ITRS realizations and their impact on VLBI combined EOP and Scale

Sabine Bachmann[1] and Daniela Thaller[1]

[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 VTRF2015q2[1], 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

[1] ccivs.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).

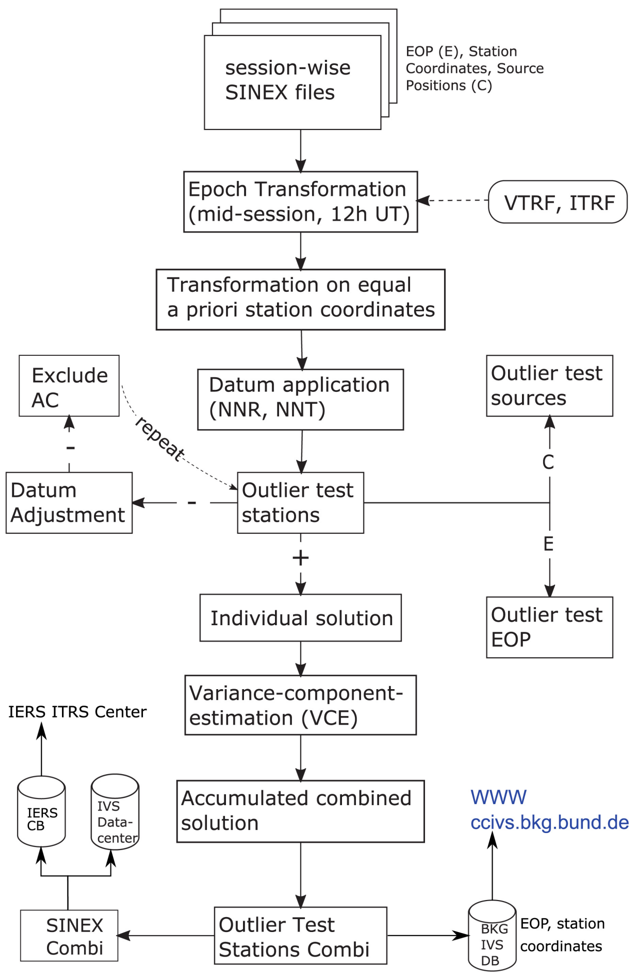

Fig. 1: *Flowchart of the session-wise combination process applied at the IVS Combination Center.*

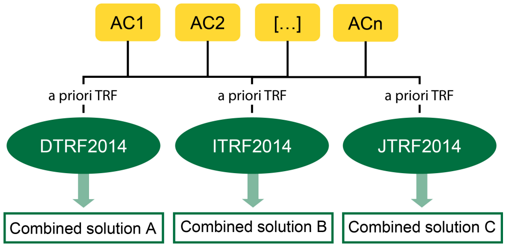

Fig. 2: *IVS combination scheme using the three different ITRS realizations.*

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 impact 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.

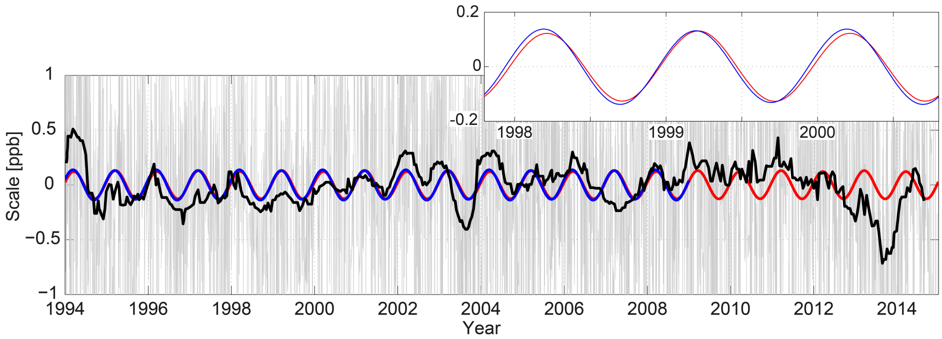

Fig. 3: *Smoothed time series of scale parameter between VTRF2014 and session-wise combined solution for the time span 1994.0–2015.0 (black) and the annual signals calculated over the ITRF2014 time span (red) and over the ITRF2008 time span (blue).*

