Comparison of latest ITRS realizations: ITRF2014, DTRF2014 and JTRF2014

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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 $\mathbf{X_{ITRF}}(t_0)$ + velocity $\dot{\mathbf{X}}_{\mathbf{ITRF}}(t_0)$ + PSD models (selected stations) + periodic signals (on request)	Position $\mathbf{X_{DTRF}}(t_0)$ + velocity $\dot{\mathbf{X}}_{\mathbf{DTRF}}(t_0)$ + NT-L models + SLR origin + residual station motions	Weekly positions $\tilde{\mathbf{X}}_{\mathbf{ITRF}}(t_i)$
Earth orientation parameters	Combined: - Terrestrial pole (PM), - PM rates from GNSS + VLBI Separate VLBI-only: - dUT1, - LOD, - Celestial pole	Combined: - Terrestrial pole (PM), - PM rates from GNSS + VLBI, - LOD from GNSS + SLR + VLBI Separate VLBI-only: - dUT1, - Celestial pole	Combined: - Terrestrial pole (PM), - PM rates from GNSS + VLBI Separate VLBI-only: - 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

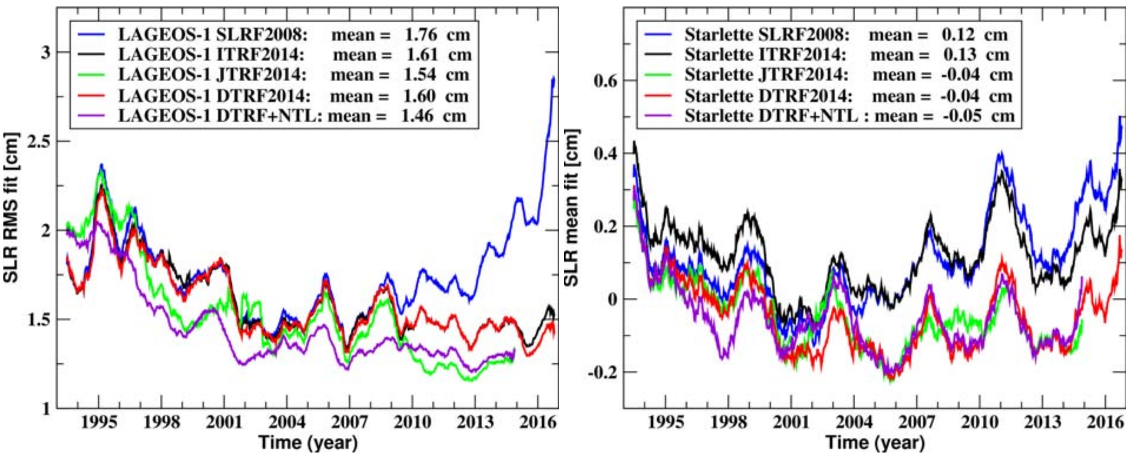

Fig. 1: *(Left) 50-week running averages of the RMS fits of SLR observations (in cm) for LAGEOS-1 orbits derived using SLRF2008, ITRF2014, DTRF2014 linear, DTRF2014+NTL and JTRF2014. (Right) 50-week running averages of the mean fits of SLR observations (in cm) for Starlette orbits derived using SLRF2008,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

