IVS Contribution to ITRF2014

Sabine Bachmann[1], Daniela Thaller[1], Ole Roggenbuck[2], Michael Lösler[3], Linda Messerschmitt[1]

Abstract Starting with the ITRF2005, the IVS contribution to the ITRF has been an intra-technique combined solution using multiple individual contributions from different institutions. For the IVS contribution to the ITRF2014 nine international institutions were used for a combined solution. The data files contain 24-hour VLBI sessions from the late 1970s until the end of 2014. 5,796 combined sessions in SINEX file format containing datum free normal equations with station coordinates and Earth Orientation Parameters (EOP) have been contributed to the ITRF2014. The overall repeatability for station coordinate time series of the combined solution are 3.3 mm for the north, 4.3 mm for the east, and 7.5 mm for the height component over all stations. The minimum repeatabilities are 1.5 mm for north, 2.1 mm for east, and 2.9 mm for height. A scale difference of 0.11 ppb (i.e., 0.7 mm on the Earth's surface) has been detected between the VTRF2014 and the DTRF2008 (DGFI-TUM realization of ITRS), and a scale difference of 0.44 ppb (i.e., 2.8 mm on the Earth's surface) between the VTRF2014 and ITRF2008. Internal comparisons between the EOP of the combined solution and the individual solutions from the Analysis Center contributions show a WRMS in X- and Y-Pole between 40 and 100 µas and for dUT1 between 5 and 15 µs. External comparisons with respect to the IERS-08-C04 series show a WRMS of 132 and 143 µas for X- and Y-Pole, respectively, and 13 µs for dUT.

1. Federal Agency for Cartography and Geodesy, Germany
2. Jade Hochschule Wilhelmshaven/Oldenburg/Elsfleth, Germany
3. Frankfurt University of Applied Sciences Faculty of Architecture, Civil Engineering and Geomatics, Germany

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1 Introduction

The International Terrestrial Reference Frame (ITRF) is the result of an inter-technique combination of all four space geodetic techniques: Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI). The International Terrestrial Reference System (ITRS) Center of the International Earth Rotation and Reference Systems Service (IERS) sent out a Call for Participation for the next ITRF containing data until the end of 2013[1]. The time span for data was later extended for one additional year until the end of 2014. The ITRF2014 is the latest realization of continuous realizations of the ITRS including all four space geodetic techniques as described in [1] and [9]. All services were requested to submit contributions for the generation of the ITRF2014. Starting with the ITRF2005, the VLBI contribution has consisted of normal equations (NEQs) derived from a combination of different individual contributions from the IVS Analysis Centers [10]. The same strategy was utilized for ITRF2008 [5] and ITRF2014. Since the IVS contribution to the ITRF2008, the VLBI combination procedure has been continuously refined with an increasing number of individual contributions. Figure 1 in [9] shows the schematic representation of the inter-technique combination process for the DTRF-

[1] IERS Message No. 225 in http://www.iers.org/Messages

2008 using all space geodetic contributions including the IVS contribution. All contributions are analyzed separately, and the daily/weekly NEQs are accumulated into one NEQ per technique. In a common process, the technique-wise NEQs are then combined into a global TRF (here the DTRF) and EOP.

The VLBI data for the inter-technique combination is provided by the International VLBI Service for Geodesy and Astrometry (IVS) [8]. The IVS is organized under the umbrella of the International Association of Geodesy (IAG) and the International Astronomical Union (IAU) and contributes to the IERS. Since ITRF2008, six years of additional observations have become available, including new sites in the continuously developing network [3].

The combination process of the VLBI contribution to ITRF2014 is described here, focusing on station positions and Earth Orientation Parameters (EOP). Overall 5,796 combined sessions were submitted to the IERS ITRS Center as the IVS contribution to the ITRF-2014. Comparisons of the scale parameter complete the work, because VLBI and SLR are presently the only two space geodetic techniques that are contributing to the scale of the ITRF.

2 Input to the IVS Combination

The IVS contribution to the ITRF2014 contains 24-hour sessions starting in 1979, but in contrast to the regular rapid solution, where only R1 and R4 sessions are used, the IVS contribution to ITRF2014 contains all 24-hour sessions (see the IVS Master Schedule[2] for more information). The IVS Analysis Centers (ACs) are advised to make use of (at least) all R1 and R4 sessions through December 31, 2014, with contributing ACs responsible for the delivery of the sessions. ACs that are contributing to operational combination EOP products do not always submit a contribution to the IVS combination for the ITRF2014, as well. Table 1 shows the ACs that are contributing to the IVS. It indicates the products to which they are contributing and which software is used to analyze the sessions. It can be seen that five ACs contributed a solution for the ITRF2014 although they do not contribute to the operational combined product. The contribution to the IVS is open to every interested institute, providing their contribution is in the correct format and meets the predefined requirements concerning the analysis method (cf. Section 3).

