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

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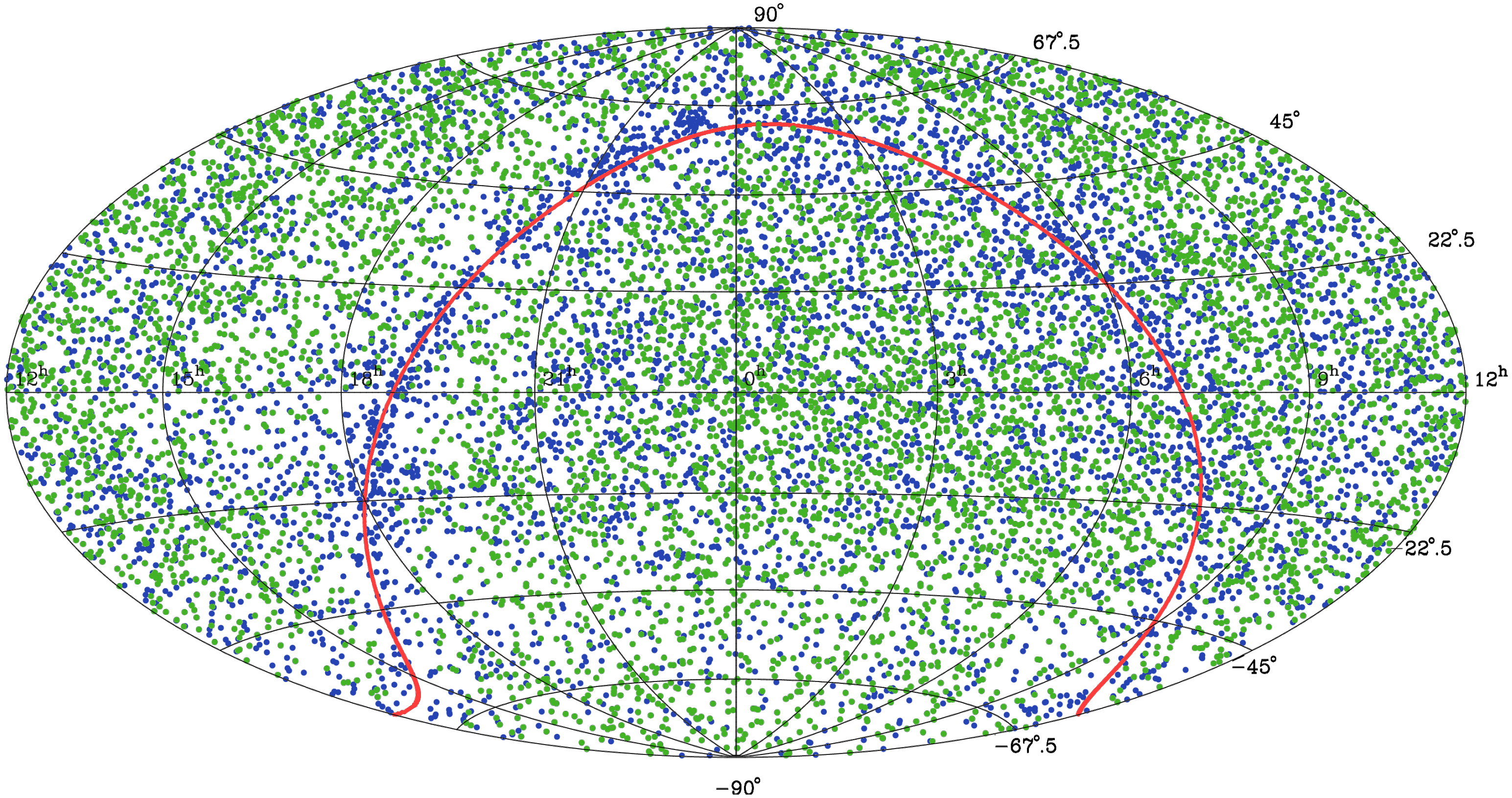
I. Science with astrometry/geodesy VLBI

