Impact of the terrestrial reference frame on the determination of the celestial reference frame

Maria Karbon\textsuperscript{a,\*}, Santiago Belda\textsuperscript{b}, Tobias Nilsson\textsuperscript{c}
\textsuperscript{a}Institute of Geodesy and Geoinformation, University of Bonn, 53115 Bonn, Germany
\textsuperscript{b}Image Processing Laboratory (IPL) - Laboratory of Earth Observation (LEO), University of Valencia, Valencia, Spain
\textsuperscript{c}Lantmateriet, 801 82 Gävle, Sweden

Abstract
Currently three up-to-date Terrestrial Reference Frames (TRF) are available, the ITRF2014 from IGN, the DTRF2014 from DGFI-TUM, and JTRF2014 from JPL. All use the identical input data of space-geodetic station positions and Earth orientation parameters, but the concept of combining these data is fundamentally different. The IGN approach is based on the combination of technique solutions, while the DGFI is combining the normal equation systems. Both yield in reference epoch coordinates and velocities for a global set of stations. JPL uses a Kalman filter approach, realizing a TRF through weekly time series of geocentric coordinates. As the determination of the CRF is not independent of the TRF and vice versa, the choice of the TRF might impact on the CRF. Within this work we assess this effect.

We find that the estimated Earth orientation parameter (EOP) from DTRF2014 agree best with those from ITRF2014, the EOP resulting from JTRF2014 show besides clear yearly signals also some artifacts linked to certain stations. The estimated source position time series however, agree with each other better than ±1 μas. When fixing EOP and station positions we can see the maximal effect of the TRF on the CRF. Here large systematics in position as well as proper motion arise. In case of ITRF2008 they can be linked to the missing data after 2008. By allowing the EOP and stations to participate in the adjustment, the agreement increases, however, systematics remain.

Keywords
Reference frames; CRF; TRF; DTRF2014; JTRF2014; ITRF2014

1 Introduction

The International Terrestrial Reference System (ITRS) is an Earth-centered, Earth-fixed reference system with its origin in the Earth’s center of mass. The realization of this system is named International Terrestrial Reference Frame (ITRF) and is commonly realized

\textsuperscript{*}Corresponding author. karbon@uni-bonn.de (M. Karbon).
through reference epoch coordinates and linear velocities of a set of points on the Earth surface serving as reference points. The current conventional realization is the ITRF2014 [1]. Accurate TRFs are indispensable for many applications, e.g. navigation and mapping on Earth, precise orbit determination for satellites, and geophysical applications, such as monitoring tectonic motions, and observing the variations of the sea level. Especially for the latter the requirements for the accuracy and long term stability are very high, i.e. better than 1 mm and 0.1 mm per year, as defined by GGOS [2], the Global Geodetic Observing System of the International Association of Geodesy (IAG). This has not been achieved yet.

Furthermore, the analysis of space geodetic observations needs the definition of a quasi inertial reference frame to which the orientation can be tied. The current realization of such a Celestial Reference System (CRS) is the second International Celestial Reference Frame (ICRF2, [3]). It consists of a set of 295 defining extragalactic radio sources. It represents the main product of astrometric VLBI (Very Long Baseline Interferometry, e.g. [4]).

The Earth orientation parameters (EOP) connect these two frames in terms of orientation. They describe the rotation of the TRF to the CRF, in conjunction with the conventional precession-nutation model IAU2006/2000 [5,6] and the coordinated world time UTC.

The determination of these two reference frames, i.e. TRF and CRF, is not independent, nor consistent with each other. For example, for the VLBI contribution to the ITRF2014 the source positions of the defining sources were fixed to their ICRF2 catalog positions. And for the determination of the upcoming ICRF, ICRF3, the VLBI station coordinates from the ITRF2014 are needed to form the terrestrial datum. Thus, any changes in one frame might propagate through the EOP to the other frame.

Within this work we will compare and evaluate the impact of three independent TRF solutions on the CRF determination: the ITRF2014 determined by the Institut national de l’information géographique et forestiére (IGN) in Paris, the DTRF2014 by the Deutsches Geodätisches Forschungsinstitut-Technische Universität München (DGFI-TUM) in Munich, and the JTRF2014 by NASA’s Jet Propulsion Laboratory (JPL) in Pasadena. We will consider the TRF as a black box, and use models and a-priori values which are standard in VLBI analysis to generate various CRF solutions.

2 CRF and TRF: dependencies, interactions, inconsistencies

The determination of the different geodetic products, i.e. TRF, CRF and EOP, is a complex procedure developed and grown over the last decades. Here only a short recap can be given, as to help the more general reader by placing the presented analysis in context with the state-of-the-art. More detailed information can be found in Ref. [7] and in the references given in this manuscript. Presently four techniques contribute to these geodetic products: VLBI, Satellite Laser Ranging (SLR), Global Navigation Satellite System (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). SLR exclusively defines the origin of the TRF, whereas its scale is defied by SLR and VLBI. The latter is the only technique to provide the link to the CRF. Today it is common practice to combine the solutions of the single analysis centers (AC) technique-wise within
the designated IAG services, and then, in a second, independent step, to combine the
technique-solutions to determine the final product of interest, i.e. TRF or EOP. Due to the
fact that only VLBI realizes the CRF, no technique-combination is carried out. Further, also
no intra-technique combination is done, hence, the ICRF2, has been computed by only one
VLBI AC, using one specific software package.

The definition and realization of the ICRS are given in the IERS Conventions [8] on the
basis of several IAU resolutions, dating back to the early 90s. Since then, for every new
realization of an ICRS the datum was defined with respect to the previous realization.
Hence, any inconsistencies of the predecessor affect the orientation of the frame of the
new, more precise frame and possibly degrades it. Furthermore, ICRF and ICRF2 have
both been computed by one IVS analysis center, using one software package. Thus, unlike
to the TRF determination, this individual solution is not controlled and validated though
a combination process, reducing its robustness. This, for instance, leads to too optimistic
formal errors. Also the effect of the imbalance between the number of VLBI stations in the
northern and southern hemisphere has not been quantified yet, same is valid for network
effects in general. Such effects are most likely the origin for the zonal errors present in the
ICRF2. Also, as the observations of the source positions get more accurate due to advances
in technology and analysis methods, the assumption that source positions are time-invariant
no longer holds. The biggest limiter of VLBI accuracy however, is the atmosphere. Hence,
VGOS (VLBI GLobal Observing System [9]) has been developed to address this issue, but is
not operational yet.

A TRF is an Earth-fixed frame, in which points at the solid Earths surface undergo only
small variations mainly due to geophysical effects caused by various dynamic processes
and forces from external bodies. The ITRF is a realization of the ITRS trough three-
dimensional positions and time variations of a network of stations observed by VLBI,
SLR, GNSS and DORIS. The data are processed by several individual analysis centers for
the different space techniques. The individual time series are then combined per technique
by the four responsible technique-specific combination centers, and finally the combined
TRF is computed (more details for the individual approaches in Section 3). Inconsistencies
arise already at the AC level, as not all use the same input data. For example, not all
VLBI-ACs provide the solutions to exactly the same set of sessions. Also the inter-technique
combination can lead to differences, e.g. the VLBI-solutions are combined on normal
equation level, whereas GNSS and SLR on the parameter level, i.e. the adjusted parameters
of the individual solutions are combined in a second least squares adjustment process.
Further, the stations of the individual techniques are distributed homogeneously on the Earth
surface, and the number of stations per technique is not balanced as well. For example, the
VLBI combination delivers station positions for 158 sites, GNSS of 1845 sites.

