Scale Evaluation of the ITRF2020 Solution

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Abstract As the next official realization of the International Terrestrial Reference System, the ITRF2020 represents the successor of the currently used frame, ITRF2014. This global solution is based on an inter-technique combination of all four space geodetic techniques—VLBI, GNSS, SLR, and DORIS—and benefits from a variety of contributions from different international institutions. In this context, the Combination Center of the International VLBI Service for Geodesy and Astrometry (IVS)—operated by the Federal Agency for Cartography and Geodesy (BKG, Germany) in close cooperation with the Deutsches Geodätisches Forschungsinstitut (DGFI-TUM, Germany)—generates the final VLBI contribution to ITRF2020. Thereafter, an intra-technique combination is applied using the individual contributions of multiple Analysis Centers (ACs) with different software packages. For the contribution to the ITRF2020, sessions containing 24-hour VLBI observations from 1979 until the end of 2020 were processed by 11 ACs and submitted to the IVS Combination Center as session-wise SINEX files. These files contain datum-free normal equations with station coordinates, source positions, and full sets of Earth Orientation Parameters (EOP). To ensure consistency between all AC contributions, normal equation transformations to equal epochs and a priori values were carried out for every AC-specific normal equation system before stacking them in order to get the IVS combined solution. The resulting individual solutions, as well as the combination, are subject to further analysis concerning EOP and station coordinates as well as the scale and a VLBI-only Terrestrial Reference Frame (VTRF). This contribution focuses on detailed investigations concerning the scale of the IVS contribution and the global solution. In this paper, we compare the IVS contribution with the combined ITRF2014 and ITRF2020 solutions. In addition, detailed statements on the accuracy of ERP estimates are carried out. In this context, the individual solutions of the different Analysis Centers are compared and investigated concerning potential AC- and/or software-related systematics.

Keywords ITRF2020, IVS, Combination, Terrestrial Reference Frame, Helmert Transformation, Scale

1 Introduction

The International Terrestrial Reference Frame (ITRF), as the realization of the International Terrestrial Reference System (ITRS), is commonly used as the official global reference frame. It includes positions and velocities of globally distributed observing stations, qualifying the ITRF as a basis for scientific research and applications in geosciences. Common examples are climate change, global sea-level rise, and crustal deformations, e.g., due to earthquakes (Métivier et al., 2014).

For ensuring the high quality of the current ITRF, an update is computed every five to six years, considering up-to-date models, parameterizations, and data evaluation. Besides newly observed satellites, the utilization of new observing stations leads to a more dense

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station network for improving the station geometry in some cases.

The upcoming ITRF2020 includes new general physical models for pole tides and high-frequency Earth rotation, as well as VLBI-specific models for galactic aberration and the gravitational deformation of the radio telescopes. The final ITRF2020 product—which replaces the current ITRF2014 (Altamimi et al., 2016)—is released by the ITRS Center of the International Earth Rotation and Reference Systems Service (IERS)[1]. The applied physical constants and mathematical models for data analysis are provided by the IERS 2010 Conventions (Petit G, Luzum B, 2010).

To benefit from the individual strengths of the different observation methods, the ITRF computation is based on an inter-technique combination of the four space-geodetic observation techniques, i.e. Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and Very Long Baseline Interferometry (VLBI; Thaller, 2008). While the first three techniques are satellite-based and therefore deliver solutions realizing an Earth-centered reference system, VLBI is the only technique observing extragalactic objects (radio sources), which enables determination of the orientation of Earth in inertial space. Consequently, VLBI delivers the full set of Earth Orientation Parameters (EOP).

The Combination Center of the International VLBI Service for Geodesy and Astrometry (IVS; Nothnagel et al., 2017) is located at the Federal Agency for Cartography and Geodesy (BKG, Germany) and works in close cooperation with the Deutsches Geodätisches Forschungsinstitut of the TU München (DGFI-TUM, Germany; cf. Bachman et al., 2017). It realizes a combination of individual VLBI solutions from multiple IVS Analysis Centers (ACs) that represents the IVS contribution to the ITRF. This intra-technique combination is based on the level of normal equations (NEQs; Venebusch et al., 2007; Böckmann et al., 2010) and realized by utilizing the software DOGS-CS. Finally, the combined IVS contribution to the ITRF2020 is delivered as session-wise SINEX files (Bachmann et al., 2016).