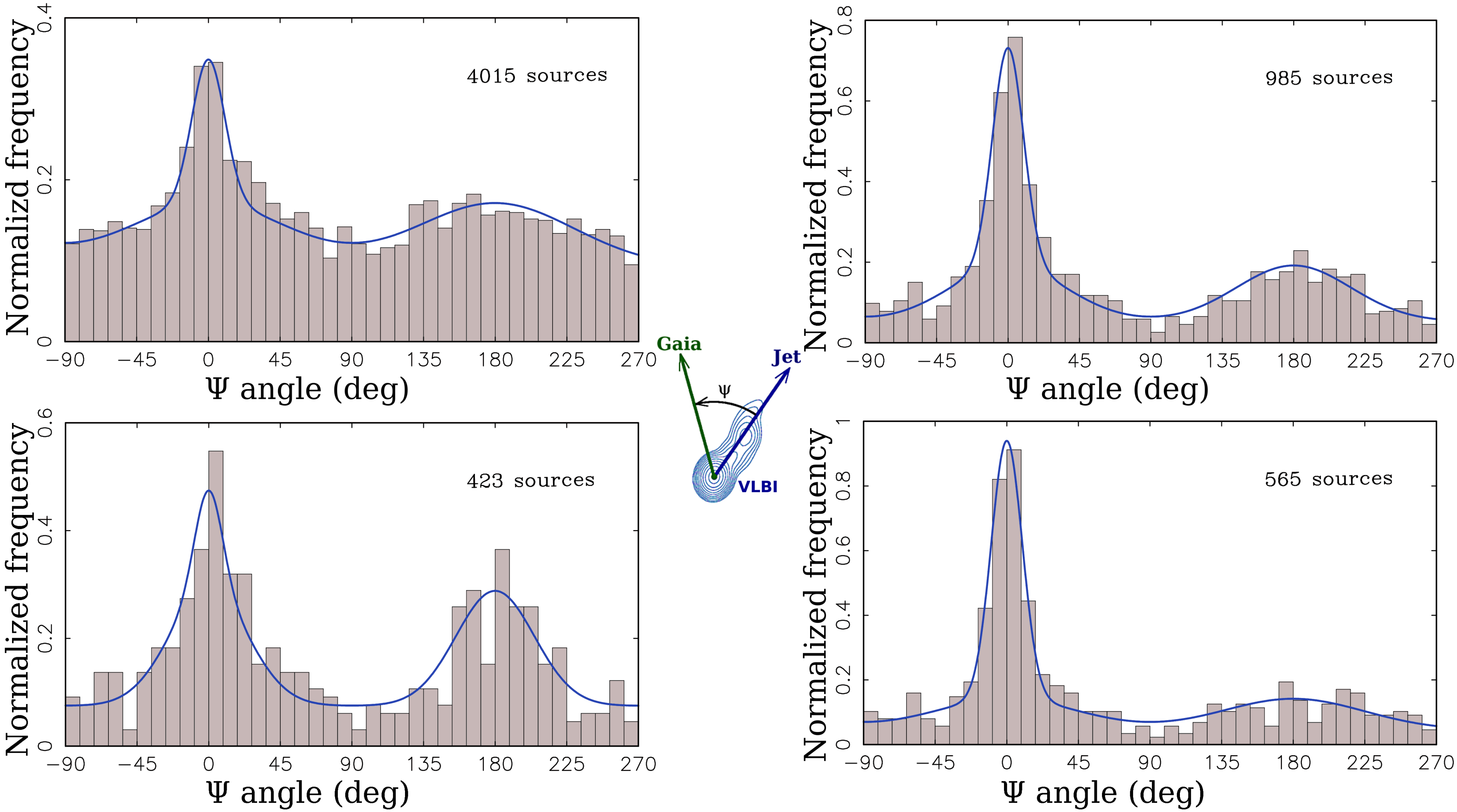
1. VLBI/Gaia offsets

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 $\tau_{\mathrm{iono-free}}$.
- $d \sim f^{-1}$ corresponds to equi-partition state and it is common
- $d \sim f^{-1}$ is violated during flares **<u>has</u>** effect on $\tau_{\mathrm{iono-free}}$.
- core-shift is changed during flares.
- core-shift changes are large.

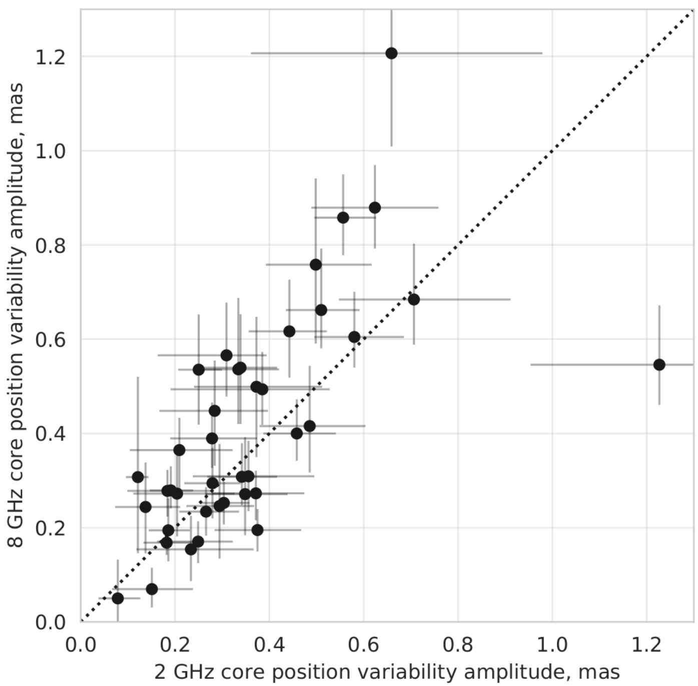


Figure 14. Variability amplitudes (difference between maximum and minimum values) of core positions at different frequencies. Error bars represent 68% credible intervals.

