3.3 Analysis Coordinator

Introduction

This is my first annual report as IERS Analysis Coordinator and I would like to express my thanks to the former Analysis Coordinator Thomas Herring from MIT EAPS for excellently serving the IERS.

In this annual report, I will address an assessment of the current consistency of IERS EOP products. The transformation between International Celestial Reference System ICRS (Arias et al., 1995) and International Terrestrial Reference System ITRS (IUGG Resolution 2, 2007[1]) is important for many scientific and societal applications. It consists of two parts. The more prominent part is referred to as Earth Orientation based on the Earth Orientation Parameters EOP that contribute to the arguments of 3d rotation matrices. The other part contains the geodesic rotations due to the different dynamics of Solar System Barycenter SSB and Geocenter expressed through the Barycentric Celestial Reference System BCRS to Geocentric Celestial Reference System GCRS transformation (IAU Resolution B1.3, 2000[2]) in a space-time context. If the latter is properly considered, the EOP of Very Long Baseline Interferometry VLBI and of satellite-based space geodetic techniques, such as Global Navigation Satellite Systems GNSS, Satellite Laser Ranging SLR and Doppler Orbitography and Radio Positioning Integrated by Satellite DORIS, coincide. The rotational effects that arise from the BCRS –> GCRS transformation are known as geodesic precession and nutation and are considered by the current precession and nutation models of IAU. Therefore, EOP from various space geodetic techniques should be unbiased and thus can be compared and combined. The EOP are a set of five parameters (dX, dY, $ERA \sim UT1$, x_p, y_p) that express the orientational difference of co-located CRS and TRS in terms of spatial rotations. While polar motion PM and ERA are absolute quantities, the celestial pole offsets dX, dY are corrections to the celestial pole coordinates (X, Y) obtained from the IAU precession-nutation models.

The theoretical implications are clear, but the practical realization, i.e. when systems are realized through frames, adds more complexity. The realization of ICRS is currently ICRF2 (IAU Res. B3, 2009[3]; Fey et al., 2015) and the realization of ITRS is ITRF2014 (Altamimi et al., 2016). Both frames, ICRF2 and ITRF2014, can be directly accessed by VLBI and hence, VLBI is a suitable tool to assess the consistency of the two frames directly and without assumptions. The assessment, however, is of course only as precise as VLBI analyses can deliver.

The axes directions of ICRF2 (at J2000.0 $=$ 2000-01-01 12:00 TT, e_1 is pointing to the vernal equinox, e_3 points to the celestial pole and

[1] http://www.iugg.org/resolutions/perugia07.pdf

[2] https://www.iau.org/static/resolutions/IAU2000_French.pdf

[3] https://www.iau.org/static/resolutions/IAU2009_English.pdf

$e_2 = e_3 \times e_1$) are obtained applying a series of processes. Within the corresponding ICRF2 Working Group the VLBI solution gsf008a was selected. This solution, gsf008a, was obtained with no net rotation NNR condition on ICRF1 involving a number of sources in common with ICRF1 (Ma et al., 1998). Thereafter, the resulting CRF was rotated onto ICRF-Ext.2 (Fey et al., 2004) using 138 radio sources in common with gsf008a-CRF. The result of which became ICRF2 by decision of the IAU General Assembly.

The axes directions of ITRF2014 (at 2010.0, e_1 points to the intersection of the terrestrial equator and the prime meridian of zero longitude, e_3 coincides with the mean pole of the Earth rotation axis and $e_2 = e_3 \times e_1$) were established within a multi-technique combination of data from the space geodetic techniques VLBI, GNSS, SLR and DORIS mentioned before. The orientation was formed by applying NNR on positions (at 2010.0) and velocities of 125 predominantly GNSS sites. In the combination process of the site coordinates, PM offsets were combined across all four techniques, whereas PM rates just involved the two techniques GNSS and VLBI. UT1 and LOD were adjusted as well but from VLBI data only and CPO were not adjusted but fixed to the values that were provided by the intra-technique combined VLBI solution, which also fixed the positions of radio sources to the ICRF2 coordinates.

Comparison of EOP when fixing or adjusting radio source coordinates

In this small study I address the effects of fixing radio source coordinates to ICRF2 (the approach taken for ITRF2014 computation) vs. taking a priori coordinates from ICRF2 plus estimating adjustments to radio source coordinates (common practice of VLBI analyses).