The local ties at co-location sites, which link the individual techniques at one site, don’t have
the same quality. Hence, a possible source for the different scale-offsets between VLBI and
SLR seen in different TRFs is the different handling of local ties. However, the weighting of
the local ties in the ITRF2017 solution and inclusion of the scale parameter as a unknown
amends that. The topic of the differences in scale between DTRF2014 and ITRF2014 are
still under investigation.
Similar to the CRF the datum is realized by transformations w.r.t. the previous TRF realization, which has proven to be a major error source [7]. A considerable issue is also the treatment of station motion, induced by geophysical processes, e.g. plate motion or earthquakes. Here each provider follows a different strategy (see Section 3).

Concerning the EOP, the capabilities of the three techniques are quite different: VLBI is the only technique to determine the nutation angles and UT in an absolute sense, whereas the satellite-techniques have access only to the time-derivatives, i.e., the nutation rates and length of day (LOD). Also concerning the time resolution of the parameters the techniques differ significantly. VLBI provides on an operational basis two sets of EOP per week, and daily estimates of UT1. GNSS provides polar motion and LOD on a daily basis, SLR on a weekly. The final EOP time series are then computed following a similar strategy as for the TRF solutions. The parameters are interpolated, filtered, averaged and weighted to generate the final daily EOP time-series. This procedure can differ for the individual providers and can change over time. Investigations also show that the varying networks of the different techniques impact on the EOP. As they lead to small misalignment of the EOP with the CRF and TRF, which can cause drifts in the EOP of dozens of μas [10].

Another crucial point are the local ties, i.e. differential coordinates connecting the instrument reference points of different techniques at one site, since more than 50% of the available SLR and VLBI tie vectors to GNSS exhibit residuals larger than 5 mm, and about 30% have residuals larger than 10 mm. Altamimi et al. [1] believe that these discrepancies are related mainly to systematic errors in the space geodetic techniques, originating in network effects. The biggest drawback of the geodetic products CRF, TRF and EOP however is that, although they base on the same data, they are all computed individually, and not in one monolithic procedure. This introduces inevitably inconsistencies. To calculate all three products in one procedure would hence be the obvious choice, as all products depend on one another, and none can be determined without a-priori information from the other, and/or needs the reference frames for the datum definition. Several groups are currently working on a combination strategy which enables such an monolithic adjustment procedure for all parameters of interest.

3  A brief introduction to current TRS realizations

All TRS realizations used in this study are based on the combination of the four space geodetic techniques VLBI, SLR, GNSS and DORIS. The integrated data sets are identical to a large extend, including all data from the individual beginning date of the techniques until March 2015. A detailed description of the data input, as well as the methods applied can be found in the given references.

3.1  ITRF2008 and ITRF2014

ITRF2014 [1] is the current conventional realization of the ITRS, it follows similar procedures as used for ITRF2008 [11], and is based on time series of station positions and EOP provided by the IAG services and the corresponding variance/co-variance matrices. The biggest advances w.r.t. its previous versions are the introduction of non-linear post-seismic deformation (PSD) models and Fourier series of the station position’s annual fluctuations.
signals, which are mainly caused by non-tidal loadings. The PSD were based on fitting
GNSS sites that were affected by major Earthquake and then applied to the three other
techniques at co-location sites. This procedure is possible as all other techniques are at
least co-located with GNSS. ITRF2014 provides the classical parameters: station positions,
station velocities and EOP, as well as the PSD models. The origin is defined though SLR,
the scale by averaging the scale derived from VLBI and SLR. The orientation is given
through the alignment of ITRF2014 to ITRF2008 applying no-net-rotation (NNR) at epoch
2010.0 to 127 stations. The stations were selected assuring the best possible site distribution,
involving as many GNSS, VLBI, SLR and DORIS stations and to minimize the post-fit
residuals of the 14-parameter transformation w.r.t. ITRF2008. ITRF2014 shows a scale
difference between SLR and VLBI of 1.4 ppb (~8.7 mm at the equator). Table 1 gives the
transformation parameters at epoch 2010.0 and their rates from ITRF2008 to ITRF2014.

3.2 DTRF2014

The ITRS realization strategy of DGFI-TUM is based on the combination of datum free
normal equations (NEQ), which are reconstructed from the input SINEX series provided by
the Technique Centres [12]. The underlying data is the same as for ITRF2014. In contrast
to the previous realization DTRF2008 [13], corrections for atmospheric, hydrologic
and oceanic loading signals provided by the Global Geophysical Fluid Center (GGFC)
are applied directly after the reconstruction. The final DTRF2014 solution comprises
additionally to the station coordinates and EOP, the SINEX files for all techniques. These
include the EOP and the full variance/co-variance matrix, the residual station position time
series, and the loading time series applied for the DTRF2014 computation. DTRF2014 is
aligned to DTRF2008 through NNR of the GNSS network at epoch 2000.0. The origin is
defined though SLR, the scale through the SLR and VLBI scale which is applied to the
GNSS- and Doris-networks. The scale parameter however is not included in the combination
model, hence not estimated. This approach is founded on the fact, that in DTRF2014
no significant scale offset between SLR and VLBI is apparent (<0.1 ppb). This leads
to a difference in scale w.r.t. ITRF2014 of ±3.5 mm for SLR and VLBI, respectively.
The cause is likely to be found in the different intertechnique combination procedures
applied for ITRF2014 and DTRF2014, and is currently under investigation. The fact that the
difference in scale of the VLBI-only-TRF VTRF2014 w.r.t. ITRF2008 is 0.44 ppb and w.r.t.
DTRF2008 is 0.11 ppb [14], enforces this assumption.

3.3 JTRF2014

JTRF2014 [15] uses a Kalman filter and smoother approach to combine time series from the
four space geodetic techniques to realize a TRF through time series of weekly geocentric
coordinates. It assimilates weekly solutions of station positions and daily EOP along with
local ties at co-located sites, as given by the input data used for ITRF2014. In addition
to secular, periodic, and stochastic components for station coordinates, the Kalman filter
state variables also include daily EOP and transformation parameters from input data
frames to the combined TRF. The final JTRF2014 solution consists of weekly combined
coordinates published in SINEX format, including the full variance/co-variance matrix. In
this time series approach the orientation is defined through NNR between the estimated
coordinates and the last (linear) ITRF realization over a core network of well-distributed
sites at all epochs. The origin is defined through SLR and the scale is realized, similar to the DTRF2014, by adjusting the DORIS and GNSS scale to the VLBI and SLR scale, respectively. The VLBI and SLR scales are not modeled and adjusted. Again, this modus operandi is in principle acceptable if VLBI and SLR were to provide the exact same scale (i.e. in the absence of scale and scale rate bias). Table 2 gives the transformation parameters and their rates from ITRF2014 to JTRF2014 at epoch 2005.0 [16]. These parameters were determined though a linear fit to a time series of weekly Helmert transformation parameters mapping the ITRF2014 station positions at the weekly epochs of the JTRF2014 onto the specific JTRF2014 station positions. No stations affected by earthquakes were included when computing them. However, the 1-sigma formal errors are overly optimistic due to the linear fitting. Besides the scale, JTRF2014 is highly consistent with ITRF2014 regarding the Helmert parameters.

4 Data and data analysis

For this study we used 3441 VLBI experiments, also called sessions, observed by the International VLBI Service (IVS, [17]) within the years 1990—2014. We chose to drop the data from the years 1979 until 1989 to prevent any contamination due to the poorer quality of the data of that time. As end date we choose the end of 2014, since the JTRF2014 does not deliver any weekly files after mid of February 2015, where the input provided by the IAG services ends. Our selection of sessions encompasses a station-polyhedron with a volume bigger than 1 Mm$^3$ and contain more than three stations. This assures a global station network, and thus, reliable EOP estimates. The single session analysis follows the IERS conventions 2010 [8]. As a-priori EOP we used the USNO final series, which is consistent with ITRF2008. The reasoning is, that not for all TRFs the corresponding, hence consistent, EOP time series were publicly available when this study was undertaken. All the involved a-priori values and models are given in Table 3.

