evident positive trend with zenith distance. Focusing on the last three years (2014–2017), where the ITRF2014 height approaches the values obtained in solutions where biases are taken into account, show no trend with zenith distance for the residuals obtained with this frame. On the other hand, as DTRF2014 follows closely the height for 7839 GRZL in the ILRS-A solution, a positive trend in the post-fit residuals is still present in the later period. Repeating this exercise for the second site shown, 8834 WTZL, leads to the same conclusions mentioned in the previous section, i.e. ITRF2014 appears to incorrectly overestimate the height of 8834 WTZL during years 2006–2009. This can be concluded from the negative residual trend in the latter period, as opposed to the flat residuals in 2001–2004, and from the flat profile in both periods for the residuals obtained with DTRF2014.

Without resorting to bias estimation, the information contained in the observation residuals can be effectively visualised and interrogated to identify the presence of inaccurate site heights. This kind of analysis, resting solely on geometric considerations, is feasible in SLR because

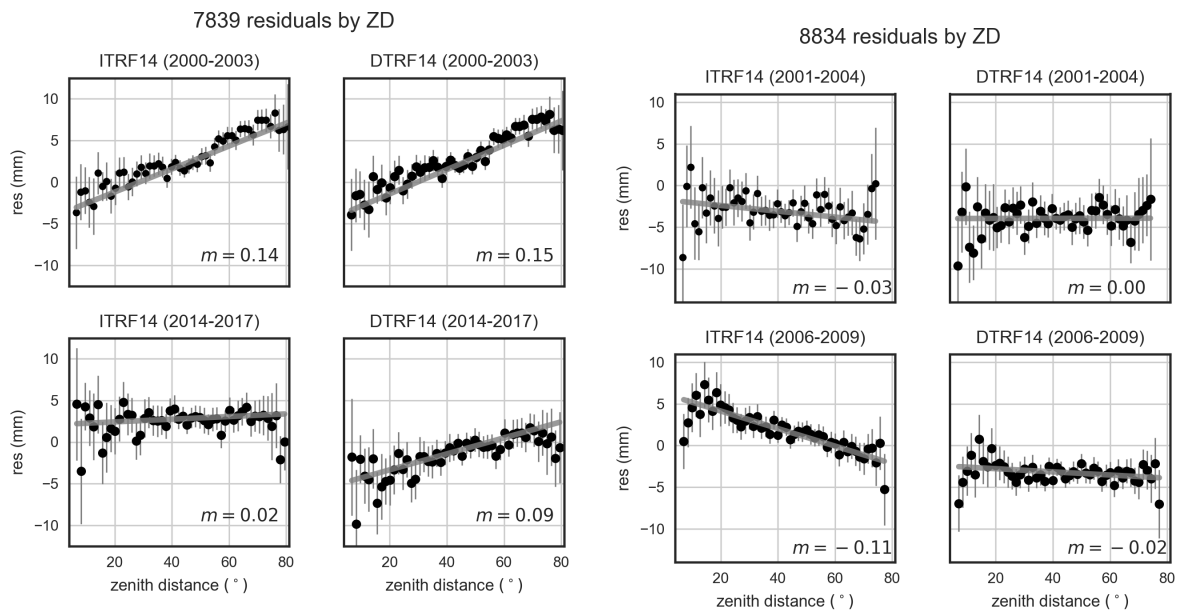


Fig. 5: Average LAGEOS post-fit residuals, in mm, of stations 7839 GRZL and 8834 WTZL, aggregated by zenith distance of the observations at bins of 1.5 degrees, employing ITRF2014 and DTRF2014 station coordinates (fixed). Error bars represent the 95% CI of the each average value. Solid line: linear fit (slope noted in each subplot)

there are very few parameters that could absorb mismodelled heights and mask the presence of systematic errors (e.g. no clocks or tropospheric delays are estimated in SLR).

Conclusions

Following a comparison of orbital solutions of satellites LAGEOS and LAGEOS-2, using the reference frames ITRF2014 and DTRF2014 to model station heights, we find in general limited differences in the basic statistics of the post-fit residuals. The performance for sites affected by earthquakes, again rather crudely assessed by the RMS values of the residuals obtained with both frames, is with few exceptions also similar (although some of the differences will tend to be magnified in the extrapolation period, post-2015). The single, greatest difference found in this work between these two TRFs is the scale disagreement of the SLR network. While in ITRF2014 the scale of the frame is computed as the arithmetic average between VLBI and SLR, DTRF2014 follows the scale of the input official ILRS solution. In light of what is known today regarding the presence of unaccounted for systematic errors in past SLR contributions, and exclusively in view of the practical, final results, the conclusion is that the strategy followed in the production of ITRF2014 (and previously ITRF2008) proved to be of merit. On average, the scale of ITRF2014 agrees better with the scale of future ILRS solutions, which will introduce strategies for systematic error mitigation and use more recent models to correct the range observations. The

conclusions regarding mismodelled site heights, for both frames, are derived from results computed with estimation of systematic errors, as well as independently from the direct examination of observation residuals, whose trends, if present, reveal inaccuracies (and their sign) in station heights.

References

- Appleby G., J. Rodríguez, and Z. Altamimi. Assessment of the accuracy of global geodetic satellite laser ranging observations and estimated impact on ITRF scale: estimation of systematic errors in LAGEOS observations 1993–2014. *Journal of Geodesy*, 90(12):1371–1388, 2016. doi: 10.1007/s00190-016-0929-2
- Luceri V., M. Pirri, J. Rodríguez, G. Appleby, E.C. Pavlis, and H. Müller. Systematic errors in SLR data and their impact on the ILRS products. *Journal of Geodesy*, 93(11):2357–2366, 2019. doi: 10.1007/s00190-019-01319-w
- Otsubo T., H. Müller, E.C. Pavlis, M.H. Torrence, D. Thaller, V.D. Glotov, X. Wang, K. Sośnica, U. Meyer, and M.J. Wilkinson. Rapid response quality control service for the laser ranging tracking network. *Journal of Geodesy*, 2018. doi: 10.1007/s00190-018-1197-0
- Rodríguez J., G.M. Appleby, and T. Otsubo. Upgraded modelling for the determination of centre of mass corrections of geodetic SLR satellites: impact on key parameters of the terrestrial reference frame. *Journal of Geodesy*, 93(12):2553–2568, 2019. doi: 10.1007/s00190-019-01315-0

