An efficient serial MultiView approach to mitigating atmospheric spatial-structure errors for VLBI astrometry

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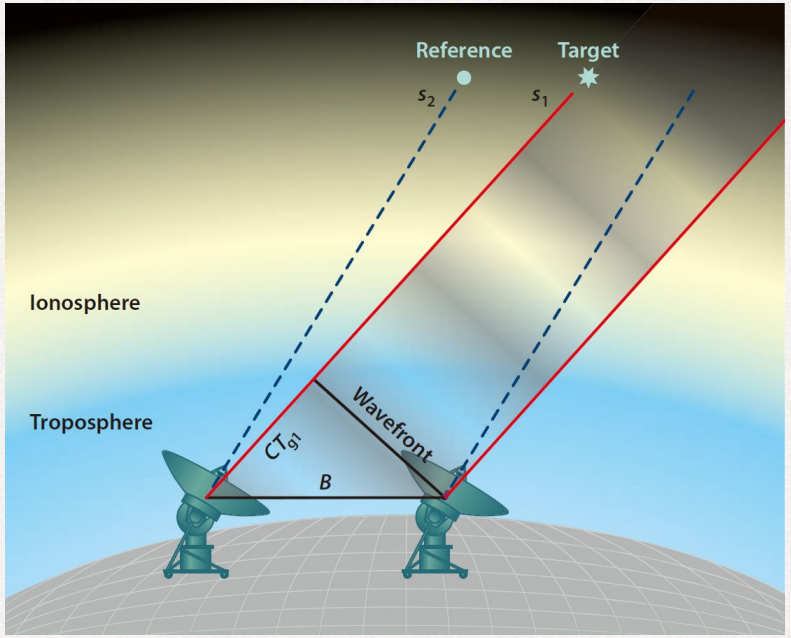
VLBI astrometry

- Phase delay vs. group delay: more precise by $\Delta\nu/\nu$
- *Absolute* phase delay is not observable due to ambiguity
- Differential techniques enable the calibration of *relative* phase delay
- Calibrate with a phase calibrator within several degrees
- Theoretical relative position accuracy: $\sim 0.5 * \frac{\lambda}{B*SNR}$
- <10 μas for VLBA (SNR=100, cm wavelength)

Hard to achieve

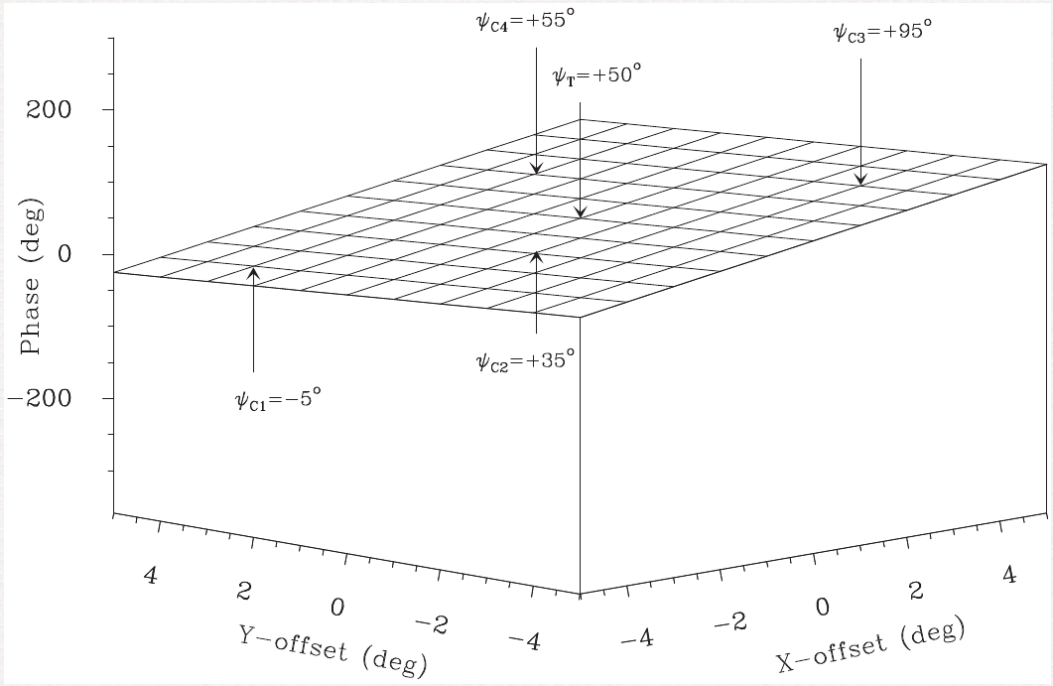
- Unmodeled errors, including *atmospheric spatial-structure errors*
- Grow with angular separation between target and calibrator
- Get worse at low elevations