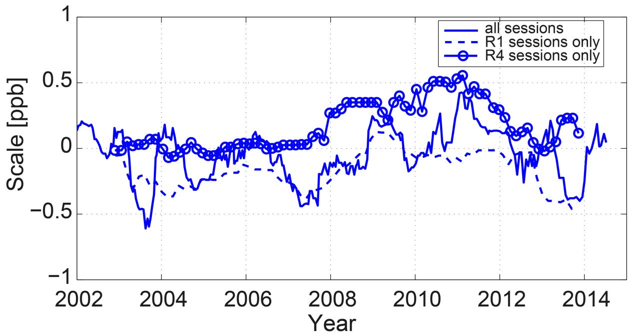

Fig. 4: *Detailed view of the smoothed time series of scale parameter between IVS combined solution and DTRF2008 (solid line), using R1 sessions only (dashed line) and using R4 sessions only (circled line).*

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.

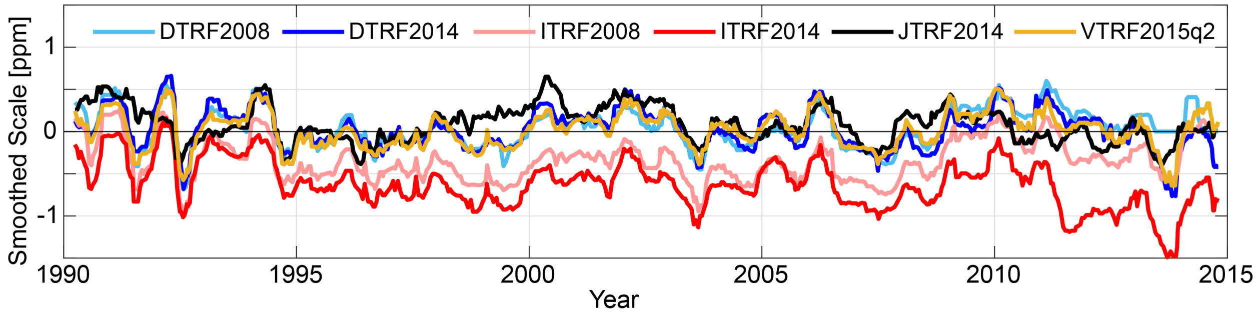

Fig. 5: *Smoothed time series of the scale between the session-wise IVS combined solutions using the different ITRS realization and the respective a priori frame DTRF2008 (light blue), DTRF2014 (dark blue), ITRF2008 (light red), ITRF2014 (dark red), JTRF2014 (black) and VTRF2015q2 (ocher).*

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 $\pm$ 0.01 (-0.1 mm)	0.88
ITRF2014	-0.59 $\pm$ 0.02 (-3.8 mm)	0.95
JTRF2014	0.19 $\pm$ 0.01 (1.2 mm)	0.78
VTRF2015q2	0.01 $\pm$ 0.01 (-0.1 mm)	0.91
DTRF2008	0.02 $\pm$ 0.02 (0.1 mm)	0.98
ITRF2008	-0.38 $\pm$ 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 communication[2]). 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-

[2] https://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 μas 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 μs and strong variations between the years 2000 and 2015. The ITRF2014-based solution shows an offset of about 2 μas 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 μs 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 μs. 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 μs (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.