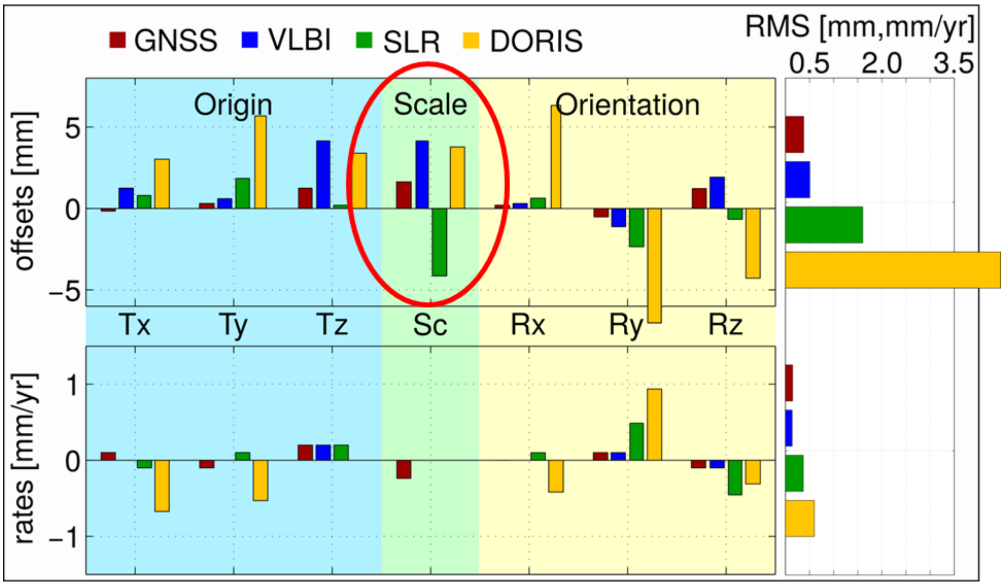

Fig. 2: *Results of technique-specific Helmert transformation between ITRF2014 and DTRF2014.*

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

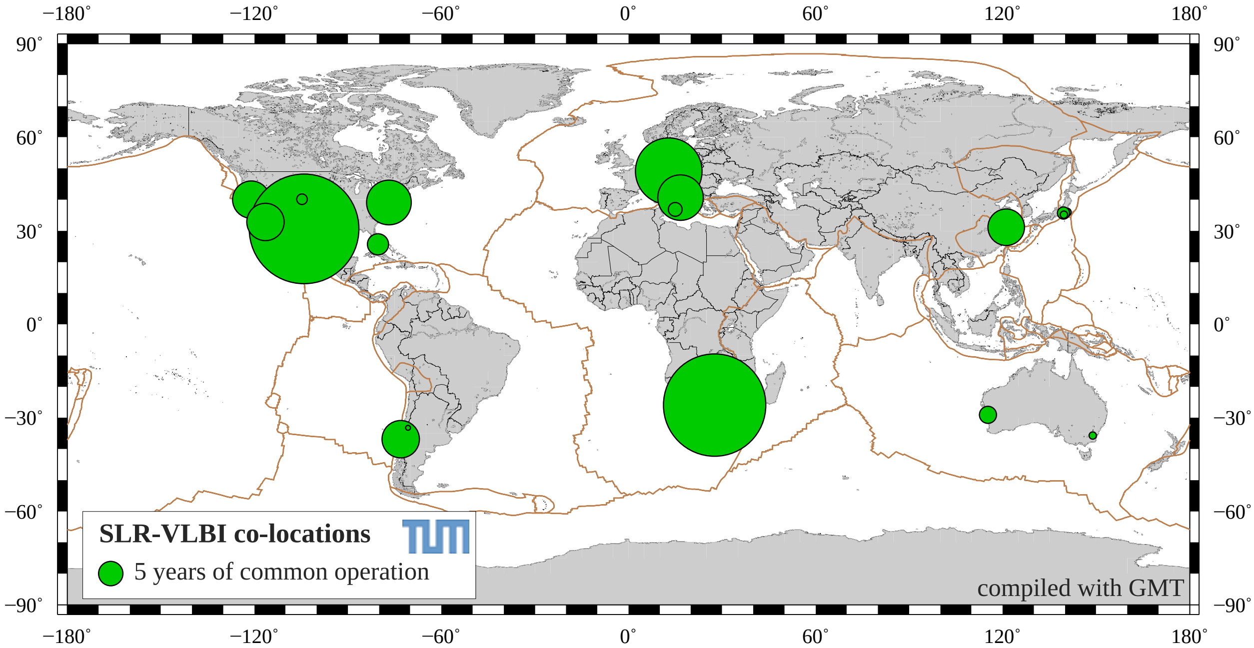

Fig. 3: *Global distribution of VLBI and SLR co-location sites. The radius of the circles indicate the common observation time span of VLBI and SLR.*

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	$\mathbf{0.7}$
10 mm	0.9 ± 0.07	26	0.3 ± 0.06	19	$\mathbf{0.6}$
15 mm	1.4 ± 0.06	34	1.3 ± 0.07	23	$\mathbf{0.1}$
25 mm	1.2 ± 0.07	36	4.5 ± 0.09	31	$\mathbf{-3.3}$