Phase referencing (PR) with a nearby calibrator
Reid and Honma, 2014

MultiView

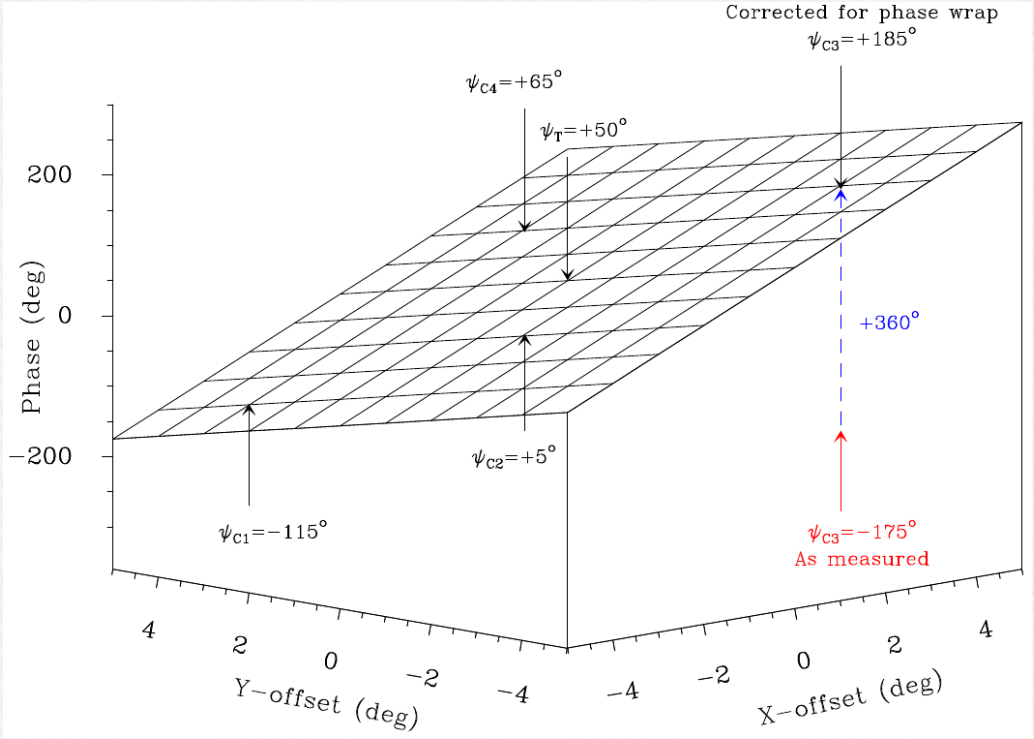
- Atmospheric spatial-structure errors:
  - Mainly comes from ionosphere at <10 GHz
  - Unpredictable & changes fast
  - Can be modeled with linear gradients on local scale
- MultiView technique (Rioja et al., 2017):
  - Several calibrators around target
  - Cyclically switch between target and all calibrators
  - Fit a phase plane across calibrators for each cycle
  - Interpolate at target's position



MultiView phase plane fitting
Reid, 2022

MultiView

- Problems of conventional MultiView (cMV) approach:
  - Low on-target time proportion, <40%
  - Long observing cycle, several minutes
  - Phase ambiguity (wrap over 2π)
    - Large position offset
    - Hard to distinguish
- What we need:
  - Do not require observing all calibrators in each cycle
  - Automatic ambiguity correction