The input contributions are normal equations stored in the SINEX[3] file format, containing station coordinates and EOP, i.e., pole coordinates (including rates), universal time, LOD, and nutation. Several new and independent software packages have also been used, which are currently under review for the operational combined products. For ITRF2008 seven ACs using four different software packages contributed to the combined solution; ten ACs using five different software packages contributed to the combined solution for ITRF2014. The analysis standards, as well as the session characteristics used as input for the combination, are described in this section. The combination process for station coordinates, EOPs and global TRF solutions are then described in the following section.

Figure 2 shows the SINEX file availability for each contributing AC as well as the combined solution. It can be seen that part of the ACs submitted data starting in 1979 and some in 1984, leaving out the very early years of VLBI observations. The number of submitted SINEX files varies between 4,545 and 6,003 sessions, resulting in 5,796 combined sessions containing 158 stations and covering a time span of almost 36 years between 1979.6 and 2015.0.

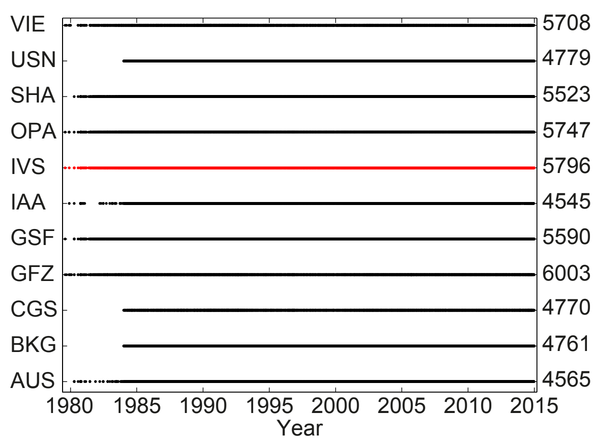

Fig. 2 SINEX file availability for different ACs and the combined contribution (in red/labeled IVS). The total number of sessions delivered are given on the right side.

[2] ftp://ivs.bkg.bund.de/pub/vlbi/ivscontrol/

[3] http://www.iers.org/sinex

Table 1 IVS Analysis Centers and their contribution to operational IVS products and to the ITRF2014.

AC	Name	Software	Operational AC	ITRF2014 submitted	ITRF2014 included
AUS	Geoscience Australia, Australia	OCCAM(LSC)	no	yes	no
BKG	Federal Agency for Cartography and Geodesy, Germany	Calc/(nu)Solve	yes	yes	yes
CGS	Centro di Geodesia Spaziale, Italy	Calc/(nu)Solve	under review	yes	yes
DGFI-TUM	German Geodetic Research Institute/TU Munich	OCCAM(LSM)	yes	no	no
GFZ	German Research Center for Geosciences	VieVS@GFZ	under review	yes	yes
GSFC	Goddard Space Flight Center, USA	Calc/(nu)Solve	yes	yes	yes
IAA	Institute of Applied Astrometry, Russia	Quasar	yes	yes	yes
NMA	Norwegian Mapping Authority, Norway	GEOSAT	no	yes	no
OPAR	Observatory of Paris, France	Calc/(nu)Solve	yes	yes	yes
SHAO	Shanghai Observatory, China	Calc/(nu)Solve	no	yes	yes
USNO	U. S. Naval Observatory, USA	Calc/(nu)Solve	yes	yes	yes
VIE	Vienna University of Technology, Austria	VieVS	under review	yes	yes

