POlarimetric MOnitoring of GEodetic Sources

Team members in alphabetic order:

Walter Alef	co-I	Max-Planck-Institut für Radioastronomie, Germany
James Anderson	co-I	Technical University of Berlin, Germany
Talvikki Hovatta	co-I	Aalto University Metsahovi Radio Observatory, Finland
Frederic Jaron	co-I	Max-Planck-Institut für Radioastronomie, Germany
Hana Krasna	co-I	Vienna Technical University, Austria
Karine Le Bail	co-I	NVI, Inc./ NASA GSFC, USA
Andrei Lobanov	co-I	Max-Planck-Institut für Radioastronomie, Germany
Ivan Marti-Vidal	co-I	Observatorio de Yebes, Spain
Leonid Petrov	PI	NASA GSFC, USA
Alexandr Pushkarev	co-I	MFTI, Russia
Anthony Readhead	co-I	Caltech, USA
Helge Rottmann	co-I	Max-Planck-Institut für Radioastronomie, Germany
Tuomas Savolainen	co-I	Aalto University Metsahovi Radio Observatory, Finland
Matthias Schartner	co-I	Vienna Technical University, Austria (*not confirmed*)
Frank Schinzel	co-I	NRAO, USA
Greg Taylor	co-I	University of New Mexico, USA

1 Problem statement

Advances in VLBI hardware and methods of data analysis identified a serious source of systematic errors that affect geodesy, astrometry, and space navigation — the presence of source structure. More than 90% of observed sources show extended structure. It has been known for four decades that variable source structure affects group and phase delays noticeably and corrupts results (Thomas 1980), but the problem has not been solved. Some authors, e.g., Anderson and Xu (2018), went as far as to claim that the presence of unaccounted source structure is the dominant source of errors in geodetic VLBI. Geodetic VLBI observations typically have baselines extending up to 0.96 Earth diameter (about 12,000 km), and the *uv*-coverage tends to be weighted much more strongly to long baselines than typical astronomical experiments, especially made with the VLBA. In order to model sources for geodetic VLBI, one needs to have observations with the appropriate baselines involved. Simply making observations at similar frequencies with the VLBA is not good enough.

It has been known for a long time (e.g., Marcaide and Shapiro 1984) that position of an optically thick core is shifted with respect to the central engine because of self-absorption, and this shift is a function of frequency. When the energy in the radiating particles equals the energy stored in the magnetic fields, the core-shift is reciprocal to frequency (Blandford and Königl 1979). It was confirmed that *on average* the power low index is close of -1 (Sokolovsky et al. 2011). It is easy to show (Porcas 2009) that the contribution of the core-shift on fringe phase for this case is the same as the contribution of the ionosphere. The use of ionosphere-free linear combinations of group delays makes results immune to the core-shift and refers coordinate estimates to the position of the central engine. Observations showed that on average, the power law of frequency dependence -1 is rather common (Sokolovsky et al. 2011). However, recent paper of Plavin et al. (2019) showed that core-shifts varies during flares that last from months to years. They have presented evidence that during flares the condition of equi-partition has to be violated, and as a result, the position estimate derived from processing dual-band group delay observations will be affected. Analysis of position time series of many very bright frequently observed sources reveals a systematic pattern that is usually ascribed to a source structure evolution (Feissel-Vernier 2003). These position variations can also be due to the core-shift. Which factor, the core-shift or the source structure contributes the most is the open question. It should be noted that effects of source structure and variable core-shift are independent: position of a source without a discernible jet, i.e. a naked core, will still be affected by the core-shift.

VGOS system records linear polarization. Analysis of linear polarization brings additional challenges: the interferometer response to a linearly polarized source is different from a response of an unpolarized one and this affects the procedure for combination of cross and parallel correlations observables to form Stokes parameter I that is used for fringe fitting. This effect is large enough to raise a concern.

In order to evaluate the contribution of these three effects, we need contemporary images at multiple frequencies and in full polarizations. Since the geodetic VLBI observing programs for EOP monitoring and improvement of the terrestrial coordinate system are open-ended, and images, core-shift, and fractional polarization are changed at scales from months to years, a monitoring program with the goal improving accuracy of geodetic VLBI is necessary. To address this challenge, we propose a POlarimetric MOnitoring of GEodetic Sources (POMOGES) program.