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

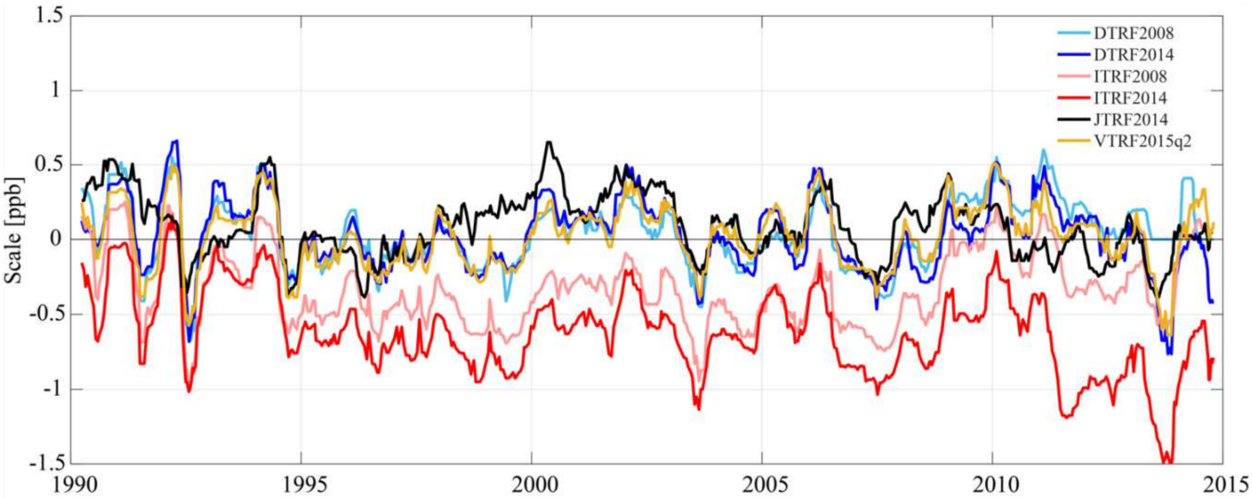

Fig. 4: *Scale of combined IVS solutions w.r.t. different TRF realizations. This plot has been kindly provided by S. Bachmann (IVS CC at BKG, Germany).*

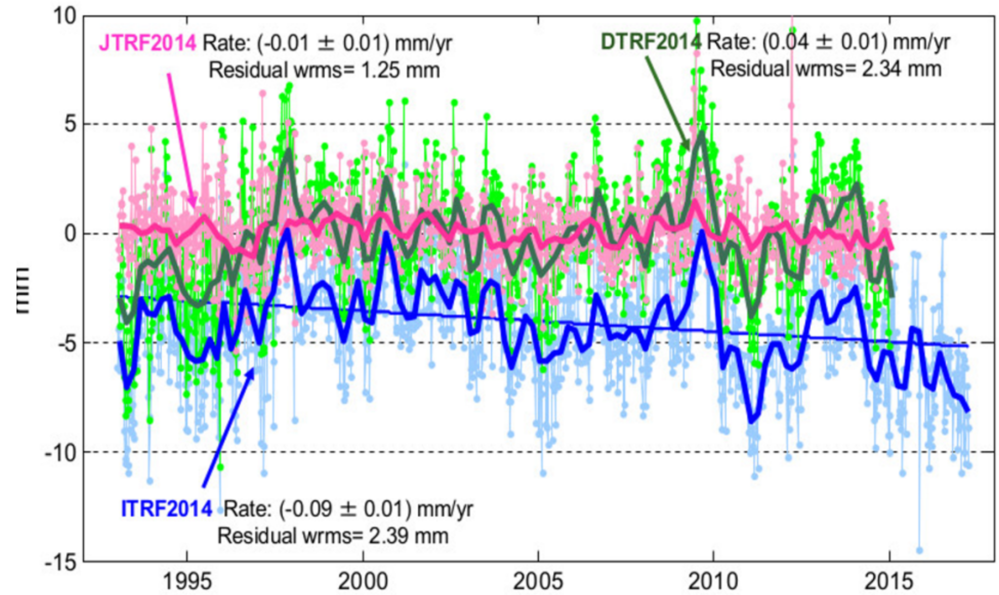

Fig. 5: *Scale of combined ILRSA solutions w.r.t. different TRF realizations. This plot has been kindly provided by C. Luceri (ILRS CC at ASI, Italy).*

