Absolute astrometry with ultra-wide bandwidth synthesis

1 Summary

We request 60 hours of VLBI time in **filler mode** for an exploratory project for testing a novel, economical way to determine *absolute position* of radio sources with accuracy better than 0.1 mas utilizing recent upgrade of VLBI hardware. The novelty of the approach: a) frequency switching C-band observations; b) bandwidth synthesis within 4 GHz wide band; c) observing triplets of near-by sources for determining frequency-dependent core-shift; d) using all tones of phase-cal signal; e) 4 hour blocks; f) using outputs of high-resolution numerical weather models for calibration for the contribution of slanted path delay the neutral atmosphere; g) using the empirical model of nutation. The goal of proposed observations is to assess the level of systematic errors and present evidence that claimed accuracy is achievable. If successful, the methodology of determination of absolute positions with accuracies 0.05–0.1 mas for less than 1/2 hours per triplet will be developed. This will allow to refine on-demand positions of those sources for which this level of accuracy is necessary.

2 Introduction

Nowadays, VLBA astrometry is a hot topic. There are claims (e.g. Reid & Honma (2014)) that microarcsecond accuracies have been achieved. A critical examination of claims shows that 1) reported uncertainties that may be as low as 10–30 μarcsec are random errors, which give the low level of true errors; 2) reported high accuracy results are determinations of *position differences*, not positions themselves.

Although estimates of *position difference* may be precise at a level better than 0.1 mas, the target *position* can not be more accurate than the accuracy of calibrator position. By 2014, the pool of calibrators[1] has 8380 objects. Their median reweighted position uncertainty along each coordinate is 0.53 mas. Position error exceeds 1 mas for 40% and 5 mas for 6% of the sources. For some important applications, such as determination of parallaxes and proper motions of galactic objects, absolute position of a target object is irrelevant, but only position differences are important. However, there are several applications that require precise accuracy in just source position, not position difference. These are

- Space navigation: VLBI observations of interplanetary spacecrafts;
- Connection of kinematic and dynamic coordinate systems by observing pulsars with VLBI.
- Comparison of radio and optical coordinate system with *Gaia*.

All these applications require accuracy in *absolute positions* of calibrators at least 0.1 mas.

3 Past methodology of absolute astrometry

Absolute astrometry programs started in 70s at JPL, then were carried out under the Crustal Dynamics Project program and finally with the VLBA (VLBI Calibrator Surveys (Petrov et al. 2008, and references therein) and regular VLBA geodesy program RDV (Petrov et al. 2009)). Typical experiment design included a) wide bandwidth coverage, 220–720 MHz, for precise evaluation of the basic observable: group delay; b) dual band S/X observations for elimination of the ionosphere contribution; c) 24 hour blocks in order to solve for daily nutation offset; d) observing a sequence of sources widely

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[1] `http://astrogeo.org/rfc`

distributed over azimuths and elevations, including low elevations, in order to solve for atmosphere path delay in zenith direction. In data analysis source structure is considered as δ-function.

Extensive analysis revealed that accuracy of group delays has a floor in a range of 15–30 ps depending on weather conditions. If for a given source group delay uncertainty reached that level, internal precision of source position estimates reaches the floor after approximately 100 observations, i.e. two scans of the 10-station VLBA. The floor is determined by unaccounted systematic errors, such as the contribution of the atmosphere. The magnitude of the internal precision floor is debatable, but is believed to be in a range of 0.05–0.1 mas.