Plavin et al, (2019) MNRAS 485, 1822–1842

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 ~ 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 (Tsys, 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:
     $\tau(t, E, A) = \tau_z(t) * m(e)$ or
     $\tau(t, E, A) = \tau_z(t) * m(e + \eta \cos(A) + \epsilon \sin(A))$
   - τ is uncorrelated time and space: $\mathrm{Cov}(\tau_1, \tau_2) = 0$

2. 2nd approximation:

   - Atmosphere is non uniform: $\tau(t) \neq f_1(e) * f_2(A)$
   - τ is correlated in time and space:
     $\mathrm{Cov}(\tau(t, e_1, A_1), \tau(t, e_2, A_2)) \neq 0$
     $\mathrm{Cov}(\tau(t_1, e, A), \tau(t_2, e, A)) \neq 0$

Approaches:

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

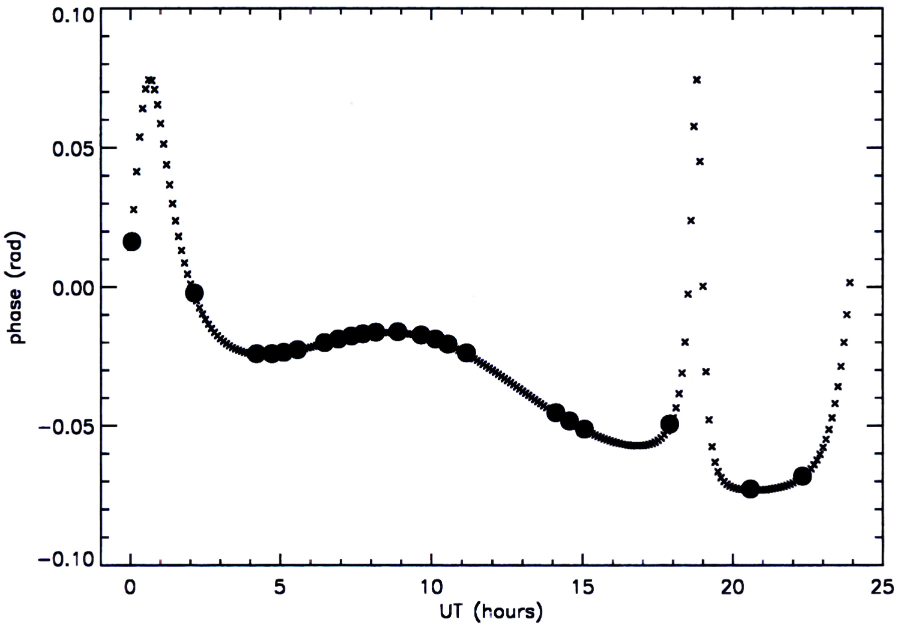


Figure 7.3: Black dots: D-term correction angle as applied by *fourfit* to the visibility phases in R1399 for the baseline Westford-Wettzell on the source 3C 418.

A. Roy 2010,
Ph.D. Thesis, p. 66.

Polarization leakage results in

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

Linear polarization makes the impact worse.

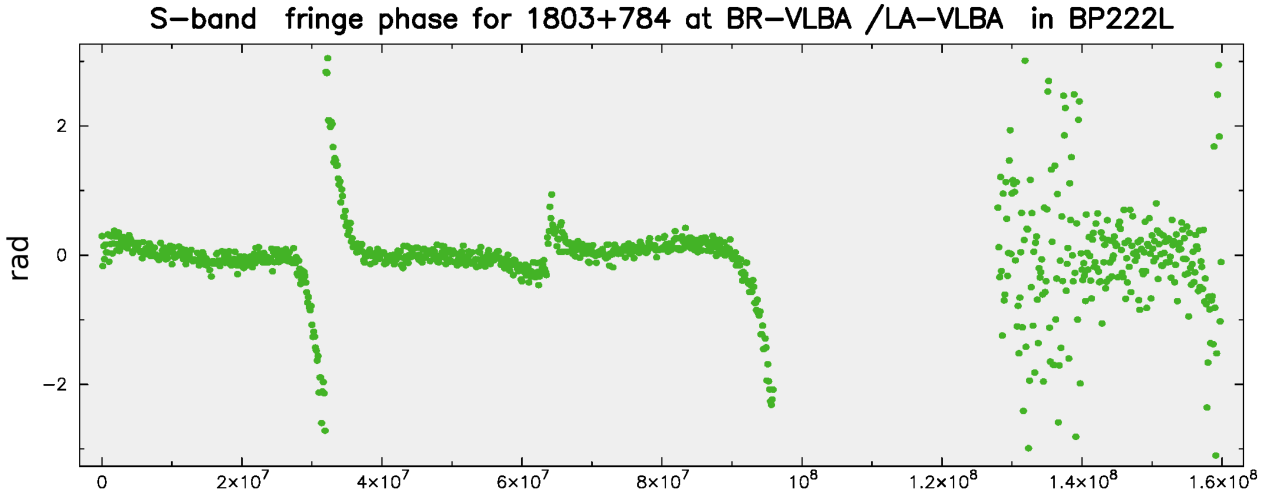
- leakage term degrades computation of polarization bandpass
- cross-talk with intrinsic source polarization