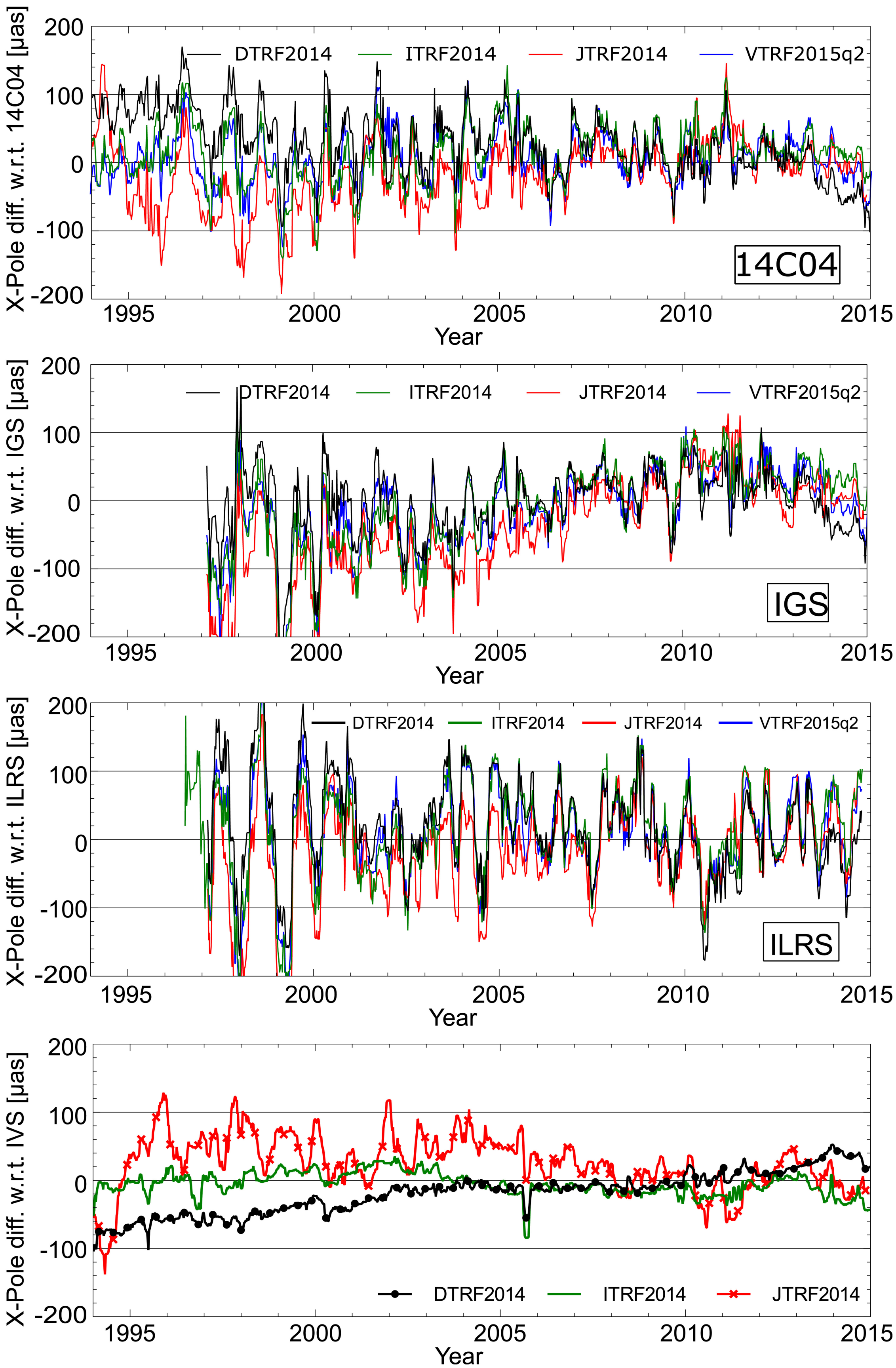

Fig. 6: *Comparison of VLBI x-pole time series based on different TRFs with the x-pole series IERS 14C04 (upper left), IGS finals (upper right), ILRS input for ITRF2014 (lower left). Additionally, the comparison of the VLBI x-pole series based on VTRF2015q2 with the VLBI x-pole series based on the three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

