VLBI Astrometry of Radio Stars to Link Radio and Optical Celestial Reference Frames

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Abstract The *Gaia* Celestial Reference Frame (*Gaia*-CRF) is aligned to the International Celestial Reference Frame (ICRF) at the faint end ($G > 13$) using quasars; but at the bright end ($G < 13$), there are no quasars available for the alignment. Very Long Baseline Interferometry (VLBI) measurements of radio stars can play a role as an independent assessment at the bright end. Currently, the number of available radio stars (< 100) is much smaller than the number of quasars (thousands), so the focus is on increasing the number of available radio stars. We have observed several stars with conventional five-parameter VLBI astrometry, and more observations are ongoing. Considering that the conventional observing strategy is high-cost, we also propose to observe with a new double-epoch strategy which, according to our simulation, is $\sim 30\%$ more efficient for CRF links.

Keywords Astrometry, Reference Systems, Very Long Baseline Interferometry, Radio Stars

1 Motivation

In the era of multi-wavelength astronomy, establishing a celestial reference frame consistent at different wavelengths is a fundamental challenge. ICRF3 is based on VLBI measurements of extragalactic radio sources. In the optical band, *Gaia*-CRF3, defined by quasars, is aligned to ICRF3 with quasar counterparts. However, there is a systematic rotation (orientation $\varepsilon = [\varepsilon_X, \varepsilon_Y, \varepsilon_Z]'$ and spin $\omega = [\omega_X, \omega_Y, \omega_Z]'$) of *Gaia*-CRF3 between the bright end ($G < 13$) and the faint end ($G > 13$)[1]. Radio stars can be detected in both radio and optical bands, and VLBI astrometry of radio stars can give an independent estimation of this systematic rotation.

There have been several related works [1, 2, 3]; however, because the number of available radio stars is small (< 100), the estimated rotation parameters are not quite reliable. Therefore, the key is to increase the number of available radio stars. VLBI observations as close as possible to the *Gaia* reference epoch will contribute more to the estimation, especially for the orientation parameters; so it is important to carry out the observations in the most recent years with an efficient observing strategy.

2 Double-epoch Observing Strategy

The double-epoch strategy is to observe each radio star for only two epochs, approximately separated by an integer number of years, so that two individual positions can be obtained. The purpose of the integer-year time interval is to cancel out parallactic offsets, so an unbiased proper motion measurement can be obtained. Along with the *Gaia* counterparts, the positions and proper motions can contribute to the estimation of CRF link parameters between two CRFs. Details of the strategy can be found in Zhang et al. (2024) [4].

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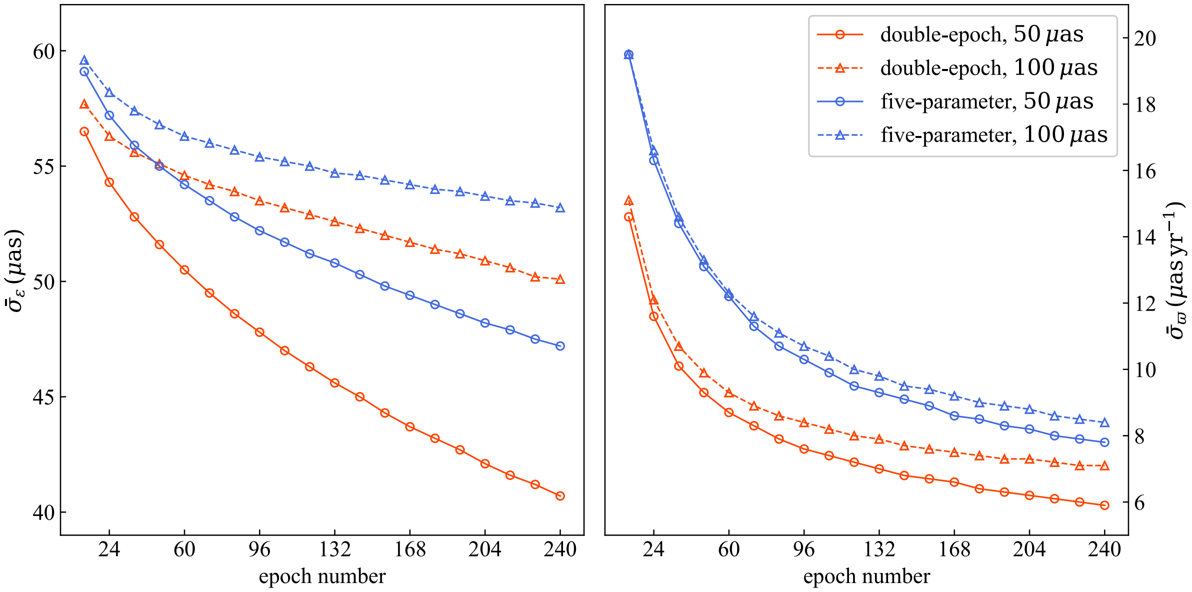

Fig. 1 Adding new observations to the “real” data using the double-epoch and five-parameter strategies, respectively.