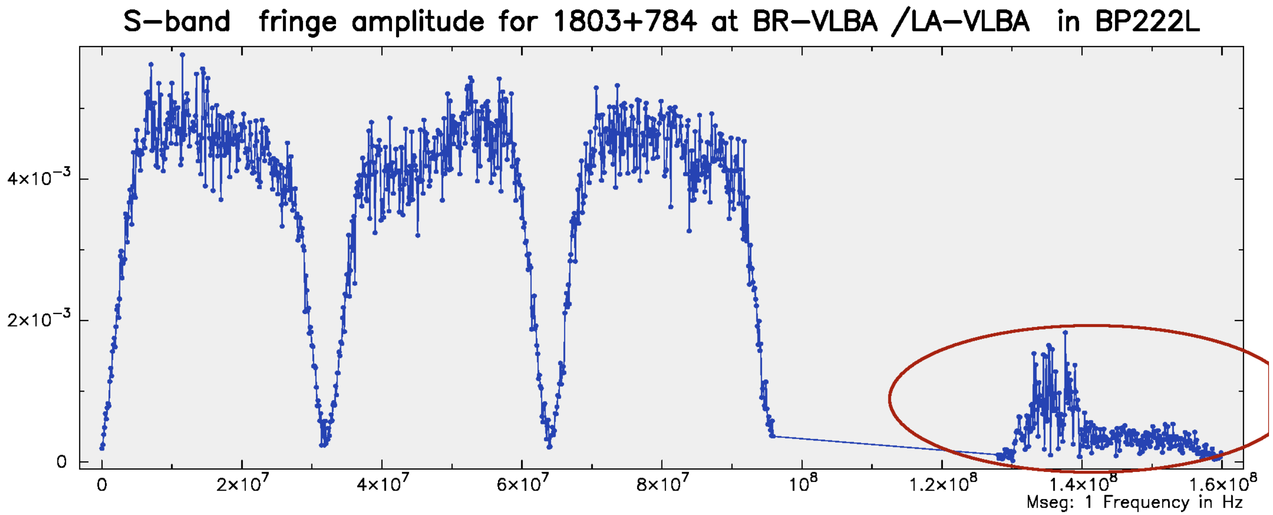
What needs to be done:

- 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

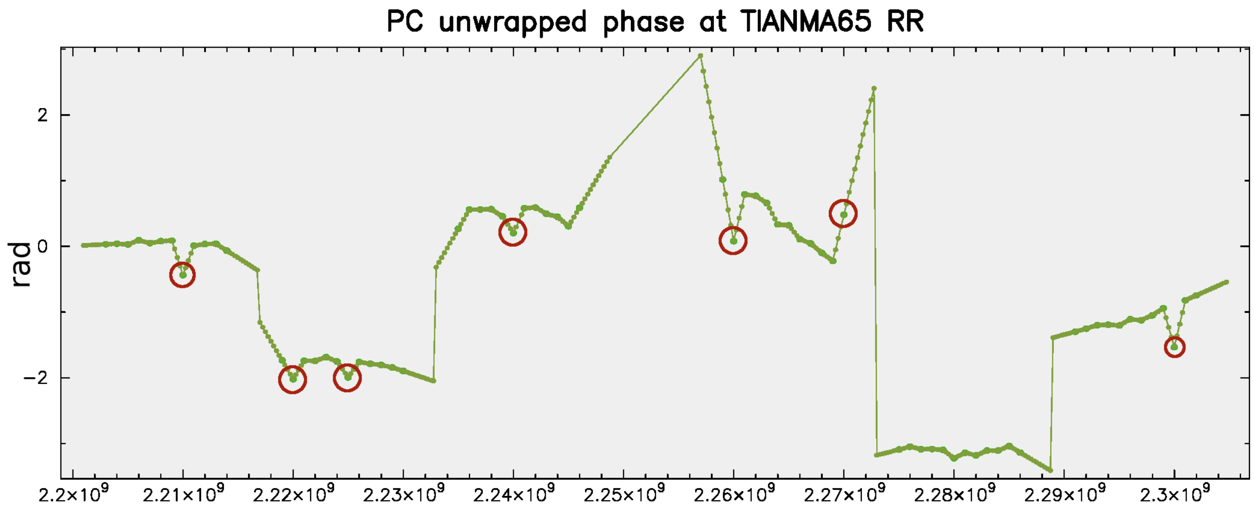
4. Mitigation of RFI

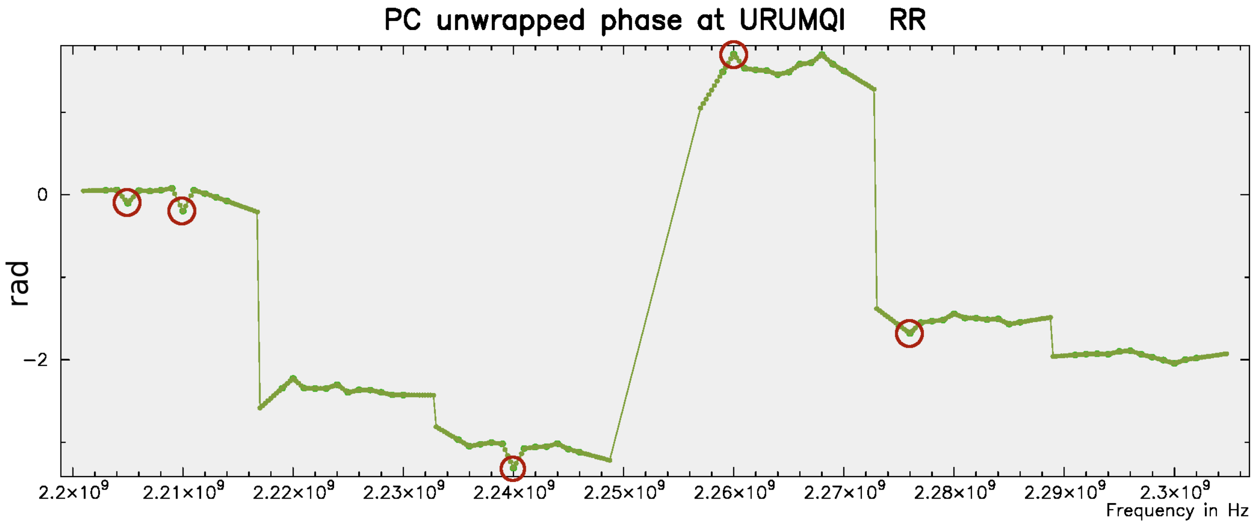
Satellite radio



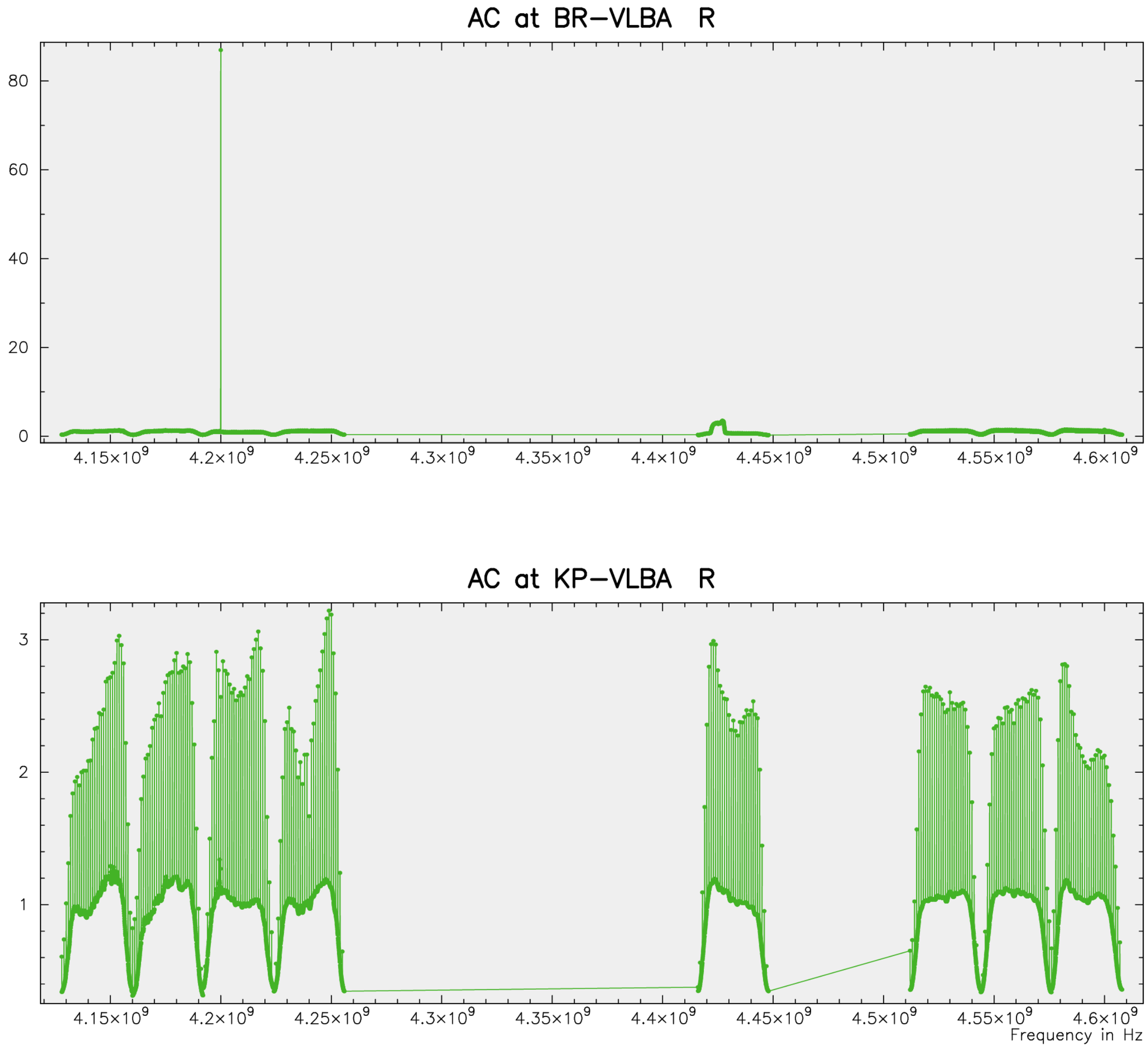


Internal RFI





