Comments on the VLBI connection between celestial and terrestrial reference frames by means of sidereal time

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Abstract. Causes of inaccurate or instable connection of the celestial and terrestrial VLBI reference frames via sidereal time are reviewed. Their effects after 1990 are in the range 5-10 μs in the short term, 2-7 μs year to year, with expected biases at the 2-5 μs level and spurious drifts smaller than 1 μs/year.

1 Introduction

In the international multi-technique project for measuring the Earth's rotation and deformations, VLBI has the unique role of providing the sidereal reference that is not accessible to the satellite-based techniques. The primary Earth Rotation Parameter (EOP) involved is Universal time UT1-TAI, a measure of the progressive departure of sidereal time with atomic time. In addition to providing the link between the terrestrial (rotating) and the celestial (inertial) reference frames, UT1 measurements provide global information on the dynamics of the various layer of our planet, from the liquid core to the upper atmosphere.

The celestial reference frame (CRF) is materialized by the equatorial coordinates of a set of extragalactic radio sources. Most objects exhibit time variations of their position in some preferred direction (Feissel-Vernier, 2003, 2005a). This is illustrated in Figure 1, which shows the envelopes of the standard deviation of yearly weighted average source positions in local equatorial frames for the most stable sources. The deficiency of sources south of declination -30^o is an effect of their relatively sparse observation history due the biased network distribution.

The terrestrial reference frame (TRF) is materialized by the cartesian coordinates of the position and velocity of the world VLBI network shown on figure 2. The most striking feature of the VLBI antenna network is its non-uniformity. The set of station positions and velocities that can

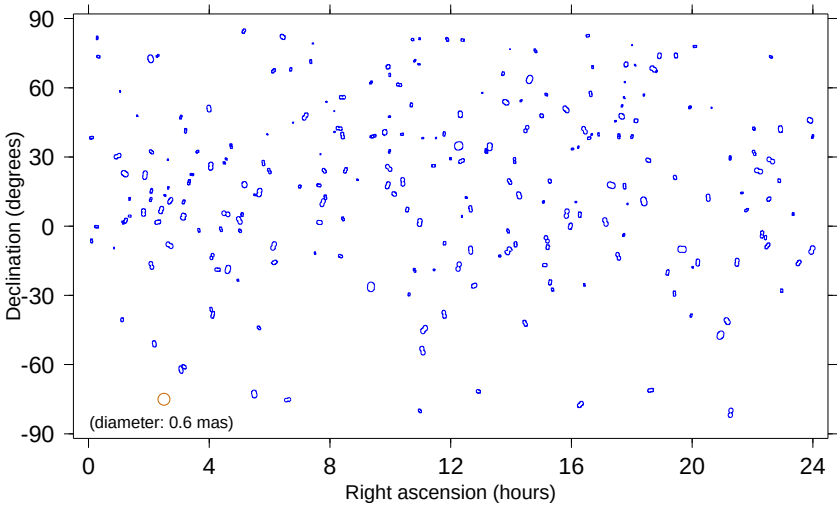

Fig. 1. Map of 245 well-observed radio sources (1989.5-2002.4) with one-year standard deviations smaller than 0.35 mas. Envelopes show the standard deviation of the yearly average coordinates in local equatorial frames ($\alpha \cos\delta$, δ).

be derived from long series of observations will not be perfectly uncorrelated. In addition, the network is normally not used in its entierety. In practice, the CRF-TRF link is implemented by series of 24-hour VLBI sessions involving 4-6 stations sampling a part of the network. On account of this weak geometrical coverage, correlations among EOP estimates can often exceed 0.5. For instance, the weekly IVS R4 network (see section 4) normally has a correlation coefficient between UT1 and polar motion X of about -0.6.

These imperfections of the realization of the celestial and terrestrial reference frames give rise to defects in the estimation of UT1. Various possible causes of inacuracy are reviewed. These concern data analysis options (section 2), the influence of the TRF and CRF incinsistencies (section 3), and the consequences of the observing strategy (section 4).