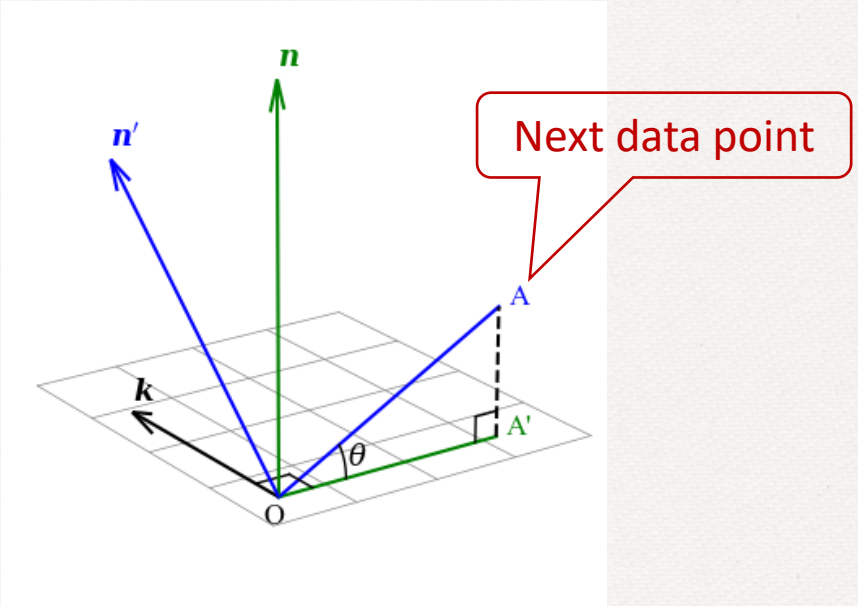
Phase ambiguity
Reid, 2022

Serial MultiView

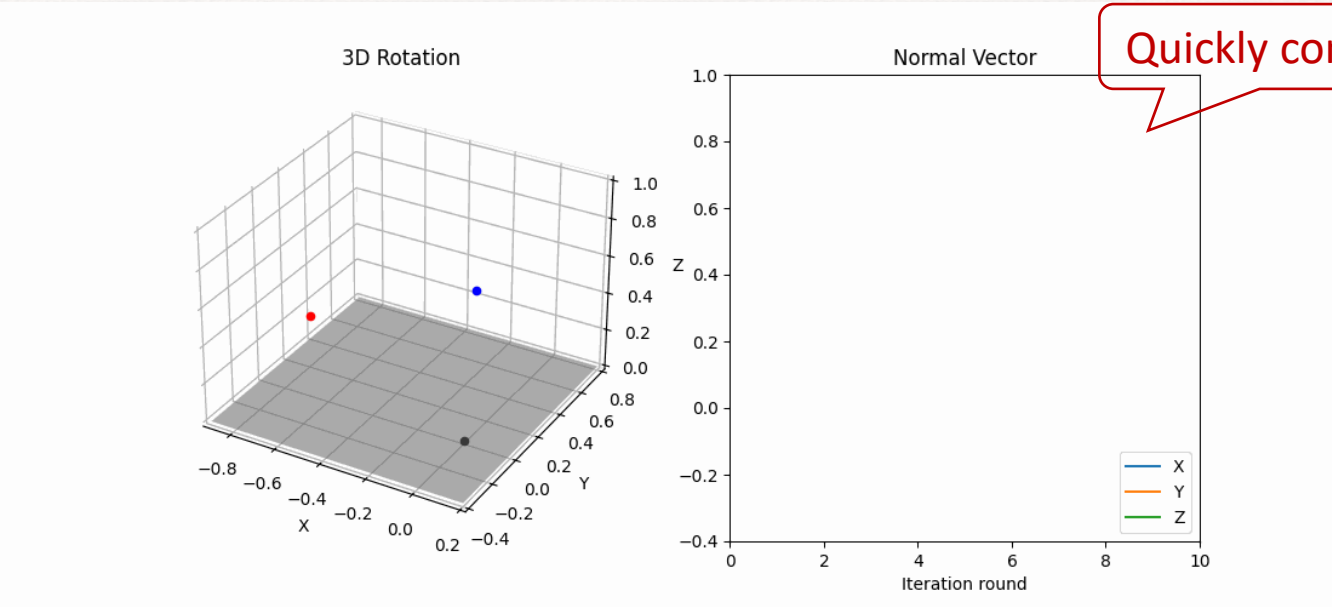
- Idea: phase referencing with additional spatial-structure phase correction
  - Based on ordinary PR, one primary calibrator
  - Insert some scans to monitor residual phases of several nearby secondary calibrators
  - Time series of the residual phases
  - *Establish a time-varying spatial structure model from the time series*
  - Calculate residual phase at target's position for each scan
  - Apply to target as additional phase bias

Serial MultiView

- From residual phase time series to time-varying spatial structure model
  - A *freely rotating* phase plane always passes through origin (0, 0, 0)
  - Iteratively rotate along residual phase time series
  - Any plane can be determined with two secondary calibrators
  - Model: time series of phase plane normal vector



