The IVS contribution to ITRF2020

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The IVS contribution to ITRF2020 is provided by the *IVS Combination Centre* located at the *Federal Agency for Cartography and Geodesy* (BKG, Germany) and the *Deutsches Geodätisches Forschungsinstitut* at TUM (DGFI-TUM, Germany). The IVS combination is an intra-technique combination of the individual contributions of 11 different IVS Analysis Centres (ACs). For the contribution to the ITRF2020, sessions containing 24h VLBI observations from 1979 until the end of 2020 were re-processed and submitted to the IERS, i.e., altogether a number of almost 6,600 sessions. As a result, datum-free normal equations, including station coordinates, source positions, and full sets of *Earth Orientation Parameters* (EOP), are delivered by each AC. The SINEX format is used in order to provide the required information in a standardized method. Table 1 shows the participating ACs and the utilized software packages.

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
GSFC	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, Sweden	ivg::ascot
USNO	United States Naval Observatory	CALC/SOLVE
VIE	Vienna University of Technology	VieVS

The variety of applied software packages is increased since ITRF2014. Although a large number of sessions over a time period of more than 40 years have been contributed from the different ACs, almost 350 sessions had to be excluded from the contribution to ITRF due to formal or numerical errors. However, 94.5% could be successfully combined, i.e., 6,240 sessions in total. In addition, sessions based on observations of the VLBI Global Observing System (VGOS) became available in the most recent years and are part of the ITRF for the first time. Figure 1 shows the global distribution of the IVS station network and the corresponding VLBI sites.

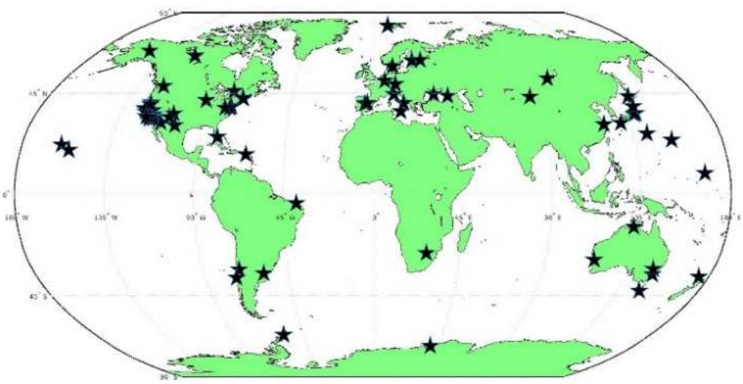

Figure 1: Global distribution of VLBI station network

In total, 255 VLBI sites contributed over the last four decades, although none of these stations is covering the entire time span.

New models for ITRF2020

New and improved models for the IVS analysis have been applied in recent years, which makes it necessary to reprocess all sessions in order to update the ITRF. In comparison to ITRF2014, the contribution to ITRF2020 includes the following new models:

1) Galactic Aberration

The secular aberration drift is caused mainly by the rotation of the Solar System barycentre around the Galactic centre. The predicted secular aberration amplitude amounts to 4-6 µas/year. This effect cannot be neglected in the long-time span as it produces the dipole systematic error of 100 µas after 20 years. Therefore, the IVS Working group[1] recommends to apply a constant drift of 5.8 µas/year on Galactic aberration. The secular drift affects the source positions with the reference point of the source catalogue for J2000 by default.

2) Pole tide

The mean pole model describes the secular variations related to the first-order perturbation in the centrifugal potential caused by the Earth´s rotation. The cubic model is applied before 2010 and the linear extrapolation model afterward with the appropriate secular coefficients. The corresponding displacement of the station positions is affected on the level of a couple of centimetres, which amount is calculated using respective Love numbers. All coefficients are taken from the latest version of the IERS Conventions (Petit & Luzum 2012).

3) Gravitational Deformation of radio telescopes

The effect of the gravitational antenna deformation impacts the reference geometry of the VLBI antenna. The elevation-dependent structural deformation affects the signal propagation path. Besides, the antenna deformation effect depends on the system type of the dish and increases with the size. At the moment, the elevation-depended corrections are available for a few of the largest antennas only: EFLSBERG, GILCREEK, MEDICINA, NOTO, ONSALA60, and YEBES40M.

4) High-frequency EOP variations

The high-frequency variations of the Earth rotation axis are described mainly by the gravitational lunar-solar interactions based on the equilibrium theory. The high-frequency Earth Rotation Parameter (ERP) variations are observed in the terrestrial reference frame as diurnal and semidiurnal tides. In contrast, the long-term variations are referred to as nutation with respect to the IERS Conventions definition. The coefficients of the diurnal and semidiurnal tidal variations in polar motion and dUT1 derived in the paper by Desai & Sibois (2016) represent the high-frequency EOP model recommended for the ITRF2020 reprocessing. The

[1] https://ivscc.gsfc.nasa.gov/about/wg/wg2/index.html

distributed set of coefficients contains 159 tidal terms. The appropriate libration terms are provided by the IVS Analysis Coordinator[2], as well.