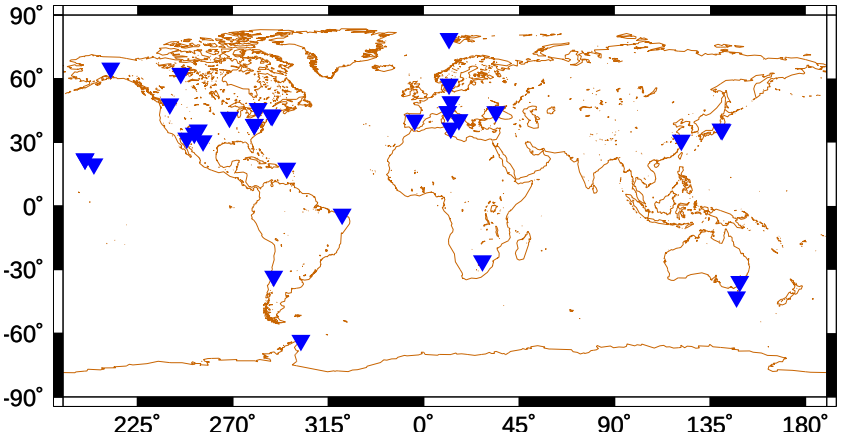

Fig. 2. Geodetic VLBI network.

2 Impact of TRF analysis status

The analysis strategies for deriving a celestial reference frame from multi-year VLBI observations include a number of choices. We consider here choices that concern the definition of the celestial and terrestrial reference frames and their connection in time. Two different approaches are used, as follows.

- In order to free the celestial frame solution from systematic errors that may be propagated from terrestrial network deficiencies, the so-called **CRF** approach was used in the derivation of the ICRF and its extensions (Ma et al., 1998; Fey et al., 2004). The stations positions are set as *arc parameters*, i.e., they are estimated independently for each observing session. Polar motion and universal time are not estimated but nutation corrections (celestial pole offsets) are obtained.
- In the so-called **TRF** approach, most station positions and velocities are set as *global parameters*, i.e. considered as valid over the total data span. Polar motion, universal time and nutation corrections are estimated for each session.

We investigate this possible contamination using test solutions based on the 1980.0-2002.7 data, described in table 1. Data analysis was performed at GSFC with the CALC-SOLVE software package. See Feissel-Vernier et al., 2005b) for more detail. The identification of stable sources is described by Feissel-Vernier (2003). The results considered are the celestial reference frames on the one hand, and the time series of UT1-TAI on the other hand.

Table 1. Test solutions: status of the sources (Global or Arc) and category of sources considered to define the orientation of the frame (No-net-rotation).

Frame	Arc sources	Global sources	No-net-rotation
TRF approach			
cne	unstable	all others	stable
cn7	none	all	ICRF *defining*
CRF approach			
cnh	unstable	all others	stable
cn8	none	all	ICRF *defining*

In order to test the possible perturbation of the orientation of the celestial reference frame due to the consideration of a global terrestrial frame, i.e. one set of station positions and velocities, we compute the relative orientations of pairs of celestial frames obtained with the same source categorization, with the **TRF** and the **CRF** approach.

The relative orientation of two celestial reference frames is modeled by three rotation angles A_1, A_2, A_3 around the axes of the equatorial coordinate system. These angles are estimated using equations (1) and (2), where α, δ are the source coordinates and $\Delta\alpha$, $\Delta\delta$ are the differences of coordinates in the two frames.

$$\Delta\alpha = A_1 \tan\delta \cos\alpha + A_2 \tan\delta \sin\alpha - A_3 \quad (1)$$

$$\Delta\delta = -A_1 \sin\alpha + A_2 \cos\alpha \quad (2)$$

The relative A_3 angles between pairs of celestial reference frames are given in table 2, for the two pairs of of celestial frames described in table 1. The inconsistency of the axes definition between the **TRF** and **CRF** approaches is at the level of 2 μas only (about 0.1 μs).

