Remaining problems in geodesy/astrometry VLBI and approaches to their solutions

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I. Science with astrometry/geodesy VLBI

1. VLBI/Gaia offsets

VLBI Radio Fundamental Catalogue (15,740 sources) on 2019.03.08 and Gaia DR2 (1.69 \cdot 10^9 objects)

Green: 9,453 VLBI/Gaia matches  \( P < 0.0002 \)

Blue: VLBI sources without Gaia matches
The histograms of the distribution of the position angle of Gaia offset with respect to VLBI position counted from the jet direction counter-clockwise.

Top left (a): all the matches with known jet directions;
Top right (b): the matches with $\sigma_\psi < 0.3$ rad;
Bottom left (c): the matches with $\sigma_\psi < 0.3$ rad and arc-lengths < 2.5 mas;
Bottom right (d): the matches with $\sigma_\psi < 0.3$ rad and arc-lengths > 2.5 mas.
Measurement of VLBI/Gaia offsets allows

- to identify the area where a flare occurs: at the core, accretion disk, or hot spot
- to measure a size of the optical jet and its relative flux density
- to measure a share of synchrotron emission wrt accretion disk emission
- to measure a jitter in optical positions

Solved problems:

- We have established the nature of $\psi = 0$ peak
- We have indirectly detected jitter in Gaia positions
Remaining problems of VLBI/Gaia offset analysis

- What is the nature of $\psi = \pi$ peak?
- How the size and strength of the optical jet is related to other AGN properties?
- Quantitative analysis of the size and strength of the optical jet sample
- How to correct Gaia positions for jitter?

What needs to be done?

- Deep images of Gaia counterparts
- Improvement in position accuracy down to 1–1.5 nrad for $> 4,000$ sources.
2. Variable core-shift

What we know:

- When core-shift $d \sim f^{-1}$ it has no effect on $\tau_{\text{iono-free}}$.
- $d \sim f^{-1}$ corresponds to equi-partition state and it is common.
- $d \sim f^{-1}$ is violated during flares has effect on $\tau_{\text{iono-free}}$.
- core-shift is changed during flares.
- core-shift changes are large.

Figure 14. Variability amplitudes (difference between maximum and minimum values) of core positions at different frequencies. Error bars represent 68% credible intervals.

Measurement of core-shift variability allows

- to probe the inner optically thick part of the jet
- to understand the mechanism of AGN flares

Problems:

- How to measure core-shift routinely?
- How to compute the contribution of the core-shift to group delay?
- How to assess the contribution of the core-shift on source positions without direct measurements?
- For how long the state of equi-partition \( (d \sim f^{-1}) \) is violated?
Technique improvement

1. Computation of the source structure contribution

We have \( \sim 80k \) images of over 14,000 sources. How to use them?

Problems:

- What is the best way to compute structure delay? CLEAN component, direct visibility usage, Gaussian models?
- How to get images from geodetic experiments?
  - We need care about amplitudes (Ts, gain curves measurement)
  - Need develop a new imaging procedure based on perturbation of known images.
- How to make images **routinely**?
- How to find an invariant point on the image?
- How to assess an uncertainty of structure delay?
What needs to be done?

• Change our mind

• Set the goal. Enough demonstrations, let us do production!

• Develop infrastructure for imaging every experiment

• Routine process experiments on the visibility level

• Focus on tuning hardware for providing excellent amplitude calibration
2. Accounting for the atmosphere turbulence

1. 1st approximation:
   - Atmosphere is uniform:
     \[ \tau(t, E, A) = \tau_z(t) \ast m(e) \text{ or } \tau(t, E, A) = \tau_z(t) \ast m(e + \eta \cos(A) + \epsilon \sin(A)) \]
   - \( \tau \) is uncorrelated time and space: \( \text{Cov}(\tau_1, \tau_2) = 0 \)

2. 2nd approximation:
   - Atmosphere is non uniform: \( \tau(t) \neq f_1(e) \ast f_2(A) \)
   - \( \tau \) is correlated in time and space:
     \[ \text{Cov}(\tau(t, e_1, A_1), \tau(t, e_2, A_2)) \neq 0 \]
     \[ \text{Cov}(\tau(t_1, e, A), \tau(t_2, e, A)) \neq 0 \]
Approaches:

- Estimation model: beyond spherical harmonics degree/order 1? Slepiian basis?

- Covariance matrix: how to get it?
  - Global regression model
  - Station-dependent regression model
  - Computation based on the output of numerical weather models

What needs to be done:

- Set the goal. Enough demonstrations, let us do production!
3. Mitigation of the polarization impurity impact

Polarization leakage results in

- contribution to group delay
- phase misclosure
- dependence on parallactic angle
- loss of sensitivity

Figure 7.3: Black dots: D-term correction angle as applied by *fourfit* to the visibility phases in R1399 for the baseline Westford-Wettzell on the source 3C418.
Linear polarization makes the impact worse.

- leakage term degrades computation of polarization bandpass
- cross-talk with intrinsic source polarization

**What needs to be done:**

- Change mind: we do care of polarization now
- Evaluate D-term and monitor it
- Routine process experiments on the visibility level
- Monitor intrinsic source polarization
4. Mitigation of RFI

Satellite radio

S–band fringe phase for 1803+784 at BR–VLBA / LA–VLBA in BP222L

S–band fringe amplitude for 1803+784 at BR–VLBA / LA–VLBA in BP222L
What needs to be done?

- Realize that we will have to live with RFIs
- Automatic RFIs detection and cleaning the data
- Analyzing the RFI source and build an empirical RFI model (t,e,A,f)
5. Scheduling

VGOS hardware provides us more freedom to make better schedules.

Are we ready to use this freedom?

**Remaining problems:**

- The problem to generate the best schedule is not solved theoretically.
- N-step lookahead versus full schedule optimization?
- To optimize the schedule for optimal **accuracies** versus **formal uncertainties**
6. Automation

Why do we still do VLBI data analysis manually??

Goal: reach full automation:

- workflow
- flagging, masking, catching breaks at the visibility level
- flagging, masking, catching breaks at the group delay level
- flagging, masking, boxing image components

An Analyst should use brain for analyzing logs, not hands for moving a mouse.

III. Measurement of antenna gravity deformations

Unaccounted antenna gravity deformations result in position biases, mainly along Up.

So far, only 6 antennas were measured

**Problems:**

- How to organize measurement of all antennas?
- How to account for events that may result in changes of gravity deformations?
- How to “measure” decommissioned antennas?
Summary:

- Scientific problems: VLBI/Gaia offset and core-shift.

- Data analysis: atmosphere turbulence, source structure contribution, accounting for polarization impurity, RFI mitigation.

- Logistics: make VLBI fully automatic; new scheduling.

- Measurement: antenna gravity deformation.
Difficulties in dealing with source structure:

Clean RR map. Array: VLBA Correlator
J0231+1322 at 8.652 GHz 2017 Feb 24

Map center: RA: 02 31 45.894, Dec: +13 22 54.716 (2000.0)
Map peak: 0.856 Jy/beam
Contours %: 0.75, 1.5, 3, 6, 12, 25, 50
Beam FWHM: 1.79 x 0.701 (mas) at -5.11°

2
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
Jy/beam

Edit all channels.
J0231+1322 at 8.652 GHz in RR 2017 Feb 24

Amplitude

Phase

Radial UV distance along P.A. 70° (10^6 λ)
Where is the core, where is the jet?