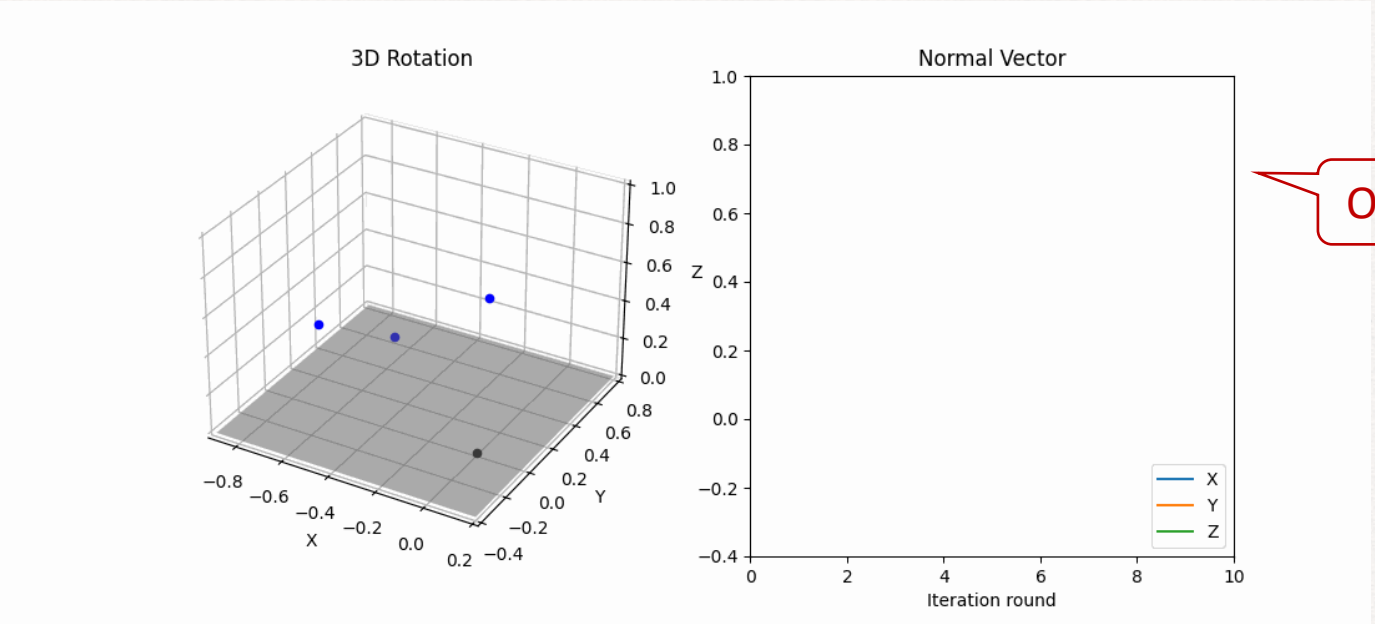
Phase plane rotation
Zhang et al., *in prep*.



Iteration of plane rotation

- Smoothing:
  - If calibrator number > 3, the phase plane may *oscillate*
  - *Outliers* in data
  - Kalman filter: smoothing & resisting outliers **BUT** phase lag
  - Low-pass filter: additional smoothing