Table 2. Relative A_3 rotation angles of celestial reference frames obtained respectively with the **TRF** and **CRF** approaches, considering either the stable sources or the conventional defining ones.

Pair	A_3 (μas)
Reference: Stable sources	
cne-cnh	-2.3 ± 0.6
Reference: *Defining* sources	
cn7-cn8	1.7 ± 1.4

3 Sensitivity to consistency of the CRF and TRF

3.1 Internal inconsistencies of the TRF

The instability of a part of the sources in the CRF have been shown to give rise to slightly significant changes in the derived precession and nutation parameters (Feissel-Vernier et al., 2004). We study here the impact of source selection on UT1.

Possible contamination of the stability of the origin of right ascensions by the source instability may be estimated from differences between series of UT1-TAI referred to all sources (*cn7*) or to the stable ones only (*cne*). When modelling these differences over 1990-2002 as a linear variation one finds a bias of 4.7 ± 0.1 μs at J2000.0, a drift of -0.82 ± 0.02 μs/year, and an rms residual of 3 μs for one session.

3.2 Internal inconsistencies of the TRF

Feissel-Vernier et al. (2004) studied how the distribution of the stations that sample the VLBI TRF from year to year may impact UT1, using two different combinations of unconstrained session solutions for station coordinates and EOPs together with the full covariance matrices (SINEX files). The global combination of these parameters in a unique terrestrial reference frame is done using the CATREF (Combination and Analysis of Terrestrial REference Frames) software (Altamimi et al., 2002). The datum definition attaches the results to ITRF2000 using a subset of stations that are judged reliable over the data span considered. Two combination strategies were compared: 1) a global analysis over 1990-2003, using an appropriate set of long-term reliable stations for the datum definition; 2) yearly analyses, with different suitable sets of datum stations for each year.

The UT1 differences derived from the two approaches are plotted in Figure 3 in the form of yearly weighted averages. The year-to-year EOP changes, which increase after 1996, are significant with respect to their internal consistencies, reaching the few-mm level for rotation on the Earth's surface. The pre-1995 TRF effect is comparable in size with the CRF effect, at the level of a few μs. When modelling these differences over 1990-2002 as a linear variation one finds a bias of 3.6 ± 0.7 μs at J2000.0, a drift of $+0.54 \pm 0.16$ μs/year, and an rms residual of 2.4 μs for one year. These effects presumably reflect mostly inconsistencies with the VLBI terrestrial frame and weaknesses in the longer-term interconnection of the network.

The annual averages of the rotation angle A3 of yearly celestial reference frames from a similar computation are also included in the figure, as errors in UT1 may result from either terrestrial or celestial frame axial instabilities. When modelling these differences over 1990-2002 as a linear variation one finds a bias of 0.4 ± 0.3 μs at J2000.0, a drift of $+0.02 \pm 0.07$ μs/year, and an rms residual of 0.7 μs for one year.