We call this precision floor internal, because it was determined from redundancy analysis of survey observations without using any external information. This does not account for the contribution of variable source structure and core-shift. Data reduction for the contribution of source structure into group delay requires imaging at all bands. Nowadays, the technology of automatic imaging is matured enough to use it not only for new proposed observations but for archived observations as well. But there is no way to evaluate core-shifts using the traditionally methodology of absolute astrometry surveys. Sokolovsky et al (2011) found that the median shift of the core position between 8 GHz and infinitely high frequency (i.e. wrt of the core-base) is 0.25 mas at X-band and 1.8 mas at L-band. Porcas (2009) noted that if the core-shift is reciprocal to frequency, then the dual-band observations absorb its contribution entirely to TEC estimates and provide position of the core-base free from the core-shift effect. Though, there are two caveats: first, not every source has has that dependency of core-shift on frequency; second, if observations are made at a single frequency, as it is usually done for phase referencing, the full magnitude of the unaccounted calibrator core-shift will affect the position estimate of the target.

Therefore, any absolute astrometry program that does not measure core-shift is doomed to suffer from systematic errors as large as 0.25 mas at X-band and 1.8 mas at L-band.

4 Proposed method of absolute astrometry

We propose the following changes in conducting an absolute astrometry campaign aimed at reaching accuracies no worse than 0.1 mas:

1. To observe at 4 frequency bands: 3.9–4.4, 5.0–5.5, 6.2–6.7, and 7.4–7.9 GHz of the C-band receiver by frequency switching between 3.9/7.4 and 5.0/6.2 GHz. The custom fringe fitting procedure provided in package $\mathcal{PIMA}$ [2] will be modified to solve in the final stage of LSQ adjustment not only for phase, phase delay rate, group delay, group delay rate, but for TEC as well within 4 GHz bandwidth. We call this approach ultra-wide bandwidth synthesis.
2. To schedule not individual target sources, but triplets of sources within 1–3° of each other. A triplet of sources will be observed in a sequence C_1—C_2—C_3—C_1—C_2—C_3—C_2. On-source time at each target is 30 s at the first pair of frequencies and 30 s at the second pair or frequencies. In total, each source will be observed for at least 60 s at each frequency. The floor of group delay precision 20 ps will be reached for a source brighter than 50 mJy. Frequency-dependent position differences between three sources will be determined using the traditional differential astrometry technique. Combination of these observables will allow us to determine core-shift vectors for each object of a triplet and separate them from the contribution of the ionosphere.
3. To organize the schedule in such a way that observations of five 9-minute-long blocks of target triplets are followed by observations of four 60-second long scans of strong reference sources at frequencies 3.9/7.4 GHz with at least two sources at elevations in a range of 20–40° at each station. The goal of these observations: a) to provide connection with existing catalogues;

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[2] http://astrogeo.org/pima

b) to improve parameter separation for estimation of residual atmosphere path delays in zenith direction; c) to serve as complex bandpass calibrators and fringe finders.

4. To calibrte instrumental group delay by using every phase calibration tone (32 tones per IF).
5. To schedule observations in short blocks of 3–8 hour long.
6. To make images at each four bands and perform data reduction for source structure.
7. To compute slanted path delay from GEOS-FP numerical weather model[3] for data reduction.

After initial analysis of a segment is finished, the final analysis will be done in a usual absolute astrometry mode: single LSQ solution using all the data from 1980 through present with applying calibration for slanted path delay, source structure contribution to group delay, and core shift will be performed.

4.1 Previous tests of elements of the new approach

Wide-band mode of spreading 8 IFs along 992 MHz bandwidth in 7.9–8.9 GHz range was successfully tested in BC196 and BC201 projects. Extending the synthesized bandwidth to 4 GHz seems feasible.

Determination of the ionosphere total electron contents (TEC) at 4.1/7.4 GHz versus 2.2/8.5 GHz was checked with quasi-simultaneous four frequency observations in BP175 project. Preliminary analysis of these observations (Petrov, 2014, paper in preparation) showed that the contribution of the differences in TEC derived from these two setups to the ionosphere-free combination of group delays at 4.1/7.4 GHz frequencies is below 10 ps, i.e. negligible.

Determination of core-shifts from four frequency observations of three close sources is done in BL196 project that is observed in 2014A semester.