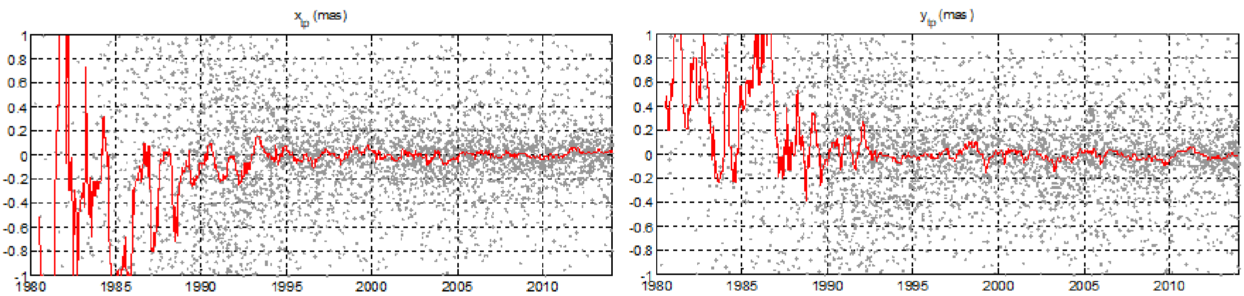

Fig. 1: *PM differences of two VLBI solutions, one with radio source coordinates fixed on ICRF2 and one with a priori values from ICRF2 and radio source coordinates estimated. The grey dots are the session-wise results and the red line shows a moving median.*

The values reported in Table 1 are obtained ignoring the data points before 1993.0. About at this time (1993.0) the VLBI technology and scheduling significantly advanced leading to more stable results than before. The shifts and drifts are not exceeding the current quality targets of geodetic VLBI for EOP, which are an accuracy of 33 μas and stability

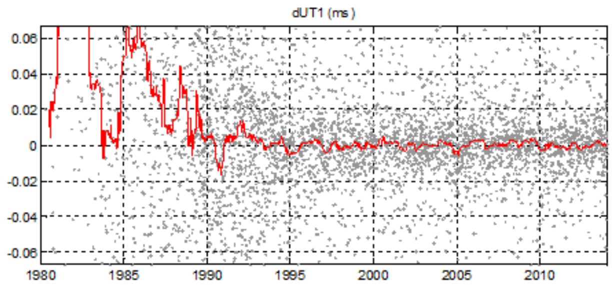

Fig. 2: *dUT1 differences of two VLBI solutions, one with radio source coordinates fixed on ICRF2 and one with a priori values from ICRF2 and radio source coordinates estimated.*

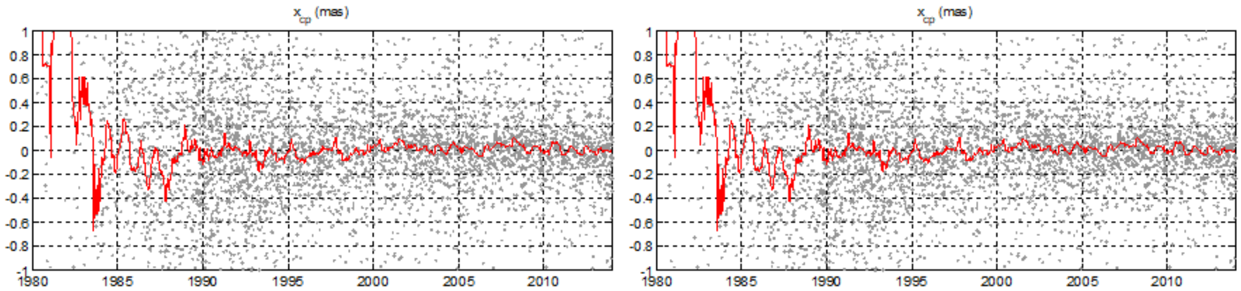

Fig. 3: *CPO differences of two VLBI solutions, one with radio source coordinates fixed on ICRF2 and one with a priori values from ICRF2 and radio source coordinates estimated.*

of 3.3 $\mu as \cdot y^{-1}$. I do not generally recommend to ignore VLBI data prior to 1993.0. With appropriate formal errors, the VLBI data prior to 1993.0 do provide important information about Earth rotation, radio source and point positions during the earlier years before the availability of the GNSS and DORIS techniques. I only discard the data points for the computation of shift and drift, which otherwise would be affected considerably, in particular as these data points are at the edge of the data set.

