One-nanoradian pulsar absolute astrometry

1 Introduction

The large program "Mapping the Galactic distribution of pulsars with the VLBA, PSRPI" (Deller et al. 2010) started in 2011 allowed us to determine proper motions and parallaxes of 60 pulsars using the method of differential astrometry at 1.6 GHz (Deller et al., 2017 in preparation). The PSRPI program is presently being continued with a second sample consisting exclusively of millisecond pulsars: MSPSRPI. As a by-product of this program, offsets of pulsars at the reference epoch with respect to the strong off-beam calibrator sources within 1–3° were determined with formal errors approaching to one nanoradian (0.2 mas). However, this does not mean that pulsar absolute positions have been determined with that accuracy. There are three factors that affect the absolute position accuracy of 1.6 GHz differential astrometry:

- The absolute position accuracy of a target can never be better than the absolute position accuracy of a calibrator. Absolute position uncertainties of used calibrators are in a range of 01–2 mas, usually exceeding the position precision of target/calibrator offsets.
- The absolute position of the calibrator sources at 1.6 GHz has a bias with respect to the positions determined using the ionosphere-free linear combinations at 2.3/8.6 or 4.4/7.6 GHz due to the frequency dependent core-shift. According to (Sokolovsky at el. 2011), the median magnitude of the bias is ~ 1 mas along the jet direction.
- The contribution of the residual ionosphere at separations 1–3° from a pulsar is at the order of 0.5–5 mas.

Considering all these factors, we assess the current accuracy of VLBI pulsar absolute position at a level of 1–2 mas. We were able to determine parallaxes with a precision typically 0.04 mas and approaching to 0.01 mas in the best cases by using an intermediary in-beam calibrator within 2–20′ of a pulsar, which greatly improved the accuracy of determination of the differential pulsar position offset relative to an in-beam calibrator. However, the absolute position of an in-beam calibrator, and therefore, a pulsar, is still limited by the factors listed above.

We propose a program for observing a sub-sample of 17 pulsars with accurate positions from timing with the objective to bring the accuracy of their absolute positions down to 0.2 mas level.

2 Scientific rationale of the proposed observations

Reported position accuracy of many pulsars is at a nanoradian or sub-nanoradian level. For instance, the median position accuracy of the NANOGrav sample is 0.26 mas according to Matthews et al. (2016). However, there is no independent check of pulsar positions at that level of accuracy. Comparison of pulsar positions with an independent technique will provide us an independent estimate of their accuracy. The estimate of pulsar timing accuracy is very important for verification of future claims of gravitational wave detection with the pulsar timing arrays. Detection of gravitational waves is an extraordinary claims and requires an extraordinary strong supporting argumentation. A non-detection of gravitation waves at the claimed level of accuracy is also important result, but the merit of upper limit estimates of gravitational wave non-detection hinges even stronger upon the validity of accuracy estimate of pulsar timing results.

A dynamical coordinate system used for referring timing observations of pulsars and a kinematic coordinate system based on VLBI observations of active galactic nuclea (AGNs) in general have an arbitrary orientation that is described with three rotation angles. In practice, these angles are determined by direct or indirect observations of common objects. The orientation of the dynamical coordinate system used for referring pulsars positions is determined by the orientation of the Earth's orbit. Analysis of the differences in the absolute positions of pulsars measured with VLBI and the absolute positions of the same pulsars measured with timing will allow us to measure the three angles that determine the orientation of the ecliptic plane with respect to remote AGNs — the fundamental quantity for the inhabitants of the planet Earth.

Previous studies (f.e., Fienga et al. 2010, Wang, Rioja et al. 2017) present evidence that the coordinate systems based on VLBI and pulsars nowadays do not differ by more than 1 mas. However, the estimates of the accuracy in these papers account only for formal uncertainties of VLBI and timing positions and do not account for systematic errors, in particular, the three factors mentioned above. Therefore, the orientation parameters reported in the cited papers have uncertainties in a range of 0.5–1 mas, significantly worse than the authors claim. **The first goal of our proposal is to determine orientation of the ecliptic plane with the accuracy of 0.05 mas** taking into account systematic errors to the 0.20 mas level (0.05 mas ≈ 0.20 mas/$\sqrt{21}$, where 21 is the number of pulsars). Since ΔDOR observations are considered essential for space navigation after the loss of Mars Climate Orbiter that did not have ΔDOR capabilities (Curkendall & Border 2013), determination of the ecliptic orientation is a matter of great practical importance. An error in the ecliptic orientation will affect spacecraft position that may result in a loss of an expensive interplanetary mission. Since the current accuracy of ΔDOR is at a level of one nanoradian or below, the ecliptic orientation error at the 5–10 nrad level is significant. VLBI observations are nowadays also used for improvement of outer planet ephemerides (Jones et al. 2015). Unaccounted, errors in the ecliptic plane orientation will propagate to the ephemerides.