Development of the Empirical Earth Rotation Model (Petrov 2007) eliminated the need to have 24 hour blocks in order to separate polar motion and nutation parameters. Coefficients of nutation parameters as well as other constituents of harmonic variations in the Earth rotation are effectively determined in a global solution. We tested this approach by artificially reducing 24 hours experiments to 3–8 hours experiments by flagging out the data and found no evidence that shortening blocks causes new systematic errors.

5 Proposed observations

We propose to observe the source from three lists:

- 20 triplets from the polar cup with $\delta > +57^\circ$. The goal is to observe each triplet in 10 nine-minutes long scans over the course of the campaign. We selected the polar cup in order to ensure that we can observe a source in almost any segment scheduled randomly in a **filler mode**. We anticipate that two scans will be sufficient to reach accuracy better than 0.1 mas, but we need significant redundancy to substantiate such a claim. Positions of these sources have been determined with claimed internal accuracy better than 0.1 mas. Core-shifts of one member of each triplet were measured by a different, so-called self-referencing method by Pushkarev et al. (2012). Comparison of positions and core-shifts determined in the proposed project with the positions determined from previous observations will be used for evaluation of accuracies. We will also investigate stability of core-shift vector estimates.
- 15 triplets that include sources used for recent VLBI observations for space navigation: 14 calibrator sources from the list of D. Jones for Cassini spacecraft observations and 2 calibrator sources (one triplet) of recent Mars EXplorer flyby observations provided by S. Pogrebenko.

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[3] ttp://gmao.gsfc.nasa.gov/products

These sources will be observed in 2-4 scans. The goal of these observations is to improve accuracy of Saturn orbit that is limited by accuracy of *absolute* positions of calibrators.

- 15 sources used as off-beam calibrators for pulsar parallax determination programs led by A. Deller. These calibrators are used for those pulsars that are being extensively observed with the pulsar timing array for gravitation wave detection, and therefore have very precise positions from timing. Timing positions are determined in the dynamic reference system, while VLBI positions are determined in the kinematic reference system. Differences in positions at two reference systems allows to improve determination of the Earth's orbit orientation and thus to anchor entire Solar system to the inertial coordinate systems referred to distant AGNs. The residual differences between pulsar positions derived by completely independent methods will provide an insight on *external* estimates of accuracies of both methods. These sources will be observed in 2–4 scans each.

Proposed observations have two goals: enhancement of the scientific output of recently observed projects and evaluation of systematic errors of the proposed method. Systematic errors will be evaluated by redundant observations of sources with known positions and core-shifts. The targets from the first list are bright. In one of the tests they will be artificially "dimmed" by masking out 7/8, 15/16 and 31/32 spectral channels in order to check accuracy of the proposed method for weaker sources. Accuracy of core-shifts will be evaluated by comparing with previous observations of 20 sources.

6 Expected outcome

We anticipate that two 1 hour blocks will be sufficient for determining positions of 5 targets with accuracy better than 0.1 mas. Proposed observations are expected to provide evidence to support (or refute) such a claim. This will allow to use a two-trier approach for absolute astrometry: medium-accuracy observations in VCS7/VCS8 campaigns (project code BP171, BP177) with a rate of 20 sources per hour and with median accuracy 1 mas, which is sufficient for the majority of phase-referencing applications, and high accuracy observations with a rate of 2.5 targets per hour, but with accuracy not worse than 0.1 mas. Since such high accuracy is required only for a small sub-sample of sources, the two-trier approach is the most economical way of doing absolute astrometry surveys.

Although the project is exploratory, the new method will be tested in real-life situations and it is aimed to contribute to improvement of accuracy of the Saturn orbit and getting positions of 15 pulsars accurate at 0.1 mas level in the kinematic reference frame.

As a by-product of this project, positions of 90 sources will be improved by a factor of 3–10, four-frequency images of 150 sources, including images in spectral indexes, as well as estimates of their core-shift vectors will be produced.

We waive proprietary period. All results will be timely available at the project web-site, similar how it has been done for VCS7 project[4].

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[4] `http://astrogeo.org/vcs7`