Using quasar physics to improve the VLBI reference frame

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Outline

① What are these radio sources we look at?
② Quantifying the effects of quasar structure
③ VieVS structure simulator
  ▪ Simulation strategy
  ▪ Effect on the reference frame
    (Station positions : mm level)
④ Mitigation strategies

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Uncooperative quasars

What you want them to be
- Bright point sources
- Fixed in space and time

What they are
- Supermassive black holes
- Jets ➞ structure
- Evolve on human timescales

Lister et al. (2009)

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Inner regions of an Active Galactic Nucleus

Image: BU / A. Marscher

One jet towards us (Doppler boosted) -> seen
One jet away from us (D. deboosted) -> unseen

jet origin

core

jet

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uv plane

interferometers measure correlated **amplitude** and **phase**

N-E plane projected in source direction

distances measured in units of wavelength $\lambda = c/\nu$
interferometers measure correlated **amplitude** and **phase**

**image**

←**FourierTransform**→

amplitudes/phases in *uv* plane

---

**uv plane**

**N-E plane projected in source direction**

*from distant quasar*

*delay in signal arrival*

*separation*

*Lister et al. (2009)*
Simulated source

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Visibility phase

N-E plane projected in source direction

different location in uv plane depending on frequency and baseline

distances measured in units of wavelength $\lambda=c/\nu$
Source structure in geodetic VLBI

✧ Group delay = \( (1 / 2\pi) (\Delta \text{phase} / \Delta \text{frequency}) \)

✧ phase depends on projected structure as seen by a given baseline

✧ function of:
  • baseline
  • observing time
  • amount and direction of structure

✧ effect is different at each of 8 sub-bands at X-band (because frequencies are slightly different)

✧ Hence group delay (= slope across band) changes
Visibility phase

N-E plane projected in source direction

different location in $uv$ plane depending on frequency and baseline

distances measured in units of wavelength $\lambda = c/\nu$
Structure phase on 9000 km baseline

\[
\text{slope} = \text{structure delay}
\]
Visibility phase

N-E plane projected in source direction

different location in $uv$ plane depending on frequency, baseline and time

distances measured in units of wavelength $\lambda = c/\nu$
Jet – baseline orientation

How a source is observed is important.

Hobart - HartRAO
Hobart - Katherine

Jet orthogonal to baseline

structure delay = 11 ps
(3.3 mm light travel time)

structure delay = 6.9 ps
(2.1 mm light travel time)

slope = extra (structure) delay

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3 effects of quasar structure

1. Measure incorrect position
   • Position offset (X, Y, Z) from “correct” value

2. Measure different positions for different schedules
   • Scatter in station positions for different baseline/schedule combinations (even with same quasars)
     ➔ increased rms for positions derived from different schedules

3. Multiple observations inconsistent with each other
   • Larger formal uncertainties, within a single session
Vienna VLBI Software (VieVS)
- Simulate geodetic observations
- Process simulated observations
  ➔ station / source positions, EOPs

Quasar structure simulations
- Quasars ≠ point-like
- Extra structure delay per observation
- (mostly) Mock source catalogues

VieVS source structure simulator
Simulated catalogues

✧ Structure indices ➔ mock quasar images
  \[ SI = 1 + 2 \log (\tau / \text{ps}) \]
  ◆ Choose SI (none, 1, 2, 3, 4, ICRF2 distribution)
  ◆ 2-component sources
  ◆ Also one “real” CONT11 catalogue

✧ Simulate realistic schedules with VieVS
  ◆ CONT11
    ○ 15 – 29 September 2011
    ○ 13 stations
    ○ 30 realizations of each day
  ◆ Additional delay term due to source structure
CONT11

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Real sources – X coord

Shabala+14, J. Geod. submitted
Real sources – Y coord

Shabala+14, J. Geod. submitted
Real sources – Z coord

![Graph showing median Z position offset in cm for real and no structure with data points and error bars for BD, HH, HB, ZC, WF, WZ, ON, Ts, Ny, Ys, Kk, Tc, and Ft labels.]
Real sources – 3D coord offset

Shabala+14, J. Geod. submitted
Real sources – 3D coord offset

Shabala+14, J. Geod. submitted
How important is quasar structure?

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Shabala+14, J. Geod. submitted

SI = 1 + 2 log (τ / ps)
How important is quasar structure?

SI = 1 + 2 log (τ / ps)

Higher SIs give worse positions.

Shabala+14, J. Geod. submitted

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How important is quasar structure?

SI = 1 + 2 log (τ / ps)
How important is quasar structure?

\[ SI = 1 + 2 \log \left( \frac{\tau}{\text{ps}} \right) \]
How important is quasar structure?