2 Goals of the program

The geodetic source list, revised in July 2019 by Karine le Bail, contains 475 objects with 434 sources above declination $-35°$. All these sources have a median correlated flux density at baseline projection lengths 5,000–8,000 km at X-band > 200 mJy and are selected to have minimum source structure. Among 434 geodetic sources with $\delta > -35°$, 260 objects have status "main" and 174 have status "candidate". The "main" sources are recommended for scheduling in geodetic observations, and candidate sources are considered as a reserve.

The long-term goal is to develop a pipeline for imaging all the sources in every VGOS geodetic experiment, and use these images and self-calibrated visibilities for data reduction for source structure. However, this approach meets obvious challenges. First, geodetic observations are optimized for geodesy, and *uv*-coverage of observed sources is to sparse for generating useful images for most of the sources. Second, sensitivity of VGOS stations (typical SEFD $\sim$2000 Jy) is too low to make good polarization images.

The solution that we propose is to have a robust monitoring program at the VLBA+VGOS network for observing each geodetic source 3 times a year and use these images as a start model for imaging VGOS-only geodetic experiments. In that mode VGOS visibilities will be used as a perturbation to the images generated from processing POMOGES data.

We formulate four goals:

- Improvement of geodetic results, such as the Earth orientation parameters, station positions, and improvement of source coordinates. This will be achieved by computing the contribution of source structure in full polarization for processing geodetic VLBI observations under IVS programs.
- Monitoring core-shift changes. We will measure the core-shift and its frequency-dependence using observations at four frequencies. We will compute the contribution of the core-shift to the ionosphere-free group delay estimates and apply to the data analysis. We will investigate the dependence of the core-shift on the correlated flux density and the core spectrum.
- Monitoring structure evolution. Time series of images will reveal jet kinematics and core flux density fluctuations. Contemporary images will be used for scheduling geodetic observations.
- Monitoring polarization evolution. It is expected that processes in the jet will change of the polarization fraction and Faraday rotation. Polarization images will be used for an advanced fringe fitting procedure. We will investigate the connection of polarization fraction and Faraday rotation changes with changes of the correlated flux density of the core and jet hot spots and the core-shift changes.

3 Proposed observations

To achieve these goals, we propose monthly 24 hour observing sessions at the full VLBA plus all VGOS antennas that are in the position to participate: GGAO12M, WESTFORD, MCDONALD, KOKEE12M, WETTZ13N,

ONSA13NE, NYALE13N, RAEGYEB, HOBART12, ISHIOKA. VLBA antennas will observe each source at four bands, 2.220–2.412, 4.128–4.608, 7.392–7.836, 8.428–8.908 MHz, R and L polarizations using two receivers, S/X and wide C-band receivers switching between these receivers during each scans. The aggregate recording rate will be 4096 Mbps. VGOS antennas will be observing these four bands, H and V polarizations, at 8192 Mbps using their wide-band receivers without frequency switching. The choice of frequency bands is determined by limitations of the VLBA hardware. There are three options: three frequencies with two receivers, 2.2/8.6 + 12.3 GHz, four frequencies with two receivers, 2.2/8.6, 4.1/7.4 GHz, five frequencies with three receivers, 2.2/8.6, 4.1/7.4 GHz, 12.3 GHz. Observations 12.3 GHz that overlaps with VGOS will be affected by the ionosphere and will be useless for sub-nanoradian absolute astrometry taken alone. Observations at 4.1/7.4 GHz can be used alone, and comparison results at 2.2/8.4 GHz and 4.1/7.3 GHz will be used as an important test of the level of the remaining contribution of the source structure, core-shift and high order ionospheric term. Using three VLBA receivers will require increasing observing time by 50% that will require reduction of the number of sources observed in each session by 33%. At the same time, adding 12.3 GHz band does not help much in determining the core-shift frequency dependence, since the core-shift is greater at low frequencies.

Table 1: Frequency allocation at the VLBA in GHz. Each IF is 32 MHz wide. Data are recorded in R and L polarizations.

S/X	C	C	S/X
2.220	4.128	7.392	8.428
2.252	4.160	7.424	8.460
2.284	4.192	7.456	8.492
2.348	4.224	7.552	8.524
	4.416	7.744	8.588
	4.512	7.776	8.620
	4.544	7.808	8.684
	4.576	7.840	8.716
			8.780
			8.812
			8.844
			8.876

We propose to observe each source in 4 scans of 120 s each. VLBA antennas record for 50 s data using the S/X receiver, then within 20 s switch to C-band receiver, and record for 50 s data using the C-band receiver. The VGOS antennas do not change receivers or frequency allocation and records for 120 s. One fourth of the geodetic list, 110 sources will be observed in each observing session assuming loss of 40% time for slewing VLBA antennas. We propose to run the program with a cadence once per month. This will allow to observe each source every 120 days.