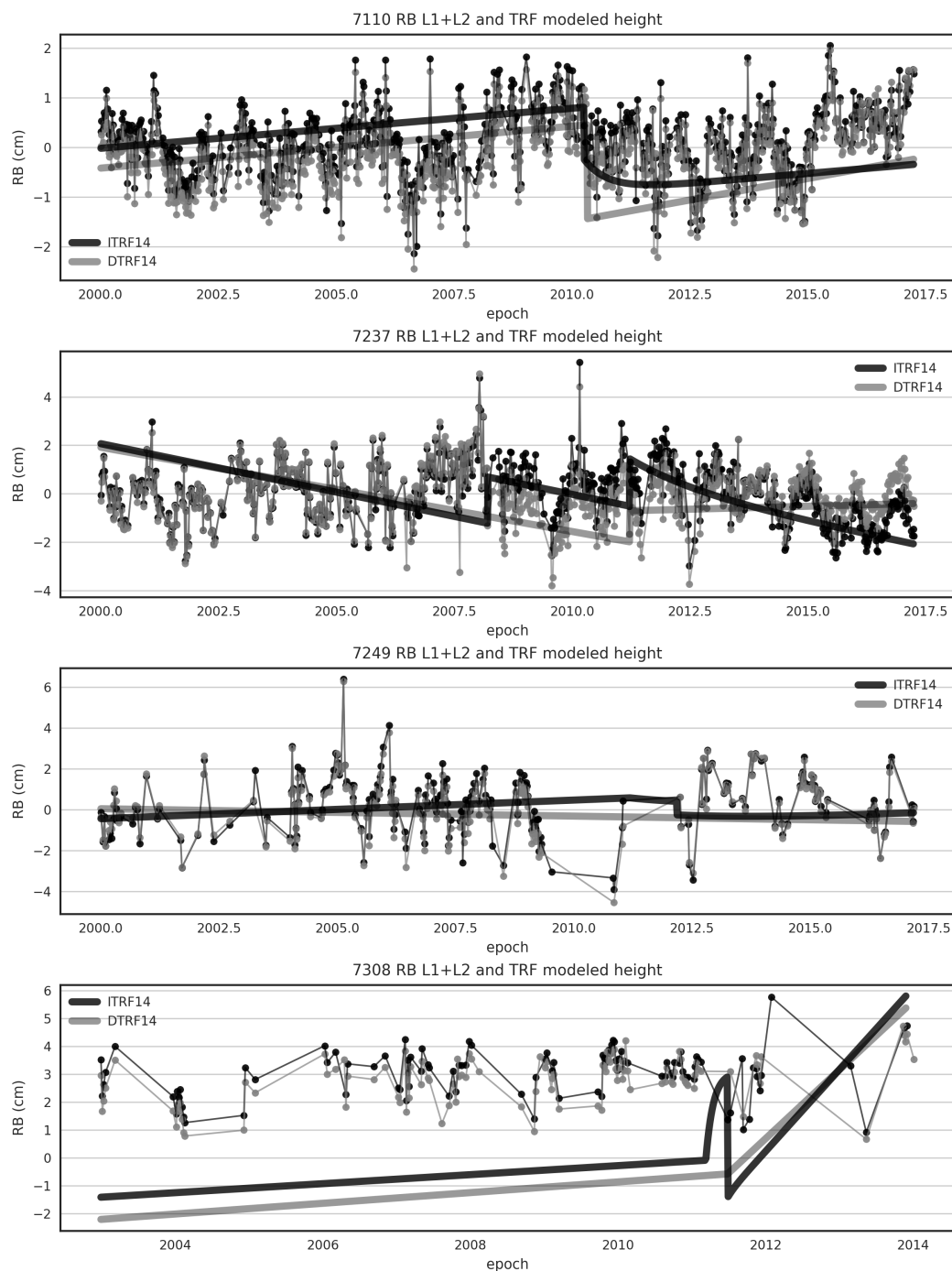


Fig. 6: Time series of estimated biases for SLR sites affected by earthquakes, computed using coordinates from ITRF2014 and DTRF2014. For reference, the solid lines show the heights modelled by these two frames, to which the average ITRF2014 height has been subtracted.

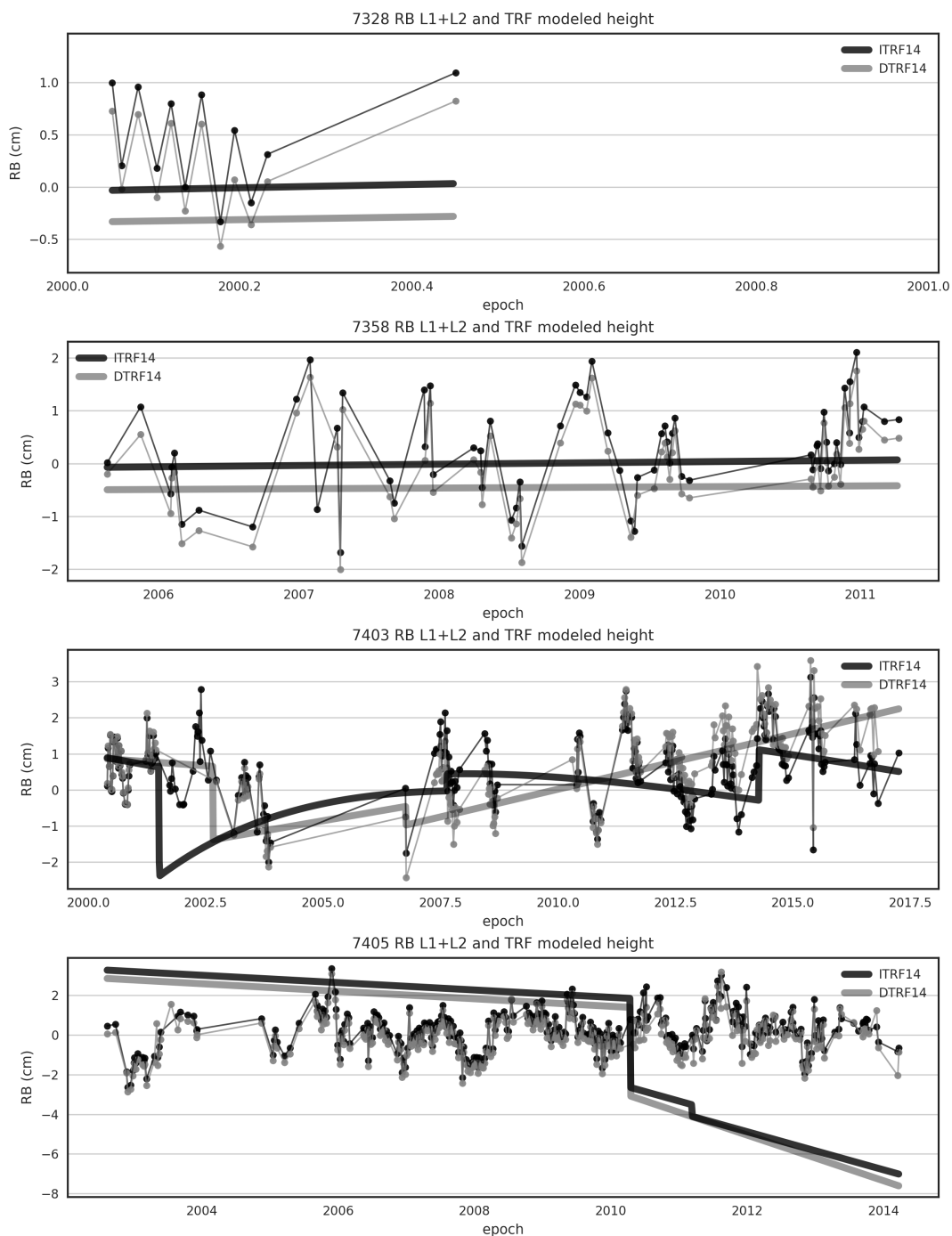


Fig. 7: Time series of estimated biases for SLR sites affected by earthquakes, computed using coordinates from ITRF2014 and DTRF2014. For reference, the solid lines show the heights modelled by these two frames, to which the average ITRF2014 height has been subtracted (continued).

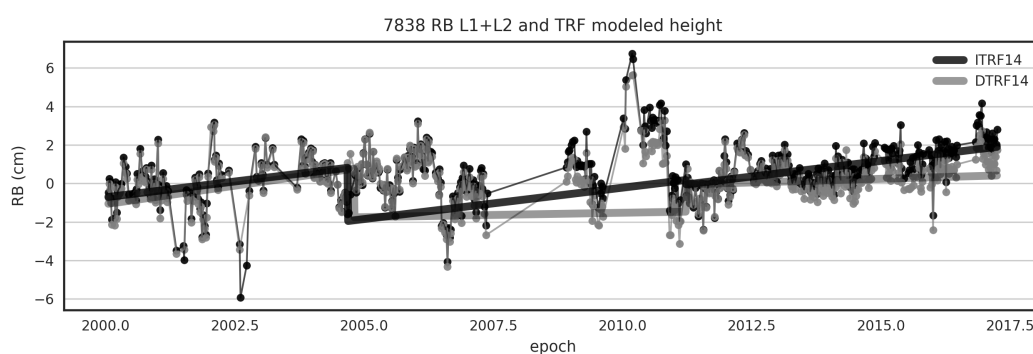


Fig. 8: Time series of estimated biases for SLR sites affected by earthquakes, computed using coordinates from ITRF2014 and DTRF2014. For reference, the solid lines show the heights modelled by these two frames, to which the average ITRF2014 height has been subtracted (continued).