Can only use small smoothing factor



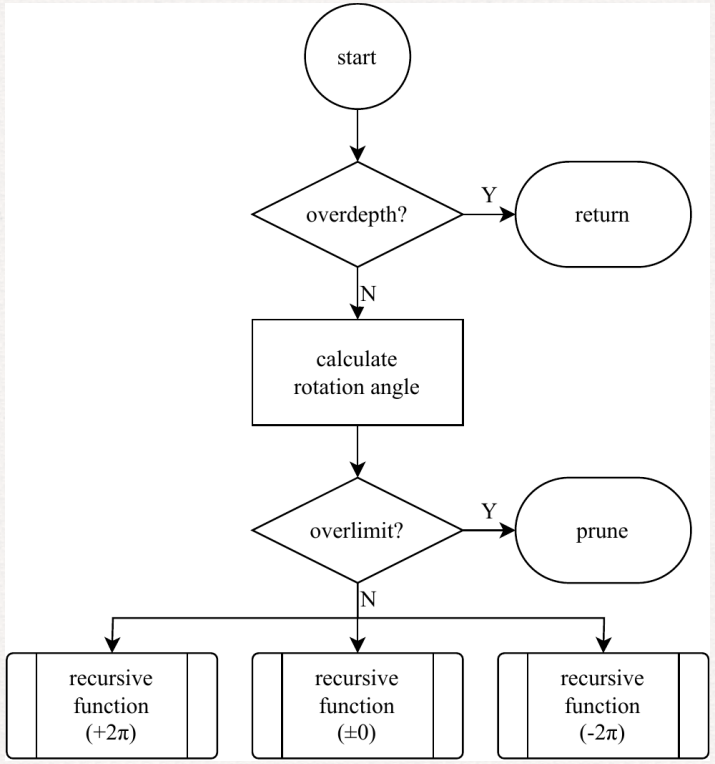
Phase plane oscillation

Ambiguity

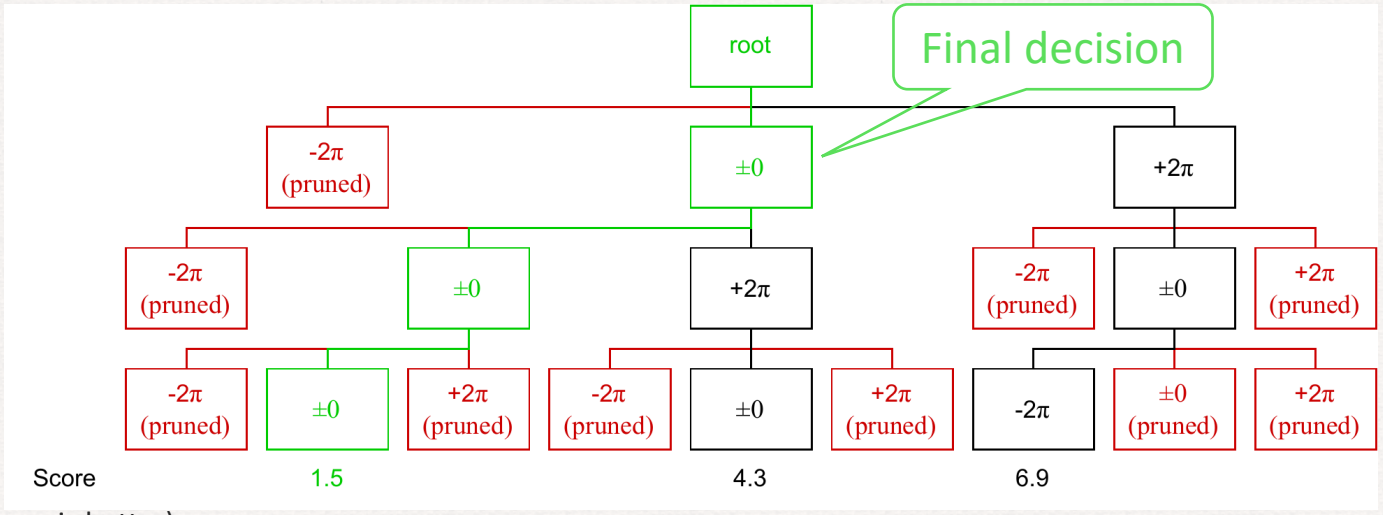
- Basic assumption: plane rotation should be steady and smooth
- Judge from rotation speed?
  - Works but is *not robust*
  - Speed threshold varies with elevation/baseline/…
  - Outliers may cause false solutions

Ambiguity

- Robust ambiguity solution:
  - Working on residual phases: within $\pm 2\pi$ between scans
  - Recursively go through all possibilities to create a *ternary decision tree*
  - Time-domain correlation: future orientation can be predicted
  - Choose the path *stays closest to predicted*
  - Speed up: *finite depth & conditional pruning*



Recursive function
Zhang et al., *in prep*.



(Lower is better)