After fitting the three angles of the dynamic coordinate system orientation with respect to the kinematic coordinate system, we will form residual offsets of pulsar timing positions with respect to VLBI positions. **Analysis of the differences of pulsar positions derived from VLBI and timing is the second goal of the proposal.** If we find statistically significant position differences, this will stimulate a study of pulsar timing systematic errors. Analysis of time series of pulsar timing results provides us estimates of **internal errors**, while comparing results with completely independent technique provides us **a measure of external accuracy**. The absence of timing errors above the one nanoradian level will strengthen quantitative estimates of the significance of gravitational waves detection or non-detection, Solar system acceleration, and other parameters derived from pulsar timing. Realistic measure of pulsar timing accuracy are essential for current and planned X-ray pulsar timing missions, such as SEXTANT and XPNAV-1.

We should mention that *Gaia* position of the off-beam calibrators will not be useful, since as it is discussed extensively in Petrov & Kovalev (2017), the *Gaia* positions have a bias with respect to VLBI positions, predominately along the jet direction at a level of several milliarcsecond due to the presence of optical structure.

3 Proposed observations

In order to determine absolute positions of a pulsar, we need solve the following problems: 1) to determine absolute positions of off-beam calibrators with accuracy better than 0.2 mas; 2) to determine the core-shifts of all off-beam calibrators and relate their position to 1.6 GHz; 3) to improve the differential position of the in-beam calibrators by accounting for the residual ionospheric contribution. We should note that we do not need determine the core-shift of the in-beam calibrators, since its contribution is canceled when we form double differences pulsar/in-beam calibrator and in-beam calibrator/off-beam calibrator. In order to solve these problems, we propose the two-part program.

We selected 17 pulsars observed in the PSRPI and MSPSRPI that are being monitored with the Pulsar Time Array and either have reached sub-mas accuracy in timing position or will reach within 1–2 years.

3.1 Determination of differential positions of in-beam calibrator

We are going to observe **four** off-beam calibrators within 1–3° of target pulsars following the multi-view technique proposed by Rioja et al. (2017) who have demonstrated that using multiple calibrators allows us to reduce the impact of the residual ionosphere by one order of magnitude. We will observe a sequence C1-I-C1-C2-I-C2-C3-I-C3-C4-I-C4, where "Ci" is the off-beam calibrator and "I" is the in-beam calibrator. One of the off-beam calibrators is the object used during the pulsar parallax program. We propose to integrate the in-beam calibrator for 180 s at each step of the cycle and integrate a bright off-beam calibrator for 40 s. Accounting 20 s slewing, observations of fringe finders, we entire block requires approximately half an hour to complete. Since for some pulsars we used more than one in-beam calibrator, we request multiple phase centers (1–3) for such fields.

We will perform analysis in line with the technique described in detail in Rioja et al. (2017) and derive positions of in-beam calibrators with respect to off-beam calibrators. In order to have a minimum redundancy for verifying that we indeed beat systematic errors caused by residual ionosphere below the 0.2 mas level, we will observe each block five times. Thus, we request 43 hours in the priority C scheduling mode for this part of the program.

3.2 Determination of absolute positions of off-beam calibrator

We propose multi-frequency observations of the off-beam calibrators used in the first part of the program at 1.6 GHz, 2.3/8.7 GHz, and 4.2/5.9 GHz with three VLBA receivers in order to determine their core-shifts. We will spread intermediate frequencies over 480 MHz bandwidth for observations at 4.2, 5.7, and 8.7 GHz in order to determine group delays with high accuracy. We will observe the calibrators in the sequence C1-C2-C3-C4-C1-C2-C3-C4, integrating each calibrator for 40 s. It will take 25 minute to observe the sequence with three receivers. We are going to observe with 2.3/8.7 GHz a 20 minute geodetic block before and after the sequence. The observations will be analyzed in three modes: a) absolute astrometry using ionosphere-free group delays of the off-beam calibrators at 2.3/8.7 GHz, 4.2/5.9 GHz, and the geodetic blocks, b) differential astrometry, and c) core-shift analysis using jet features. The objective of the first mode of analysis is to improve absolute positions of the calibrators. In the second mode of analysis wE WILL determine positional offsets for every pair of calibrators at each frequency band from the differential astrometry analysis. Assuming the core-shift of every off-beam calibrator is aligned along a straight line, we will be able to separate variables and determine the core-shift independent positions and the parameters of the core-shift dependence on frequency for every object. In addition, for control, in the third mode of analysis we will determine the core-shift using the jet feature method as it was done by Sokolovsky at el. (2011). Unlike to the previous approach, the jet feature method allows us to determine the core-shift only for those objects that have a distinctive feature on a jet at all frequencies.

We propose to observe each quartet of off-beam calibrators with three receivers in two sequences separated by 4–8 hours in hour angles in order to get reliable images. Thus, we request 34 hours in the priority C scheduling mode for this part of the project.

We developed automatic scheduling software that has web interface. In order to generate a schedule, the array operator using Web-form specifies the start and stop dates during a gap between normal priority projects and subsequently retrieves the key file after 1–2 minutes. **priority C scheduling mode**, this project does not compete or displace normal projects.

4 Data release plan

We waive the proprietary period for the data release. Raw data will be available to the community within several days after correlation. We will provide images in FITS format at all frequencies, accompanied with postscript maps and rad-plots, as well as improved source positions on the project web page immediately upon the quality control check.

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