ITRS realizations and their impact on VLBI combined EOP and Scale

Sabine Bachmann¹ and Daniela Thaller¹

¹ *Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, Germany*

Abstract. In this article we investigate the impact of different realizations in framework of the generation of the International Terrestrial Reference Frame (ITRF), Earth Orientation Parameters (EOP), and scale resulting from Very Long Baseline Interferometry (VLBI) intra-technique combination. The first section reviews the input contribution of the International VLBI Service for Geodesy and Astrometry (IVS) to the ITRS realizations. The second section shows the results of using the three different inter-technique combined ITRS realizations as a priori station coordinates in the IVS combination process. We found significant differences in the scale when comparing the results to the respective a priori frames DTRF2014, ITRF2014, and JTRF2014. The scale differences are -0.01 ppb for DTRF2014, -0.59 ppb for ITRF2014, and 0.19 ppb for JTRF2014, with residual WRMS of 0.88 ppb for DTRF2014, 0.95 ppb for ITRF2014, and 0.78 ppb for JTRF2014. In terms of EOP, the differences of using DTRF2014, ITRF2014, and JTRF2014 as a priori values for station coordinates are less distinct. We found differences in particular parameters, i.e. x-pole, y-pole, LOD, and dUT1, using the three different TRS realizations as a priori station coordinates. However, the differences do not emphasize one or another ITRS realization as preferable TRF for VLBI combination. Moreover, we found significant differences in dUT1 when using IERS 08C04 or IERS 14C04 as EOP reference series, which might indicate inconsistencies between these two reference series.

Introduction

In this chapter we review the IVS contribution to the ITRF2014 and the adjunctive combination process before investigating the impact of the three ITRS realizations on VLBI combined Earth Orientation Parameters (EOP) and scale. The scale parameter is particularly interesting, as VLBI – together with Satellite Laser Ranging (SLR) – are the only space geodetic techniques with reliable access to this parameter. In the framework of the latest realization of the International Terrestrial Reference System (ITRS), each of the three ITRS Combination Centers of the IERS (DGFI-TUM, IGN, JPL) provides an inter-technique combined terrestrial reference frame (TRF) using different station coordinate parameterizations. DGFI-TUM provides the DTRF2014, using a piece-wise linear station model with improved geophysical modeling of loading deformation (Seitz et al., 2016). The official ITRF solution, ITRF2014, is provided by IGN, using a piece-wise linear station model and an additional post-seismic deformation model (Altamimi et al., 2016). Finally, JPL provides the JTRF2014, using Kalman filtered weekly estimations of station coordinates with the noise of the time-series triggered by geophysical loading models (Abbondanza et al., 2017).

In the following sections the internal VLBI evaluation of the scale parameter is discussed, then we compare the scale parameter between the combined solution resulting from the VLBI-only combination using

the three different ITRS realizations and the quarterly IVS combined solution as a priori station information. Furthermore, we investigate the impact on combined EOP using the three different ITRS realizations and (for comparison reasons) the quarterly IVS combined solution as a priori station information. The resulting EOP are compared to internal VLBI reference series and the external EOP series provided by IERS, IGS, and ILRS. Additionally to the current IERS 14C04 series, we compare dUT1 to IERS 08C04 (aligned to ITRF2008) and to the EOP time series which are commonly estimated with the respective ITRS realizations, i.e., DTRF2014, ITRF2014 and JTRF2014 (denoted DGFI, IGN and JPL hereafter). These external EOP time series, provided by the IERS ITRS Combination Centers along with the respective TRF, are compared to the IVS EOP long-term combined time series using the IVS quarterly combined global solution (VTRF2015q2) for a priori station coordinates.

Input contributions and combination strategy

The VLBI input contribution is provided by the International VLBI Service for Geodesy and Astrometry (IVS). IVS Analysis Centers (AC) prepare individual session-wise datum-free normal equations in SINEX format containing station coordinates and EOP. The combination is performed session-wise on the normal equation level using the contributions provided by the IVS ACs. The analysis and combination procedure used here is similar to that applied to the operational IVS combination (see Bachmann et al., 2016). The detailed combination process is shown in Figure 1. First, a transformation on the same epoch for every contribution is done (12 h UT to be conform with the other space geodetic techniques). Then, a transformation to equal a priori station coordinates is done. For this step precise a priori values are important for the quality and reliability of the combination result. For the present investigations the a priori values for station coordinates are taken from the three different ITRS realizations as well as the latest VLBI-only combined long-term (quarterly) solution VTRF2015q2¹, which is the one with the most up-to-date global VLBI solutions available. This scenario is sketched in Figure 2.

The next step of the session-wise combination includes an outlier test for station coordinates. The Least Median of Square method (LMS) approach is applied (see Bachmann and Lösler, 2012). Based on normal equations with identical epochs and identical a priori values, the individual solution for each AC is generated. The individual weighting factor is determined using a variance component estimation (VCE). The combined normal equation is then generated by accumulating the weighted contributions of the ACs. Applying no-net rotation (NNR) and no-net translation (NNT) conditions for station coordinates removes the

¹ccivs.bkg.bund.de/vtrf

datum defect of the normal equation and allows its inversion. Stations where no reliable coordinates can be determined for specific sessions are excluded from the datum definition and treated as free parameters. A SINEX file containing the datum-free normal equation of the combined solution for the respective session is then provided to the IERS ITRS Center and submitted to the IVS data center and the IERS Central Bureau.

For our investigations this process is applied to generate three different combined EOP solutions, using DTRF2014, ITRF2014, and JTRF2014 as a priori station coordinates as shown in Figure 2, denoted here as DTRF2014-based, ITRF2014-based and JTRF2014-based solution, respectively. Additionally, we include a fourth solution in our comparisons, which is a routine VLBI-only combined quarterly TRF solution called VTRF2015q2 (aligned to ITRF2008).

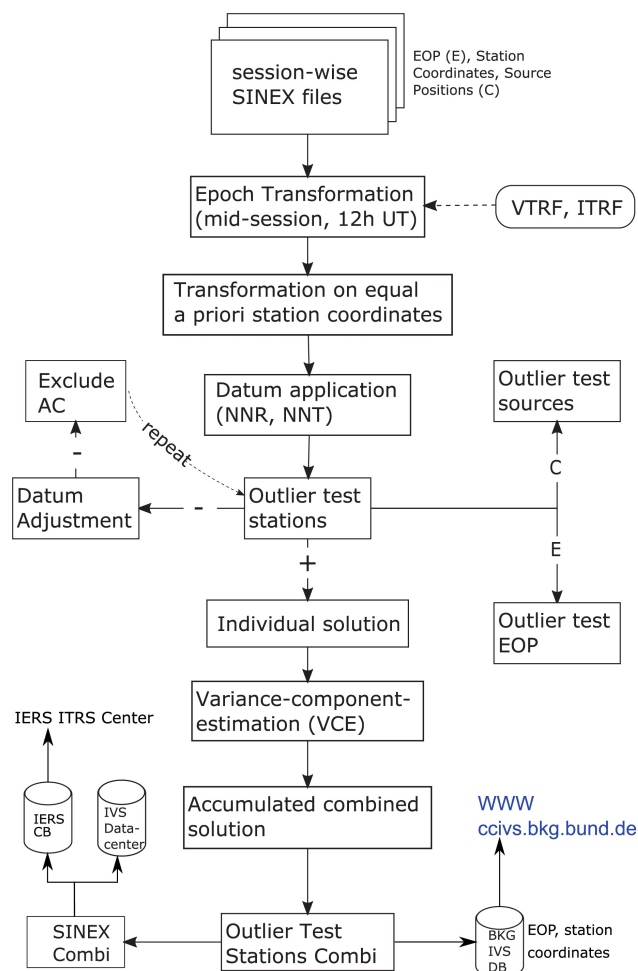


Fig. 1: Flowchart of the session-wise combination process applied at the IVS Combination Center.

