# Mitigating Source-Structure in Geodetic Level-1 VLBI Data

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NASA VLBI Seminar

NASA Goddard Space Flight Center
Greenbelt, MD, USA

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# Source Structure in VGOS Fringe-Fitting (SOFT)

FWF Österreichischer Wissenschaftsfonds

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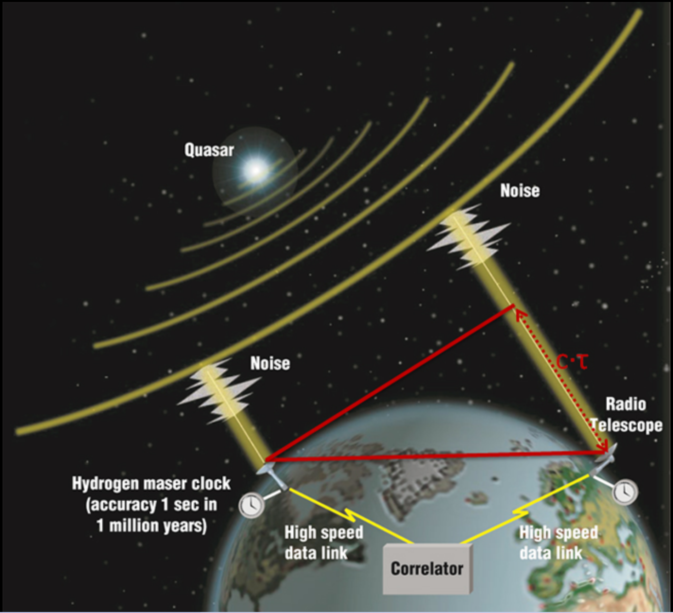
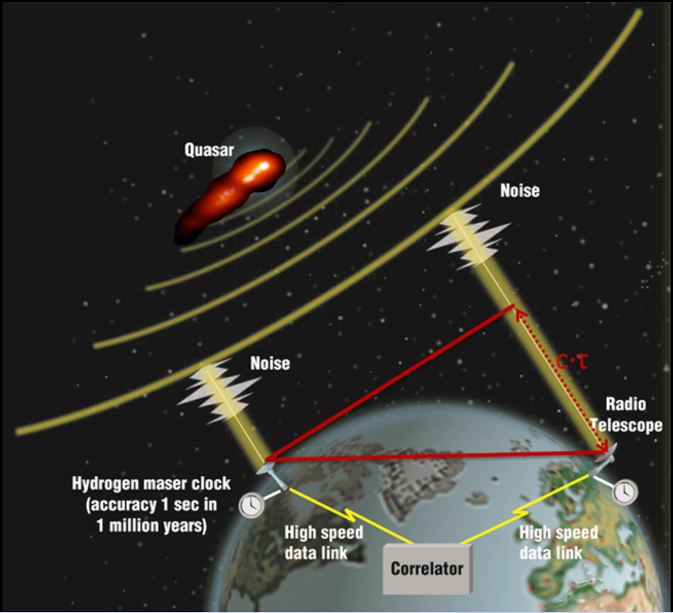
université de BORDEAUX

VNIVERSITAT DE VALÈNCIA

GOBIERNO DE ESPAÑA MINISTERIO DE FOMENTO INSTITUTO GEOGRÁFICO NACIONAL OAN


Quasar
Noise
Noise
$c \cdot \tau$
Radio Telescope
Hydrogen maser clock (accuracy 1 sec in 1 million years)
High speed data link
High speed data link
Correlator

Credit: NASA


Quasar
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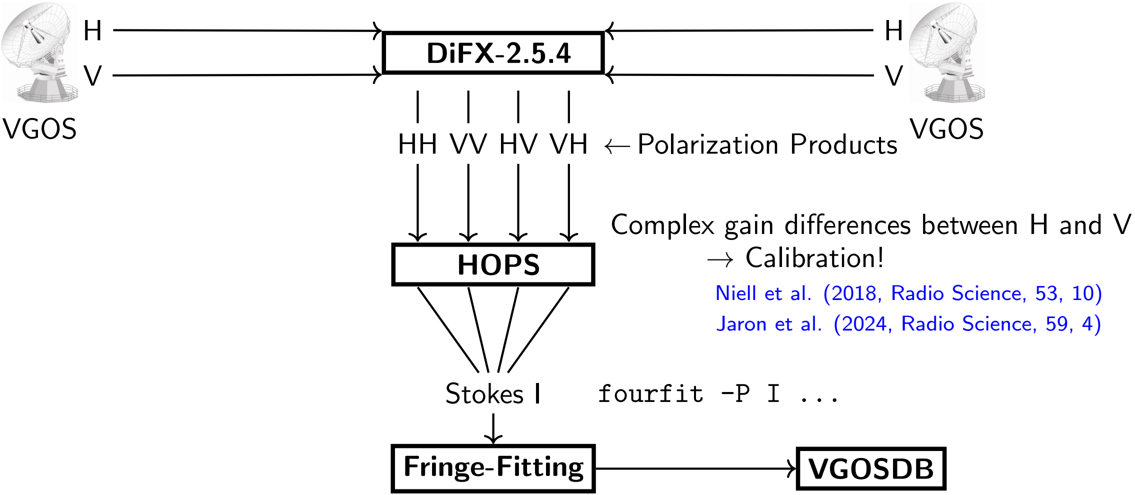
Correlator

