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VLBI2020: From Reality to Vision

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Abstract

The individual apparent motions of distant radio sources are believed to be caused by the effect of intrinsic structure variations of the active galactic nuclei (AGN). However, some cosmological models of the expanded Universe predict that systematic astrometric proper motions of distant quasars do not vanish as the radial distance from the observer to the quasar grows. These systematic effects can even increase with the distance, making it possible to measure them with high-precision astrometric techniques like VLBI. The Galactocentric acceleration of the Solar System barycenter may cause a secular aberration drift with a magnitude of 4 μas/yr. The Solar System motion relative to the cosmic microwave background produces an additional dipole effect, proportional to red shift. We analyzed geodetic VLBI data spanning from 1979 until 2009 to estimate the vector spherical harmonics in the expansion of the vector field of the proper motion of 687 radio sources. The dipole and quadrupole vector spherical harmonics were estimated with an accuracy of 1-5 μas/yr. We have shown that over the next decade the geodetic VLBI may approach the level of accuracy on which the cosmological models of the Universe could be tested. Hence, it is important to organize a dedicated observational program to increase the number of measured proper motions to 3000.

1. Introduction

Technological development over the last decade has led to an increase in the precision of geodetic VLBI data. This increased precision has allowed a detailed study of the stability of the International Celestial Reference Frame (ICRF). Table 1 shows a statistical comparison of the two ICRF catalogs, ICRF1 [1] and ICRF2 [2].

Table 1. Statistical comparison of the ICRF1 and ICRF2 catalogs.

	ICRF1	**ICRF2**
Year	1995	2009
Number of defining sources	212	295
Formal error (μas)	60	7
Inflated error (μas)	250	41

The International Celestial Reference System (ICRS) is based on several assumptions and definitions from the early 1990s. Hence, the improvement in accuracy of the ICRF realization has highlighted some previously unknown problems. For instance, the proper motions of reference radio sources are assumed to be negligible, and only the apparent motion due to a change of the intrinsic structure is considered as measurable. This assumption opens a way to impose no-net-rotation (NNR) constraints to fix the fundamental ICRS axes. Indeed, the individual apparent motions reach several hundred μas/yr and may result in a 'spurious' rotation of the ICRF. However,

they are not correlated for all sources around the sky. Therefore, the problem comes down to the appropriate deselection of the radio sources with large individual proper motions.

A detailed statistical analysis of the reference radio source individual motions is highly desirable. The proper motion of reference radio sources, caused by some physical reasons, have a smaller magnitude, but they are highly correlated over the sky. Therefore, their impact on the ICRF stability and accuracy could also be significant. Once the fundamental axes of the ICRS are tied with the position of defining radio sources, a systematic effect, if it exists, causes instability of these axes. As a result, orthogonality of the reference axes may be lost. Some authors, therefore, warned that the basic assumptions should be verified on a regular basis [3] to be sure that they are consistent with the current observational results.

2. Possible Reasons for a Non-zero Proper Motion

There are several reasons which could cause systematic effects in proper motion.

1. Secular aberration drift which appears due to the galactocentric acceleration of the Solar System. This results in a dipole systematic effect in the proper motions of all radio sources irrelevant to distance. Vectors of all source motions are streamed towards the Galactic center with a theoretical magnitude of 4-5 μas/yr [4], [5], [6], [7], [8], [9].

2. Anisotropic expansion of the Universe. In the Friedman-Robertson-Walker-Lemetre (FRLW) model the expansion of the Universe is isotropic, and the systematic proper motions are zero. Any deviation from the isotropy will result in a quadrupole systematic effect described by electric-type second degree vector spherical harmonics [10], [11].

3. Primordial gravitational waves. This results in a variation of the metric at the early stage of the Universe expansion. The systematic is described by electric- and magnetic-type second degree vector spherical harmonics. These systematic proper motions could increase with distance (red shift) [5], [10], [12].