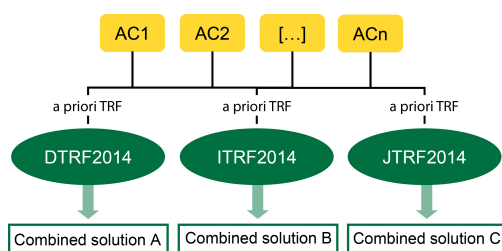


Fig. 2: IVS combination scheme using the three different ITRS realizations.

Scale parameter VLBI internal scale validation

To compare the resulting scale parameters, a session-by-session Helmert transformation is calculated between the combined solution with respect to the global TRF solution VTRF2014, i.e. the TRF solution based on session-wise SINEX intended for ITRF2014. This comparison is shown in Figure 3, where the scale factor is smoothed by a sliding median using a 90-day window and a 7-day moving step. The individual (unsmoothed) sessions are shown in gray.

The annual signal of the scale parameter is shown in red calculated using the time span of ITRF2014 (i.e. 1979.6-2015.0) and in blue calculated using the time span of ITRF2008 (i.e. 1979.6-2009.0). The figure clearly shows a correlation between the scale parameter and the annual signal. Around the year 2010 the scale shows a reduced annual signal and higher frequency variations. Accordingly, a reduction of the amplitude may be expected if the whole ITRF2014 time span is used in contrast to the shorter time span of ITRF2008. Comparing the amplitudes of both annual signals, the amplitude of the red curve is reduced for about 0.01 ppb and has a phase shift of 7 days (see detailed plot on the right top of Figure 3). The variations starting in 2010 can thus be assumed as high-frequency noise covering the annual signal. Two epochs show irregularities: in the end of 2003, and towards the end of the data set, before 2014. The corresponding periods contain many regional sessions with an disadvantageous global station distribution for scale determination. A closer look at the scale parameters for this time periods using only R1 or R4 sessions is provided in Figure 4.

The regularly observed IVS R1 and R4 sessions (i.e., once per week each) contain a minimum number of well-distributed participating stations which lead to a reduction of the peculiarities around 2003/2004 for both R1 and R4 sessions. We observe that, in consequence, the irregularity around 2004 disappears for a network with at least seven stations, while the sessions around 2004 seem to be dominated by regional and small networks. Since sessions with more than seven stations are not observed frequently or regularly, the effect of the smoothing in the scale time series is rather theoretical and should be handled with care. An im-

fact on the regional level seems to be caused by natural effects such as flood or drought, which may explain the scale irregularities, considering that especially 2003 was a year of exceptional drought in the Northern hemisphere. The second irregularity around 2014 is influenced by the fact that both reference frames (DTRF2008 and ITRF2008) contain data observed until the end of 2008, meaning that estimated station coordinates beyond this period need to be extrapolated for several years. Additionally, the selection of datum stations for the Helmert transformation is reduced, since the VLBI network contains more new VLBI telescopes which have not yet been part of DTRF2008 and ITRF2008. Between 2010 and 2012, many severe earthquakes have affected stations within the IVS network. Consequently several new epochs and discontinuities have been introduced into the VTRF2014. This also leads to a more variable scale for these years.

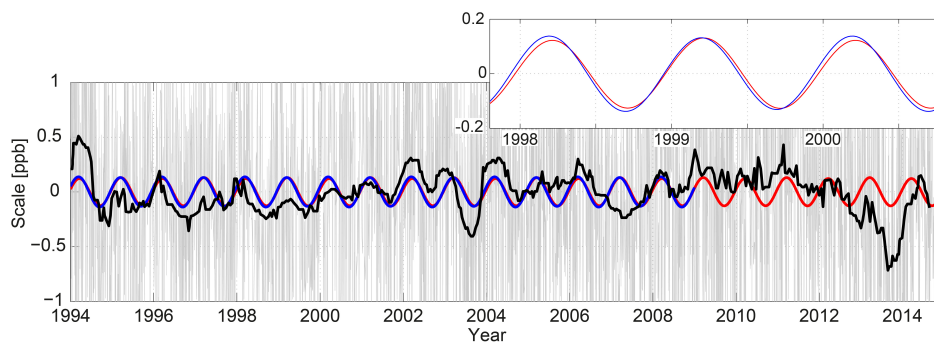


Fig. 3: Smoothed time series of scale parameter between VTRF2014 and session-wise combined solution for the time span 1994.0–2015.0 (black) and the annual signals calculated over the ITRF2014 time span (red) and over the ITRF2008 time span (blue).

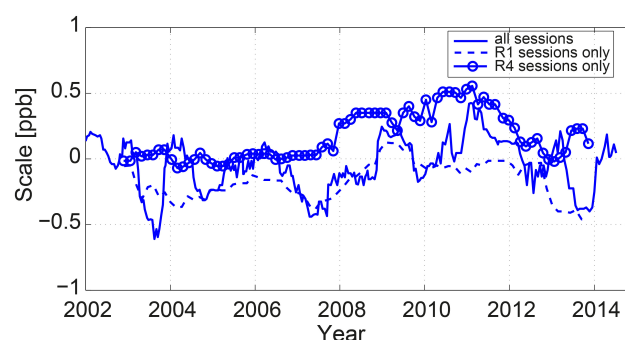


Fig. 4: Detailed view of the smoothed time series of scale parameter between IVS combined solution and DTRF2008 (solid line), using R1 sessions only (dashed line) and using R4 sessions only (circled line).

Scale results using DTRF2014, ITRF2014, and JTRF2014

To evaluate the scale using the three different ITRS realizations, a session-wise Helmert transformation with respect to the routine quarterly combined solution VTRF2015q2 is calculated. Sessions observed between 1990.0 and 2015.0, i.e., that time-span with good VLBI session,

are used as input for the ITRF2014. Stations with discontinuities (e.g. caused by Earthquakes) are excluded from the datum definition. Figure 5 shows the smoothed scale time series between the session-wise IVS combined solution and the ITRS realizations investigated in our study (DTRF2014, ITRF2014 and JTRF2014). Additionally, previous ITRS realizations, like DTRF2008 and ITRF2008, as well as the VTRF2015q2 (a TRF based on combined VLBI sessions) are shown.

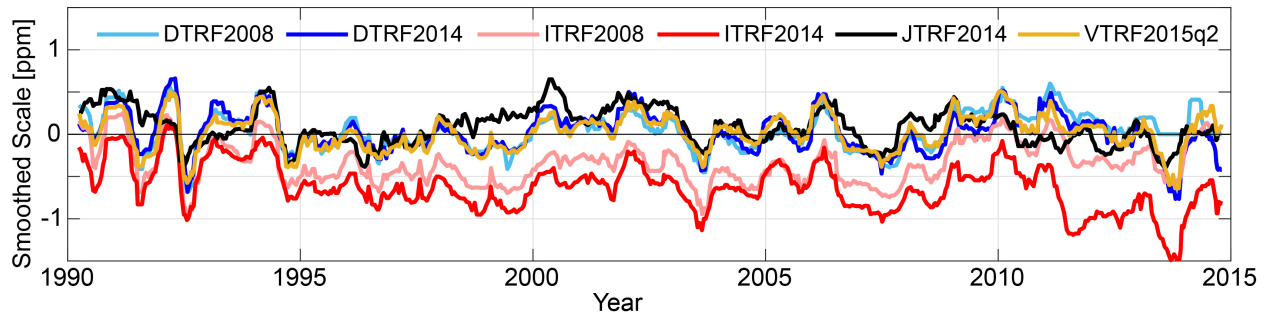


Fig. 5: Smoothed time series of the scale between the session-wise IVS combined solutions using the different ITRS realization and the respective a priori frame DTRF2008 (light blue), DTRF2014 (dark blue), ITRF2008 (light red), ITRF2014 (dark red), JTRF2014 (black) and VTRF2015q2 (ocher).