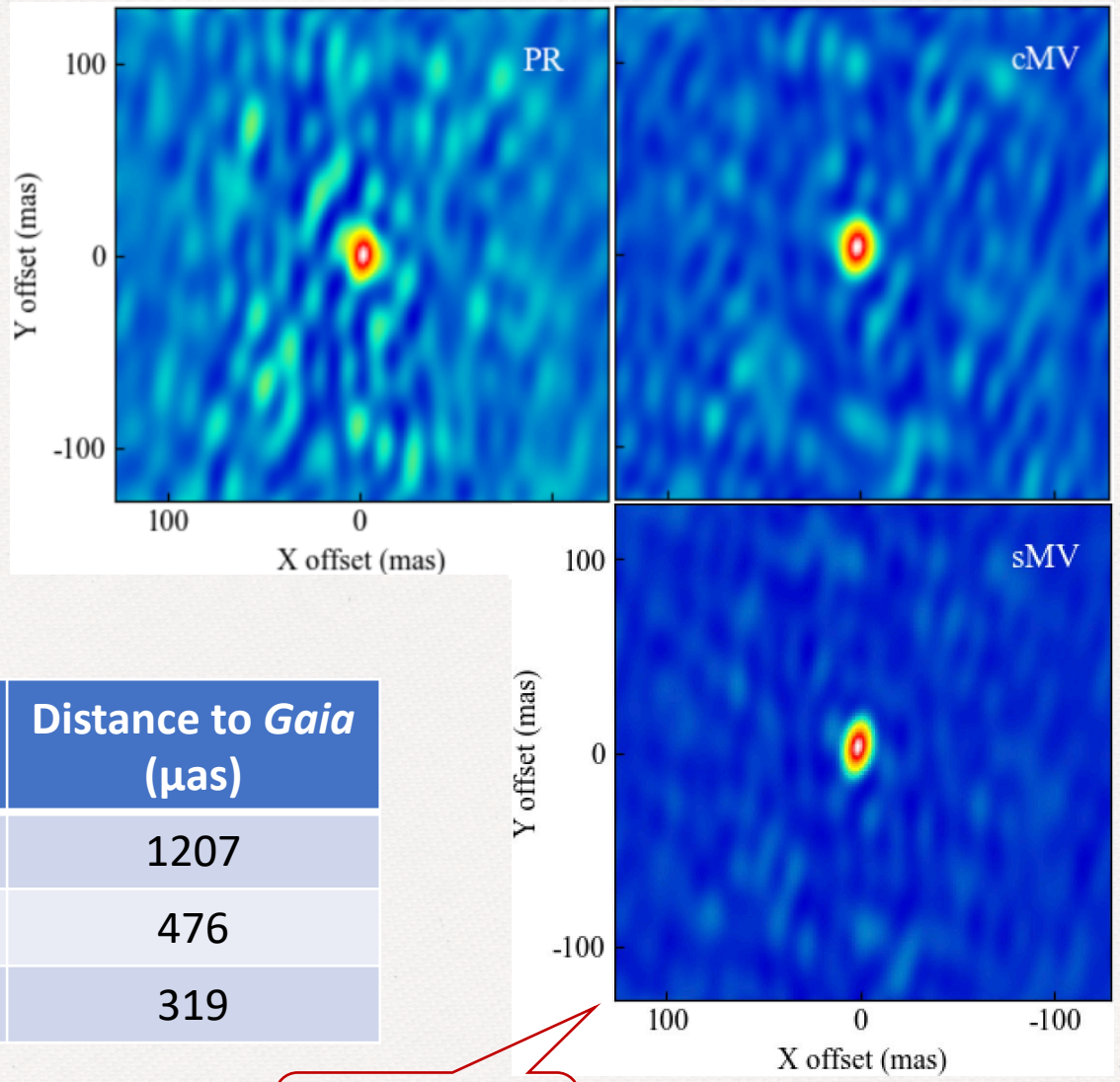
Ternary decision tree
Zhang et al., *in prep*.

Example

- VLBA observation BZ087B1, C band
- 8 antennas, MK & SC not included
- Radio star V1859 Ori, 4 calibrators
- Sequence C_1, C_2, T, C_3, C_4, …
- Theoretical residual RMS: 42 μJy/Beam

Tech	Flux density (mJy/Beam)	Residual RMS (μJy/Beam)	SNR	σ_{RA} (μas)	σ_{DEC} (μas)	Distance to *Gaia* (μas)
PR	3.8	165	25.6	51.7	76.5	1207
cMV	4.1	121	34.7	38.5	57.5	476
sMV	4.8	80	63.6	17.4	31.2	319

Most improved



Less artifacts & point-like

Images of V1859 Ori
Zhang et al., *in prep*.