2.1 Simulation for Strategy Assessment

The strategy is assessed and compared with the conventional five-parameter and single-epoch strategies through simulation. The costs of different strategies are kept the same so that they can be compared with each other: 120 epochs in total, 120 stars × 1 epoch, 60 stars × 2 epochs, and 20 stars × 6 epochs for single-epoch, double-epoch, and five-parameter strategies, respectively. The epochs of simulated VLBI measurements are between 2023.5 and 2024.5, and the position uncertainties of VLBI measurements are set to be 50 µas, while *Gaia* DR3 uncertainties are used for optical counterparts. Results of the simulation are shown in Table 1, which show that the double-epoch strategy performs better than the other two strategies (∼ 30% better than the five-parameter strategy). Figure 1 shows the expected uncertainties of adding new observations to currently available data, with VLBI position accuracies of 50 µas and 100 µas.

2.2 Practical Observing Epoch Scheduling

The time interval between the two epochs is practically difficult to be exactly an integer number of years, which will bring parallactic displacement. This is corrected by an offset calculated from the *Gaia* parallax ϖ_{Gaia}. Suppose a bias exists between ϖ_{Gaia} and the “true” parallax; the displacement would not be perfectly corrected. This will affect the independence of the CRF link and reduce the accuracy of the measured position and proper motion of the radio star.

Table 1 Comparison between different observing strategies. σ_{ε} and σ_{ω} are formal uncertainties of orientation and spin parameters, respectively.

Strategy	σ_{ε} (µas)			σ_{ω} (µas yr^{-1})		
	X	Y	Z	X	Y	Z
single-epoch	352.9	458.5	486.8	44.5	57.7	61.7
five-parameter	121.1	156.3	149.2	16.5	21.3	20.7
double-epoch	82.6	101.7	96.3	11.0	13.6	13.1

The trend of the impact of the possible parallax bias with time depends on positions in the sky. Two examples are given in Figure 2, showing the impact on position (c_p) and proper motion (c_{μ}) for two positions in the sky. c_p is a function of position and epoch, while c_{μ} is in addition related to the time interval between epochs: how long and how exact it is, close to an integer number of years. In most cases, for the minimization of the impact of the possible parallax bias, it is advised to choose a pair of epochs with a lower c_p and extend the time interval between epochs and tightening constraints on observation dates to reduce c_{μ}.

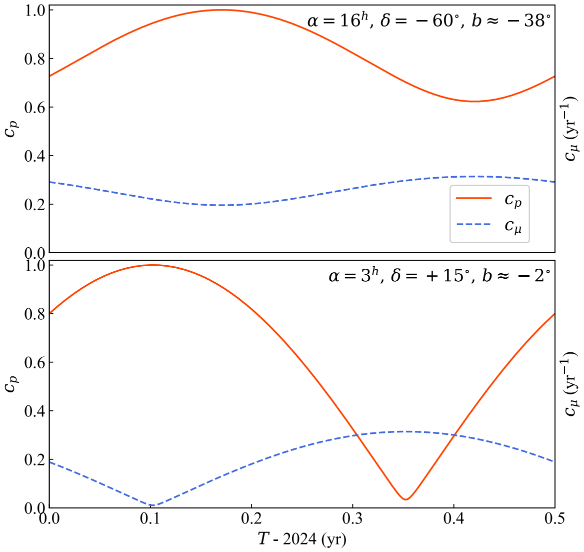

Fig. 2 The impact of the possible parallax bias on position c_p and proper motion c_μ as a function of epoch T. The amplitude of variation depends on the Ecliptic latitude b.

3 Observations

Over 20 radio stars, including both old and new ones, were confirmed detectable through the European VLBI Network (EVN) and the Australian Long Baseline Array (LBA) snap-shot observations. Then two Very Long Baseline Array (VLBA) pilot projects for five stars were carried out using the conventional five-parameter strategy, for which the result of one project was published [5]. Two projects are ongoing: a VLBA project (five-parameter strategy) for 11 stars and an LBA project (double-epoch strategy) for five stars. There will be more observations to come, and the number of detectable radio stars is hopeful to increase with more and more radio surveys and fast-developing facilities.

References

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