The terrestrial datum was realized with no-net-rotation/no-net-translation (NNR/NNT) conditions on the stations contained in the VTRF2014 catalog [14], the celestial with a NNR condition on the ICRF2 defining sources. In case of ITRF2008, the stations not contained (f.ex. AuScope) or stations affected by major earthquakes (f.ex. TIGO) were not included in the NNR/NNT station datum conditions, the a-priori station coordinates are then taken from our own TRF based on VLBI data analysis.

For each TRF introduced in Section 3 we generated for each session the normal equations (NEQ), and estimated one set of station coordinates, EOP and source positions per session. The results are presented in Section 5.1.

By stacking the four different sets of datum-free NEQ obtained from the single session analysis, four global normal equation systems were formed, containing only the parameters of interest, i.e. the source positions and proper motions, which will be estimated as global parameters. The local parameters (determined at the single session level) were reduced from the NEQ. These parameters are the zenith wet delays, tropospheric gradients and clock parameters and are dependent on a finite amount of time. The reduction means an implicit estimation of such parameters from the session-wise NEQ by a least squares adjustment.
It has to be kept in mind that also the EOP cannot be determined independently from the TRF; in case of USNO finals the EOP are consistent with ITRF2008. By a final inversion of this NEQ-system the global parameters, in our case the source positions and proper motions, were obtained. Positions and proper motions of sources were only estimated for sources which were observed in at least two sessions over at least two years and have in total at least 15 observations. The coordinates of the so called special handling sources were reduced.

To test the effect of the TRFs on the CRF we followed two different estimation schemes: (I) The station positions were fixed to the a-priori, i.e. the respective TRF, as well as the EOP. This assures, that all systematics and errors of the TRF propagate directly to the CRF, without risking any absorption by the EOP. (II) EOP are reduced and station positions estimated. For the terrestrial datum definition we applied a NNR and NNT with respect to a selection of well determined VLBI core sites. This is the commonly used method estimating CRFs. The results are presented in Section 5.2.

It shall be kept in mind, that for all TRFs the processing strategy, parameterization, and modeling was kept identical (except the terrestrial datum definition for ITRF2008). We use the TRFs as is, following the publishers recommendations.

5 Results

5.1 Single session solution

First we look at the key parameters estimated within the single session solutions, namely the EOP, and the positions of selected stations and sources. This allows a first assessment of the performance of the TRFs as the EOP are very sensitive to changes within the station networks. Also, several big earthquakes happened since 2008 (end of the input for ITRF2008), and the TRF realizations follow different strategies on how to deal with such discontinuities.

5.1.1 EOP—Fig. 1 shows the differences between the EOP based on ITRF2014 and the various TRS realizations, i.e. from left to right: in blue $\Delta EOP_{ITRF2008}$, in red $\Delta EOP_{DTRF2014}$ in black $\Delta EOP_{JTRF2014}$.

Looking at $\Delta EOP_{ITRF2008}$ one can clearly see the increasing scatter in all the parameters after 2008. This stands to reason, as 2008 marks the end of the input data for this TRF. Within the last years more and more new stations joined the network, with coordinates that are inconsistent with the old frame, thus introducing discrepancies. Further, we see a formation of populations of estimates in the early years, most significant in x-pol. This effect is caused by different network configurations and session types, exemplarily shown on the left in Fig. 2 where the difference of the estimates in x-pol for ITRF2014—ITRF2008 within the years 1990—1993 is plotted. This inset is marked in Fig. 1 with a red rectangle.

The green dots in the left plot in Fig. 2 are residuals generated without exception by IRIS-S sessions, the station that makes this session type stand out is Hartebeesthoek, South Africa. The map in Fig. 2 (modified from: http://ivs.nict.go.jp/mirror/stations/ivsnetmap.gif) shows, also in green, the convex hull of the most common station configuration of this
session type. By replacing Hartebeesthoek with Richmond in Florida the network in cyan is established, resulting in the cyan x-pol differences. The majority of these sessions are IRIS-A sessions. Expanding the network by adding Fort Davis (not shown in the map) the purple estimates running in parallel to the cyan dots are generated. The black dots running almost parallel to the zero-line are estimates based on IRIS-P sessions, featuring Hobart, Australia and Kashima (34 m), Japan; whereas the red, also horizontal line of estimates is generated exclusively by R&D sessions containing Gilmore Creek, Alaska and Kokee Park, Hawaii. The interesting station forming the magenta dots (MVEUR-D sessions) is the mobile station in Trysil, Norway. By exchanging this station with Matera, Italy (IRIS-A), we get the orange x-pol differences. One can observe, that the core stations are all located at northern mid-latitudes. Adding stations in the far south (Hobart, Hartebeesthoek) introduces a positive bias, and stations in the far north (Gilmore Creek, Trysil) a negative one. It should be noted, that the differences between the a-priori station coordinates from ITRF2008 and ITRF2014 don’t exceed 1 cm for any stations within this time span (exception: Goldstone). The drifts seen in the green, cyan and purple networks might be introduced by Richmond, the only station common to all sessions which shows a noticeably different velocity between ITRF2014 and ITRF2008.

Lambert and Gontier [22] have investigated the impact of the R1- and R4-session networks on the EOP and detected biases between the solutions up to several hundreds of μas over a year. Malkin [23] expanded the study to more IVS session types and detected a power law between network size and EOP accuracy. Here we found, that the choice of the a-priori TRF also has an effect and that the change of one station in the network already has an impact on the EOP, although the effect is 1000 times smaller compared to the findings of Refs. [22,23]. However, this effect seems to diminish as the networks grow in size and diversity and the precision of the VLBI system increases.

By looking at the weighted root mean square (wrms) in Table 4 one can observe, that the EOP of ITRF2014 and DTRF2014 deviate on a minimal level, for polar motion a few μas, for dUT1 and the celestial pole offset by far less. In case of ITRF2008 the differences are about a factor 100 bigger. The largest discrepancies are between ITRF2014 and JTRF2014, originating mainly from the seasonal signals incorporated in JTRF2014.

When estimating linear trends over the time period 1990—2014, the resulting slopes are in the range of a few nas/y, ns/y respectively. However, the p-value for a significantly non-zero slope exceeds the 5% significance level only for a few of the components, marked as bold values in Table 4. These results can be confirmed visually to some extent for polar motion for ΔEOP_{ITRF2008} and ΔEOP_{DTRF2014} in Fig. 1. In case of ΔEOP_{ITRF2008} the interpretation gets more difficult, firstly due to the seasonal variations, secondly due to the offsets visible in the early years, and lastly due to the distinct feature within the year 2010. The seasonal signals incorporated in the Kalman filter solution of JPL are clearly visible in the EOP differences, especially in the early years. In these years only a few observations usually of poorer quality are available, so that the filter significantly relies on the background model. With time, the number of observations and their quality increase, stabilizing the estimates.
The feature in JTRF2014 however, needs an other explanation. It begins in March 2010 and ends in March 2011. The most obvious cause would be earthquakes, and indeed, two major earthquakes happened around that time: the Chile Earthquake with its main shock on 27.02.2010, and the Tohoku Earthquake on 11.03.2011. Also, all the sessions deviating from the expected EOP include station TIGO in Concepcion, Chile, or Tsukuba, Japan and by excluding them from the analysis, the feature vanishes. Nonetheless, there are also sessions including these stations, which do not deviate.

In this regard, in the next section we will take a look at the station positions and the definition of the discontinuities in the TRFs.