Internal RFI



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??

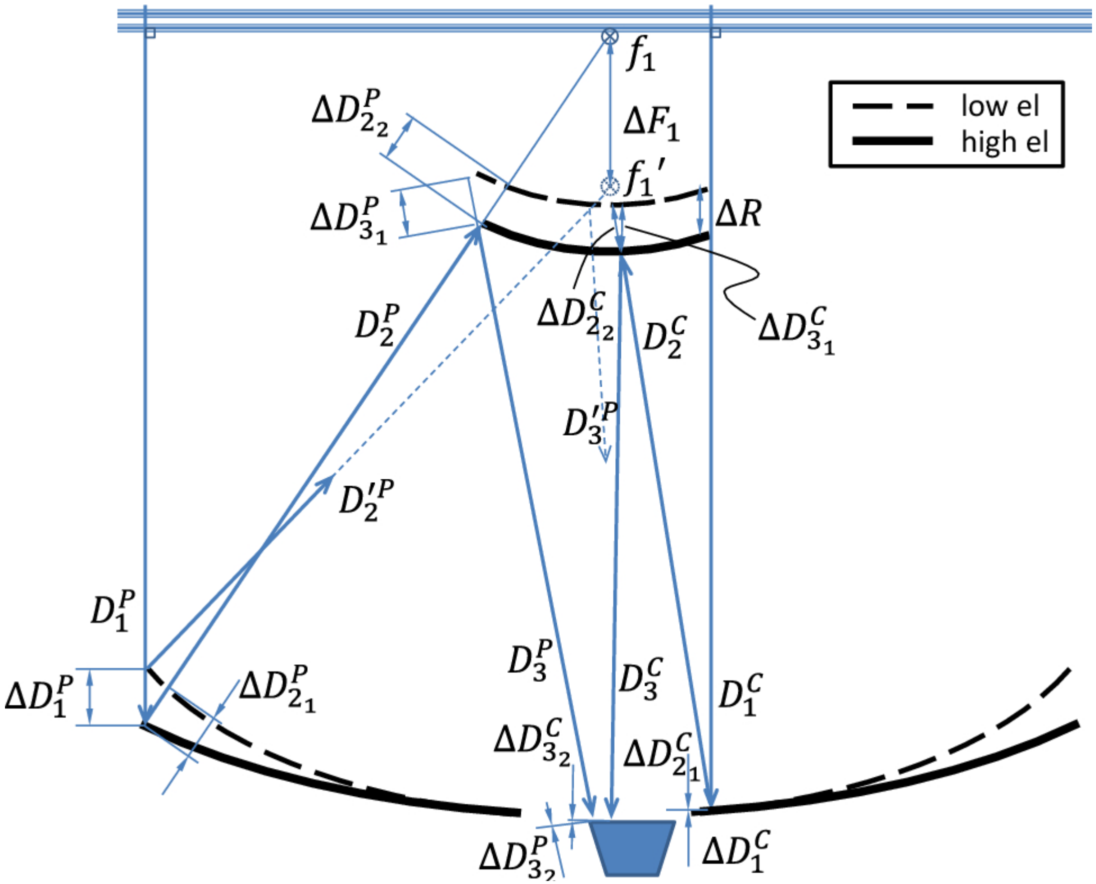
Goal: reach full automation:

- 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.

Feasible? **YES!** Key Stone Project (1994–1996)