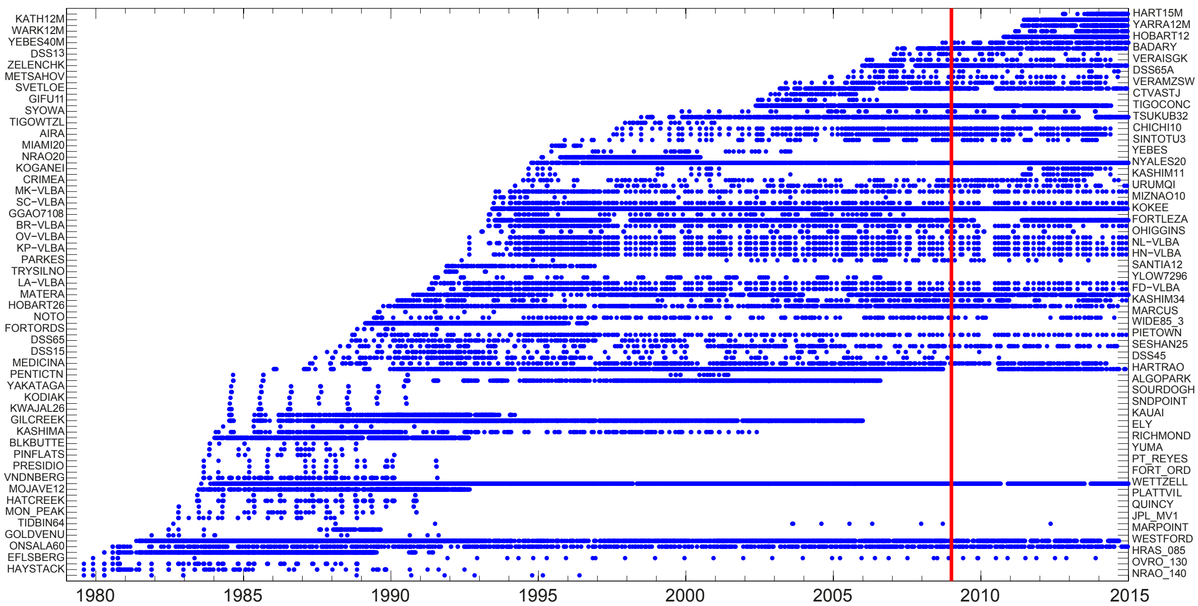

Fig. 1 Station participation. The data on the right hand side of the vertical red line are additional data to the ITRF2014. Only stations with more than ten observed sessions are shown.

Figure 1 shows the station participation stored in the SINEX files. Only stations with more than ten observed sessions are shown. The left hand side of the vertical red line marks the time span of the data included in the preceding ITRF2008. Data on the right hand side are additional data included in the ITRF-2014; thus six years of additional data are included in the latest ITRS realization, coming along with several new stations. Furthermore, stations which started observing a short time before the vertical line and are, thus, not included in the preceding ITRF now have sufficient observations to be included in the ITRF2014.

3 Analysis

The combination process itself has been described in several publications, e.g., [5] and [2]. The underlying hypotheses of the combination approach is that improved statistics for a combined solution compared to the individual solutions are expected. The combination is done on the level of normal equations with predefined analysis conventions (e.g., models, absolute terms, etc.). The major differences between the IVS contribution to the ITRF2008 and ITRF2014 are as follows:

- Transformation on 12h UT for all parameters (ITRF2008: mid-session).
- Improved dynamic outlier test (ITRF2008: static / fixed threshold).
- Solid Earth Tide, Pole Tides: IERS Conventions 2010 (ITRF2008: IERS Conventions 2003).
- Nutation: IAU2006 (ITRF2008: IAU2000A).
- Gradients: Chen-Herring Gradients (ITRF2008: MacMillan (1995) with wet VMF1).
- Source positions: constrained on ICRF2 *a priori* position for defining sources (ITRF2008: Constrained on ICRF1+Ext.1 or individual CRF).

Major differences to IVS routine (rapid / quarterly) combinations are:

- Common epoch 12h UT instead of mid-session as for the routine combination.
- Non-tidal atmospheric loading not applied (annual / semi-annual model applied *a posteriori*).
- Dedicated IVS ITRF2014 axis offset information file.

Figure 3 shows the combination process applied for the IVS contribution to the ITRF2014. The combination is based upon session-wise SINEX files containing datum-free normal equations for station coordinates and EOP.

The first step is an epoch transformation on the same epoch for every contribution. For the ITRF2014 contribution, the IVS decided — for the first time — to transform each session to 12h UT, instead of to mid-session as in operational IVS combinations, in order to conform with the other space geodetic techniques. The second step of the combination processing strategy is a transformation to equal *a priori* station coordinates. Precise *a priori* values are important for the quality and reliability of the combination result. The *a priori* values for station coordinates are taken from the latest combined long-term (quarterly) IVS solution, which is the one with the most up-to-date global VLBI solutions available[4]. Different incidents such as earthquakes or station repairs lead to non-linear antenna displacements, so the determination of accurate station positions can be needed on short notice. This is also the case for newly built telescopes.

The next step of the session-wise combination includes an outlier test for station coordinates. In this