Table 1: *Shift and drift between two VLBI solutions, one with radio source coordinates fixed on ICRF2 and one with a priori values from ICRF2 and radio source coordinates estimated. dUT1 is given in μas for better comparison with the other EOP.*

parameters	**shift (μas)**	**drift ($\mu as \cdot y^{-1}$)**	**RMS (μas)**
x_p	-5.8	1.0	282.6
y_p	-14.7	-0.2	307.0
$dUT1$	-5.8	2.2	269.3
dX	-3.7	0.3	281.3
dY	-8.3	0.0	254.4

Comparison of input data of ITRF2014 and ICRF2

The input data used for the calculation of ITRF2014 were

- session-wise VLBI data of IVS between 1980.0 and 2015.0,
- GNSS data of IGS with daily resolution between 1994.0 and 2015.1,
- SLR data of ILRS with weekly / fortnightly resolution between 1983.0 and 2015.0,
- DORIS data of IDS with weekly resolution between 1993.0 and 2015.0, and
- epochal local tie vectors at co-location sites.

All input data series are intra-technique combined data sets provided by the respective technique combination centers. The pre-combined solutions are based on a variety of VLBI data analysis software. For ICRF2 only session-wise VLBI data of IVS was used between August 1979 and April 2009. The VLBI data input was an individual solution, no combination and hence, a single VLBI data analysis software was used. Accordingly, ITRF2014 and ICRF2 differ very much in terms of input data. EOP that refer to ITRF2014 and ICRF2 link two reference frames to each other that are obtained using very different input data. From the point of view of the input data, ITRF2014 and ICRF2 cannot be consistent. The two frames can still be connected to each other through the set of transformations mentioned above. The procedure with the daily average EOP can still be applied, but these parameters have a limited scientific meaning only as the reference frames that are linked are inconsistent.

In order to assess the effect of the different input data, two VLBI solutions are compared, one solution fixes the station coordinates to ITRF2014 (the inter-technique combined frame), the other solution to VTRF2014 (Bachmann et al., 2016). VTRF2014 is a TRF determined by VLBI data only but from the same input data forwarded to the ITRF2014 combination. Accordingly, VTRF2014 and ITRF2014 most of all differ in terms of geodetic datum. The origin of VTRF2014 is taken over from ITRF because VLBI is insensitive to the exact position of the origin of the coordinate system. The network scale parameters of VTRF2014 and ITRF2014 differ, however, this does not affect rotations. The following figures show the EOP differences between these solutions. When ignoring data points before 1993.0, the differences in the x_p components are small and stable, whereas the y_p components show a linear trend. The linear drift determined by regression indicates this as well (Table. 2).

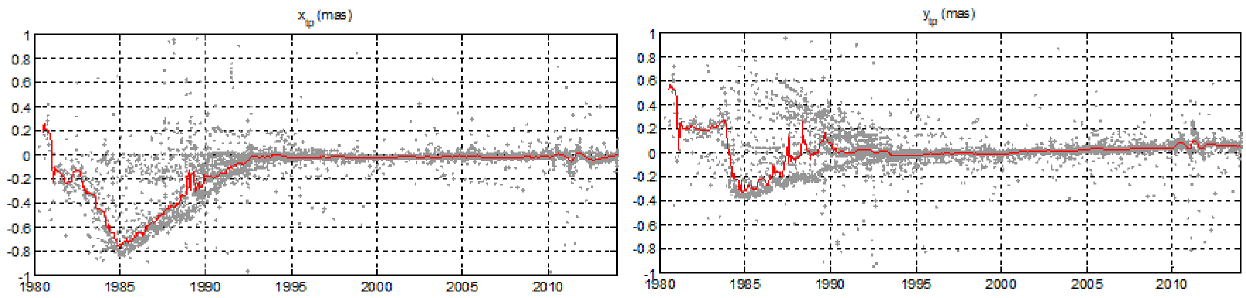

Fig. 4: *PM differences of two VLBI solutions, one with station coordinates fixed on ITRF2014 and one with station coordinates fixed on VTRF2014.*