5.1.2 Station positions—Fig. 3 shows exemplarily the a-priori station positions for TIGO (Transportable Integrated Geodetic Observatory), Concepcion, from September 2009 until the end of June 2010. The 2010 Chile Earthquake with a magnitude of 8.8 on the Richter scale occurred on 27.02.2010, and it is marked with a yellow vertical line and arrow in Fig. 3. The TRFs are color coded as follows: blue and green for ITRF2008 and ITRF2014, respectively, red for DTRF2014, and black for JTRF2014. The breaks, as reported in ITRF2008, ITRF2014 and DTRF2014 are marked with vertical lines in the corresponding color, the exact date is given together with arrows at the bottom. In case of JTRF2014 the black vertical line marks the date, when the station position reported in the weekly files jumps to the post-seismic position.

All TRFs have set the break at different epochs, and only in case of ITRF2014 it coincides with the actual date of the Earthquake. This is due to the different strategies used for the determination of the break epochs. ITRF2014 uses GNSS-time series in combination with Earthquake catalogs to localize the breaks, whereas for DTRF2014 and for JTRF2014 the discontinuity detection is purely data-driven. Also, for JTRF2014 it has to be kept in mind, that it is organized in weekly files, thus, any breaks can only occur from one week to the next.

The differences in the placing of the break epochs leads to problems in the estimation of the station positions using JTRF2014, more so, as TIGO is also included in the terrestrial datum definition. There are around ten sessions in this study, which where observed between 23.12.2009 (JTRF2014 break) and the date of the Earthquake, which include TIGO. Hence, for this period JTRF2014 already applies the post-seismic position, which at this point is wrong by up to 3 m. This then leads to wrong station position estimates for TIGO within this time period (Fig. 4). Anyhow, this effect does not leak into the EOP on a noticeable level, as within this period no conspicuous features appear in the differences. Also excluding TIGO from the datum within the two month prior of the earthquake mitigates this effect. The break position in DTRF2014 does not pose a problem, as within 27.02.2010 and 16.03.2010 no VLBI sessions containing TIGO were observed, as the station was offline.

However, it has to be noted, that in most cases the dates where breaks are inserted are not identical for all TRF realizations. Some breaks are only defined in one TRF but not in the others. For example the break at Ohiggins, Antarctica, on 02.02.2010 of about 10 cm related to an antenna repair can only be found in ITRF2014, but not in the other two frames.
5.1.3 Source positions—As a last parameter group we will look at the source positions time series. On the top in Fig. 5 we have in green the time series for the estimates in right ascension (\(\alpha\)) and declination (\(\delta\)) for datum source 0552 + 398 with half-year mean values in black, estimated using ITRF2014. On the right in red the same for special handling source 4C39.25. The plots on the bottom show the differences of the half-year mean values w.r.t the different TRFs: in blue for ITRF2008, in red DTRF2014, and in black JTRF2014. Overall the differences are very small, they seldom exceed 1 \(\mu\)as. These small differences are reasonable, as the source coordinates are the last parameters in the chain coming from the TRF. Bigger differences only arise, when the observation density decreases considerably, what again can be expected. This effect is visible in 0552 + 398 for 2010, and for 4C39.25 within the years 2010—2014, where the differences w.r.t. ITRF2014 increase for all TRFs. Overall DTRF2014 shows again the best agreement with ITRF2014. Interestingly all source positions, not only the two shown here, show larger differences from the late 90s until early 2000s. There are multiple possible explanations: various big earthquakes happened, e.g. Denali 03.11.2002 (M7.9), Hokkaido 25.09.2003 (M8.3) where inconsistencies in the setting of the discontinuities could be introduced; several new stations went online, e.g. Tsukuba32 or TIGO, leading to similar effects and changes in the networks.

5.2 Global solution

In this section we compare the individually determined CRFs by looking at the sources common to all CRF solutions, which have a standard deviation in position \(\sigma_{\alpha/\delta} < 0.2\) mas and in proper motion \(\sigma_{\mu_{\alpha/\delta}} < 0.2\) mas/y. This criterion is fulfilled by 700 sources. This study is empirically done by performing several VLBI data analysis. In the first approach, we examine the CRFs estimated by fixing EOP and TRF to the a-priori values (I), while in the second one the CRFs is estimated reducing EOP and estimating station positions (II).

5.2.1 Source positions (I)—By fixing EOP and the stations positions to their respective a-priori values taken from the respective catalogs, we can examine the maximal effect of the TRF on the CRF, as the EOP and the station positions cannot absorb any rotations or shifts introduced by the different TRFs. One method to assess CRFs is to model the differences using a coordinate transformation that takes into account the global rotation between the catalogs as well as low-degree de-formations. We choose a 6-parameter transformation between the individual CRFs including three rotational angles \(A_1, A_2, A_3\) around the X, Y and Z axes of the celestial frame, respectively, and \(D_{\alpha}\) and \(D_{\delta}\) as drifts in right ascension and declination as a function of the declination (\(\delta_0\) can be set to 0); and \(B_{\delta}\) as a bias in declination [24]:

\[
\Delta\alpha = A_1 \cos \alpha \sin \delta + A_2 \sin \alpha \sin \delta - A_3 + D_{\alpha}(\delta - \delta_0),\\
\Delta\delta = -A_1 \sin \alpha + A_2 \cos \alpha + D_{\delta}(\delta - \delta_0) + B_{\delta}
\]

Table 5 summarizes the values for the transformation of the individual CRFs onto the one determined using ITRF2014. Note that since EOP and station positions are fixed to their a-priori values to get the full effect, larger values were expected. It can be seen at the rotation angles, where all the figures exceed the ICRF2 axis stability criteria (10 \(\mu\)as), and all show relevant drifts in both coordinates as well as biases in declination. On the other
hand the drift $D_\delta$ and the bias $B_\delta$ of DTRF2014 and JTRF2014 show an opposed sign to ITRF2008. Nonetheless, the rotation angles are within the range of the different catalogs submitted for the ICRF2 [3].

The artificial displacement of the sources towards the poles was a subject in several earlier works (e.g., [24–27]). It is explained as an artifact resulting from the asymmetry of the station networks, especially within the earlier years of VLBI. Since most stations and thus also observed sources were in the north, the networks and analysis were strongly sensitive to the troposphere thickness at the equator. For these reasons our study is solely based on post-1990 data for better quality. Consequently, all the subsequent analysis is exactly the same for all CRFs. Hence, for such an effect showing up in the differences, the TRFs must carry such a deformation within them, as the determination of a TRF is never independent from the CRF, as long as VLBI is included.

The values $\text{wrm}_{\alpha/\delta}$ and $\text{wrm}_{\mu_\alpha/\mu_\delta}$ in Table 5 give the weighted RMS of the source coordinates and their proper motion components. Whereas for ITRF2008 $\text{wrm}_{\alpha}$ is bigger than $\text{wrm}_{\delta}$, for the other two $\text{wrm}_{\delta}$ is clearly dominating. This is in agreement with the transformation parameters.

For the visual inspection we plotted in Fig. 6 in the left column the differences of the global source positions estimated within the global solution w.r.t. ITRF2014, in blue for ITRF2008, in red for DTRF2014 and in black for JTRF2014. Note the different scale for ITRF2008. To make a visual assessment easier, as the vector directions are projected, the differences in right ascension and declination are plotted as bubbles in the middle and right columns, respectively. Red stands for positive differences, i.e. the vectors point east/north, blue for negative, i.e. the vectors point west/south. The size of the bubble gives a qualitative measure of the difference, and is chosen so that the plots of the individual components are easy to compare. In Table 6 we present the $\text{wrm}$ of the individual solutions, separately for the blue and red groups. The number in parentheses gives the percentage of the sources within this group.