The minimum SNR at each band of observing a source with correlated flux density at longest baselines 200 mJy is 25 at VGOS–VGOS baselines, 35 at VLBA–VGOS baselines, and 100 at VLBA–VLBA baselines. However, these are the lowest estimates, since the median flux density of the sample at the longest projected baseline lengths is 300 mJy, 1.5 higher, and many observations will be made at projected baseline lengths shorter than 5,000 km, and therefore, the SNR will be higher. The expected image noise rms is 0.1 mJy, and therefore, dynamic range 2000–5000 will be achieved.

We propose to correlate the data with DiFX at Socorro.

4 Previous work

Science team members have extended experience in processing VLBI data. We have processed all publicly available VLBI data suitable for absolute astrometry (e.g., Petrov 2013), produced images (e.g., Piner et al. 2012), including polarization images (e.g., Lister et al. 2018), calibration of linearly and circular polarized data (e.g., Martí-Vidal et al. 2016), and computation of the source structure contribution for using it in VLBI data reduction (Petrov and Kovalev 2017).

In 2013 we ran a VLBA project BP175 in a mode similar to that we propose: VLBA switched frequency bands 4.1/7.3 and 2.2/8.4 GHz in single R polarization within each scan. We fringe fit data separately in each band and confirmed that differences in TEC derived from 4.1/7.3 and 2.2/8.4 GHz were consistent within formal errors. At that time we did not attempt to run a bandwidth synthesis 2.2 through 8.4 GHz because of problems with phase calibration, now resolved, associated with early version of DiFX.

In 2014 we ran a VLBA project BP185 with similar frequency switching mode within the same C-band receiver: 3.9/7.3 and 5.1/5.9 GHz in single R polarization. That time the DiFX correlator was able to extract all 32 tones per IF, and we were able to solve logistical problems associated with processing frequency switching data and perform fringe fit over the 3.9 GHz bandwidth.

5 Expected outcomes

The major scientific question that we strive to solve is to assess the contribution of the core-shift variability to source positions. This is a new scientific question that emerged in the literature in 2019 Plavin et al. (2019) and we do not know how large this contribution may be. Estimation of this effect, even in a form of upper limit, has a profound consequence for space geodesy, space navigation, and high accurate astrometry. This will dictate the strategy for maintaining sub-nanoradian accuracy in source positions. If the contribution of the core-shift variability in source positions derived from multi-frequency observations is above a certain threshold, say 0.5 nrad or 0.1 mas, dedicated programs for core-shift monitoring, like POMOGES, are necessary for maintaining that position accuracy. This result will also help us to evaluate the floor of position accuracy if no reduction for core-shift is taken into account during data analysis.

Proposed observations will contribute in the following areas:

5.1 Geodesy

- Common observations of the VLBA network and new VGOS network are very important for ties of VGOS stations with the ITRF. Since VGOS stations in most of the past and future observations observe mainly with themselves due to technical limitations, they form a disjoint network. Without any common observations, such a network may have an arbitrary rotation and translation with respect to the ITRF. Accuracy of the attachment of the VGOS network to the ITRF is determined by the accuracy of common observations between VGOS and legacy stations. We expect that within 1–2 years of POMOGES observations accuracy of ties will fall below 1 mm.

- We expect station position estimates will be improved due applying reduction for source structure. The source structure contribution is probably the largest effect that is not used for data reduction on a routine basis. The images produced from POMOGES program will be used for computation of the source structure contribution to data reduction.

- Polarimetric images will allow us to improve fringe fitting linear polarized sources at VGOS antennas. A simplified algorithm for computation of Stokes I parameter used for fringe fitting assumes a sources is not polarized. A presence of significant cross-polarization amplitude after reduction for parallactic angle and instrumental phases for some sources, for instance, J0555+3948, demonstrates that the simplified procedure has limits of its validity. Unaccounted, linear polarization of observed sources distorts fringe fitting and reduces the SNR. Applying a polarization image, either as a brightness distribution or as a δ-function, is expected to mitigate this kind of systematic error.