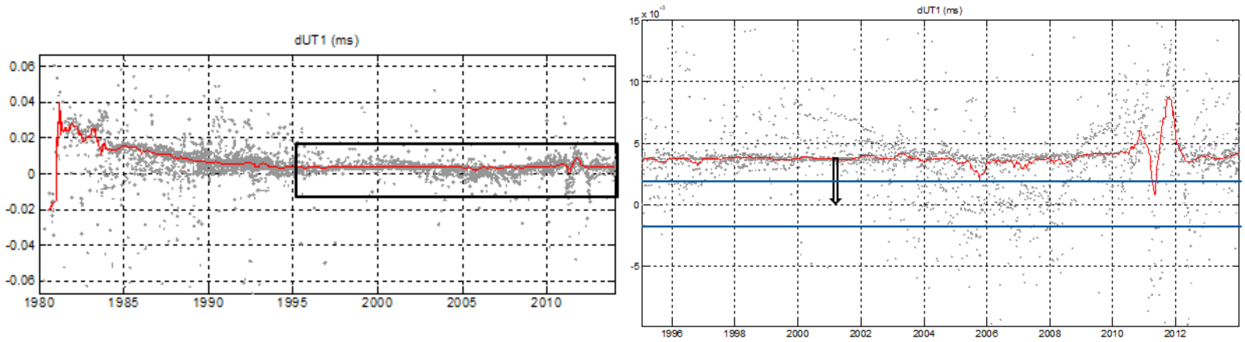

Fig. 5: *dUT1 differences of two VLBI solutions, one with station coordinates fixed on ITRF2014 and one with station coordinates fixed on VTRF2014. The black rectangle in the left panel indicates the area that is displayed with a zoom factor on the right. The two blue horizontal lines inserted at $\pm 33 \mu as$ visualize the desired quality level w.r.t. a constant shift, which is clearly exceeded (black arrow). The wavelet-like difference around the year 2011 is caused by different modeling of co- and post-seismic effects of the Tōhoku megathrust quake on 2011-03-11. As long as station coordinates are estimated, the differences play no role.*

Table 2: *Shift and drift between two VLBI solutions, one with station coordinates fixed on ITRF2014 and one with station coordinates fixed on VTRF2014.*

parameters	**shift** (μas)	**drift** ($\mu as \cdot y^{-1}$)	**RMS** (μas)
x_p	-16.6	-0.2	67.3
y_p	4.3	3.3	81.3
$dUT1$	57.3	-1.3	85.5
dX	-0.1	-0.0	11.7
dY	-0.2	0.0	8.3

The systematic effects on the CPO are insignificant (Table 2). The CPO RMS (11.7 μas, 8.3 μas) are also very small at the level of the assumed axes stability of ICRF2 of 10 μas. When applying different terrestrial reference frames, there is no significant effect on CPO, but the $dUT1$ can be distorted. The differences in phase of Earth rotation $dUT1$ are stable around 57.3 μas an equivalent of almost 2 mm on the Earth surface.

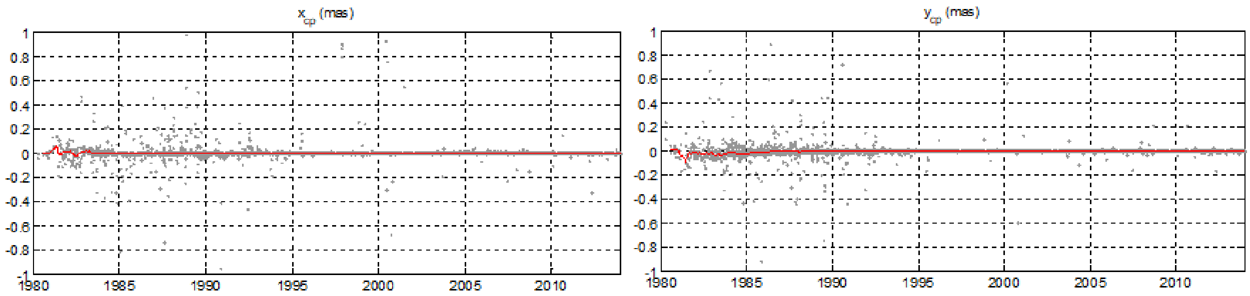

Fig. 6: *CPO differences of two VLBI solutions, one with station coordinates fixed on ITRF2014 and one with station coordinates fixed on VTRF2014.*

The realization of the reference frame orientation by VLBI (VTRF2014) and by multi-technique combination (for ITRF2014 the orientation is realized mainly through GNSS sites) results in a systematic shift of $dUT1$. The identified dUT1 offset could be a consequence of a small rotation of the VLBI subnetwork w.r.t. the NNR datum stations of ITRF. My recommendation to the IERS ITRS combination centers here would be to check whether the choice of common stations used for the no net rotation (NNR) condition for ITRF does also stop the rotation for each of the involved four space geodetic techniques subnetworks precisely and free of bias.

Comparison of analytical models of ITRF2014 and ICRF2

The models used for the data analysis leading to ITRF2014 and ICRF2, respectively, are compared in this chapter.