This paper gives an overview of the IVS contribution to ITRF2020. Section 2 describes the data basis of the pre-analyzed VLBI contributions, and Section 3 summarizes the IVS combination procedure. Section 4 presents the evaluation of the contributions by the individual IVS ACs and the combined product. The scale w.r.t. the current ITRF2014 and the upcoming ITRF2020 is investigated and analyzed concerning offset and trend behavior. In addition, the impact of the weighting strategy of the different software packages on EOP estimation is investigated.

2 Contribution by IVS Analysis Centers

For the ITRF2020 contribution, the individual ACs deliver 24-hour session-wise VLBI re-processed data from 1979 until the end of 2020. The required SINEX format contains datum-free normal equations, including station coordinates, source positions, and EOP. The guidelines for the homogeneous analysis were provided by the IVS Analysis Coordinator[2]. The different ACs contributed to the IVS Combination Center almost 6,600 sessions that were subjected to several quality controls (numerical stability, completeness and format, and application of the required precession and nutation models) to ensure consistency. Within the combination process (Section 3) an outlier detection based on a *three-sigma range test* rejects contributions with low quality. Finally, 94.5% of the submitted sessions could be successfully combined. Table 1 summarizes the different ACs and the utilized software packages, respectively.

Table 1 Software packages used by the different IVS ACs.

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

[1] https://itrf.ign.fr/en/solutions/ITRF2020

[2] https://ivscc.gsfc.nasa.gov/IVS_AC/IVS-AC_ITRF2020.html

The goal of the combination is to benefit from the diversity of contributions and improve the quality of estimated parameters compared to the individual solutions delivered from the ACs. In our case, 11 ACs submitted their re-processed solutions, and seven different software packages were utilized.

For ITRF2020, almost 92% of the combined sessions (i.e., 5,725) include the contributions of nine or more ACs. On the other hand, 122 submitted sessions include three to four ACs only and are mostly characterized by a poor configuration of small regional networks.

3 IVS Combination Process

The main goal of the intra-technique combination is the generation of precise and stable session solutions through the reduction of the analysis noise characterized by the individual data analysis and modelling. In addition, AC-specific systematics are identified and considered. Furthermore, the combination on the level of normal equations, as performed here, allows for a correct consideration of correlations between all (explicitly and implicitly) included parameters.

The actual procedure of the combination process comprises several steps which ensure consistency of the different contributions, an outlier detection for rejecting data with poor quality, and the setting of datum conditions for estimating station coordinates and EOP. Therefore, a session-wise transformation to equal epochs and a priori values is carried out. The reference epoch is the middle of the observation interval, and the TRF is defined by the latest IVS Quarterly solution (VTRF 2020/Q2), which represents an update of the reference frame ITRF2014.

For computing individual solutions, No-Net-Rotation (NNR) and No-Net-Translation (NNT) conditions w.r.t. the a priori reference frame are applied based on a subset of core stations. The source positions are fixed to ICRF3 and are eliminated from the equation system. In contrast, the full set of EOP is estimated as free parameters. The individual parameter estimates (station coordinates and EOP) are subject to an outlier detection (Rousseeuw et al., 2005; Bachmann et al., 2012). Finally, the combined solution consists of the accumulated and relatively weighted contributions from all ACs with stacked station coordinates and EOP. The individual weighting factors result from a variance component estimation (VCE) procedure respecting the global variance factor.

4 VLBI Evaluation Results

In order to assess the quality of the IVS product, evaluations of the resulting estimates were carried out. In this work, we focus on the scale determination of the combined product w.r.t. the ITRF2020 and—for obtaining information about changes to the current ITRF—the ITRF2014. Furthermore, it is shown how software-related systematics affect the applied weighting strategy.

The scale between the VLBI solutions and the ITRF2014/2020 is computed by session-wise seven-parameter Helmert-transformations using a predefined network of 155 globally distributed core stations with high accuracy. Characterized by an adequate number of observations over a time period of several years, uncertainties within the scale estimation due to the station network are assumed to be minimal.