Rms and $\sigma$ underestimate how wrong the solution really is.

$$\text{SI} = 1 + 2 \log \left( \frac{\tau}{\text{ps}} \right)$$
EOP rms

![Graph showing EOP rms vs structure index]

- $x_{pol}$
- $y_{pol}$
- (UT1-UTC)

- Shabala+14, J. Geod. submitted

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What happens if we include troposphere?
Station positions (with trop.)

SI = 1 + 2 \log (\tau / \text{ps})

Troposphere dominates

Shabala+14, J. Geod. submitted

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EOP rms (with troposphere)

![Graph showing EOP rms with different structure indexes and troposphere effects](image)

Shabala+14, J. Geod. submitted

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Source structure: effects on CRF

Simulation (Cont11), with troposphere & measurement noise

**NO STRUCTURE**

**STRUCTURE, SI=3**

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Source structure: effects on CRF

Simulation (Cont11), with troposphere & measurement noise

**NO STRUCTURE**  
**STRUCTURE, SI=3**

Systematic displacement ~ 100 μas
Source structure : effects on CRF


More structure = worse source positions

More structure = worse source positions

OBSERVED

more structure
Problem summary

✧ Quasar structure simulations with VieVS
  ✧ mock + real quasar catalogues

✧ Station positions
  ◆ offset from true values
  ◆ larger formal uncertainties
  ◆ increased rms
  ◆ important at mm level

✧ EOPs and source positions also get worse with increasing structure
How do we improve the Reference Frames?
(with quasar physics)

Good news

① We can image quasar structure
(and make corrections)

Lister et al. (2009)  
Stas Shabala - REFAG14
How do we improve the Reference Frames?
(with quasar physics)

**Good news**

① We can image quasar structure
(and make corrections)

**Bad news**

Quasars evolve
(need to do this often)

Lister et al. (2009)

Stas Shabala - REFAG14
How do we improve the Reference Frames?
(with quasar physics)

Good news

① We can image quasar structure

② Jet direction remains constant (avoid unfavourable baseline – jet orientation)

Bad news

Quasars evolve
How do we improve the Reference Frames?
(with quasar physics)

Good news

① We can image quasar structure
② Jet direction remains constant
③ Quasars evolve! (observe quasars when they are “well behaved”)

Bad news

Quasars evolve
How do we improve the Reference Frames?
(with quasar physics)

Good news

① We can image quasar structure
② Jet direction remains constant
③ Quasars evolve!

Bad news

Quasars evolve

Strategies

① Use real sources to correct observations
② Minimize projected structure through clever scheduling
③ Include / exclude sources at appropriate times

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1. Quasar structure corrections

Corrected using available images

Raw observations rms

CONT11 OBSERVATIONS

OBSERVED

Stas Shabala - REFAG14
1. Quasar structure corrections

Corrected using available images

Raw observations rms

Improvement = raw - corrected

OBSERVED

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1. Quasar structure corrections

Small improvement
- 45 bl better: +0.22 mm
- 33 bl worse: -0.12 mm
< 1 mm
... but promising...

Problems
- Dominated by troposphere
- Many quasars don’t have images
- Quasars evolve

Future
- Imaging from geodetic VLBI data
1. Quasar structure corrections

Small improvement
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Problems
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Future
- Imaging from geodetic VLBI data

Baseline repeatability

Long baselines most improved

Baseline length [10³ km]

Difference in mm!
2. Re-analysis using source structure

- Jet direction is constant
- Worst case: parallel, long baselines

R1/R4 of Oct 2013, SI=3

... median value & % of observations
2. Re-analysis using source structure

- Jet direction is constant
- Worst case: perpendicular, long baselines

R1/R4 of Oct 2013, SI=3

- Half the data is ok
- ¼ of data downweighted

Angle + length of baseline

... median value & % of observations

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2. Re-analysis using source structure

Simulation test
- Downweight 23% of observations
- Structure only simulations

Improvement
- Station positions by 22%
- Formal uncertainties by 30%

Problem
Need these observations to resolve troposphere!

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2. Re-scheduling w.r.t. source structure

Scheduling
• Complex task
• Optimizing for max. number of scans, sky coverage, etc.

Strategy
• Schedule w.r.t. relative orientation and baseline length
• Simulate

First results appear promising

SIMULATED

R1/R4 (re-scheduled) of Oct 2013

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3. Quasar evolution

![Graph showing the relationship between structure index (SI) and flux density (Jy) for X-band sources over the years 1995 to 2005.]

- **Source 1357+769**

  - **New!**
    - Structure anti-correlates with flux density
    - Observe sources when flux density is high (and so structure is small)

- Data points are represented as follows:
  - Red squares for SI
  - Blue squares for X-band

- Key observations:
  - The X-band shows higher flux densities and smaller structure indices compared to the SI.
  - The SI shows a decreasing trend over time, indicating a correlation with flux density.