- Contemporary images made at the global network will be used for scheduling, and thus, improve efficiency of geodetic schedules. At the moment, geodetic scheduling software using over-simplified one-dimensional model of sources. Such an approach is very far from the state of the art. POMOGES images will provide a much more precise basis for the prediction of the correlated flux density at a given baseline at a given moment of time.

- For test purposes the sources will be imaged using only VLBA sub-network, VGOS sub-networks, and mixed polarization VLBA/VGOS baselines only. The consistency of these images will be analyzed and conclusions about systematic errors will be made. If systematic errors will be found, the collected dataset will allow to characterize them and propose approaches for their mitigation. Accuracy of Tsys measurements at VGOS stations will be evaluated.

- We will investigate stability of instrumental polarization and feasibility of using D-term derived from analysis of POMOGES observations to analysis of VGOS data.

- We will investigate the impact of frequency-dependent source structure on fringe fitting over ultra-wide bandwidth typically used for processing VGOS observations.

- Images collected at POMOGES program will be used as a start model for imaging VGOS data under IVS geodetic programs instead of δ-function used in traditional imaging. In the framework of this approach, IVS VGOS data will be used as a perturbation of images collected under POMOGES program. Thus, this project will contribute to the long-term goal: imaging observed sources in every geodetic experiment for accounting for source structure.

5.2 Astrometry

- Discovery of the core-shift variability Plavin et al. (2019) that necessarily violates $\sim f^{-1}$ frequency law poses the question of the contribution of the core-shift variations to variations of the source position derived from analysis dual-band group delays. **The key question of the project is whether the variable core-shift is a marginal factor that can be neglected or it is the dominating factor.** Proposed observations will answer this question. We expect improvement in absolute astrometry due to reduction for core-shift variability, although we do not have yet even a rough estimate of the improvement. The criteria of improvement is reduction of the scatter in the source time series. This is a new topic, and any outcome of this project will result in a high profile paper that will have a long-standing impact in the field of radio astrometry. If the contribution of the core-shift is significant – an results of this project will provide a quantitative measure, dedicated observations are needed to mitigate its impact.

- We expect improvement in absolute astrometry due to reduction for source structure using the images collected from the proposed observations. We are going to analyze the data using the source images for computation of source structure.

- We will process the data at 2.2/8.4 and 4.1/7.4 GHz bands independently. The consistency of source positions from observations at these bands will provide an important measure of possible residual frequency-dependent systematic errors.

5.3 Astrophysics

- The variability of the core-shift recently discovered Plavin et al. (2019) allows us to trace the processes occurred in the optically thick core. We will investigate the connection of the core-shift variations with variations of the core flux density, spectral index, variations of the polarization degree, and the Faraday rotation, We will investigate whether changes of the core-shift can be used for prediction of the ejection of the new component tractable at sources images.

- We will make polarization images and investigate variations of degree of polarization at the core region and on jet components. It is known that flaring activity increases the degree of polarization (a notable example: 3C48). A large sample of over 400 sources will help us to accumulate statistics of such variations and related it with source morphology, flux density variations and other features.
- The outflows mainly manifest two types of jet features, quasi-stationary and those moving downstream. While the former are present at every observing epoch typically close to the core, the latter are emerged on scales from months to years (Lister et al. 2019). The long-term monitoring observations will enable us to investigate structural evolution of the sources, trace changes of jet component positions and measure the corresponding speeds, and possibly accelerations as well for some sources. The speeds measured at different frequencies would be of a particular importance, as there are indications coming from the MOJAVE 15 GHz and Boston University 43 GHz monitoring programs that they can very with frequency. We will also analyze jet kinematics separately for sources of different spectral classes, gamma-ray brightness and synchrotron peak position.
- We will investigate changes in the Faraday rotation maps. So far, rotation measure observations on the parsec scale have been limited to small numbers of sources, so this larger sample would be of great interest for a study of variability of rotation measures. We already know that the Faraday screen can change on time scales of months, so we are likely to learn more about the nature of the screen.
- we will compute light curves and spectra of Fermi LAT. We will explore the connection between morphological changes of AGN and their GeV emission on a regular basis and over a large population.