First we concentrate on right ascension, i.e. the middle column in Fig. 6. In case of ITRF2008 we find for $\Delta \alpha \cos(\delta)$ mostly red bubbles (72%), i.e. eastward shifts. Between $0^\circ$ and $-30^\circ$ latitude the differences are mostly negative, i.e. the sources shift west. Keeping in mind, that the input data of ITRF2008 ends with 2008 and the new Australian stations within AuScope (Australian geodetic VLBI network) started regular observations in June 2011, this effect might be easily explained.

Excluding all sessions which include any AuScope stations, we get the corresponding plots in the top row in Fig. 7: focusing on $\Delta \alpha \cos(\delta)$ (in the middle column) the red bubbles which are located in the far south almost vanish completely. Consequently the $\text{wrm}$ of the differences decreases of about 25% (ITRF2008_{woAuScope} in Table 6). By limiting the data input until the end of 2008 the aforesaid differences diminish more than 50% (see bottom row in Fig. 7, note the scale on the left plot, and the $\text{wrm}$ for ITRF2008_{short} in Table 6). In addition the transformation parameters are then reduced to $A_1$: 23.8 $\mu$as, $A_2$: 8.95 $\mu$as, $A_3$: 5.69 $\mu$as. Nonetheless, the big majority of the sources (93%) moves westwards. This might
be explained by the transformation parameters between ITRF2014 and ITRF2008 in Table 1, where $R_z$ shows a small rotation rate of 0.06 μas/y.

Plotting $\Delta \alpha \cos(\delta)$ for DTRF2014 one can notice immediately the eastward shift (middle row in Fig. 6); all but 8 sources show a positive difference w.r.t. ITRF2014. Moreover, the gradients towards the poles are very prominent. In case of JTRF2014, we get a very similar picture; the majority of the sources shifts east, most west-wards shifts occur in the southern hemisphere. Overall, the differences of DTRF2014 and JTRF2014 w.r.t. ITRF2014 are on average 90% smaller than ITRF2008—ITRF2014, and 60% smaller than ITRF2008 short—ITRF2014. In contrast to ITRF2008 excluding AuScope or limiting the data set to the end of 2008 has no significant impact on the solutions using DTRF2014 or JTRF2014.

Now, by focusing on declination (the right column in Fig. 6), a clear blue pattern can be easily identified for ITRF2008, i.e. most of the source positions are shifted south. By excluding again all sessions containing an AuScope station from the analysis, the majority of the bubbles within the latitudes 0° and -30° switch to red, meaning the shift in this region becomes positive (top right plot in Fig. 7). A plausible explanation could be due to AuScope network is located close to this region of interest. By further excluding all data after the end of 2008, the remaining differences vanish, resulting in a homogenous pattern (bottom right plot in Fig. 7). This is also confirmed by the wrms of the differences as shown in Table 6: Starting from ITRF2008, over ITRF2008 woAuScope, to ITRF2008 short the respective values diminish considerably. However, while for ITRF2008 and ITRF2008 woAuScope more than 70% of the sources shift north, for ITRF2008 short the ratio flips. Anyhow, the differences in declination between ITRF2008 and ITRF2014 seem to be caused mainly by the longer time span, since ITRF2008 does not take into account the post-seismic deformations after 2008. On the other hand, AuScope seems to have only a regional impact. Also, in contrast to the differences with DTRF2014 and JTRF2014 no clear gradient is visible in ITRF2008.

For DTRF2014 and JTRF2014 the bubbles representing $\Delta \delta$ are mostly red (99% of DTRF2014, 97% of JTRF2014), i.e. the source positions are shifted north, and clear gradients towards the poles are discernible. DTRF2014 generates negative gradients towards both poles with the bulge around -30° hinting to the afore mentioned network effects, whereas JTRF2014 shows mainly a negative north gradient what could be connected to the different origins of the frames. For DTRF2014 the average shift in $\delta$ in terms of wrms is +0.01 mas, only 2 sources out of the 700 show a negative shift of $-1e^{-4}$ mas. For JTRF2014 these numbers change to a positive shift of 0.003 mas for 675 sources and a negative one for 61 sources of on average $-0.02$ mas. The majority of these sources is located in the south-west. However, excluding all sessions containing an AuScope station, or shortening the time span, has no influence on these patterns.

Besides the network effects inherent of the solutions, an additional factor to the shifts in declination seen in Fig. 6 might be the difference in the origin of the individual reference frames. Whereas the translation in $z$ for ITRF2014 to ITRF2008 is positive (2.4 mm @2010.0) with a negative rate of $-0.1$ mm/y, the one for ITRF2014 to JTRF2014 is negative ($-0.53$ mm @2010.0) with a positive rate of 0.19 mm/y (see Tables 1 and 2). Secondly, the scales show a significant difference, due to the differences in its determination.
Unfortunately, for DTRF2014 no transformation parameters were released yet, which could help to clarify this point.

5.2.2 Proper motions (I)—The picture changes dramatically when the proper motions of the sources are meticulously examined. Fig. 8 shows a plot like Fig. 6, but now not the differences in position, but in proper motion. Note the different scale for ITRF2008 in the first column. As before, the bubbles are scaled to facilitate an easy comparison between the different components of the solutions.

Firstly, we take a look at the differences in right ascension first. Here, similar patterns to the ones for the positions can be quickly distinguished, although color-swapped. \( \Delta \mu_\alpha \cos(\delta) \) for ITRF2008 shows a hemisphere dependency, i.e. the majority of the northern sources show a negative difference (\( \text{wrms: 0.114 mas/y} \)), whereas the southern sources exhibit smaller positive differences (\( \text{wrms: 0.021 mas/y} \), see also Table 6). This pattern remains largely unchanged when excluding AuScope. Note that the pattern is homogenized when the input data are limited until the end of 2008, i.e. the differences diminish and are mostly negative. Exceptions are some sources in the far south, where large positive differences were detected. However, this stands to reason, since many of the southern sources had a short observation history. The corresponding plots are not shown.

For DTRF2014, we have one dominating color for \( \Delta \mu_\alpha \cos(\delta) \), blue, i.e. the velocities have a negative difference and point west-wards (Table 6). And again we find pronounced gradients towards the poles. Excluding AuScope has no impact on this pattern what-soever. On the contrary, limiting the data to the end of 2008 creates big positive outliers in the south, as it was the case for ITRF2008.

The case of JTRF2014 \( \Delta \mu_\alpha \cos(\delta) \) shows a more diverse pattern, where the colors are more balanced (35%/64%), and significant outliers appear. These outliers might be connected to the discrepancies in the setting of the discontinuities. We notice that the exclusion of AuScope has no effect, however, the limitation of the data to the end of 2008 creates, like for the others, big outliers in the south.

Lets switch again to declination, i.e. the third column of plots in Fig. 8. For ITRF2008 we see for \( \Delta \mu_\delta \) the same patterns as we have seen before for DTRF2014 in \( \Delta \delta \): clear gradient towards the poles, with the biggest differences around \(-30^\circ\) latitude. In this case limiting the input data does not resolve that issue. However, by omitting the data after 2008 the differences are diminished by 99%.

The case of DTRF2014 \( \Delta \mu_\delta \) shows a distinct behavior depending on the hemisphere, in the northern most sources move east (red), whereas in the south most seem to move west (blue). By excluding AuScope the pattern changes to what we see for DTRF2014 in \( \Delta \delta \), i.e. mostly positive differences with gradients towards the poles. By further limitation of the data the pattern homogenizes, i.e. the colors are balanced, no gradients are discernible. For JTRF2014 the hemisphere-dependency in \( \Delta \mu_\delta \) is not that pronounced, the colors are almost perfectly balanced. The exclusion of AuScope and the limitation of the data to the end of 2008 has similar effects as for DTRF2014, however a hemisphere-dependency remains.
5.2.3 Source positions (II)—Now we investigate the CRFs using the common estimation scheme, i.e. reducing EOP and estimating the station positions. This allows a certain absorption of the TRF-induced rotations and de-formations by the EOP. When looking at the parameters in Table 7, most of the rotations and shifts increase, whereas the wrms decrease significantly. This means, that the TRFs generate systematically different CRFs. Most drastic is the increase of the drift and bias parameters, which result to be very similar, with the exception of Dδ and Bδ for DTRF2014.