Sampling rate

- Test lower calibrator sampling rate:
  - Simulate through flagging some calibrator scans
  - Keep all primary calibrator scans
  - About $1/3$ *sampling rate* for secondary calibrators
  - If succeeded, on-target time proportion *36%* → *50% - 64%*

    cycle length *140s* → *100s*

Add to target

Skip flagged scans

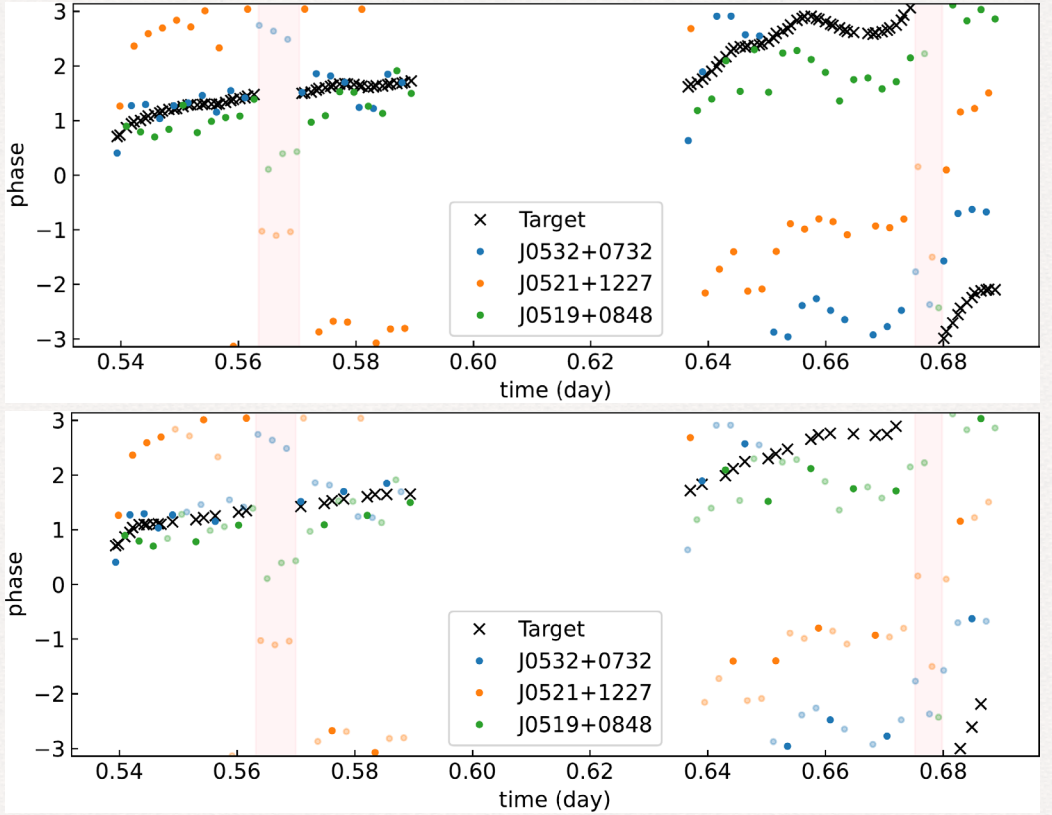
original	C1	C2	T	C3	C4	C1	C2	T	C3	C4	C1	C2	T	C3	C4
flagged	C1	C2	T			C1		T	C3		C1		T		C4

Original and flagged sequences
Zhang et al., *in prep*.

Sampling rate

- Test results of lower calibrator sampling rate:
  - Slightly lose high-frequency details
  - Almost the same Flux & residual RMS level

sequence	Flux density (mJy/Beam)	Residual RMS (μJy/Beam)	SNR	σ_{RA} (μas)	σ_{DEC} (μas)
original	4.78	80	63.6	17.4	31.2
flagged	4.71	85	59.0	18.9	33.6