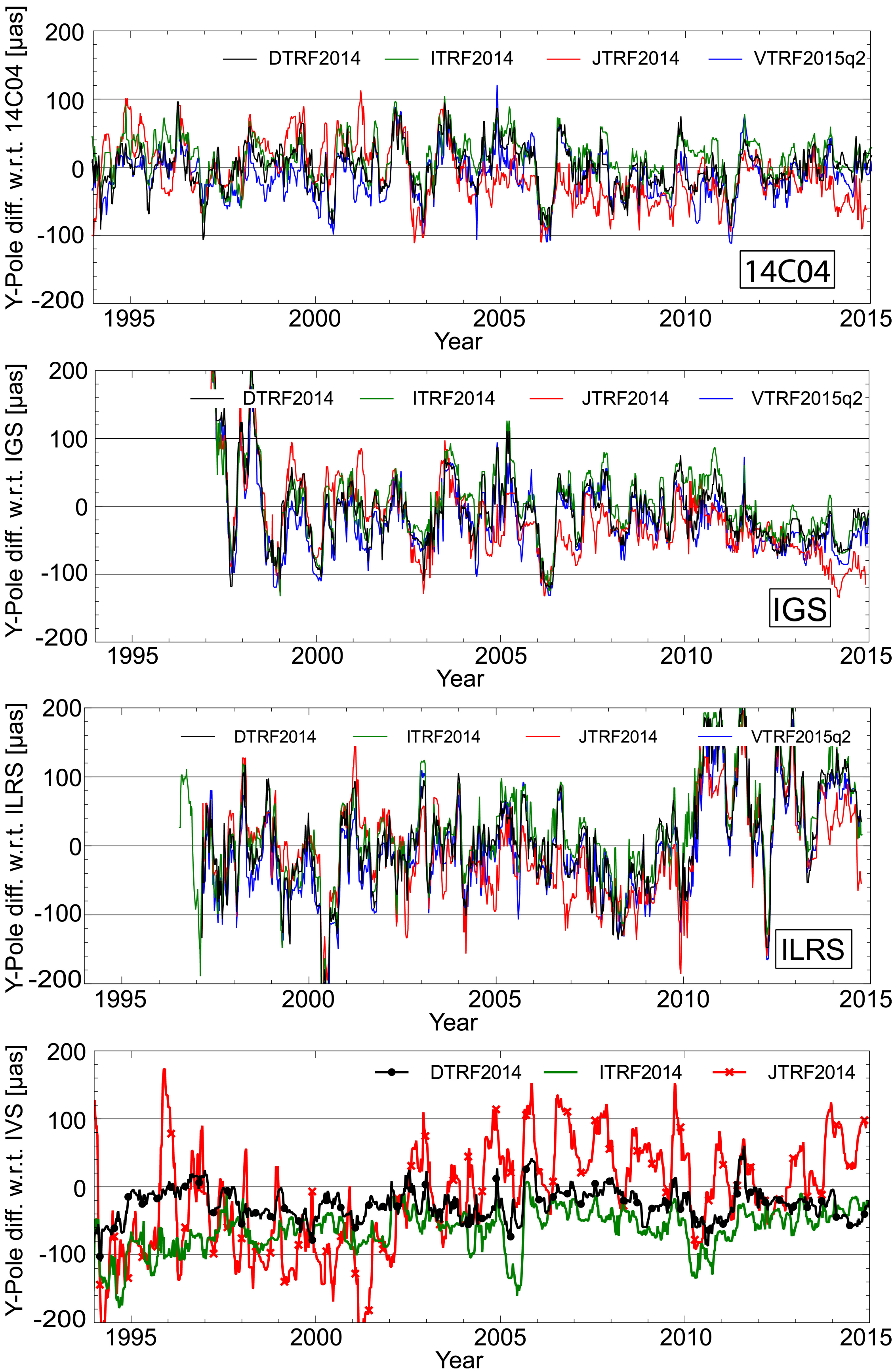

Fig. 7: *Comparison of VLBI y-pole time series based on different TRFs with the y-pole series IERS 14C04 (upper left), IGS finals (upper right), ILRS input for ITRF2014 (lower left). Additionally, the comparison of the VLBI y-pole series based on VTRF2015q2 with the VLBI y-pole series based on the three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