- IERS Conventions: basically, ITRF2014 applied IERS Conventions 2010 (Petit & Luzum, 2010), whereas ICRF2 adheres to IERS Conventions 2003 (McCarthy & Petit, 2004).
- Atmospheric pressure loading: for ITRF2014 tidal atmospheric loading was used; for ICRF2 tidal and non-tidal.
- Ocean tidal loading: the correction is applied for both reference frames but based on different tide models.
- Ocean pole tide loading: this model was introduced in IERS Conventions 2010. It is applied for ITRF2014 computation, but disregarded for ICRF2.
- Pole tide loading: the correction is applied for both reference frames but based on different mean pole models.
- Ephemerides: for ITRF2014 it is DE 421, whereas for ICRF2 it is DE 405.
- Cut off elevation angle: is not applied for ITRF2014, but for ICRF2 it is applied.

- Tidal variations of Earth rotation: the tidal corrections are applied for both reference frames; for ITRF2014, however, additional long-periodic ocean tidal effects on PM are considered.

Accordingly, ITRF2014 and ICRF2 substantially differ in terms of model application. The differences caused by these individual model choices should be assessed in order to quantify the level of inconsistency between ICRF2 and ITRF2014.

Summary, Conclusions & Outlook

I partly assessed the inconsistency of ICRF2 and ITRF2014 directly by comparing results of VLBI data analyses. The assessment is therefore limited to the quality of the VLBI data analysis. In the tests, CPO were affected insignificantly, whereas Earth Rotation Parameters, PM and $dUT1$, partly show considerable systematics. Prior to 1993.0, VLBI shows larger deviations of ERP likely because of the VLBI networks. The number of stations and radio sources included in earlier sessions is smaller (Fig. 7). The other very likely reason is that the ITRF orientation is mainly based on GNSS stations, what can cause small but significant shifts in comparison to an orientation based on VLBI only, in particular because GNSS data is only included after 1994.0. The offset we found between the VLBI-only and the primarily GNSS-based $dUT1$ should be investigated in more detail, in particular because $dUT1$ is effectively taken over from VLBI into the ITRF computation, what might create inconsistency between the ITRF and $dUT1$.

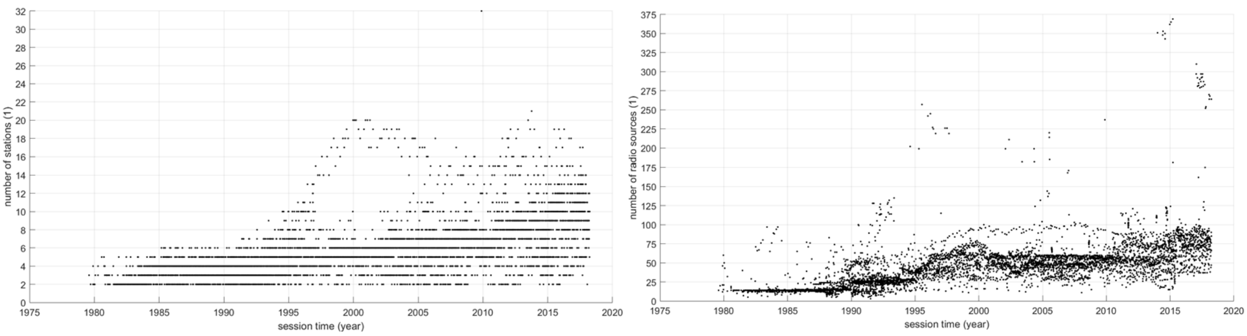

Fig. 7: *Number of stations (left panel) and number of radio sources (right panel) that effectively took part in IVS 24h sessions.*

Any inconsistencies of the terrestrial and celestial reference frames are inevitably applying to the EOP. The most consistent EOP can thus only be obtained together with TRF and CRF in a single solution based on the same input data and analytical models. Such a solution allows also the stochastic models of terrestrial and celestial parts to interact with each other, leading to consistent and comparable formal errors of station coordinates, radio source coordinates, and EOP.

The inconsistencies between terrestrial and celestial reference frames are assumed small, but they are unavoidable following the currently applied realization procedure. For a user, who is just interested in carrying out the ICRF2 to ITRF2014 transformation or vice versa, they do probably not matter at all. For scientific applications, however, the inconsistency of the two reference frames and the EOP is of very high relevance because it has the potential to affect scientific results and their interpretation. Among the scientific topics that are likely to be affected through reference frame inconsistencies are the interaction of terrestrial and celestial reference frames and EOP interpretation for geoscientific or climate studies. Utilizing inconsistent EOP series for validation purposes is highly questionable as well.

Concluding, more efforts need to be made for the quantification of the inconsistency of the current conventional reference frames and EOP. This will be the mission of the IERS Analysis Coordinator in the upcoming term.

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