III. Measurement of antenna gravity deformations



S. Bergstrand, et al., J. Geodesy, in press 2019.

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

So far, only 6 antennas were measured

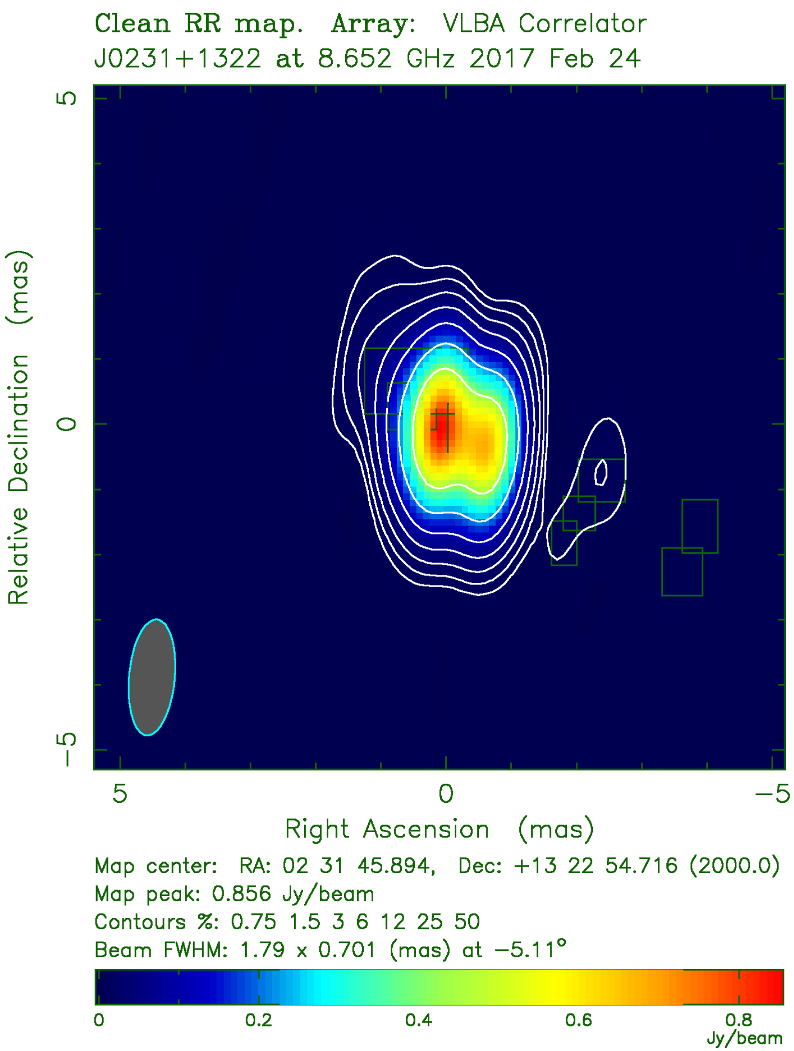
Problems:

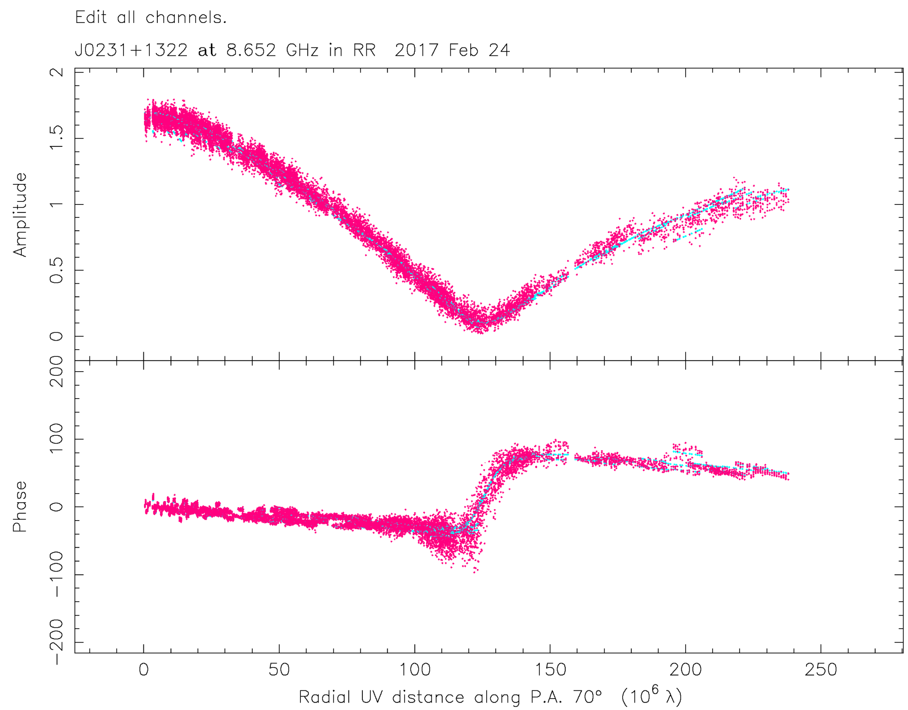
- How to organize measurement of all antennas?
- How to account for events that may results in change of gravity deformations?
- How to “measure” decommissioned antennas?