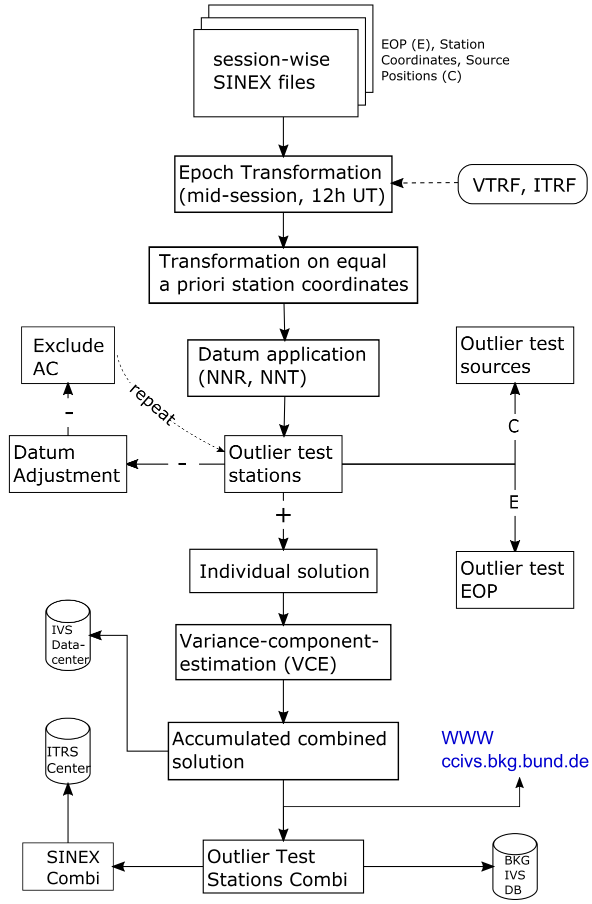

Fig. 3 Schema of the combination procedure.

step, major changes have been applied compared to the precedent procedure for ITRF2008. For ITRF2008, contributions were rejected as outliers in station position if the following two criteria were met [5]:

1. the correction to the *a priori* position was larger than 5 cm in the horizontal and 7.5 cm in the vertical component, and
2. the parameter correction was larger than three times its formal solution error.

This static approach has been replaced by a dynamic approach using the Least Median of Square method (LMS) described in detail in [2]. Based on normal equations with identical epochs and identical *a priori* values, the individual solution for each AC is generated. Comparing these individual solutions, a weighting factor is determined using a variance component estimation (VCE). The median of the weighting factors for each AC vary between 1 and 1.2.

[4] http://www.ccivs.bkg.bund.de/EN/Quarterly/VTRF-Results/VTRF-Stations/vtrf-stations_node.html

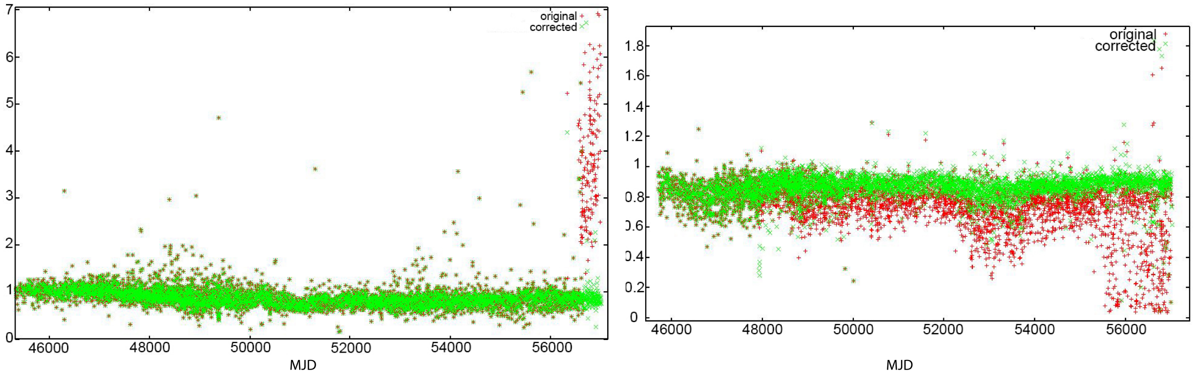

Fig. 4 Variance factor of AC SHAO (left side) and AC USNO (right side) before (red/dark crosses) and after correction (green/light crosses).

The combined normal equation is 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 datum defect of the normal equation and allows its inversion. Stations for which no reliable coordinates can be determined for specific sessions falling in a particular time span (e.g., by reason of station displacements due to earthquakes, maintenance work at the antenna, or too few observations) are excluded from the datum definition and treated as free parameters. As soon as these stations are again stable enough to determine a reliable station coordinate, they are used as datum stations. A SINEX file containing the datum-free normal equations of the combined solution is then submitted to the IERS ITRS Center and the IVS Data Center[5].

In the beginning of the data collection phase, different problems had to be corrected, e.g., different axis offsets or eccentricity files, problems with writing routines, or inconsistencies in parameter naming. Furthermore, inconsistencies in the variance factors had been found in the pre-analysis of the contributions. Examples are shown in Figure 4. The red/dark crosses show the variance factor as reported in the SINEX files before the corrected analysis and the green/light crosses after the correction was done. The reason for the discrepancies was found in *a priori* station positions for new stations or inconsistent re-analysis of the additional year 2014.

[5] ftp://ivs.bkg.bund.de/pub/vlbi/ITRF2014/daily_sinex/ivs2014a/

4 Results

4.1 Station Coordinates

Figure 5 shows time series of station coordinates as differences between the combined solution and the individual AC solutions for the east component of station Wettzell, Germany. Figure 6 shows the height component. The station serves as an example for common VLBI station time series. In the early 1990s, station position accuracy became better due to a larger network size, a better global distribution of the stations, and an elevated number of observed sources. While the differences of the east component are in a range of about ± 2 mm, the scatter of the height component is technique-dependent and larger — about ± 3-4 mm.