5.4 Deliverables

- Time series of Stokes images at 2.3, 4.1, 7.4 and 8.5 GHz of every observed source.
- Time series of core-shifts as a function of frequency for the sources that have a component on their jets that can be used for anchoring the images.
- Source positions derived from 2.2/8.4 GHz and 4.1/7.4 GHz data with and without applying reduction for sources structure and core-shift.
- The global TRF solutions produced using all VLBI data since 1980.
- Time series of baseline lengths.
- The Earth orientation parameters derived from the VLBA sub-network and from the VGOS sub-network separately, and from the entire network as well.
- Time series of D-term estimates at VGOS antennas.

We waive proprietary period. The results of correlation will become publicly available immediately. Our results of data analysis will be posted online at the project web site within 30 days of experiment correlations.

6 Methodologies

6.1 Scheduling

The source list will be split into 4 parts of 120 sources each equally distributed over right ascensions. The schedule will pick up each target source to be observed in 4 scans of 120 sec each. The schedule will be optimized using the following criteria: 1) good *uv*-coverage; 2) good astrometric accuracy; 3) each station should observe at least two scans at elevation angles 7–20° and 60–85° every hour for better separation of estimated atmosphere path delay parameters from other variables; 4) a number of polarimetric calibrators with a good parallactic angle coverage will be included in the schedule.

6.2 Data analysis

The dataset collected under POMOGES project will be used as a testbed for software that are being developed for processing VGOS data. The main route will be using NASA $\mathcal{PIMA}$ software package for fringe fitting, bandpass calibration, calibration for D-term, and generation of output datasets of calibrated visibilities after applying results of fringe fitting. These datasets will be imported to Difmap for source imaging. The results of fringe fitting will be imported to database files suitable for their processing with NASA VTD/p-Solve software package for geodesy and absolute astrometry.

At the moment, the path for producing astrometry/geodesy results and Stokes I images using $\mathcal{PIMA}$ is tested. The path for producing polarization images using a mixture of linear and circularly polarized data is under active development and is not yet tested. One of the reasons of slowness in development is a lack of high quality data from a project with a strong scientific goal that would motivate the developers. It will be developed and tested in the course of project.

We will continue work on an alternative way for processing linearly polarized data, "polconvert" approach, which allows us to fringe-fit directly on Stokes I (not pseudo-I, but the **true I**), which is independent of the linear polarization of the source. Besides, this strategy would combine naturally with the VGOS-VLBA fringes, which would become pure circular. In general terms he problem hence reduces to:

- quantifying and accounting for the residual post-conversion leakage (of the order of a few pro cents in circular polarization). Although we can solve for this D-terms following a standard procedure, we will be developing a CASA task to optimize it for the case of wide fractional bandwidth.
- taking into account the spectral-index structure of the source in the fringe fitting over the whole bandwidth 2.3 to 8.6 GHz. Although we have already been able to fringe-fit the EU-VGOS observations using a dispersive term for the lower frequencies capturing the contribution of the ionosphere, the effects from the spectral dependence of Stokes I are still not considered and the work is in progress.
- Performing amplitude calibration using antenna gain curves and Tsys measurements.

6.3 Risk assessment

We are aware that this project is very ambitious: it requires observing mode never used before and require data analysis tools that are under development now. In particularly, the following problems have to be solved:

- Transfer data to the correlator, $\sim$60 Tb per station, per experiment.
- Some VGOS antenna do not provide Tsys measurements. Work should be done to implement and test it.
- Antenna gain curves for VGOS antennas are not yet available. be done to implement and test it.
- Dual-band S/X mode at 4 Gbps at VLBA have never been used, and work should be done to implement and test it.
- Processing mixed-mode from visibility to astrometric results and images is not yet implement with $\mathcal{PIMA}$ or any other software packages and and work should be done to implement and test it.
- Synthesizing polarization images in an efficient way with minimum manual intervention requires substantial work.

- Intensive work should be done for assessment of the optimal scheduling for such a large network satisfying scheduling goals, constraints, and providing sufficient number of observations for calibration.

These challenges will be addressed in the course of the project. They are not unique to POMOGES, but reflects the efforts to catch up hardware development the emerged from implementation of the VGOS project: wide bandwidth, high recording rate, and linear polarization. The efforts to catch up these technological development must be done anyway to fully use VGOS hardware. The proposed project provides an incentive to do it and a rich dataset that can be used as a testbed.