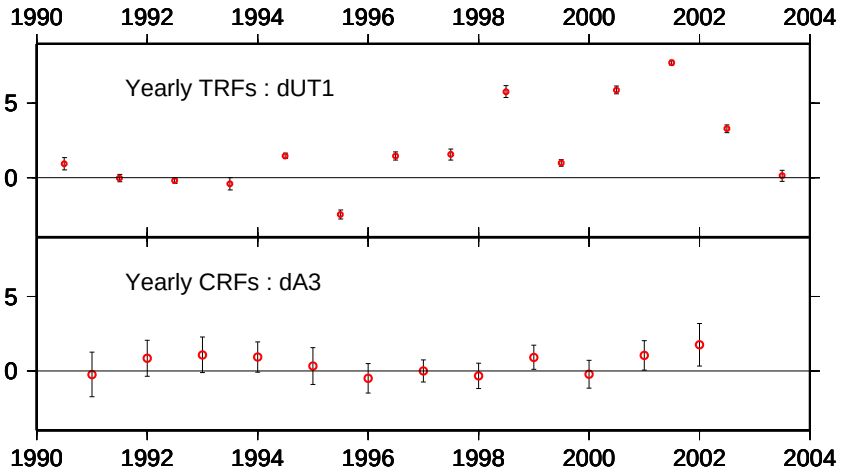

Fig. 3. Yearly average UT1 differences between solutions with the ITRF2000 tie performed separately each year and globally over 1990-2003. Similar variations of the axial rotation of yearly celestial reference frames are shown in the bottom. Unit: μs

4 Impact of the observing strategy

In this section we give two examples of short term effects of internal TRF inconsistencies associated with the VLBI TRF defects.

- The first example, taken from Feissel-Vernier et al. (2004), concerns the weekly operation of the IVS R1 and R4 24-hour EOP sessions, each using different networks. They are run since 2002 on Mondays and Thursdays, respectively, and each includes five to seven stations. Three stations are common: Gilcreek, Wettzell and Concepcion. The differences in the UT1 values derived from either type of session over 2002.0-2003.8 can be modelled as a bias: 1.9 μs, and an rms residual per session: 9.6 μs. The magnitude of the differences is equivalent to 3 to 5 mm on the Earth's surface, probably reflecting station coordinate inconsistencies at a similar level.
- Ray et al. (2005) studied methods for combining GPS and VLBI series of station coordinates together with the corresponding polar motion measurements and evaluated the outcome by comparing the geodetic series with series inferred from the atmospheric and oceanic excitation of Earth orientation variations. They show that
  - the consideration of VLBI polar motion in the combination degrades the accuracy of the GPS-only time series;
  - using GPS polar motion alone indirectly improves the VLBI-based estimation of universal time. The match of Length of Day (LOD) with geophysical data is improved by about 4 μs. The improvement is tiny - about 1% of the residual variance - but systematic. They also suggest that, conversely, the joint consideration of the two series of polar motion globally improves the alignment of the VLBI and GPS reference terrestrial frames.

5 Summary

Table 3 summarizes the orders of magnitude of the perturbation of the VLBI-derived UT1.

Table 3. Level of perturbation of VLBI UT1 due to celestial or terrestrial reference frames defects.

Perturbating Ref. frame	Bias	Drift	Medium term	Short term
TRF	2 μs	0.5 μs/year	7 μs	10 μs
CRF	4 μs	0.8 μs/year	2 μs	5 μs

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References

Altamimi, Z., P. Sillard and C. Boucher, 2002, JGR 107B, 1, 2002.

Bizouard, C., 2005, This volume.

Feissel-Vernier, M., 2003, A&A 403, 105.

Feissel-Vernier, M., Ray, J., Altamimi, Z., Dehant, V., de Viron, O., 2004, IVS ...

Feissel-Vernier, M., Ma, C., Gontier, A.-M., Barache, C., 2005a, A&A (in press).

Feissel-Vernier, M., 2005, This volume.

Feissel-Vernier, M., Ma, C., Gontier, A.-M., Barache, C., 2005b, IERS Technical Note in preparation, C. Ma (ed.).

Fey, A. L., Ma, C., Arias, E. F., Charlot, P., Feissel-Vernier, Gontier, A.-M., Jacobs, C. S., Li, J., MacMillan, D., Sovers, O. J., 2004, AJ, 127, 3587.

Ma, C., Arias, E. F., Eubanks, T. M., Fey, A. L., Gontier, A.-M., Jacobs, C. S., Sovers, O. J., Archinal, B. A., Charlot, P., 1998, AJ 116, 516

Ray, J., Kouba, J., Altamimi, Z., 2005, Journal of Geodesy (in press)