Combination strategy

The IVS Combination Centre performs the combination of the level of datum-free normal equations using the software DOGS-CS. The combination procedures applied for generating the input to ITRF2020 follows the procedures applied for generating the IVS combination for the rapid sessions as well as for the quarterly solutions (see Bachmann et al. (2021) for more details).

In general, the combination on the level of normal equations leads to more stable equation systems in comparison to the individual solutions. In addition, the correct correlations between the different parameters are considered. For ensuring a reliable data basis, several quality checks concerning the required SINEX format, numerical stability and the quality of the estimated parameters are carried out. This includes the completeness of the parameters and models (e.g. full set of EOPs, existence of all station IDs, applied precession and nutation models), as well as an outlier detection for rejecting contributions with low quality.

The remaining normal equations are subject to the session-wise IVS combination procedure, which is visualized in Figure 2. A transformation to equal epochs and equal a priori values achieves consistency between the individual contributions. Thereby the reference epoch is the middle of the 24h observation interval, and the a priori TRF is defined by the latest IVS Quarterly solution (2020/Q2) as an update of the ITRF2014. The IERS 14C04 series is used as a priori values for EOPs. For the outlier test, individual solutions are computed by applying No-Net-Rotation (NNR) and No-Net-Translation (NNT) conditions on core stations for datum definition. The positions of the radio sources are fixed to the ICRF3 and become eliminated from the equation system. For the remaining contributions, a variance-component estimation (VCE) computes AC-specific weightings, so that the combined session-wise normal equation consists of the accumulated and weighted individual NEQs, with station coordinates and EOPs being stacked.

The IVS contribution to the ITRF combination consists of two series: one series is based on the mid-epoch of each VLBI session and the second series contains all parameters transformed to noon epochs (UTC) in order to be consistent with other techniques. For assessing the quality of the combination, the combined EOPs and station coordinates are estimated by applying adequate datum constraints (NNR/NNT) to a subset of stable high-quality core stations.

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

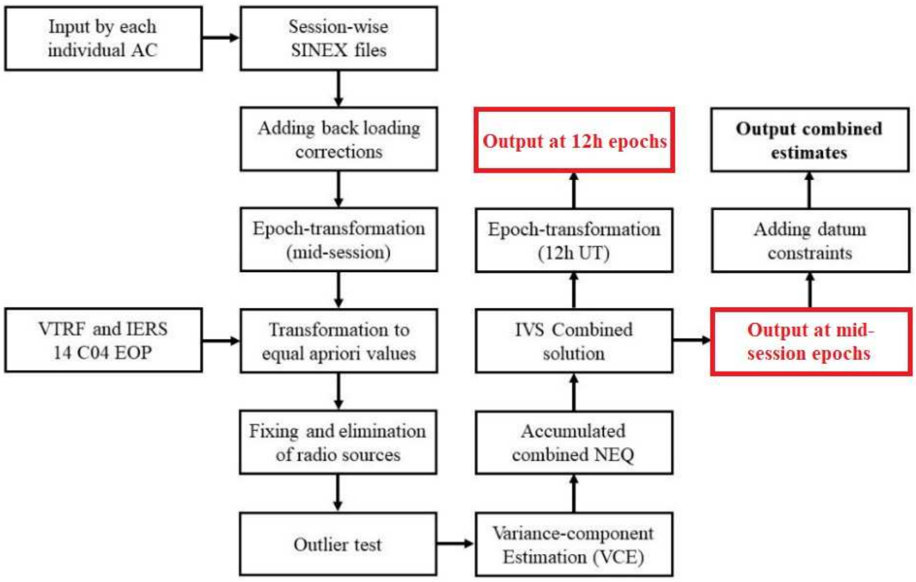

Figure 2: Combination procedure for the session-wise IVS combination.

IVS combination results

The final combination estimates are evaluated session-wise concerning station coordinates and EOPs in order to assess the combined product's quality. Comparisons of the combined and the individual AC solutions w.r.t. the external IERS Bulletin A time series are carried out, leading to Mean and Weighted-Root-Mean-Square (WRMS) values for differences. In addition, the accuracy of the station coordinates are derived by an evaluation w.r.t. the current IVS quarterly solution.