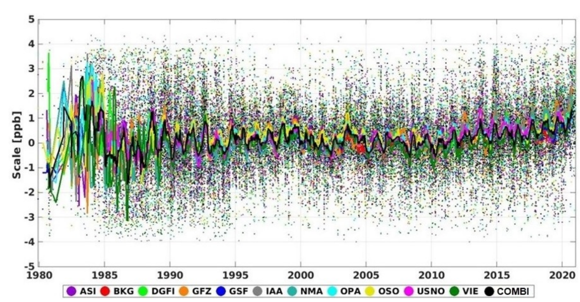

Fig. 1 The scale difference of individual solutions and the IVS combination w.r.t. ITRF2020.

Figure 1 shows the scale differences of the individual and the combined solutions w.r.t. ITRF2020. The dots illustrate the raw scale parameters for each session, and the continuous graphs result from applying a moving median filter of 90 days. The combination, in this case, mathematically describes a weighted mean of the individual solutions.

The first years are characterized by large variations at all solutions with a maximum value of ± 3 ppb at the 90-day median. This can be explained by the weak network configuration in the early years before 1990, when only a fraction of the current VLBI station network was operating. However, after 1990, a nearly constant scatter is observed.

Furthermore, an annual oscillation becomes obvious over the whole time span due to non-tidal loading deformations. These are not corrected within the ITRF2020 contribution and are causing a seasonal signal within the scale. In addition, the time series are characterized by a significant drift after 2015, where the absolute scale differences w.r.t. ITRF2020 increased by a factor of four in comparison to the constant part of the time series. The reason for the drift is still not explained and is the subject of further research. Nevertheless, a good agreement on the scale estimates could be reached between all ACs, and—as expected—the combined solution appears in the middle of the individual estimates.

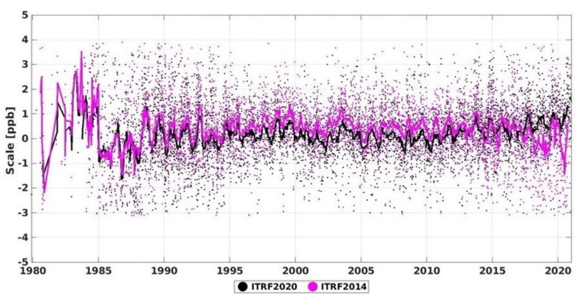

Fig. 2 The scale difference of the IVS combination w.r.t. ITRF2014 and ITRF2020.

Figure 2 shows the comparison of the scale difference between ITRF2014 and ITRF2020 w.r.t. the combined solution. After the initial uncertainty, both time series show a similar behavior until 2015. A divergence can be recognized for the last five years. Although the ITRF2020 scale shows an explicit drift, a reduction of the scatter could be reached compared to ITRF2014. This is a result of an extended data basis for the ITRF2020 contribution. Finally, a mean offset of 0.25 ppm and 0.40 ppm for the constant parts of ITRF2020 and ITRF2014, respectively, could be derived.

As supplements, Figure 3 and Figure 4 show the unweighted offsets and WRMS values of the scale for the individual and the combined solutions w.r.t. ITRF2014 and ITRF2020, respectively. In the first case, the WRMS values of all solutions are in the range of about 1.5 ppm. Thereby, the combination is

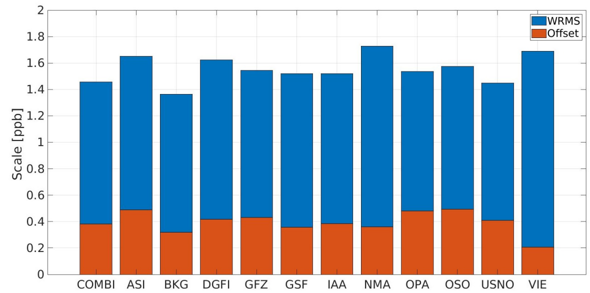

Fig. 3 Mean scale offsets of the individual and the combined solutions w.r.t. ITRF2014.

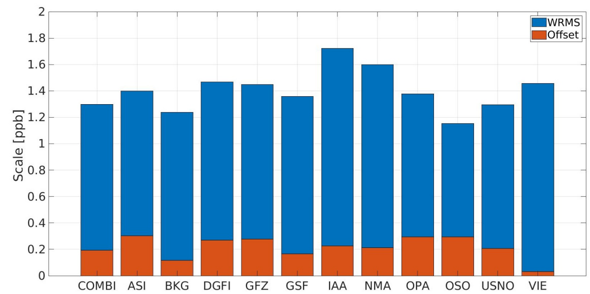

Fig. 4 Mean scale offsets of the individual and the combined solutions w.r.t. ITRF2020.

characterized by the highest accuracy compared to the individual solutions (only the BKG AC has a lower WRMS value because this AC delivered fewer SINEX files compared to other ACs, especially in the early years).