Peculiarities before 1994 as well as around 2004 and 2014, that are visible in each of the TRFs, can be explained by unfavorable network geometry (see previous section and Figure 4). The figure shows a good agreement between the two DTRF solutions (DTRF2008, DTRF2014), the VTRF2015q2 solution and the JTRF2014 solution, scattering around the zero line. Between about 1998 and 2002 a variation of the JTRF2014-based scale can be observed. We see a noticeable difference for the two ITRF solutions, with an offset for both solutions and an additional trend for the ITRF2014-based solution. Table 1 shows the weighted mean of the scale time series in addition to Figure 5.

Table 1: Weighted mean and WRMS of the scale time series. The values given in [mm] are computed on the Earth surface.

ITRS realization	Weighted Mean (ppb)	WRMS [ppb]
DTRF2014	-0.01 ± 0.01 (-0.1 mm)	0.88
ITRF2014	-0.59 ± 0.02 (-3.8 mm)	0.95
JTRF2014	0.19 ± 0.01 (1.2 mm)	0.78
VTRF2015q2	0.01 ± 0.01 (-0.1 mm)	0.91
DTRF2008	0.02 ± 0.02 (0.1 mm)	0.98
ITRF2008	-0.38 ± 0.02 (-2.4 mm)	1.02

The two DGFI solutions as well as the VTRF solution show no significant offset for the weighted mean. A weighted mean of 0.19 ppb is calculated for the JTRF2014, which primarily results from the scale irregularities between 1998 and 2002. For the ITRF2008-based solution, a weighted mean of -0.38 ppb (corresponding to -2.4 mm on the Earth's surface) was calculated. The ITRF2014-based solution on the other hand shows a weighted mean of -0.59 ppb (i.e. -3.8 mm on the Earth's surface). For comparison, the scale offset estimated using SLR with respect to ITRF2014 is about 0.7 ppb as found by V. Luceri for the SLR intra-technique combined solution (personal communication²). Looking at the WRMS of the scale time series, the JTRF2014-based solution shows the smallest value of 0.78 ppb, which can be most likely explained by the method of epoch reference frames in JTRF2014, allowing the best-possible adaption for each week. The highest value has been detected for the ITRF2008-based solution having 1.02 ppb, which is also not astonishing as this is an older reference frame (similar to DTRF2008).

EOP results

In this section we investigate the impact of the various ITRS realizations on combined EOPs derived from VLBI observations. First, we compare EOPs resulting from the combination as described above with external EOP series from IERS 14C04, IGS finals, and ILRS combined EOP time series resulting from the ILRS input contribution to the ITRF2014. Additionally, we compare dUT1 to IERS 08C04. Then, we compare the EOP time series which are provided by the IERS ITRS Combination Centers along with the respective TRFs, i.e., by DTRF2014, ITRF2014 and JTRF2014 (denoted DGFI, IGN and JPL hereafter, respectively), with the long-term EOP IVS combined time series using the VTRF2015q2 as a priori station coordinates.

Comparison to IERS 14C04, IGS, and ILRS

Figures 6 to 9 show the comparison of the x-, y-pole, LOD and dUT1 resulting from the combination using DTRF2014, ITRF2014, JTRF2014 and VTRF2015q2 as a priori station coordinates with external series. For consistency we keep the same order of the sub-figures for all parameters (except for dUT1): IERS 14C04 (upper left figure), IGS (upper right figure), ILRS (lower left figure) and the differences with respect to the VTRF2015q2 shown in the lower right figure.

The x-pole comparisons in Figure 6 with respect to the IERS 14C04 series show no evident characteristics and a scatter around zero common to each of the EOP solutions. The same yields for the comparison to the ILRS solution, except for a characteristic peak around 2010/2011 (leaving aside the early, less accurate years before 2000). In contrast, for the comparison to the IGS finals, we observe a slope between the years around 2002 and 2015. This slope is associated with IGS anal-

²https://ilrs.cddis.eosdis.nasa.gov/docs/2017/ILRS_ASC_EGU2017_PRESENTATIONS.pdf.

ysis only, since it is not visible in ILRS comparisons. We notice an offset and a larger scatter of the JTRF2014-based EOP until 2007 comparing to the IVS VTRF2015q2-based solution. Also, the differences between the various TRF solutions become larger again from 2013 onwards. Furthermore, we see a drift for the differences with respect to the DTRF2014-based solution, but no significant characteristic for the ITRF2014-based solution is visible. The reason for the drift remains unclear.

The y-pole comparisons illustrated in Figure 7 show characteristic differences with respect to the different external time series. We see a peculiarity around 2006 for each EOP solution compared to IERS 14C04 and IGS. Whereas the comparison to IERS 14C04 shows a scatter about zero with no visible characteristics, we observe a drift in the IGS comparison starting around 2011 and an offset from 2010/2011 onwards in comparison with the ILRS solution. These characteristics are common for each of the EOP solutions. According to SLR analysts, this offset is due to modifications in the network configuration, and not induced by earthquake affected stations. As already seen in the x-pole comparison, the differences between the three TRF solutions become larger from 2013 onwards. Common to the x-pole, the inter-TRF-based comparison for the y-pole shows an offset of the JTRF2014-based solution, as well, with negative sign before 2002/2003 and positive sign afterward. Also, a larger scatter can be seen in the JTRF2014-based series than for the DTRF2014- and ITRF2014-based solution. The latter two solutions show a small offset of about $50 \mu\text{s}$ between the respective EOP solution.

The comparison of LOD shows little characteristic differences with respect to external time series with a regular scatter around zero common to all solutions with respect to IERS 14C04, IGS, and ILRS (not shown). Also, the comparison with the VTRF2015q2-based IVS solution shows a homogeneous scatter around zero with a moderately larger amplitude for both ITRF2014-, and JTRF2014-based solutions as shown in Figure 8. This means that other effects than the choice of the a priori TRF have an impact on the estimated LOD parameter.

Contrary to the comparison of the LOD estimates, the dUT1 parameter series show significant differences comparing to IERS 14C04 (see Figure 9). The DTRF2014- and JTRF2014-based solutions show an offset of about $5 \mu\text{s}$ and strong variations between the years 2000 and 2015. The ITRF2014-based solution shows an offset of about $2 \mu\text{s}$ and strong variations between 2000 and 2015 as well. However, the VTRF2015q2-based solution does not show any noticeable offset, and a regular scatter around zero. For the dUT1 comparison significant differences between the IERS 14C04 (aligned to ITRF2014) and IERS 08C04 (aligned to ITRF2008) are visible. A noticeable discontinuity can

be seen in the year 2000 for the IERS 08C04 comparison for each of the solutions. This discontinuity disappears when comparing the dUT1 time series with the IERS 14C04 series. It is somehow surprising that this discontinuity disappears for the VTRF2015q2-based solution as well, since this solution is still aligned to ITRF2008. We conclude that this discontinuity is independent of the a priori TRF used for the EOP generation, but related to the IERS 08C04 series itself. In comparison to the VTRF2015q2-based dUT1, offsets for all three TRFs can be observed, as well as a larger scatter for the JTRF2014-based solution.

Comparison to the EOPs provided along with individual TRFs

The ITRS Combination Centers at DGFI-TUM, IGN, and JPL provide EOP time series that are generated consistently with the respective ITRS realizations. To identify analysis-induced systematics, we compare these series with the VTRF2015q2-based EOP time series as well as the IERS 14C04 series. The x- and y-pole component comparisons show inconspicuous variations between the three solutions, therefore these comparisons are not given here. For the dUT1 differences (also not shown here), the most noticeable effect is an offset of all three EOP time series of about $-5 \mu\text{s}$ with respect to the VLBI-only combined dUT1 solution. Furthermore, a systematic time-dependent signal can be accounted for all three EOP differences in a range of about $\pm 5 \mu\text{s}$. The reason for the offset is not yet clear and will be subject of further investigations. Figure 10 displays the LOD comparison, since LOD shows the largest variations among all investigated EOPs. The left figure shows larger variations of the DGFI EOPs up to $20 \mu\text{s}$ (black line), while the LOD differences for the ITRF and the JTRF EOP solutions agree on the μs level. The right figure shows the comparison with respect to the IERS 14C04 series, where the DGFI solution shows the smallest variations of all compared LOD series (DGFI-TUM, IGN, JPL, and VTRF2015q2). The reason for these differences can be found within the inter-technique combination procedure applied at the different ITRS Combination Centers. DGFI-TUM incorporates all space geodetic techniques into the LOD parameter, whereas the combination procedures applied at IGN and JPL use only VLBI for LOD determination. This leads to higher differences when comparing to intra-technique VLBI-only EOPs and at the same time to a better accordance to the IERS 14C04 series.