In Fig. 9 we plotted again the differences between the CRFs in terms of position, in the same way as in Fig. 6. From top to bottom: ITRF2008—ITRF2014 (blue), DTRF2014—ITRF2014 (red), JTRF2014—ITRF2014 (black); from left to right: vector field of differences, bubble plots for the differences for right ascension and for declination. Compared to Fig. 6 the different scales have to be noted, in case of ITRF2008 a factor of 10 smaller and for DTRF2014 and JTRF2014 a factor of 2 bigger.

For Δα cos(δ) we can distinguish for all three a zonal pattern with a tilted axis. However, the colors for DTRF2014 and JTRF2014 are swapped compared to ITRF2008. In the latter 91% of the sources are shifted west (red), and only a small number of sources close to the poles experiences a eastward shift; similar in pattern and numbers JTRF2014, however color swapped.

The Δδ ITRF2008 shows larger differences in the region located between 20°and 60°south, which can be attributed once more to the missing data after 2008. Besides that, the picture is comparable to the one of Δα cos(δ), however the values are significantly smaller. Again, JTRF2014 shows a very similar picture, although the numbers are accordingly bigger. For DTRF2014 the majority of the bubbles seems to be divided by the ecliptic (solid line), where most of the red ones are situated in the south.

5.2.4 Proper motions (II)—The proper motions for ITRF2008 and JTRF2014 in Fig. 10 show almost an inverted image of Fig. 9. However, DTRF2014 shows for μα more scatter in color as well as in size of the bubbles, with no clear pattern. On the other hand, for μδ, the majority of the sources (93%) shifts northwards (red), with only 48 out of the 700 shift south (blue).

Overall, it can be concluded that the inclusion of the EOP and stations in the estimation process highly mitigates the effects introduced by the ITRF2008. In case of DTRF2014 and JTRF2014 the differences overall decrease by a factor of 2 or more (Table 8). However, for all TRFs the rotation angles, drifts and biases are not improved when estimating station positions, however the wrms of the source positions as well the proper motions are reduced significantly (see Tables 5 and 7).

6 Conclusion

We compared four different TRF realizations in terms of their effect on the CRF estimation, by looking at interim results at various stages of the analysis. Within the EOP we found that ITRF2014 agrees best with DTRF2014, as on one hand ITRF2008 is getting less reliable as time moves on after 2009 and on the other hand JTRF2014 incorporates significant yearly
signals. Additionally we see some artifacts in the JTRF2014 EOP time series, related to TIGO and Tsukuba. We could also detect a dependency on the station networks within the early years. However, any trends that we could find between the time series are, if even significant, in the nas/y, ns/y regime. Further, we noticed significant differences within the setting of the discontinuities, which in case JTRF2014 gives severely wrong station positions for TIGO for two months before the Earthquake. But for almost all major earthquakes, the four investigated TRFs do not set the discontinuities at the same epoch. Within the estimated source time series we did not detect big differences, they mostly range between ±1μas. Generally, when the observations are sparse, the solutions deviate more. Anyhow, within the years 1995—2005 the differences seem to slightly increase for all sources.

In case of estimation scheme (I), i.e. fixation of EOP and station positions, we found that all resulting CRFs show significant rotations, but more important are the biases in declinations and the shifts in both coordinates. In case of ITRF2008 they can again be tracked back to the lack of data after 2008. For DTRF2014 and JTR2014 however, the explanation is not that straight forward. A part might be caused by the differences in origin and the definition of the scale. By plotting the differences in positions of the common sources, the picture gets more detailed. Here we detected significant declination shifts and gradients towards the poles, which commonly are associated with network asymmetries. In our case however, these symmetries must be inherent of the TRFs, as the determination for all CRFs was identical, and thus network effects introduced by our analysis should be canceled out. But also in right ascension we found systematics, most prominently for ITRF2008, which could be followed back to the limited input data. For proper motion we also found systematics, similar to the ones in source position. ITRF2008 shows gradients towards the poles, DTRF2014 distinct behavior depending on the hemisphere, JTRF2014 a more diverse pattern with a weaker hemisphere-dependency.

When estimating station positions together with the sources, the picture changes dramatically. Mostly a zonal pattern can be seen, which might be explained by the increased rotation ad drift parameters. Overall, however, the solutions are profiting from the introduction of the stations, as all the parameters have a reduced wrms. The exclusion of AuScope, or the omission of the data after 2008, however, has no longer an effect, except for ITRF2008.

Concluding we can say, that we found that all TRFs introduce specific systematics to the CRFs. Where for ITRF2008 this is easy to explain, and more of an academic interest, for DTRF2014 and JTRF2014 this is more critical, and cannot easily be dismissed. These systematics can pose a serious problem, when trying to unmask small phenomena, like the secular aberration drift. The effect of the different TRFs on such galactic parameters will be the focus of our next study.

Altogether, ITRF2014 is from the mathematical point of view the most consisted TRF w.r.t. ICRF2, and that fact will also be valid for ICRF3. Simply because for the ICRF3 determination the ITRF2014 is used, as well as a ITRF2014-consistent set of EOP. Unfortunately, at this point it is difficult to nail down the accuracy criteria needed for the reference frames and EOP to be able to reach the GGOS goals. The major drawbacks are
for one the independent determination of the frames and EOP within separate algorithms and estimation schemes. Presently no level of consistency is guaranteed. The solution would be to estimate CRF, TRF and EOP in one monolithic approach. Currently several groups are working on that topic. The second point is, that all radio sources are considered un-moving, hence have time-invariant coordinates. This however, does not apply to reality. We showed in [28] that a parameterization of the source coordinates in form of splines improves the estimated parameters considerably, especially the nutation parameters. The impact on the CRF-determination is currently under evaluation.

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Biography

Maria Karbon obtained her Diploma in Geodesy & Geophysics from the Technische Universität Wien in 2009, where she also worked as a project assistant until the end of 2012 and obtained her PhD. Since 2013, she works as a postdoctoral researcher at the German Research Centre for Geosciences, Potsdam.

Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| AC           | analysis center |
| AuScope      | Australia geodetic VLBI network |
| CRF          | celestial reference frame |
| CRS          | celestial reference system |
| DGFI-TUM     | Deutsches Geodätisches Forschungsinstitut-Technische Universität München |
| DORIS        | Doppler Orbitography and Radiopositioning Integrated by Satellite DTRF20xx: TRF determined by TUM-DGFI |
| EOP          | earth orientation parameter |
| ERP          | earth rotation parameter |
GGFC  global geophysical fluid center
GGOS  global geodetic observing system
GNSS  global navigation satellite system
IAG   International Association of Geodesy
IAU   International Astronomical Union
IGN   Institut national de l’information geographique et forestiere
IUGG  International Union of Geodesy and Geophysics
IVS   International VLBI Service
ICRF  international celestial reference frame
ICRS  international celestial reference system
IERS  international earth rotation service
IRIS  international radio interferometric surveying — IVS session type
      ITRF20xx: international terrestrial reference frame
ITRS  international terrestrial reference system
JPL   jet propulsion laboratory
JTRF2014 TRF determined by JPL
NASA  National Aeronautics and Space Administration
      NEQ: Normal EQuations
NJR   no-net-rotation
NNT   no-net-translation
PSD   post-seismic-deformation
R1/R4 rapid turnaround — IVS session type
R&D   research and development — IVS session type
SLR   satellite laser ranging
TIGO  transportable integrated geodetic observatory
TRF   terrestrial reference frame
TRS   terrestrial reference system
TUM   Technische Universitat München
USNO  United States Naval Observatory
UT1   universal time I
**UTC**  
universal time coordinated