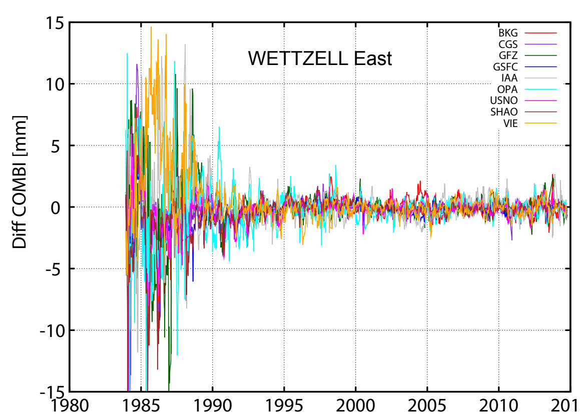

Fig. 5 Time series of the east component differences between the combined solution and the individual solutions for station Wettzell, Germany.

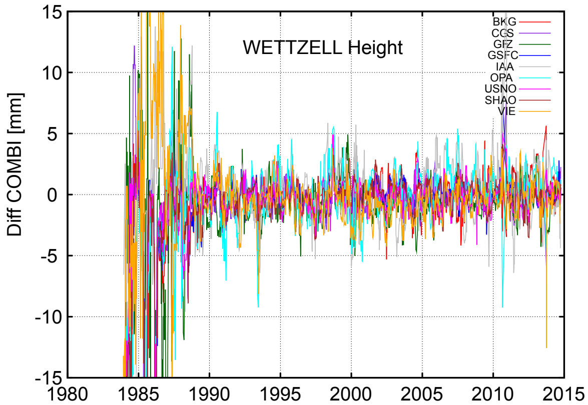

Fig. 6 Time series of the height component differences between the combined solution and the individual solutions for station Wettzell, Germany.

Station precision and repeatability is determined by calculating the WRMS of the session-wise time series of each station, as well as the overall WRMS for all stations. These statistical values give information about the quality of the contributions for every station. The median of station repeatability is better than 4.4 mm in north, 5.8 mm in east, and 9.3 mm in the height component. The minimum repeatability is 1.5 mm in the north component for stations BR-VLBA (Brewster, USA) and NL-VLBA (North Liberty, USA) (using 211 observed sessions each), 2.1 mm in the east component for station ONSALA60 (Onsala, Sweden) (using 839 observed sessions), and 2.9 mm in the height component for station HAYSTACK (Haystack, USA) (using 88 observed sessions). The maximum is 21.2 mm in the north component for station MARPOINT (Maryland Point, USA) (using 76 observed sessions), 28.9 mm in the east component for station SINTOTU3 (Kabato, Japan) (using 88 observed sessions), and 49.9 mm in the height component for station OHIGGINS (O'Higgins, Antarctica) (using 127 observed sessions). These numbers have to be handled with care, because of the station's situation; it is isolated in Antarctica.

The overall WRMS from the session-wise analysis over all stations and for all ACs as well as the combined solution is shown in Figure 7 for the north (violet / left bar), east (green / middle bar), and height (black / right bar) components. The WRMS values are between 3-4 mm for the north component and between 4-6 mm for the east component, while the height component value is about 7-9 mm; this is technique-limited, due to imperfect observing networks and tropospheric mismodeling.

Comparing the values of the combined solution with the values for the ACs, visualizes the underlying hypothesis of the combination: the combined solution is more accurate than the individual ACs (cf. [5]), although the improvement is hardly visible. The WRMS for the combined solution is 3.3, 4.3, and 7.5 mm for north, east and height, while for the individual solutions the WRMS is between 3.4 and 4.5 mm (with a median of 3.6 mm) for north, between 4.4 and 5.7 mm (with a median of 4.7 mm) for east, and between 7.7 and 9.2 mm (with a median of 8.3 mm) for the height component.

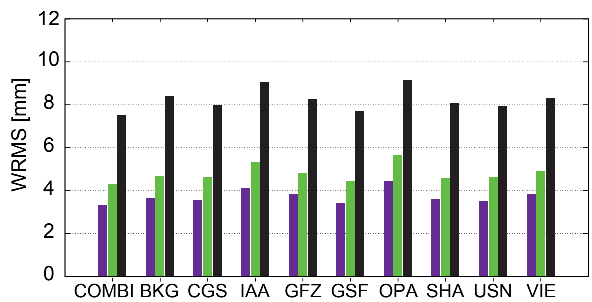

Fig. 7 WRMS over all station for north (violet / left bar), east (green / middle bar), and height (black / right bar) component.