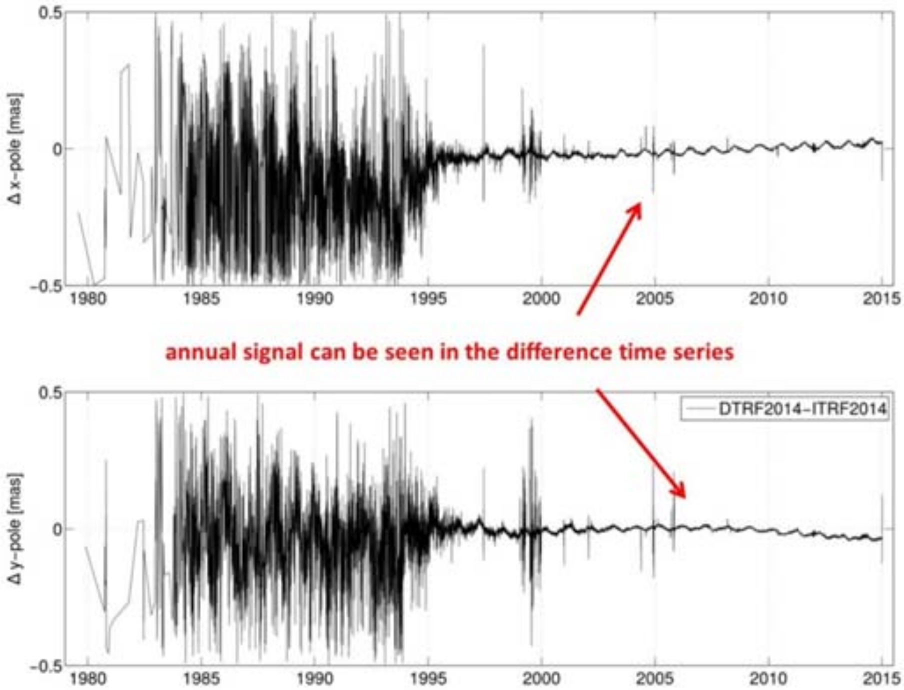

Fig. 6: *Differences in the x- and y-pole obtained from ITRF2014 vs. DTRF2014+NTL.*

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

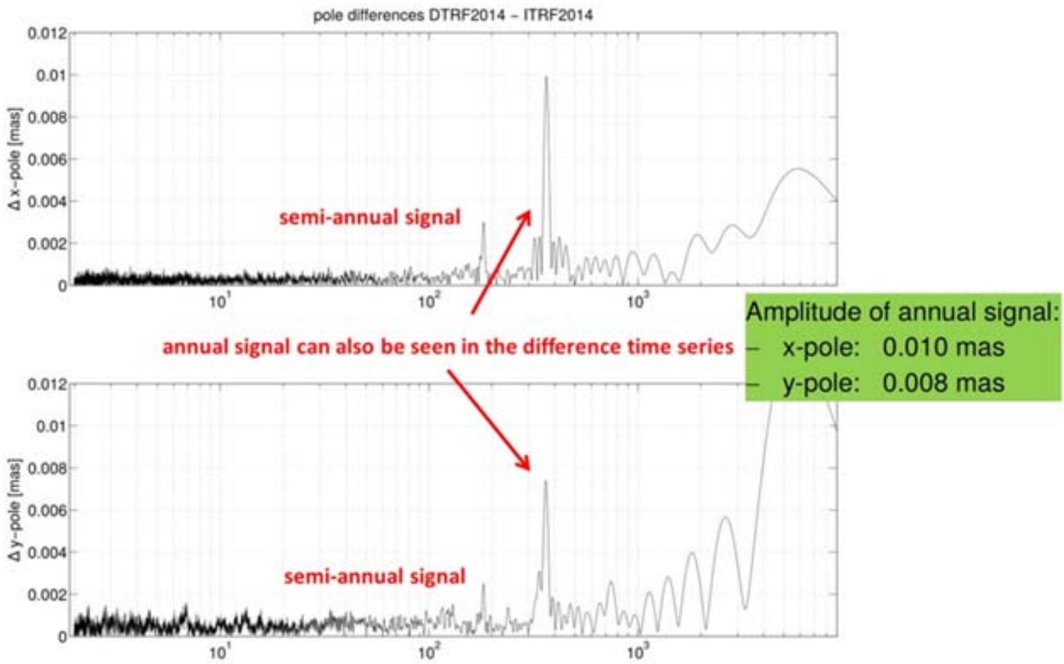

Fig. 7: *Spectra of x- and y-pole differences obtained from ITRF2014 vs. DTRF2014+NTL.*

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.

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