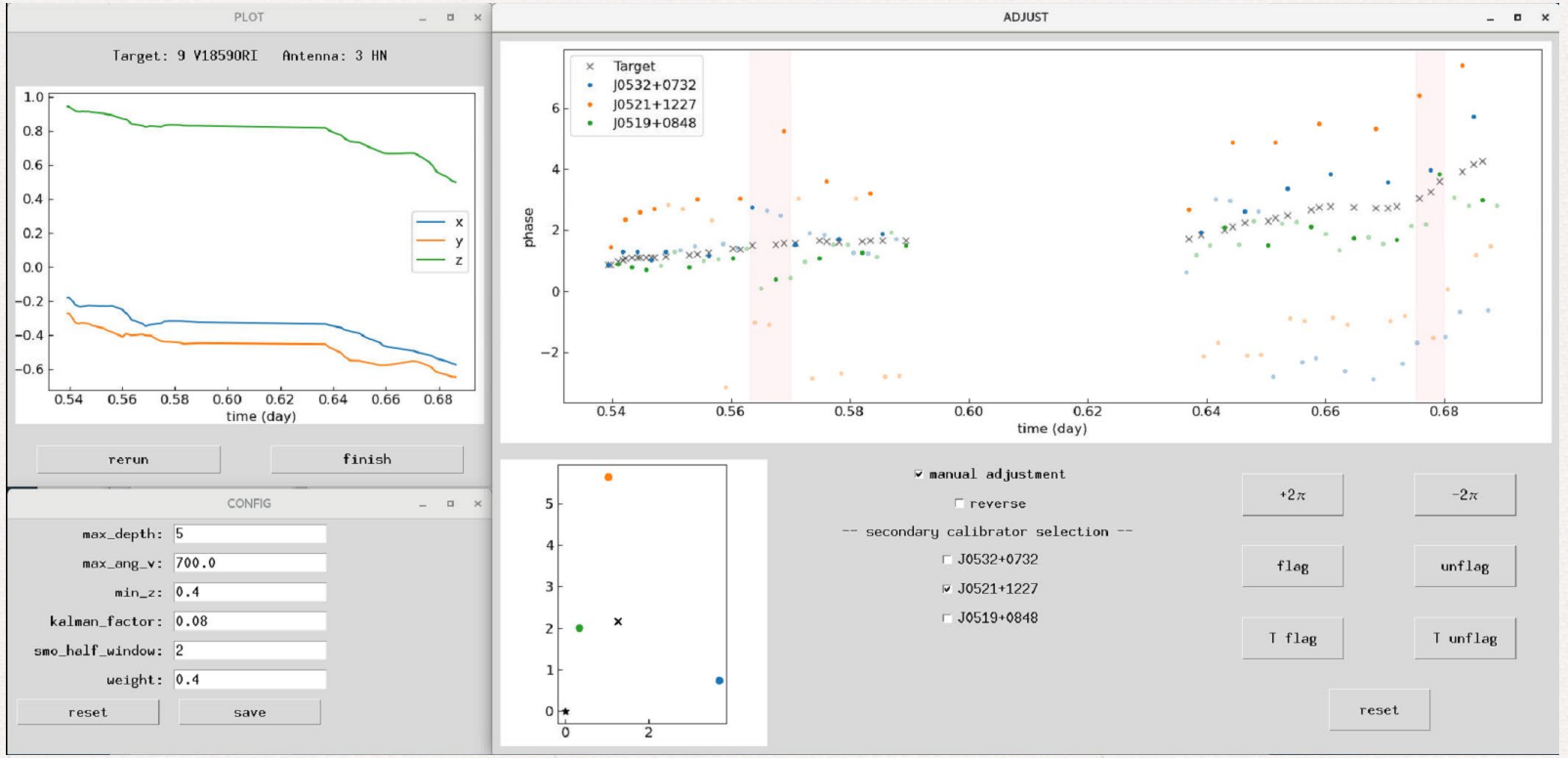
Residual and estimated phases (HN-PT)
Zhang et al., *in prep*.

Possible to significantly improve on-target time proportion!

Software

- Lucas Hyland's scripts only work for SPIRALS
- A Python software for serial MultiView:
  - AIPS & ParselTongue required
  - Pipeline for VLBA data
  - Highly automated
  - Allows for manual adjustment
  - ~20 min from FITS to results

https://github.com/FrdCHK/serial-MultiView



GUI for manual adjustment
Zhang et al., *in prep*.

Summary

- Atmospheric spatial-structure errors limit VLBI astrometry accuracy
- A new approach, serial MultiView, which offers:
  - High on-target time proportion
  - Short cycle length
  - Automatic ambiguity correction
  - Flexibility with calibrator numbers (≥ 2) & observing sequences
- Easy-to-use and open-source software, *welcome to try!*

References

- Microarcsecond Radio Astrometry, M.J. Reid and M. Honma, ARA&A, 2014, https://doi.org/10.1146/annurev-astro-081913-040006
- MultiView High Precision VLBI Astrometry at Low Frequencies, M. J. Rioja et al., AJ, 2017, https://doi.org/10.3847/1538-3881/153/3/105
- Techniques for Measuring Parallax and Proper Motion with VLBI, M. J. Reid, AJ, 2022, https://doi.org/10.1088/1538-3873/acabe6
- Inverse Multiview. I. Multicalibrator Inverse Phase Referencing for Microarcsecond Very Long Baseline Interferometry Astrometry, L. J. Hyland, ApJ, 2022, https://doi.org/10.3847/1538-4357/ac6d5b
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Thank you!

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