- **Note:** Stas Shabala - REFAG14
3. Quasar evolution

- Structure anti-correlates with flux density
- Observe sources when flux density is high (and so structure is small)
- Position scatter decreases for sources with high flux density

Source 1357+769
Summary

- **Quasars are not point sources**
  - extra group delay
    - Baseline-, time-, frequency-dependent
  - systematic error → simply more observations won’t help

- **Quasar structure simulations** with VieVS 2.2
  - new source structure simulator module
  - mock + real quasar catalogues
  - station positions affected at mm level
  - troposphere dominates (for now)

- **Mitigation strategies**
  - corrections using source images in analysis
  - not scheduling unfavourable jet / baseline combinations
    - avoid long baselines parallel to jet
  - source selection
    - radio sources vary in structure on year timescales
    - more compact when flaring (bright)
Inner regions of an Active Galactic Nucleus

Image: BU / A. Marscher

One jet towards us (Doppler boosted) -> seen
One jet away from us (D. deboosted) -> unseen

Synchrotron self-absorption
¬ core location depends on frequency
¬ “Core Shift”

Image: Kovalev et al. (2008)
Quasar structure in VGOS

Expected delay accuracy **2-4 ps**

Quasar structure > **20 ps**

How do we connect phases across 10 GHz?
Quasars

What you want them to be
✧ Bright point sources
✧ Fixed in space and time

What they are
✧ Supermassive black holes
✧ $10^6$ times more distant than stars

- Quasars are really far away ($z \geq 1$)
  ($z = 1$ is half the age of the Universe)
- Use quasars because...

$$D(z = 1 \text{ quasar}) = 6.7 \times 10^9 \text{ pc}$$
$$D(\text{stars at Galactic centre}) = 8 \times 10^3 \text{ pc}$$

⇒ quasi-inertial reference frame
Structure delay (ps)
EOP formal error (structure only)

![Graph showing EOP formal error for different structure indices.](image)

- **x_p**ol
- **y_p**ol
- (UT1-UTC)

**Structure index**
- none
- 1
- 2
- 3
- 4ICRF2
- real

**Pol formal error / mas**

**(UT1-UTC) formal error / ms**

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EOP formal error (with trop.)

The graph shows the formal error in polar motion and UT1-UTC as a function of structure index. The graph includes the following elements:
- $x_{pol}$ and $y_{pol}$ for polar motion
- (UT1-UTC) formal error

The structure index is represented on the x-axis, ranging from "none" to "4ICRF2 real". The y-axis represents the polar formal error in mas and the (UT1-UTC) formal error in ms.

The graph includes data points for different structure indices, with lines connecting them. The error values are indicated by markers, with different colors and styles for each type of error.
Median position offset

median of 15 x 30 realizations

average distance to other stations / km

median position offset / cm

no structure

OnWz YsNyZc BdWf FtTs Hb Kk Tc Hh
Median position offset

SI=1
no structure

Shabala+14, J. Geod. submitted
Median position offset

SI=1  SI=2  SI=3  no structure

Shabala+14, J. Geod. submitted
Median position offset

Shabala+14, J. Geod. submitted

SI=1
SI=2
SI=3
SI=4
no structure

average distance to other stations / km

median position offset / cm
Median position offset

On
Wz
Ys
Ny
Zc
Bd
Wf
Ft
Ts
Hb
Kk
Tc
Hh

SI=1
SI=2
SI=3
SI=4
ICRF2
no structure

median position offset / cm

average distance to other stations / km

Shabala+14, J. Geod. submitted
Median position offset

Shabala+14, J. Geod. submitted
Median position offset

![Graph showing median position offset vs. average distance to other stations. The graph includes data points for different stations labeled as OnWz, YsNyZc, BdWf, FtTs, Hb, Kk, Tc, and Hh. The x-axis represents the average distance to other stations in km, ranging from 6000 to 10000 km. The y-axis represents the median position offset in cm, ranging from 0.001 to 1 cm. The graph includes multiple data sets distinguished by colors and symbols, including SI=1, SI=2, SI=3, SI=4, ICRF2 real structure, and no structure. The data points are scattered across the graph, with some trends visible. The source of the data is Shabala+14, J. Geod. submitted.](image-url)
Median position offset

![Graph showing median position offset against average distance to other stations. The graph plots stations such as Shabala, REFAG14, and others, with different symbols and colors representing various intervals (SI=1 to SI=4) and structures (real and no structure). The x-axis represents the average distance to other stations in km, ranging from 6000 to 11000. The y-axis represents the median position offset in cm, ranging from 0 to 2.0. The graph includes a legend with symbols for each station and structure type.](image)

Shabala+14, J. Geod. submitted

Stas Shabala - REFAG14