4.2 Scale

Figure 8 shows the smoothed session-wise scale parameter of the combined solution with respect to DTRF2008, ITRF2008, and VTRF2014. In the first years of VLBI data acquisition (before 1994), the scale shows a more scattered behavior with an amplitude between -1 and +1 ppb for all comparisons (cf. red/medium, green/light, and black/dark curves in Figure 8). The scatter of the scale flattens out in the following years, when the VLBI network contains more antennas and more sources are observed within one session. A mean offset of 0.3 ppb can be seen between the DTRF2008 and ITRF2008 starting around 1995. The scale calculated with a Helmert transformation is 0.11 ppb between the VTRF2014 and the DTRF2008 and 0.44 ppb between the VTRF2014 and the ITRF2008.

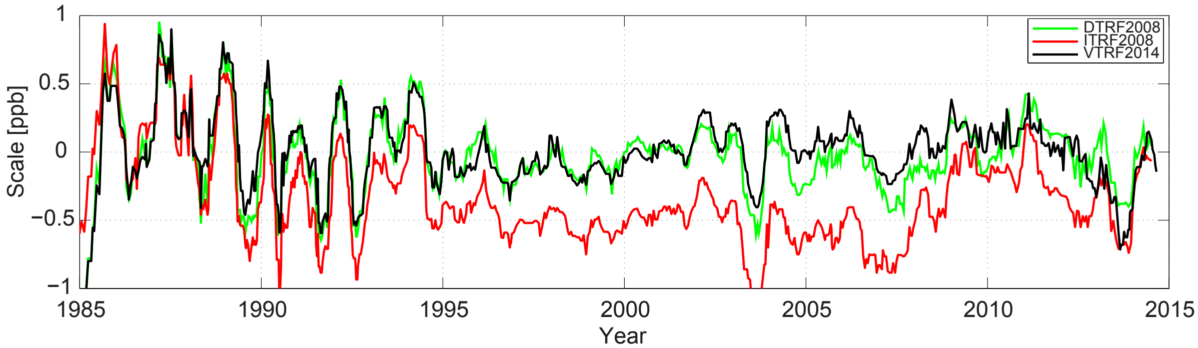

Fig. 8 Smoothed scale parameters between session-wise combined solution and DTRF2008 (green/light), with respect to ITRF2008 (red/medium), and with respect to VTRF2014 (black/dark).

Starting in 2010, the VLBI network experienced significant antenna displacements due to several severe earthquakes in the Chilean and Japanese regions. These changes in the network and the corresponding choice of datum stations for determining Helmert transformation parameters are also visible in the evolution of the scale in Figure 8. The plot shows the same two peculiarities around 2004 and towards the end of the observations in 2014. In the years around 2003/2004, the scale parameter suddenly seems to decrease to -0.6 ppb. Inspecting the sessions included in these two striking years, no particular antenna can be identified to introduce this effect (e.g. with a displacement or a replacement). The corresponding period contains many regional sessions with an unfavorable global station distribution for scale determination. A closer look at the scale parameters for this time period using only R1 or R4 sessions is provided in Figure 9. The dashed line shows the scale containing only R1 sessions and the circled line the scale containing only R4 sessions while the solid line contains all sessions that correspond to the scale shown in Figure 9. The regularly observed (i.e., each once per week) IVS R1 and R4 sessions contain a minimum number of well-distributed participating stations. A reduction of the peculiarities around 2003/2004 are observed for both R1 and R4 sessions. Additionally, investigations have been done on the scale parameter development and dependency on the number of stations within the respective sessions in 2004. It can be observed that for a network with at least seven stations, the irregularity around 2004 disappears. But because sessions with more than seven stations are observed neither frequently nor regularly, the observed scale smoothing effect should be handled with care. This study corresponds to the assumption made before: the sessions around 2004 seem to be dominated by regional and small networks. Impacts on the regional level are natural effects such as flood or drought, which have to be considered as possible explanations for the visible scale irregularities. Especially, 2003 was a year of exceptional drought in the Northern hemisphere. Investigations to quantify these impacts on the scale parameter have to be done in the future in order to consider them for the weighting model.

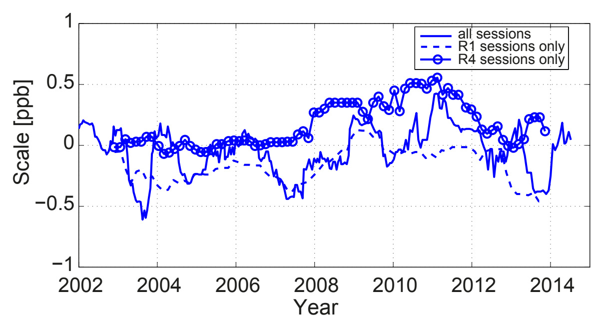

Fig. 9 Detailed view of the smoothed scale parameter between session-wise combined solution and DTRF2008 (solid line, agreeing with Figure 8), when only R1 (dashed line), and when only R4 (circled line) sessions are used.