**VLBI**  
very long baseline interferometry

**VTRF**  
VLBI terrestrial reference frame

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Fig 1.
Differences of the estimated EOP, from left to right: in blue ITRF2014—ITRF2008, in red ITRF2014—DTRF2014, in black ITRF2014—JTRF2014.
Fig 2.
Left: Close up of the difference of the x-pol estimates for ITRF2014—ITRF2008 of 1990—1993. The colors indicate different networks and session types. Right: Map with the convex hull of the station networks (modified from ivscc.gsfc.nasa.gov).
Fig 3.
Station coordinates for TIGO, Concepcion given by the various TRFs for the period 01.09.2009—31.06.2010: in blue ITRF2008, in green ITRF2014, in red DTRF2014 and in black JTRF2014. The breaks are marked with vertical lines in the color of the TRF and the according date. The date of the main shock is marked in yellow.
Fig 4.
Residuals of the station coordinates for TIGO in xyz estimated using the various TRFs as a-priori for the period 01.09.2009—31.06.2010: in blue ITRF2008, in green ITRF2014, in red DTRF2014 and in black JTRF2014. The breaks are marked with vertical lines in the color of the TRF.
Fig 5.
On the top left in green the coordinate residuals of datum source 0552 + 398 and in red of special handling source 4C39.25, in black the corresponding half-year mean values. On the bottom the respective differences of the half-year mean values, in blue: ITRF2014—ITRF2008, in red ITRF2014—DTRF2014 and in black ITRF2014—JTRF2014.
Fig 6.
Differences of the estimated source positions, from top to bottom: ITRF2008—ITRF2014 (blue), DTRF2014—ITRF2014 (red), JTRF2014—ITRF2014 (black). The middle column shows the differences in $\alpha \cos(\delta)$ plotted in red if positive, in blue if negative; the right column in $\delta$. The size of the circle is proportional to the magnitude in $\Delta \delta$ and $\Delta \alpha \cos(\delta)$, bubbles of big outliers are excluded.
Fig 7.
Top: The difference between the source positions when excluding all AuScope sessions, bottom: when excluding all sessions after 2008; for ITRF2008—ITRF2014. The middle column shows the differences in $\alpha \cos(\delta)$ plotted in red if positive, in blue if negative; the right column in $\delta$. The size of the circle is proportional to the magnitude in $\Delta \delta$ and $\Delta \alpha \cos(\alpha)$, bubbles of big outliers are excluded.
Fig 8.
Left column: Differences of the estimated proper motions, from top to bottom: ITRF2014 —ITRF2008 (blue), ITRF2014—DTRF2014 (red), ITRF2014—JTRF2014 (black). The middle column shows the differences in $\mu\alpha \cos(\delta)$ plotted in red if positive, in blue if negative; the right column in $\mu\delta$. The size of the circle is proportional to the magnitude in $\mu\delta$ and $\mu\alpha \cos(\delta)$, bubbles of big outliers are excluded.
Fig 9.
Differences of the estimated source positions, from top to bottom: ITRF2008—ITRF2014 (blue), DTRF2014—ITRF2014 (red), JTRF2014—ITRF2014 (black). The middle column shows the differences in $\alpha \cos(\delta)$ plotted in red if positive, in blue if negative; the right column in $\delta$. The size of the circle is proportional to the magnitude in $\Delta \delta$ and $\Delta \alpha \cos(\delta)$, bubbles of big outliers are excluded.
Fig 10.
Left column: Differences of the estimated proper motions, from top to bottom: ITRF2014—ITRF2008 (blue), ITRF2014—DTRF2014 (red), ITRF2014—JTRF2014 (black). The middle column shows the differences in $\alpha \cos(\delta)$ plotted in red if positive, in blue if negative; the right column in $\delta$. The size of the circle is proportional to the magnitude in $\mu_\delta$ and $\alpha \cos(\delta)$, bubbles of big outliers are excluded.
Table 1
Transformation parameters at epoch 2010.0 and their rates from ITRF2014 to ITRF2008, units are mm for the translations and mm/yr for 2010. The values in parentheses are the 1-sigma formal errors.

|     | $T_x$  | $T_y$  | $T_z$  | $S$    | $R_x$  | $R_y$  | $R_z$  |
|-----|--------|--------|--------|--------|--------|--------|--------|
| Offset | 1.6 (0.2) | 1.9 (0.1) | 2.4 (0.1) | -0.02 (0.02) | 0.00 (0.06) | 0.00 (0.06) | 0.00 (0.06) |
| Rate   | 0.0 (0.2) | 0.0 (0.1) | -0.1 (0.1) | 0.03 (0.02) | 0.00 (0.06) | 0.00 (0.06) | 0.00 (0.06) |
Table 2

Helmert transformation parameters mapping ITRF2014 to JTRF2014, units are mm for the translations and mm/yr for the rate, mas and mas/yr for the rotation angles and their rates. The scale is given in part-per-billion (ppb) and ppb/year, respectively. The reference epoch is January 1, 2005. The values in parentheses are the 1-sigma formal errors.

|       | $T_x$      | $T_y$      | $T_z$      | $S$       | $R_x$      | $R_y$      | $R_z$      |
|-------|------------|------------|------------|-----------|------------|------------|------------|
| Offset| $-0.57$ (0.03) | $-0.03$ (0.03) | $-1.48$ (0.04) | $-1.64$ (0.06) | $0.57$ (0.02) | $0.75$ (0.02) | $0.25$ (0.02) |
| Rate  | $-0.12$ (0.01) | $-0.04$ (0.01) | $0.19$ (0.01) | $0.20$ (0.01) | $0.11$ (0.00) | $-0.09$ (0.00) | $-0.17$ (0.00) |
### Table 3
Parameterization, models, and a-priori of the analysis.

| Parameters                  | Estimation                      | Models and frames | Single session | Global solution |
|-----------------------------|---------------------------------|-------------------|----------------|-----------------|
|                             |                                 | (I)               | (II)           |                 |
| Station positions           | 24 h                            | Fixed             | Reduced        |
| Station velocities          | —                               | Fixed             | Fixed          |
| Source positions            | 24 h                            | Global            | Global         |
| Proper motions              | —                               | Global            | Global         |
| EOP                         | 24 h                            | Fixed             | Reduced        |
| Clock parameters            | 1 h                             | Reduced           | Reduced        |
| ZWD & gradients             | 1h & 6h                         | Reduced           | Reduced        |
| CRF                         | ICRF2                           |                   |                |
| EOP                         | USNO finals + effect of ocean tides and libration on ERP |                   |                |
| Precession/nutation model   | IAU 2006/2000A [5,6] incl. FCN |                   |                |
| Atm. tidal loading          | APL [18]                        |                   |                |
| Ocean tidal loading         | FES2004 [19]                    |                   |                |
| A-priori tropospheric gradients | DAO [20]                   |                   |                |
| Mapping functions           | VMF1 [21]                       |                   |                |
### Table 4

Weighted RMS w.r.t. ITRF2014, linear trends of the differences of the time series for x- and y-pol, dUT1 and the celestial pole offsets $\delta X$ and $\delta Y$. In parentheses the p-value for a significantly non-zero slope ($p < 0.05$: trend is statistically significant).

