Stability of ICRF, a Time Series Approach

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Abstract

The qualification and the maintenance of the International Celestial Reference Frame (ICRF) source directions are currently based on global statistics on the complete data set of observations. As the founding hypothesis in the selection of extragalactic objects for accessing a quasi-inertial reference system is that their directions are fixed in space, the time variability of some of the sources is only used as a rejection criterion. We show that a significant proportion of the sources have apparent motions with non-random noise spectrum. We suggest that time series statistics be introduced in the computation of ICRF in order to take into account the error spectrum of the source motions. Test computations using different statistical approaches are performed. Their results are compared with those of the classical method.

1. Introduction

The IAU recommended in 1997 to use as conventional celestial reference system the International Celestial Reference System (ICRS) (see Feissel and Mignard 1998), materialized by coordinates of extragalactic compact radiosources observed with VLBI, the International Celestial Reference Frame (ICRF). The initial realization of the ICRS was published in 1997 (Ma et al. 1998, see also Ma and Feissel 1997). It includes 608 objects. The most recent update and extension, ICRF-Ext.1, is now available with 667 objects. (IERS 1999: http://hpiers.obspm.fr/webiers/results/icrf/README.html). The computation for ICRF-Ext.1 is based on the same analysis options as that for ICRF.

The radiosource coordinates in ICRF and ICRF-Ext.1 are derived from the complete set of observations over 1979–1999. They are qualified in two ways, 1) by ascribing realistic uncertainties that take into account both the random and systematic errors, and 2) by categorizing them, in decreasing order of confidence, as “defining”, “candidates”, and “other”. This complex assessment scheme is made necessary by the existence of variabilities in the apparent directions of the sources. Thanks to the computation of the session-per-session coordinates of over 500 sources of ICRF-Ext.1, it is possible to investigate this instability in a time series approach.

According to Ma et al. (1998) there are two major causes for the current limitation in accuracy of source positions.

- Tropospheric delay modelling. The uncertainty in the modelling of the propagation delay due to the wet component of the troposphere, combined with deficiencies in the network geometry (majority of stations in the northern mid-latitudes, short N-S components of the baselines yielding to the observation of low declination objects at low elevation, where the mis-modelling of the delay has the largest effect), may give rise to systematic errors in declination at the level of 0.5 mas (milliarcsecond) in the zone around the equator. The consequences of this defect can be investigated on the basis of time series.
• Source structure. No radiosource is really point-like when observed in centimetric wavelength with baseline lengths around 6000 km. If the source structure is extended or not circular, its apparent direction may change as a function of the length and orientation of the baselines. This effect should be minimized with the practice of running 24-hour sessions, during which the Earth’s sidereal rotation leads to the diversification of the projections of the baselines on the source structure. Moreover, despite the selection of quiet objects for astro-geodetic work, any of them may exhibit changes in their emission structure that will make their apparent direction change with time. In principle it is possible to accurately correct this effect, provided that repeated maps of the sources are available (Charlot & Sovers, 1997). In the framework of the ICRF maintenance, a systematic program for source mapping (Fey 1999; http://maia.usno.navy.mil/ormf/rrfid.html) and astrometric correction computation (http://www.observ.u-bordeaux.fr/public/radio/PCharlot/structure.html) is under way. However, the overall correction procedure is not yet implemented in the existing global analysis softwares. This mismodelling may propagate errors into the source positions at the level of 0.2 mas. We investigate this effect hereafter, based on the computed coordinates of the radiosources in a homogeneous reference frame, with one determination for each of the sessions in which the source was observed (Eubanks 1999).

2. Time Series Statistics on Radio Source Coordinates

For historical reasons, the numbers of observations per source are extremely uneven. Some sources that were used to provide reference directions in the early years of VLBI appeared too variable or too extended after some years and were discarded to the benefit of other, fainter sources that became usable thanks to the progress in technology. Some sources considered as best fitting the astro-geodetic needs are repeatedly observed, while others, considered as less useful for this purpose, are re-observed less frequently, mainly for astronomical studies.

![Figure 1. Histograms of rates of observations over 1988-99 for the 208 best observed ICRF sources](image_url)

Our study is based on the computed coordinates of the radiosources in a homogeneous reference frame, with one determination for each of the sessions in which the source was observed (Eubanks 1999). Figure 1 shows the histograms of rates of observation for the 208 most regularly observed...
sources over 1988-1999. These sources provide the backbone of the ICRF. About half of them have less than 1500 observations in less than 60 sessions. Twenty-one sources have more than 30 thousand observations in more than 1000 sessions.

The spectral characteristics of the time series of source coordinates can be investigated using the Allan variance method (Allan 1966, see a review of these methods in Rutman 1978). The Allan variance analysis allows one to characterize the variability power spectrum from time series of measurements. This method identifies white noise (spectral density $S$ independent of frequency $f$), flicker noise ($S$ proportional to $f^{-1}$), and random walk ($S$ proportional to $f^{-2}$), and it allows one to specify the time frame in which a given type of noise is valid. Note that one can simulate flicker noise in a time series by introducing steps of random amplitudes at random dates. In the case of a white noise spectrum (an implicit hypothesis in the current ICRF computation strategy), accumulating observations with time eventually leads to the stabilisation of the mean position. In the case of flicker noise, extending the time span of observation does not improve the quality of the mean coordinates.

An example of spectral characterisation is given by Gontier et al. (1999) for the 65 best observed sources over 1988-1999. About 3/4 of the series of coordinates have white noise and 1/4 have flicker noise. This classification is uncorrelated with the “definition/candidate/other” classification currently used in the ICRF maintenance process.

3. Time Series of Celestial Reference Frames

For two sets of sources with reasonably continuous observations selected with two different levels of accepted interruptions, we consider yearly differential celestial reference frames based on the average differences with the mean coordinates for each source. The two sets of selected sources include 208 objects for the looser continuity condition (135 categorized as “definition” or “candidates” in the ICRF, and 73 “other”) and 68 sources for the tighter condition (resp. 36 and 32). We then compute the systematic differences under the classical parametrisation of rotation angles $dA_1$, $dA_2$, $dA_3$ around the axes of the equatorial system of coordinates. Figure 2 shows the time evolution of the $dA_1$, $dA_2$, $dA_3$ angles in the two cases (blue/dark for the 208 sources selection, brown/light for the 68 sources one), estimated both by weighted minimum L2-Norm (least squares) and minimum L1-Norm analyses, with weighting based on the standard error of each yearly average. The L2-Norm results are shown as isolated points (circles for the 208 sources selection, diamonds for the 68 sources) with their standard errors, and the L1-Norm results are connected by a line. The double horizontal line shows the band of ± 0.2 μas that the authors of the ICRF claim to be the accuracy of the definition of the ICRF axes. The effective numbers of sources present in each yearly solution are given with the $dA_2$ graph (bottom line for the 208 source selection, upper line for the 68 sources).

A striking feature is that the least square solutions are not regularized by doubling the number of sources. This effect, added to the least sensitivity of the L1-Norm solutions to the number of sources, suggests that even at the level of yearly averages source coordinates have large irregularities, as the L1-Norm estimation is known to be more robust with respect to outliers than the L2-Norm estimation.

The preliminary results presented here show that the analysis approach based on time series analysis deserves further development in the context of the maintenance of the ICRF.
Figure 2. Relative rotation angles of yearly CRFs
(see explanations in the text)
References