Credit: NASA

# VLBI Global Observing System (VGOS)

- Introduced by Petrachenko et al. (2009, IVS Annual Report 2008) as VLBI2010
- Aims: Station coordinate accuracy of 1 mm, reference frame stability of 0.1 mm/year.
- Broad bandwidth (four bands between $\sim 2$ and 15 GHz)
- Ionosphere (dTEC) is estimated during fringe-fitting.
- Dual linear polarization
- Network is still growing
- DiFX-2.5.4 is the version currently to be used for VGOS correlation.
  Credit: Jan Wagner
  Some details in Jaron et al. (2021, EVGA Proceedings).

NASA VGOS antenna in McDonald, Texas, USA. Credit: MIT Haystack Observatory




⇒ Increased signal-to-noise ratio, compared to legacy S/X observations.

⇒ Systematic errors become more significant, e.g., **Source Structure**!

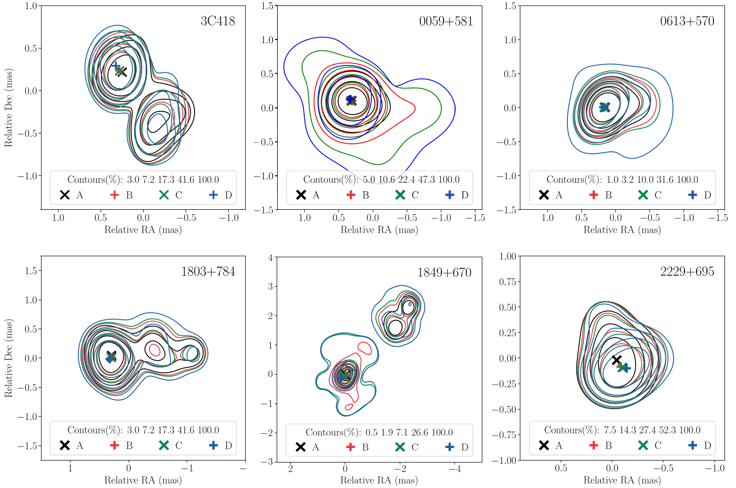
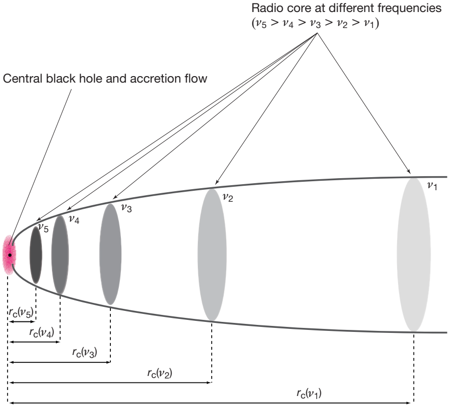
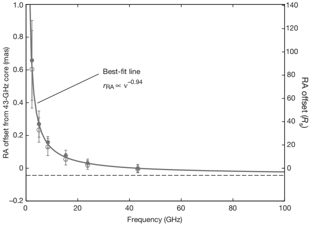


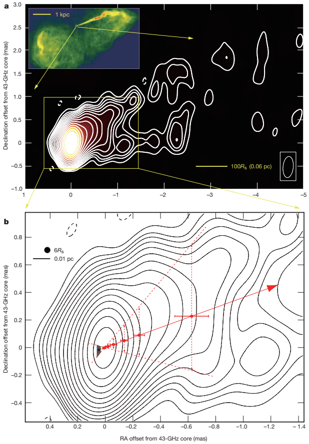

**Fig. 11.** Total intensity maps from VGOS experiment VO2187 obtained from the multifrequency image and the spectral index map. The contours are shown at five levels of the peak percentage, specified in the legend of the plots. Each contour color represents the map for the central frequency of each band: 3.25, 5.5, 6.75, and 10.5 GHz.