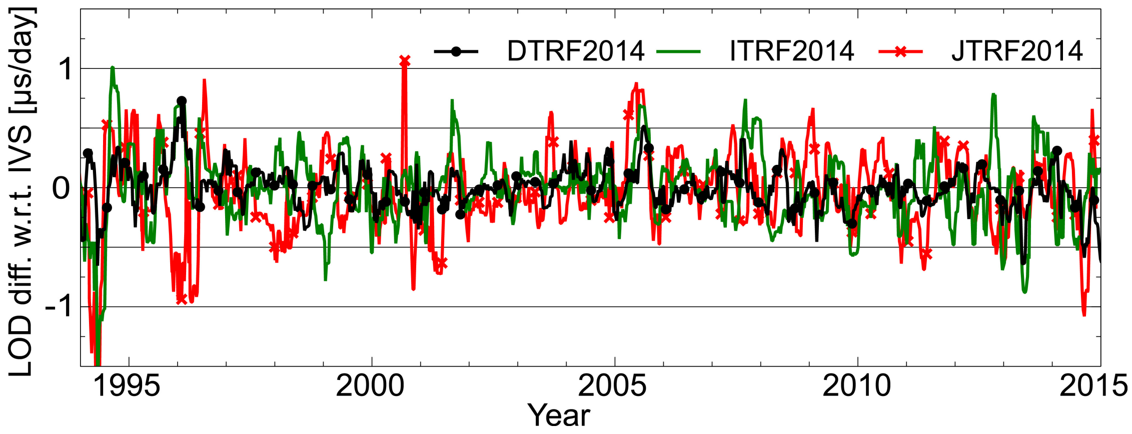

Fig. 8: *LOD differences between the solutions based on the different TRFs and the VTRF2015q2-based IVS solution are shown. 90 days median values are shown.*

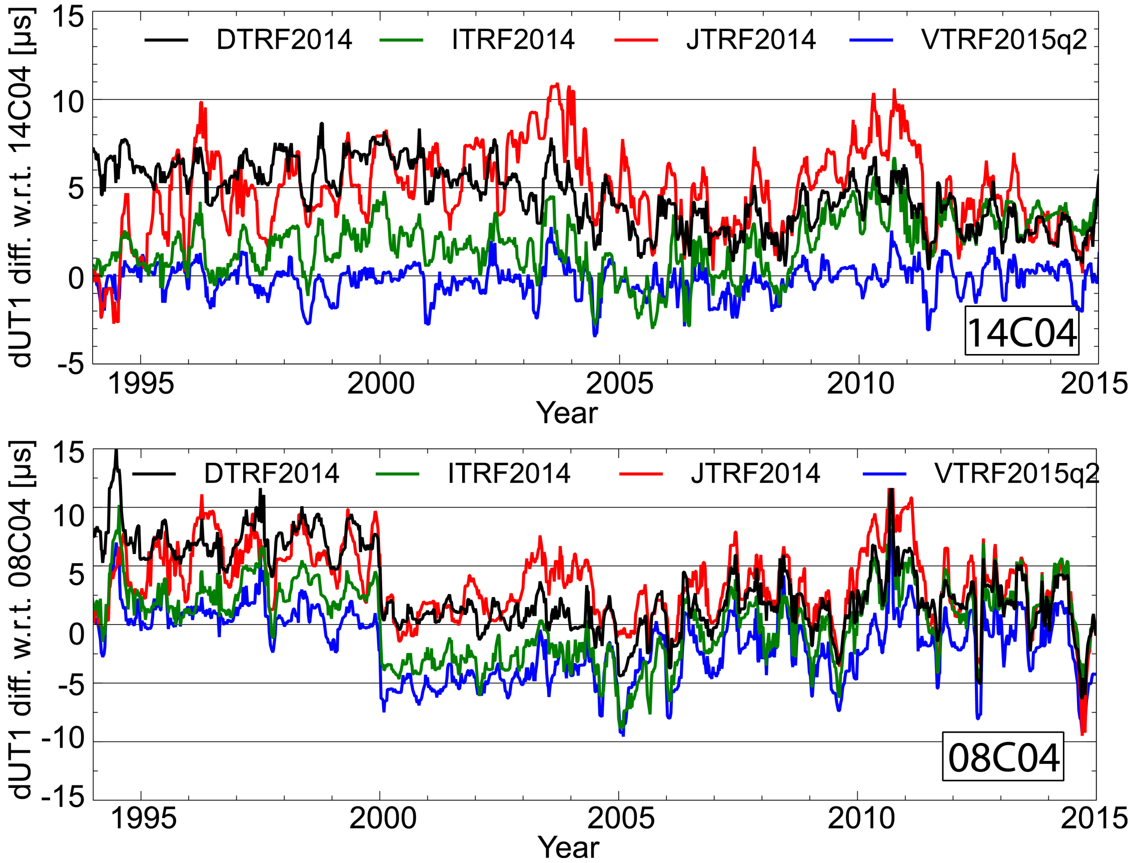

Fig. 9: *dUT1 differences between the solutions based on the different TRFs and IERS 14C04 (left), and IERS 08C04 (right). 90 days median values are shown.*