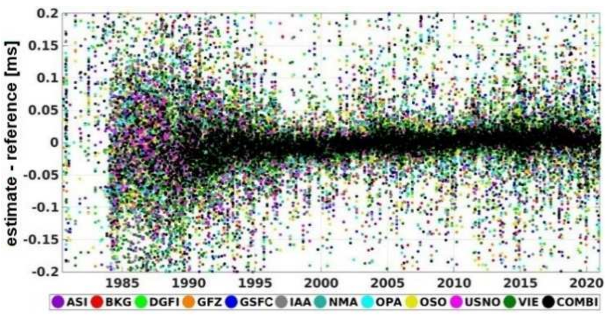

Figure 3: Difference of dUT1 estimates w.r.t. IERS Bulletin A

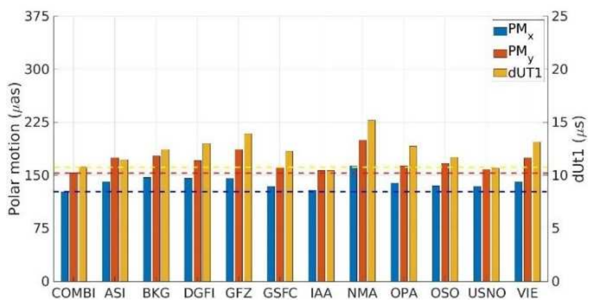

Figure 4: WRMS of the differences of the EOP estimates w.r.t. IERS Bulletin A

Figure 3 shows the comparison of the estimated dUT1 time series with IERS Bulletin A. Based on a space-fixed reference VLBI is the only technique which can determine the time depending parameter dUT1 directly, while satellite-based techniques rely on integrating the time derivative LOD. Therefore, the quality of the VLBI-derived dUT1 estimates is crucial also for the combination with the other space-geodetic techniques. It is evident from Figure 3, that a reliable estimation of dUT1 could be achieved since the middle of the 1990s. While the fluctuation within the first 10 years reaches up to $\pm$ 0.2 ms, the accuracy could be increased to $\pm$ 0.05 ms since the middle of the 1990s. It is also clear that the combination (black dots) is characterized by fewer fluctuations than the individual AC solutions, which clearly demonstrates the benefit of a combination.

Figure 4 shows the corresponding WRMS deviations of all ACs and the combination. The axes are scaled in such a way that the angles of dUT1 and PM are commensurate, i.e. 10 µs of dUT1 corresponds to the same angular displacement as 150 µas of Polar Motion. The vertical dashed lines, which represents the level of the combination, are below the WRMS levels of the individual solutions, so that an accuracy enhancement through the combination is confirmed. Furthermore, we can see from Figure 4, that the external agreement for Polar Motion is slightly better than for dUT1.

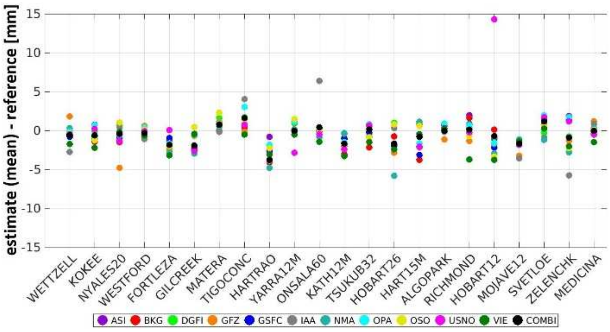

Figure 5: Session-wise comparison of station heights with IVS quarterly solution (2020Q2): Mean values shown for best performing stations.

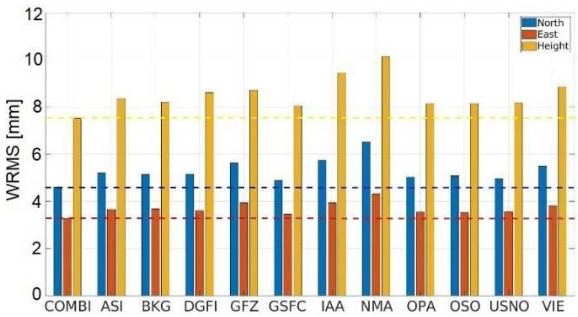

Figure 6: WRMS of the session-wise station coordinates of Wettzell compared to the quarterly solution 2020Q2.

For validating the station coordinates, we compare the session-wise estimates with the IVS quarterly solution 2020Q2 that we use as reference. The mean values per station and coordinate component over the entire time span from 1979 until 2020 serve as a quality criterion for the IVS contribution to ITRF2020.
Figure 5 shows these mean differences for the height component exemplarily for the best 22 best-performing stations. The combined solution (black dots) for every station is well within the range spanned by the individual solutions. Due to the variance component estimation and the applied weighting factors, the combination mathematically describes a weighted mean of the AC contributions. A benefit from the diversity of software packages becomes clear. For getting more detailed information about the station coordinates' repeatability, the WRMS deviations in all three components are shown in Figure 6 exemplarily for one station, i.e., Wettzell. Similar to the conclusions drawn from Figure 4, all individual AC solutions show higher WRMS values than the combination. Consequently, the benefit of the combined product compared to the individual solutions is confirmed for all three components of the station coordinates.
More details on the IVS combination for ITRF2020 including its validation can be found in Hellmers et al (2022).

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