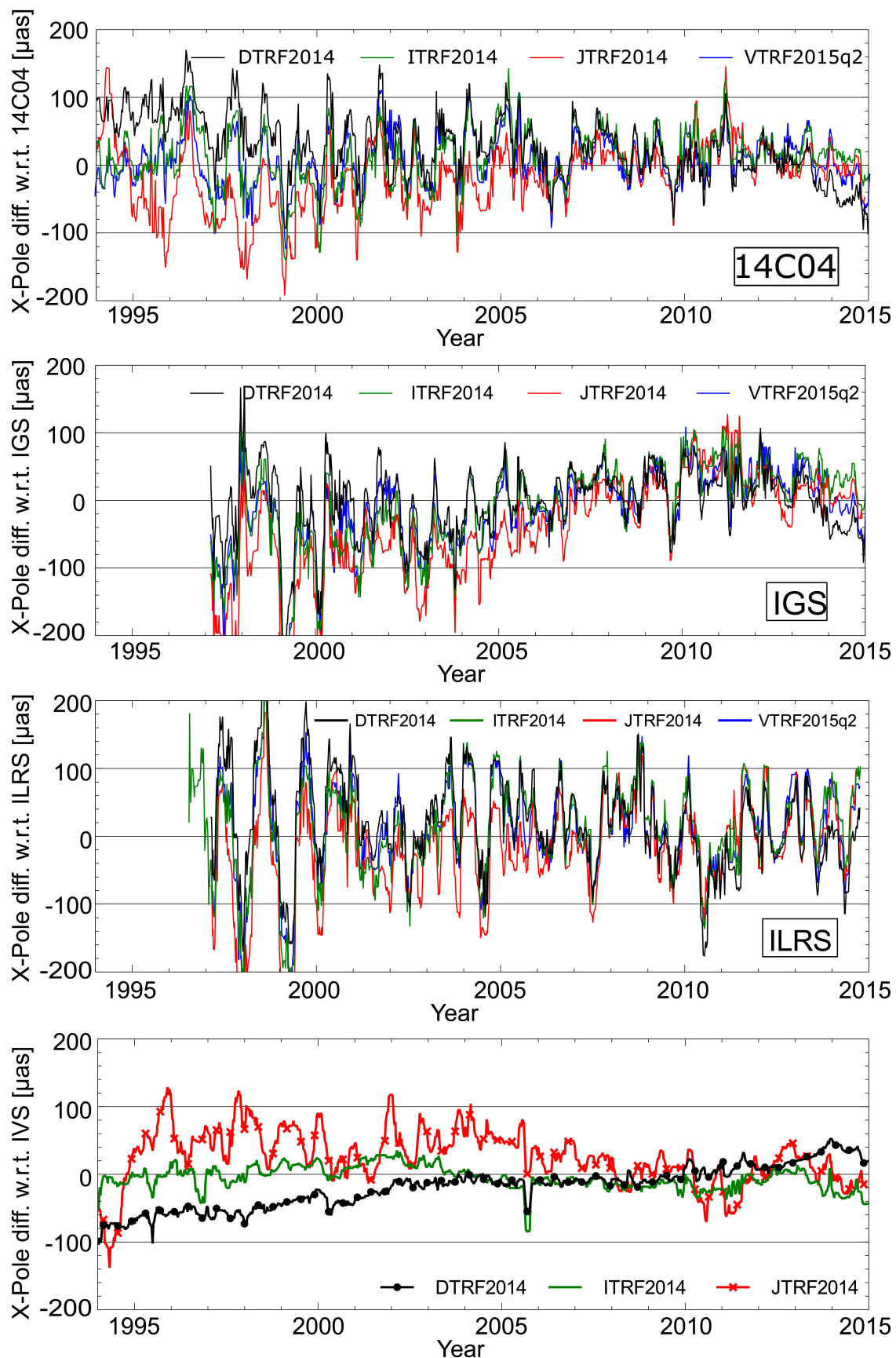


Fig. 6: Comparison of VLBI x-pole time series based on different TRFs with the x-pole series IERS 14C04 (upper left), IGS finals (upper right), ILRS input for ITRF2014 (lower left). Additionally, the comparison of the VLBI x-pole series based on VTRF2015q2 with the VLBI x-pole series based on the three other TRFs is shown in the lower right figure. 90 days median values are shown.

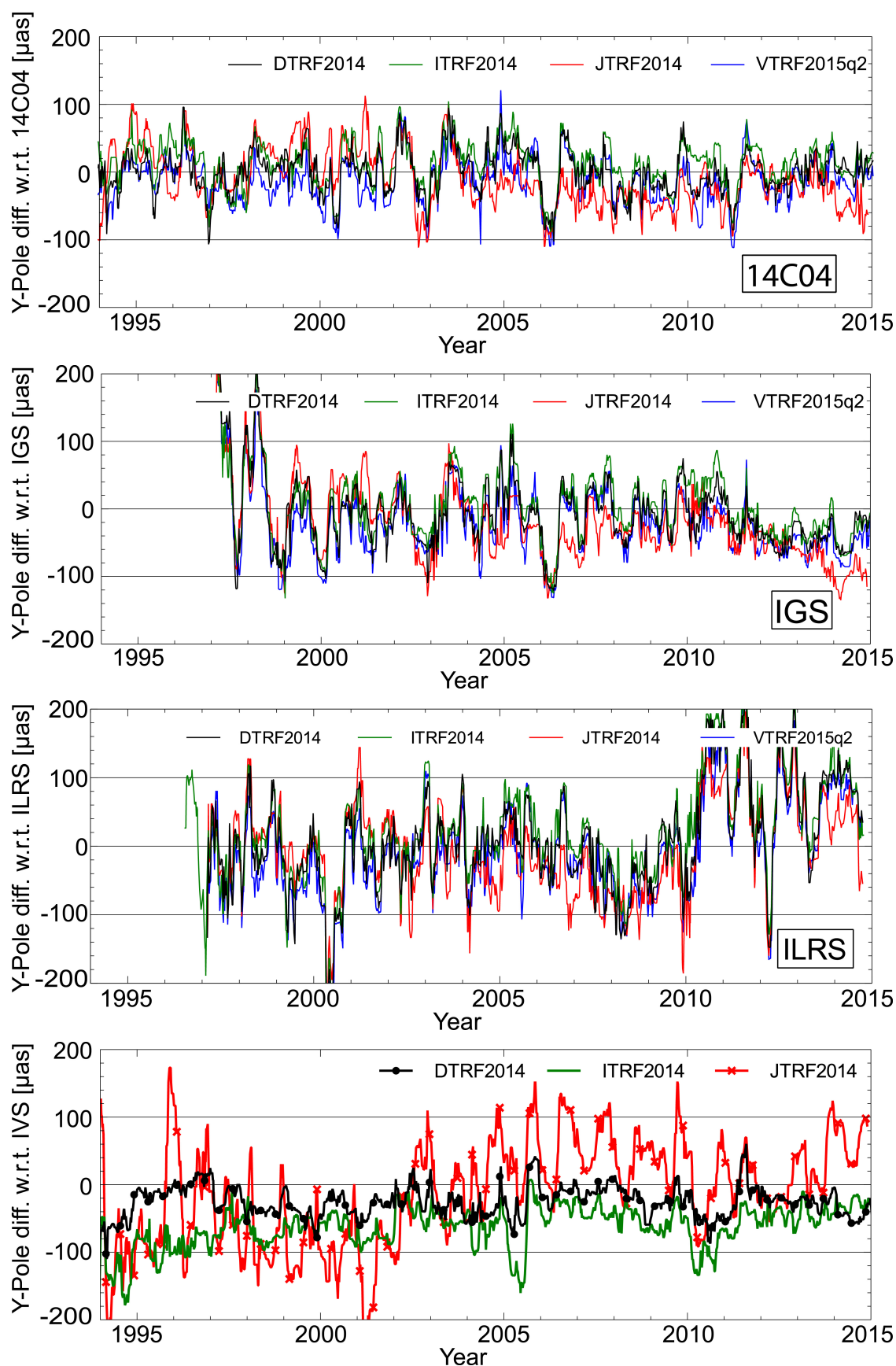


Fig. 7: Comparison of VLBI y-pole time series based on different TRFs with the y-pole series IERS 14C04 (upper left), IGS finals (upper right), ILRS input for ITRF2014 (lower left). Additionally, the comparison of the VLBI y-pole series based on VTRF2015q2 with the VLBI y-pole series based on the three other TRFs is shown in the lower right figure. 90 days median values are shown.