It could be assumed that the second irregularity around 2014 is influenced by the fact that both reference frames (DTRF2008 and ITRF2008) contain data only until the end of 2008. For sessions observed beyond this period, station coordinates must be extrapolated for several years. Furthermore, the VLBI network contains more new VLBI telescopes (cf. Fig-

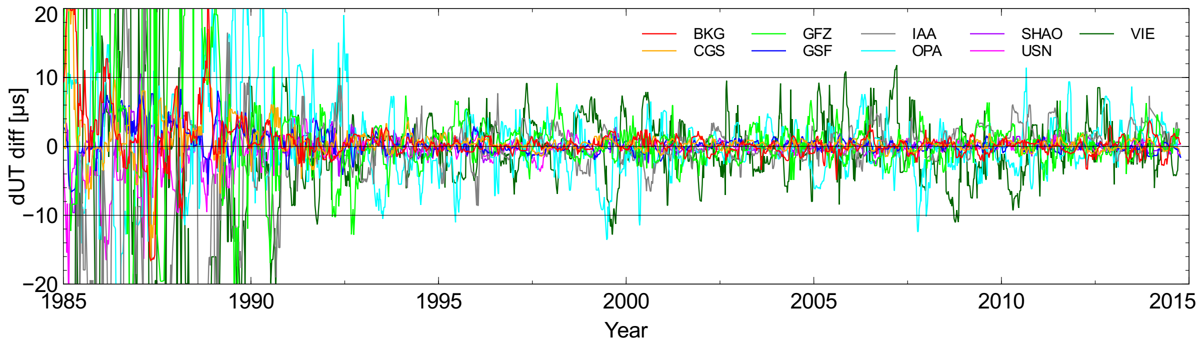

Fig. 10 dUT1 differences between individual and combined solutions smoothed with a 70-day moving median filter.

ure 1) which are not part of DTRF2008 and ITRF2008. This decreases the selection of datum stations for the Helmert transformation. However, the same irregularities can be observed for the scale with respect to the VTRF, where these characteristics do not apply.

4.3 EOP

EOPs are the second parameter type besides station coordinates resulting directly from the combination. The EOPs contain pole coordinates (X- and Y-Pole) and rates, UT1-UTC (dUT1) and the rate LOD (Length of Day), and nutation parameters dX and dY. VLBI is the only geodetic space technique that provides a full set of EOPs, including a link to the celestial reference frame. EOPs are estimated by fixing datum station coordinates to their a priori values within 0.001 mm, which makes it critical to carefully select station a priori values and datum stations. For the first time, all parameters of the combined normal equations are transformed to 12h UT in order to be consistent with the other geodetic space techniques. IVS 24-hour sessions are usually scheduled between 17:00 UT and 17:00 UT of the following day. EOP and station positions determined at 12h UT are shifted by about seven hours compared to the routine IVS combination where all parameters are estimated at mid-session. Therefore, the EOPs estimated at 12h are expected to be degraded compared to what VLBI would be able to deliver in an optimal way.

Figure 10 shows the smoothed time series of the differences between the individual AC solutions and the combined solution for dUT1, which is shown as an example for all EOPs. Similar to the station coordinates, the first years of VLBI data collection were still very scattered until the VLBI observations' accuracy increased in the early 1990s. The median differences between the individual AC solutions and the combined solution vary between −10 and 10 µs for dUT1 and between −50 and 50 µas for X-Pole (leaving out the years before 1994) including some peaks.

Figure 11 shows the WRMS of the differences between the individual solutions and the combined solution for X-, Y-Pole (red / left and green / middle bar, respectively) and dUT (blue / right bar). The respective rates (X- and Y-Pole rates and LOD) are shown in Figure 12. Only sessions which were analyzed successfully by all ACs were used for the comparisons.

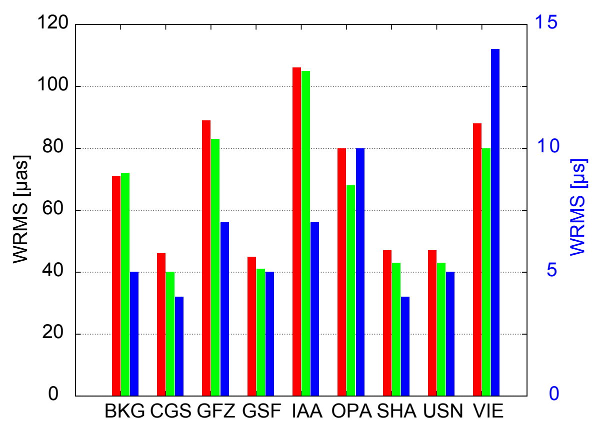

Fig. 11 WRMS of the differences between the individual and combined solutions for X- (red / left bar), Y-Pole (green / middle bar), and dUT (blue / right bar).