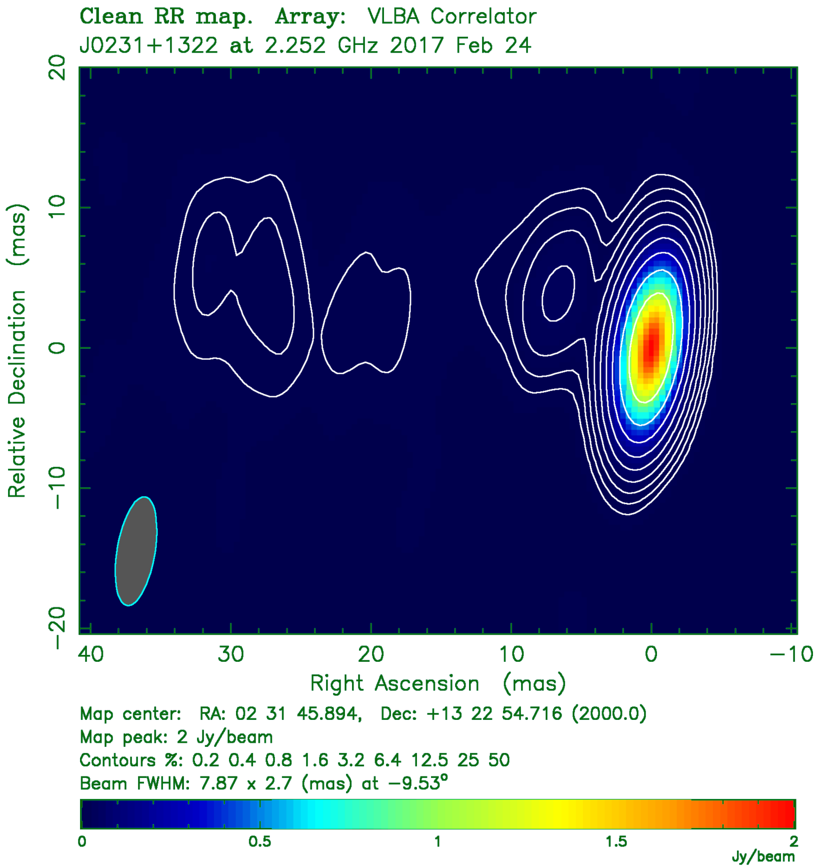
Summary:

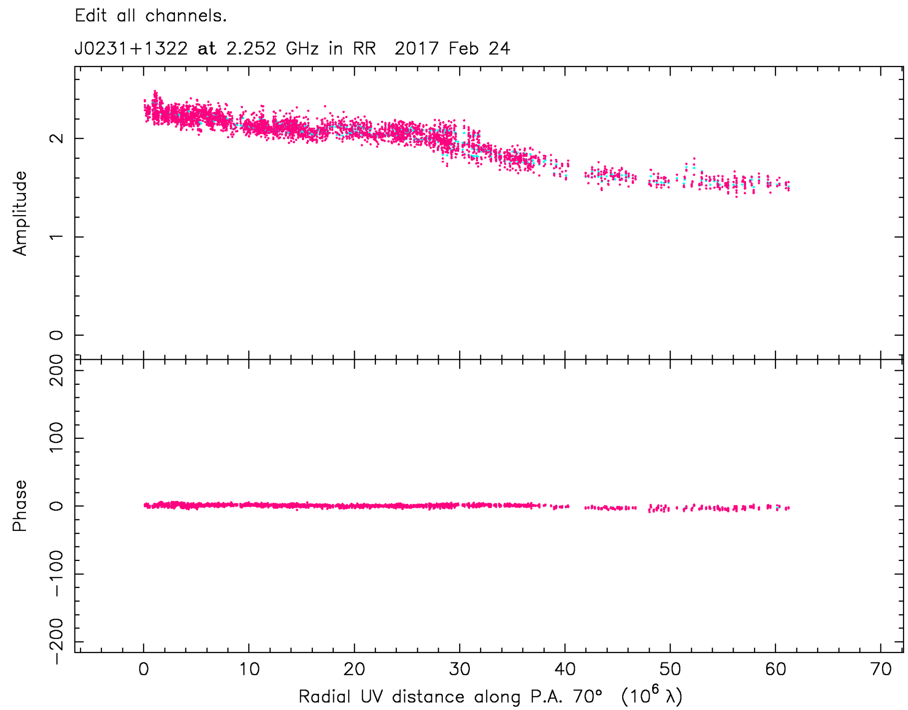
- Scientific problems: VLBI/Gaia offset and core-shift.
- Data analysis: atmosphere turbulence, source structure contribution, accounting for polarization impurity, RFI mitigation.
- Logistics: make VLBI fully automatic; new scheduling.
- Measurement: antenna gravity deformation.

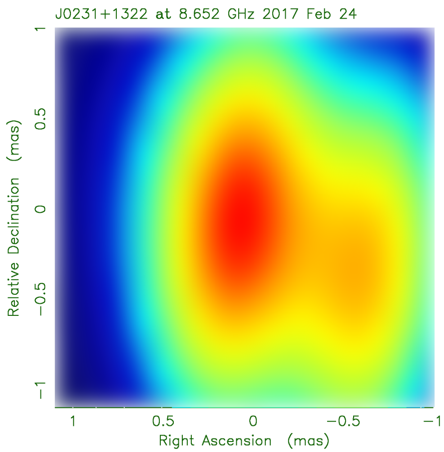
Difficulties in dealing with source structure:











Where is the core, where is the jet?