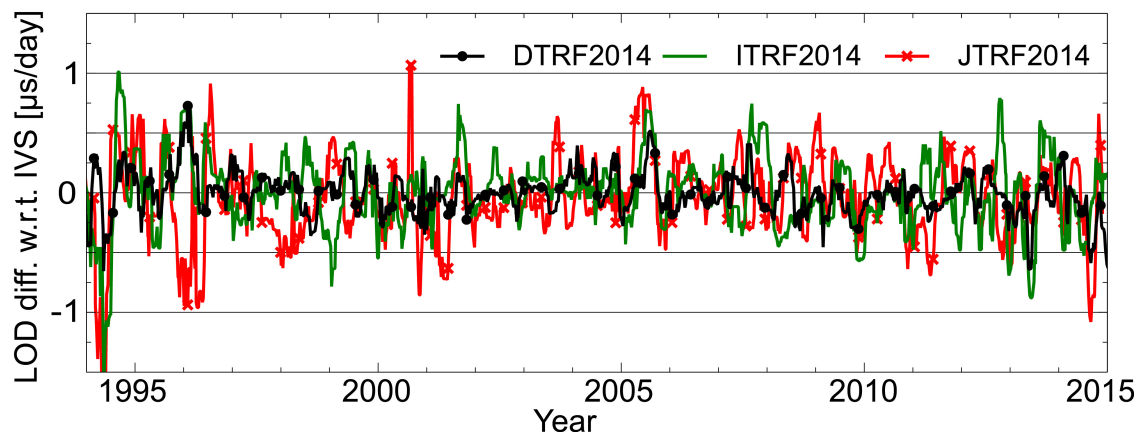


Fig. 8: LOD differences between the solutions based on the different TRFs and the VTRF2015q2-based IVS solution are shown. 90 days median values are shown.

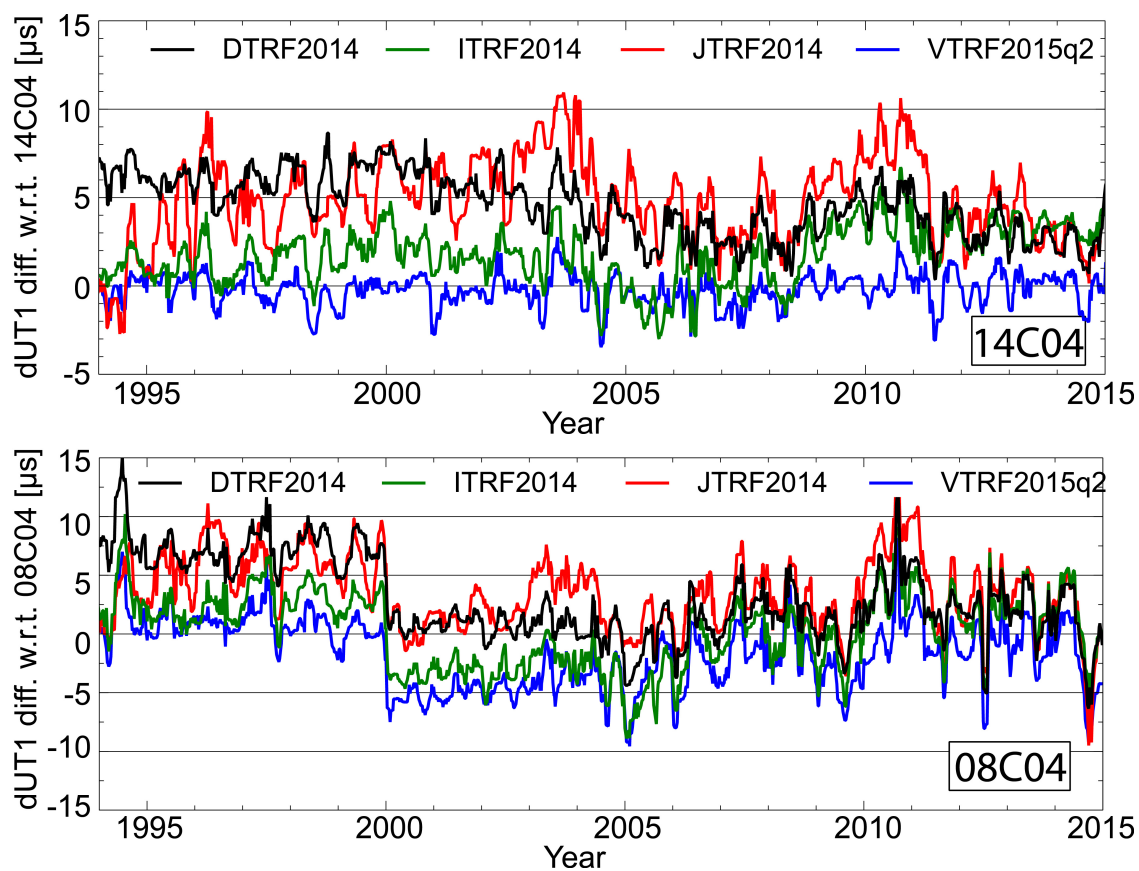


Fig. 9: dUT1 differences between the solutions based on the different TRFs and IERS 14C04 (left), and IERS 08C04 (right). 90 days median values are shown.