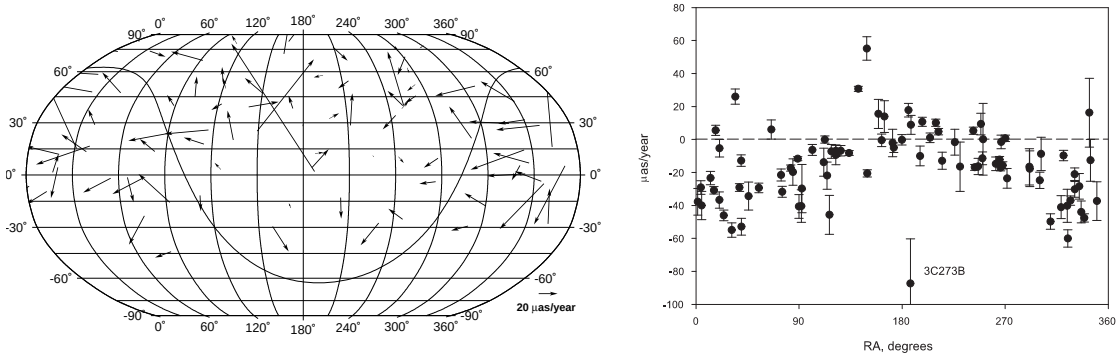
4. Instantaneous velocity of the Solar System with respect to the cosmic microwave background (CMB) [13]. The rectilinear velocity of the barycenter (about 380 km/sec) causes another dipole effect depending on the distance to the sources. While for most of the quasars this effect is small (≤ 1 μas/yr), it might be large for close galaxies (up to 14 μas/yr for M81) [14].

3. Data Analysis

Figure 1a shows the vector field of the individual proper motions for the 86 most observed radio sources, and Figure 1b shows the proper motion component $\mu_\alpha \cos\delta$ as a function of right ascension. Two systematic effects were found. The first was the non-zero mean proper motion indicating a net rotation of the radio sources. The second was a cosine-like signal leading to a dipole systematic. In spite of the fact that most of the frequently observed radio sources are astrometrically unstable, the only obvious outlier is the quasar 3C273B. This demonstrates that the risk of 'spurious' rotation of the fundamental reference system induced by apparent motion of an individual astrometrically unstable radio source [17], [18], [19], [20] is overestimated.

A more rigorous analysis was completed using the proper motions of 687 radio sources observed in at least three epochs, and having at least three group delays in each epoch. It was found that 42 of the 687 sources were outliers, and they were removed from the final solution.

The second solution is based on the radio sources with a smaller number of observations;

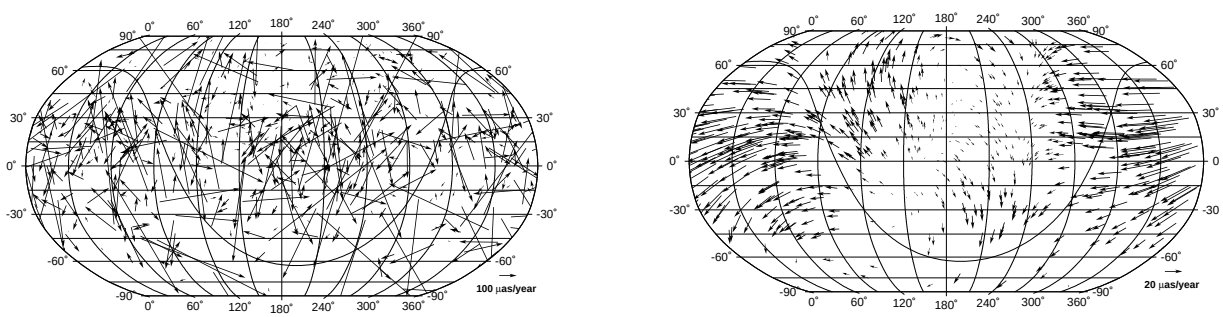


a) Individual proper motions on sky map.

b) Proper motion component $\mu_\alpha \cos\delta$ as a function of right ascension.