7 Roles of the team members

The work will be distributed among science team members in these areas:

- Scheduling: M. Schartner, L. Petrov, F. Jaron;
- Astrometric analysis: L. Petrov, H. Krasna, J. Anderson;
- Stokes I imaging: L. Petrov, A. Lobanov;
- Polarization imaging: I. Marti-Vidal, T. Hovatta, T. Savolainen;
- Core-shift measurement: A. Pushkarev;
- Investigation of the impact of source structure on source positions: K. Le Bail, L. Petrov, H. Krasna, J. Anderson;
- Testing 4Gbps dual-band X/S mode with VLBA: F. Schinzel;

8 Observation plan

We consider this as a long term multi-year project. Considering the challenges mentioned above, we request 10 minute long observing slots for fringe tests first. Upon a successful fringe test, we request observing time for one 24 hour session at the full network as a pilot project. The purpose of the pilot project is to check the overall station performance, to test our data analysis tools, and examine results. We plan to present a detailed report of the pilot project to the Time Allocation Committee. Upon delivery of the successful pilot project report, we will either re-submit the full POMOGES proposal amended for the experience gained during the pilot phase or request the second pilot experiment if analysis will reveal a need of changes in the observing schedule and then prepare additional report and re-submit the proposal.

References

Anderson, J. M. and M. H. Xu (2018), "Source Structure and Measurement Noise Are as Important as All Other Residual Sources in Geodetic VLBI Combined." *Journal of Geophysical Research (Solid Earth)*, 123, 10,162–10,190.

Blandford, R. D. and A. Königl (1979), "Relativistic jets as compact radio sources." *ApJ*, 232, 34–48.

Feissel-Vernier, M. (2003), "Selecting stable extragalactic compact radio sources from the permanent astrogeodetic VLBI program." *A&A*, 403, 105–110.

Lister, M. L., M. F. Aller, H. D. Aller, M. A. Hodge, D. C. Homan, Y. Y. Kovalev, A. B. Pushkarev, and T. Savolainen (2018), "MOJAVE. XV. VLBA 15 GHz Total Intensity and Polarization Maps of 437 Parsec-scale AGN Jets from 1996 to 2017." *ApJS*, 234, 12.

Lister, M. L., D. C. Homan, T. Hovatta, K. I. Kellermann, S. Kiehlmann, Y. Y. Kovalev, W. Max-Moerbeck, A. B. Pushkarev, A. C. S. Readhead, E. Ros, and T. Savolainen (2019), "MOJAVE. XVII. Jet Kinematics and Parent Population Properties of Relativistically Beamed Radio-loud Blazars." *ApJ*, 874, 43.

Marcaide, J. M. and I. I. Shapiro (1984), “VLBI study of 1038+528A and B: discovery of wavelength dependence of peak brightness location.” *ApJ*, 276, 56–59.

Martí-Vidal, I., W. H. T. Vlemmings, and S. Muller (2016), “Dual differential polarimetry. A technique to recover polarimetric information from dual-polarization observations.” *A&A*, 593, A61.

Petrov, L. (2013), “The Catalog of Positions of Optically Bright Extragalactic Radio Sources OBRS-2.” *AJ*, 146, 5.

Petrov, L. and Y. Y. Kovalev (2017), “Observational consequences of optical band milliarcsec-scale structure in active galactic nuclei discovered by Gaia.” *MNRAS*, 471, 3775–3787.

Piner, B. G., A. B. Pushkarev, Y. Y. Kovalev, C. J. Marvin, J. G. Arenson, P. Charlot, A. L. Fey, A. Collioud, and P. A. Voitsik (2012), “Relativistic Jets in the Radio Reference Frame Image Database. II. Blazar Jet Accelerations from the First 10 Years of Data (1994-2003).” *ApJ*, 758, 84.

Plavin, A. V., Y. Y. Kovalev, A. B. Pushkarev, and A. P. Lobanov (2019), “Significant core shift variability in parsec-scale jets of active galactic nuclei.” *MNRAS*, 485, 1822–1842.

Porcas, R. W. (2009), “Radio astrometry with chromatic AGN core positions.” *A&A*, 505, L1–L4.

Sokolovsky, K. V., Y. Y. Kovalev, A. B. Pushkarev, and A. P. Lobanov (2011), “A VLBA survey of the core shift effect in AGN jets. I. Evidence of dominating synchrotron opacity.” *A&A*, 532, A38.

Thomas, J.B. (1980), “An analysis of source structure effects in radio interferometry measurements.” *JPL Publication*, 80–84.