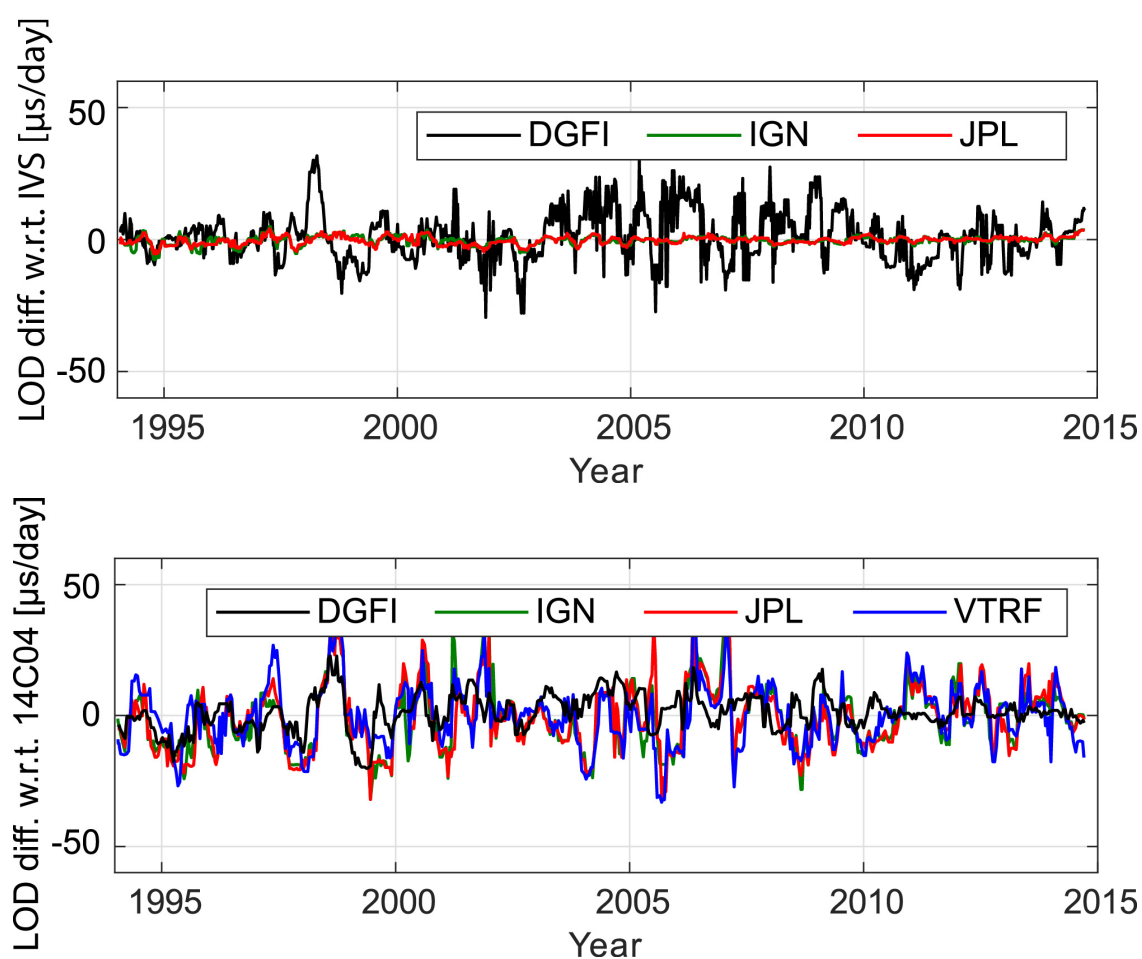


Fig. 10: Differences between the DGFI (black), IGN (green) and JPL (red) LOD with respect to the VTRF015q3-based solution (left) and to IERS 14C04 (right). 90 days median smoothed values are shown.

Conclusions We used the three ITRS realizations (DTRF2014, ITRF2014, and JTRF2014) as a priori TRF within the session-wise VLBI combination and investigated the impact on the parameters of interest, i.e. station coordinates, scale, and EOPs. Regarding the station coordinates and their repeatability we did not find significant differences. Though, we found significant differences in the scale factor when comparing the results to our routine IVS combined solution (i.e. VTRF2015q2). The scale factor of the ITRF2014-based solution shows a significant offset (weighted mean over the scale time series) of -0.59 ppb. For the JTRF2014-based solution we found an offset of 0.19 ppb, whereas for the DTRF2014-based solution no significant offset was found.

The EOP time series generated using different TRFs as a priori within the VLBI combination are compared to EOP time series provided by IERS, IGS, and ILRS. For x- and y-pole, the comparison shows specific effects when comparing to IERS 14C04 (a decline starting in 2013 for x-pole, no irregularities for y-pole), IGS (an offset until 2006 followed by a sinusoidal signal for x-pole and a decline starting around 2011 for y-pole) and to ILRS (no irregularities for x-pole, but a discontinuity in 2010 for y-pole). Comparing to the VTRF2015q2-based solution we found significant differences for the x-pole for the DTRF2014-based and JTRF2014-based solutions, and an offset of the y-pole for all three solutions with an additional larger scatter for the JTRF2014-based solution. For LOD, we found no significant differences between the different EOP time series and the reference EOP series. Using ITRF2014 or JTRF2014 leads to marginal larger scatter with respect to the VTRF-based EOP series. The most significant impact can be seen for dUT1, where all three solutions based on the three ITRS realizations show a significant offset comparing to IERS 14C04, while the VTRF2015q2-based solution does not reveal any offset. In contrast, comparing to IERS 08C04, a significant discontinuity for each EOP series was found in 2000, but no offset for DTRF2014 and JTRF2014 afterward. As a consequence, it can be assumed, that the differences are represented in the IERS C04 series. The comparison to the VTRF2015q2-based solution shows an offset for all three TRF-based solutions. The comparison of the EOP time series provided by the ITRS Combination Centers along with the TRFs reveals a significant difference for LOD in case of the DGFI series. This difference can be explained by the combination procedure (see section above) as it disappears when comparing these EOP series to IERS 14C04.

Acknowledgments

We would like to thank the IVS Analysis Centers who provided the input data for the combination process. We also want to thank the responsible persons at the IERS ITRS Combination Centers at DGFI-TUM, IGN, and JPL who provided valuable remarks on the combined sessions. Furthermore we thank Vincenza Luceri for providing the ILRS combined EOP time series for our comparisons.

References

- Abbondanza C, Chin TM, Gross RS, Heflin MB, Parker J, Soja BS, van Dam T, Wu X (2017) JTRF2014, the JPL Kalman filter, and smoother realization of the international terrestrial reference system. *J Geophys Res Solid Earth* 122:8474-8510.
DOI 10.1002/2017JB014360
- Altamimi Z, Rebischung P, Métivier L, Collilieux X (2016) ITRF2014: a new release of the international terrestrial reference frame modeling nonlinear station motions. *J Geophys Res Solid Earth* 121:6109–6131.
DOI 10.1002/2016JB013098
- Bachmann S, Lösler M (2012) IVS combination center at BKG – Robust outlier detection and weighting strategies. In: Behrend, D., Baver, K. (eds) IVS 2012 General Meeting Proceedings, NASA/CP-2012-217504, p. 266–270
- Bachmann S, Thaller D (2017) ITRS realizations in the framework of ITRF2014: impact of different TRF parameterizations on VLBI combined products. In: Proceedings of the 23rd European VLBI Group for Geodesy and Astrometry Working Meeting (2017). Edited by Rüdiger Haas and Gunnar Elgered. ISBN 978-91-88041-09-8, p. 157–161
- Bachmann S, Thaller D, Roggenbuck O, Lösler M, Messerschmitt L (2016) IVS contribution to ITRF2014. *J Geod* 90:631–654.
DOI 10.1007/s00190-016-0899-4
- Bizouard C, Lambert S, Becker O, Richard JY (2017) Combined solution C04 for earth rotation parameters consistent with international terrestrial reference frame 2014. Observatoire de Paris, SYRTE, 61 av. de l'Observatoire, Paris.
<http://hpiers.obspm.fr/eoppc/eop/eopc04/C04.guide.pdf>
- Böckmann S, Artz T, Nothnagel A, Tesmer V (2010) International VLBI Service for Geodesy and Astrometry: Earth orientation parameter combination methodology and quality of the combined products. *J Geophys Res* 115, B04404.
DOI 10.1029/2009JB006465
- Nothnagel A, Artz T, Behrend D, Malkin Z (2017) International VLBI Service for Geodesy and Astrometry – Delivering high-quality products and embarking on observations of the next generation. *J Geod*

91(7):711–721.

DOI 10.1007/s00190-016-0950-5

Seitz M, Bloßfeld M, Angermann D, Schmid R, Gerstl M, Seitz F (2016)
The new DGFI-TUM realization of the ITRS: DTRF2014 (data).
Deutsches Geodätisches Forschungsinstitut, Munich (2016).
DOI 10.1594/PANGAEA.864046

Index of authors

Abbondanza, Claudio	17, 95
Altamimi, Zuheir	4, 71
Angermann, Detlef	5, 79
Bachmann, Sabine	151
Bloßfeld, Mathis	5, 79, 95
Capdeville, Hugues	95
Chin, Toshio Michael	17
Collilieux, Xavier	71
Ferrage, Pascale	95
Gross, Richard S.	17
Heflin, Michael B.	17
Lemoine, Jean-Michel	95
Métivier, Laurent	71
Moreaux, Guilhem	95
Parker, Jay W.	17
Rebischung, Paul	71
Rodríguez, José	135
Rudenko, Sergei	79
Seitz, Florian	5
Seitz, Manuela	5, 79
Soja, Benedikt S.	17
Thaller, Daniela	151
van Dam, Tonie M.	17
Wu, Xiaoping	17