The WRMS is between 40 and 100 µas for X-Pole, and Y-Pole and between 5 and 15 µs for dUT1. Because the VIE AC provided piecewise linear offsets for all EOPs instead of an offset and a rate, a transformation

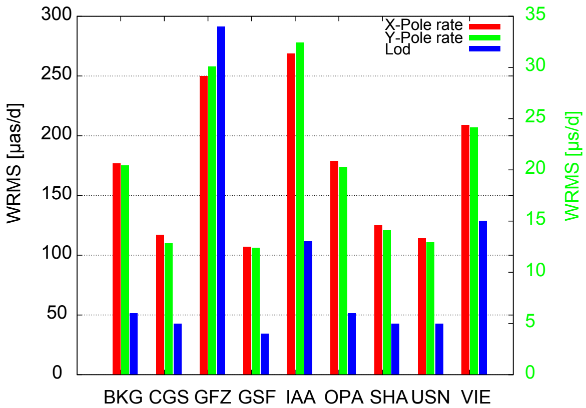

Fig. 12 WRMS of the differences between the individual and combined solutions for X- (red / left bar) and Y-Pole (green / middle bar) rates and LOD (blue / right bar).

to the offset and the rate was included *a priori* to the combination process, which seems to be not as accurate as if the parameterization were directly introduced within the analysis process. The WRMS for X- and Y-Pole rates are between 100 and 250 $\mu as/d$ and for LOD between 5 and 15 $\mu s/d$. Further studies are required in order to find the reason for the increased LOD WRMS found for the GFZ AC. The WRMS for the nutation parameters (not shown) are between 30 and 80 µas for dX and dY. An elevated WRMS of ∼140 µas can be found for nutation for the OPA AC. The reason for the increased nutation differences for the OPA AC is still open to investigation.

For an external comparison, the combined EOP results are compared to the IERS C04 series (cf. [4]). Here, the WRMS values for the differences are 132 and 143 µas for X- and Y-Pole, respectively, and 482 and 454 µas/d for their rates. The WRMS is 13 µs for dUT1 and 39 µs/d for LOD. The WRMS for the nutation parameters are 63 and 67 µas for dX and dY, respectively.

4.4 Presentation of Results

The original IVS contribution to the ITRF2014, including the individual contributions of the ACs as well as the combined solution in SINEX format, are freely available at the three IVS Data Centers at BKG, CDDIS, and OPAR[6,7,8]. Results are presented on the newly designed IVS Combination Center's website (http://ccivs.bkg.bund.de, see also [6]), comprising time series of station coordinates, baselines, EOP, and time series of the scale parameter of the individual solution as well as of the combined results. Furthermore, a data DOI (10.5880/GFZ.1.1.2015.002, to be cited as [7]), has been established in order to provide the ability to reference the data set and thereby to pay tribute to the contributors, including the complete VLBI data acquisition chain (stations, correlator, analysis, and combination), see Figure 13. The data DOI was established at GFZ, Germany. It contains links to the SINEX files, as well as meta data in the form of an abstract, keywords, contact information, and data description.

Fig. 13 Landing page of DOI.

[6] ftp://ivs.bkg.bund.de/pub/vlbi/ITRF2014/daily_sinex/ivs2014a/

[7] ftp://ivsopar.obspm.fr/vlbi/ITRF2014/daily_sinex/ivs2014a/

[8] ftp://cddis.gsfc.nasa.gov/pub/vlbi/ITRF2014/daily_sinex/ivs2014a/

5 Conclusions

In total 5,796 combined 24-hour sessions for the ITRF-2014 contribution, covering a time span from 1979 to the end of 2014, have been submitted containing 158 stations overall. Eleven IVS Analysis Centers using five different software packages submitted contributions to the combined solution, from which nine contributions using three different software packages were included in the combined solution.

Compared to the IVS contribution to the ITRF-2008, an improved outlier test and weighting strategy was implemented. The station repeatability over all stations (WRMS) is 3-4 mm for the horizontal components (north and east) and 8-9 mm for the height component for all included Analysis Centers. 75 % of the stations have a repeatability of better than 6.9 mm for north, 9.3 mm for east, and 12.7 mm for the height component. Within recent years the VLBI network expanded in size and in quality, so that it can be expected that this will also have a positive impact on the station coordinate quality within the upcoming years. Improving the session weighting by considering the geometric network characteristics for global VTRF solutions is one of the next steps.

Comparisons to the ITRF2008 show a scale offset of 0.44 ppb, while comparisons to the DTRF2008 show a scale offset of only 0.11 ppb. Upcoming developments in the frame of VGOS will provide the opportunity to make further investigations into the VLBI scale parameter.

EOP comparisons show generally a good agreement between the individual contributions and the combined solution. The WRMS of the differences are between 40 and 100 µas for X- and Y-Pole, between 5 and 15 µs for dUT1, and between 5 and 35 $^{\mu s}/_{d}$ for LOD.

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