|            | $\Delta$ITRF2008 | $\Delta$DTRF2014 | $\Delta$JTRF2014 |
|------------|------------------|------------------|------------------|
| **x-pol**  |                  |                  |                  |
| wrms [mas] | 0.373            | 0.004            | 2.819            |
| trend [nas/y] | $-2$ (0.82)   | $-14$ (<2e$^{-19}$) | $-35$ (0.027)   |
| **y-pol**  |                  |                  |                  |
| wrms [mas] | 0.180            | 0.002            | 0.347            |
| trend [nas/y] | $-44$ (0.05)  | $-7$ (<2e$^{-6}$) | $1$ (0.91)      |
| **dUT1**   |                  |                  |                  |
| wrms [μs]  | 2.29             | 0.10             | 7.37             |
| trend [ns/y] | $-1.1$ (0.11)  | $-0.7$ (<1e$^{-12}$) | $-1.9$ (0.013) |
| **$\delta X$** |             |                  |                  |
| wrms [nas] | 10.89            | 0.09             | 2.01             |
| trend [nas/y] | 0.02 (0.74)    | $<3e^{-4}$ (0.98) | 0.16 (0.09)     |
| **$\delta Y$** |             |                  |                  |
| wrms [nas] | 6.68             | 0.11             | 0.54             |
| trend [nas/y] | 0 (0.87)       | 0 (0.6)          | $-0.07$ (0.22)  |
Table 5
Relative orientation and deformation parameters between ITRF2014 w.r.t. ITRF2008, DTRF2014 and JTRF2014 solutions. All units are μas except for Dα and Dδ which are in μas/rad. wrmsα and wrmsδ are the weighted RMS of the residuals in α cos δ and δ in mas, wrmsμα and wrmsμδ the weighted RMS of the estimated proper motions in mas/y, respectively. Estimation scheme (I).

|               | A1     | A2     | A3     | Dα     | Dδ     | Bδ     | wrmsα  | wrmsδ  | wrmsμα | wrmsμδ |
|---------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| ITRF2008      | -148.71| -195.81| 88.76  | 575.03 | -205.43| 219.08 | 22.98  | 12.86  | 2.45   | 9.72   |
| σ             | 210.96 | 204.99 | 174.78 | 287.74 | 288.66 | 174.68 |        |        |        |        |
| DTRF2014      | -5.69  | 15.02  | -23.61 | 84.03  | 71.89  | -131.47| 3.45   | 9.67   | 2.03   | 0.02   |
| σ             | 23.64  | 22.97  | 19.59  | 32.25  | 32.35  | 19.58  |        |        |        |        |
| JTRF2014      | -136.14| -40.01 | -107.81| -220.51| 87.47  | -166.03| 1.64   | 5.78   | 0.03   | 0.39   |
| σ             | 66.17  | 64.31  | 54.82  | 90.26  | 90.55  | 54.79  |        |        |        |        |
Table 6
Weighted RMS of the differences between ITRF2014 w.r.t. ITRF2008, DTRF2014 and JTRF2014 for the positive and negative values in Fig. 6 (positions [mas]) and Fig. 8 (proper motions [mas/y]). The value in parenthesis gives the number of sources in %. Estimation scheme (I).

|                          | wrms(Δα cos δ) | wrms(Δδ) |
|--------------------------|----------------|----------|
|                          | Red            | Blue     | Red            | Blue     |
| ITRF2008                 | 0.534 (72)     | 0.196 (28) | 0.004 (23)     | 0.020 (77) |
| μα,δ                     | 0.114 (46)     | 0.021 (54) | 0.009 (98)     | 1.51e⁻⁴ (2) |
| ITRF2008_WeAuScope       | 0.484 (62)     | 0.109 (38) | 0.003 (29)     | 0.013 (71) |
| μα,δ                     | 0.046 (15)     | 0.071 (85) | 0.007 (97)     | 2.78e⁻⁴ (4) |
| ITRF2008_short           | 0.205 (7)      | 0.054 (93) | 1.77e⁻⁴ (74)   | 7.38e⁻⁴ (26) |
| μα,δ                     | 0.040 (10)     | 0.011 (90) | 4.02e⁻⁵ (88)   | 3.89e⁻⁵ (14) |
| DTRF2014                 | 0.056 (98)     | 0.012 (2)  | 0.009 (99)     | 9.92e⁻⁵ (0.2) |
| μα,δ                     | 0.003 (3)      | 0.005 (97) | 1.59e⁻⁶ (73)   | 5.45e⁻⁶ (27) |
| JTRF2014                 | 0.041 (75)     | 0.092 (25) | 0.016 (97)     | 0.079 (3)  |
| μα,δ                     | 0.039 (35)     | 0.005 (65) | 4.02e⁻⁴ (44)   | 3.58e⁻⁴ (56) |
### Table 7

Relative orientation and deformation parameters between the ITRF2014 and the ITRF2008, DTRF2014 and JTRF2014 solutions. All units are μas except for $D_\alpha$ and $D_\delta$ which are in μas/rad. wrms$_\alpha$ and wrms$_\delta$ are the weighted RMS of the residuals in $\alpha \cos \delta$ and $\delta$ in mas, wrms$_{\mu \alpha}$cos(δ) and wrms$_{\mu \delta}$ the weighted RMS of the estimated proper motions in mas/y respectively. Estimation scheme (II).

|       | $A_1$ | $A_2$ | $A_3$ | $D_\alpha$ | $D_\delta$ | $B_\delta$ | wrms$_\alpha$ | wrms$_\delta$ | wrms$_{\mu \alpha}$ | wrms$_{\mu \delta}$ |
|-------|-------|-------|-------|------------|------------|------------|---------------|---------------|-------------------|-------------------|
| ITRF2008 | −75.65 | −136.53 | 133.30 | 432.80 | −363.73 | 131.97 | 4.94e−5 | 9.65e−5 | 4.94e−5 | 8.96e−5 |
| $\sigma$ | 64.62 | 61.27 | 80.52 | 124.32 | 124.11 | 80.38 | |
| DTRF2014 | −18.40 | −112.01 | 116.93 | 473.03 | −618.56 | 404.93 | 0.009 | 0.027 | 0.009 | 6.94e−4 |
| $\sigma$ | 100.21 | 95.01 | 124.86 | 192.78 | 192.45 | 124.64 | |
| JTRF2014 | −89.05 | −123.37 | 69.79 | 538.22 | −365.13 | 112.49 | 0.012 | 0.006 | 0.012 | 3.67e−5 |
| $\sigma$ | 65.99 | 62.57 | 82.23 | 126.96 | 126.74 | 82.08 | |
Table 8

Weighted RMS of the differences between ITRF2014 and ITRF2008, DTRF2014 and JTRF2014 for the positive and negative values in Fig. 9 (positions [mas]) and Fig. 10 (proper motions [mas/y]). The value in parenthesis gives the number of sources in %. Estimation scheme (II).

|          | wrms (Δα cos δ) | wrms (Δδ) |
|----------|----------------|-----------|
|          | Red           | Blue      | Red     | Blue     |
| ITRF2008 | 0.008 (91)    | 0.006 (9) | 6.08e⁻⁵ (25) | 3.64e⁻⁵ (75) |
| μα/δ     | 5.36e⁻⁴ (20)  | 9.01e⁻⁴ (80) | 3.27e⁻⁷ (81) | 2.49e⁻⁷ (19) |
| DTRF2014 | 0.120 (27)    | 0.108 (73) | 0.016 (22) | 0.009 (78) |
| μα/δ     | 0.017 (65)    | 0.016 (35) | 1.42e⁻⁴ (93) | 1.32e⁻⁴ (7) |
| JTRF2014 | 0.066 (3)     | 0.104 (97) | 0.003 (72) | 0.005 (28) |
| μα/δ     | 0.009 (96)    | 0.011 (4) | 2.45e⁻⁵ (54) | 1.77e⁻⁵ (46) |