In comparison to that, the WRMS values of the ITRF2020 scales are in the range of 1.3 ppb and, hence, indicate a higher accuracy compared to the previous case. Except for the contributions of BKG and OSO, the combination reaches the highest accuracy level in comparison to the individual solutions. Moreover, the

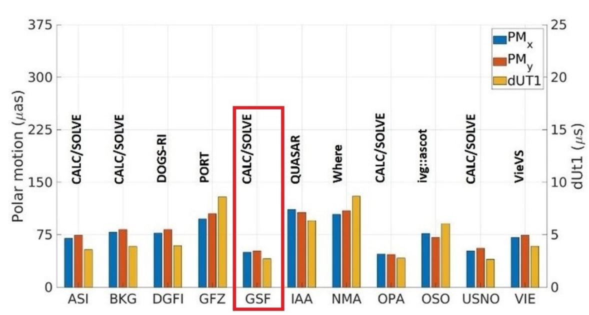

Fig. 5 WRMS of ERP estimation (AC minus Combination). Individual weights per AC are applied.

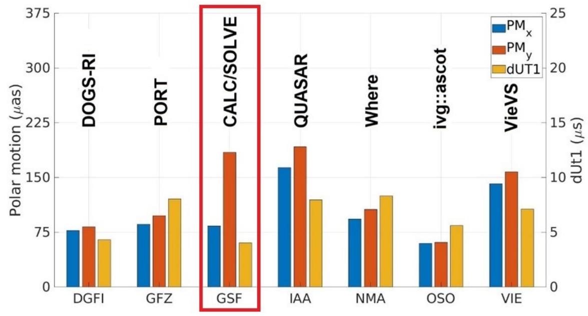

Fig. 6 WRMS of ERP estimation (AC minus Combination). Only one contribution per software.

scale offsets are almost in the range of 0.2 ppb. Consequently, the mean scale difference w.r.t. ITRF2014 could be reduced by about a factor of two.

In addition to the findings about the scale, we carried out a detailed investigation concerning software dependencies on the weighting strategy. Figure 5 shows the WRMS values of polar motion and dUT1 for all individual ACs w.r.t. the combined solution. The fact that five ACs utilize the CALC/SOLVE software package causes a strong dependency of the combination on these contributions. A higher accuracy level in comparison to the remaining ACs can be observed. The GSF solution is characterized by significantly smaller WRMS values for all three ERP components. Reducing the impact of CALC/SOLVE, a second combination type was calculated, using every software-specific contribution only once. Figure 6 shows the WRMS values of the remaining seven ACs. In this case, the GSF represents the CALC/SOLVE solution.

It becomes evident that the accuracy level for GSF decreases (especially for the polar motion), confirming that a significant impact on the number of software appearances exists. Applying an equally distributed utilization of the software packages leads to a more independent combination, which will be respected in further works. An adapted weighting strategy concerning software tools will be focused on.

5 Conclusion and Outlook

Detailed investigations about the scale of the IVS contribution to ITRF2020 were presented in this paper. The IVS Combination Center delivers a session-wise combination of the individual contributions of 11 Analysis Centers. For that, a combination on the level of normal equations is carried out, where EOP and station coordinates are stacked. The source positions are fixed to ICRF3 and are eliminated from the equation system. Based on a variance component estimation, individual weightings for each AC are determined for obtaining unbiased estimations, taking statistical information and correlations between the parameters into account. After applying NNT and NNR conditions, estimates of the full set of EOP and station coordinates are obtained.

Based on seven-parameter Helmert-transformations the scale differences between our IVS contribution and the ITRF2014/2020 are computed. It is evident that an improvement of the scatter for ITRF2020 scale could be reached. However, a significant trend within the last years of the time series can be observed. The behavior is not finally investigated and will be focused on in the future.

We performed a further investigation regarding the software-specific impact of the weighting strategy. It could be shown that the number of identical software packages affects the combination. The more identical software packages are included, the higher is the accuracy level of these contributions w.r.t. combination.

Further investigations will therefore focus on a reliable weighting strategy, taking multiple appearances of equal software tools into account.

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