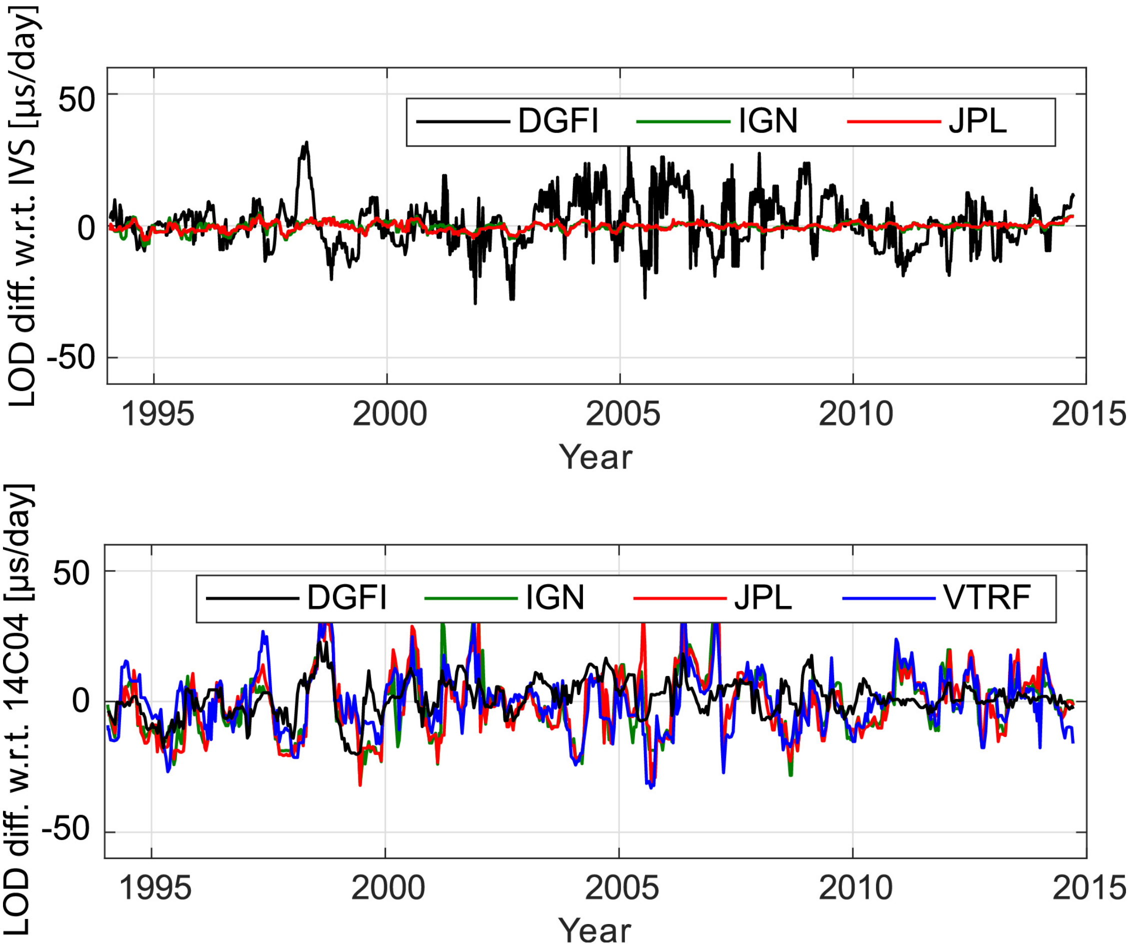

Fig. 10: *Differences between the DGFI (black), IGN (green) and JPL (red) LOD with respect to the VTRF015q3-based solution (left) and to IERS 14C04 (right). 90 days median smoothed values are shown.*

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 AstrometryWorking 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