Figure 1. Proper motions of 86 radio sources measured in $\geq$ 200 sessions with $\geq$ 15 group delays in each session.

therefore, the pattern of the individual proper motion in Figure 2 is noisier than in Figure 1, and the scale of the plot was increased to 100 μas/yr. For this reason, the systematic effect is not as clear as in Figure 1. Nonetheless, due to an increase of the total number of proper motions and better coverage across the celestial sphere, the parameter estimates for this new solution are more robust. The estimate of the dipole component has a magnitude of 13.5 $\pm$ 1.3 μas/yr, and the total magnitude of the second degree vector spherical harmonics is about 10 $\pm$ 2 μas/yr.

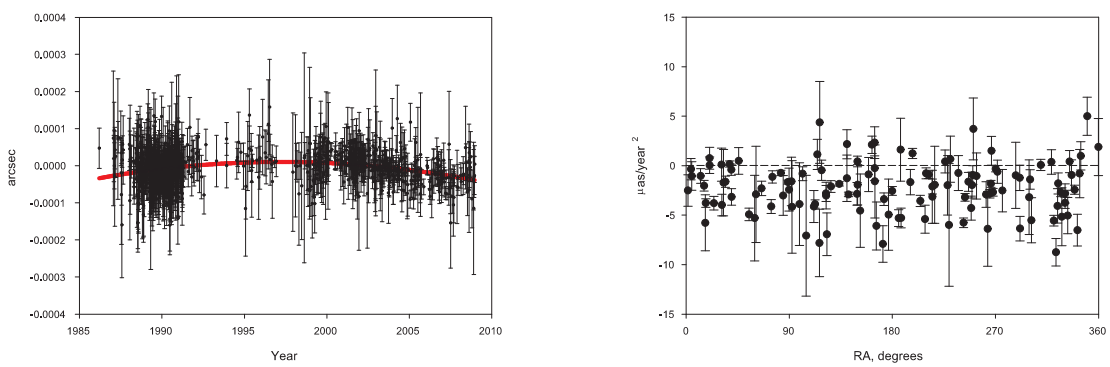


a) Individual proper motions on sky map.

b) Systematic of first and second order.

Figure 2. Individual motion and resultant systematic of 645 radio sources measured in $\geq$ 3 sessions with $\geq$ 3 group delays in each session.

Figure 3a shows the quadratic trend of the time series of right ascension of radio source 2121+053 with $A_\alpha \cos\delta = -5.5 \pm 0.6$ μas/yr^2. Figure 3b shows the proper 'acceleration' component $A_\alpha \cos\delta$ for the 86 most observed radio sources as a function of right ascension. The mean value of the effect is equal to -2.2 μas/yr^2. We have no obvious explanation for this effect.



a) Time series of 2121+053 right ascension; quadratic trend of -5.5 ± 0.6 μas/yr^2 is shown.

b) Proper 'acceleration' component $A_\alpha \cos\delta$ as a function of right ascension.

Figure 3. Proper 'acceleration' $A_\alpha \cos\delta$ for source 2121+053 and for the 86 radio sources measured in ≥ 200 sessions with ≥ 15 group delays in each session.

4. Conclusion

About 3000 radio sources have been observed by VLBI in the geodetic and astrometric programs. Unfortunately, most of the radio sources were observed in one or two epochs only. Therefore, reliable proper motions can only be estimated for about 700 radio sources. This paper has shown that the apparent motions of individual radio sources are not random on the sky, and some interesting systematics are detected at the accuracy level of 10 μas/yr. More signals will be expected, if the standard error of the estimates reduces to 0.1 μas/yr for the dipole effect. All the discussed systematic effects will be estimated with a higher accuracy if the remaining 2300 sources are observed several times by 2020. We believe that scheduling each of the 2300 sources in three to four sessions (with four to five scans for each session) for the next 10 years will allow an increased accuracy of the estimated systematic effects. If this program is realized, the geodetic VLBI will approach the level of accuracy required to test the cosmological models of the Universe.

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