Pérez-Díez *et al.* (2024, A&A, 688, A151)

# Explicit measurement of frequency dependent core position for radio galaxy M87




Hada *et al.* (2011, Nature, 477, 7363)

In general, the structure phase is given by

$$\phi_s = \frac{2\pi}{\lambda}\mathbf{B}\cdot\mathbf{OP_0} + \tan^{-1}\left(\frac{-Z_s}{Z_c}\right), \tag{1}$$

with

$$Z_c = \iint_{\Omega_s} I(\mathbf{P},\lambda,t)\cos\left(\frac{2\pi}{\lambda}\mathbf{B}\cdot\mathbf{OP}\right)\mathrm{d}\Omega, \tag{2}$$

$$Z_s = \iint_{\Omega_s} I(\mathbf{P},\lambda,t)\sin\left(\frac{2\pi}{\lambda}\mathbf{B}\cdot\mathbf{OP}\right)\mathrm{d}\Omega, \tag{3}$$

| | |
|---|---|
| $\mathbf{B}$ | Baseline vector, |
| $\mathbf{O}$ | Origin of local coordinate system, |
| $\mathbf{P_0}$ | Reference point within the source, |
| $\lambda$ | Observing wavelength, |
| $I(\mathbf{P},\lambda,t)$ | Source brightness distribution. |

Charlot (1990, AJ, 99, 1309)

$$Z_{\mathrm{c}} = \sum_{k=1}^{n} \left[ S_k \mathrm{e}^{-2\pi^2 \left( a_k^2 U_k^2 + b_k^2 V_k^2 \right)} \cos\left( \frac{2\pi}{\lambda} \mathbf{B} \cdot \mathbf{OP}_k \right) \right],$$

$$Z_{\mathrm{s}} = \sum_{k=1}^{n} \left[ S_k \mathrm{e}^{-2\pi^2 \left( a_k^2 U_k^2 + b_k^2 V_k^2 \right)} \sin\left( \frac{2\pi}{\lambda} \mathbf{B} \cdot \mathbf{OP}_k \right) \right],$$

with

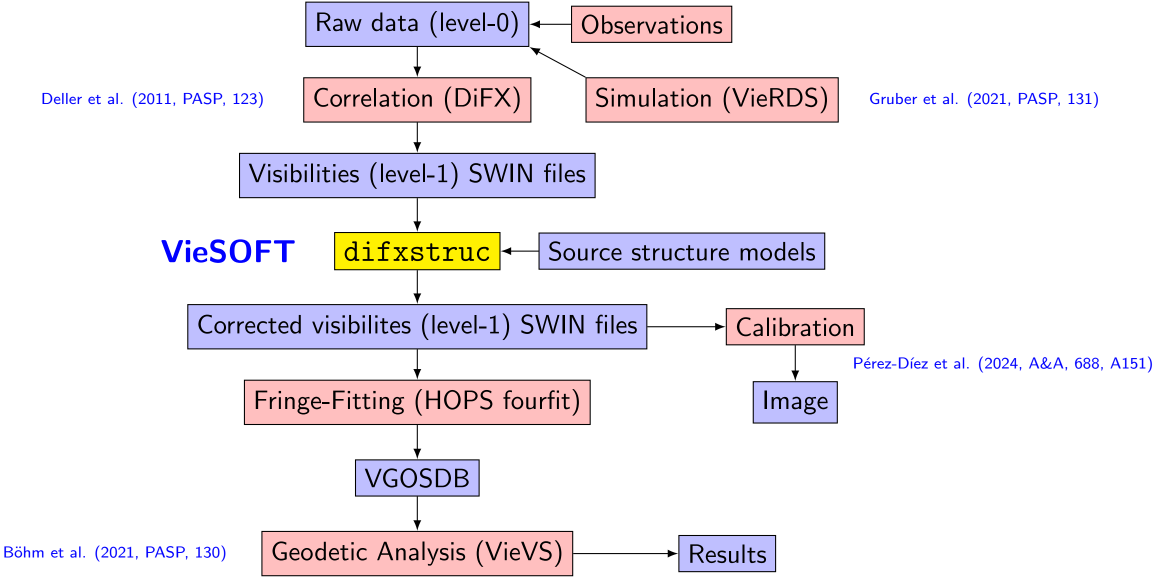
$$a_k = \frac{\mathrm{FWHM}_k(\text{major axis})}{2\sqrt{2\log 2}},\ \ b_k = \frac{\mathrm{FWHM}_k(\text{minor axis})}{2\sqrt{2\log 2}},$$

and

$$U_k = u \sin\psi_k + v\cos\psi_k,\ \ V_k = -u\cos\psi_k + v\sin\psi_k,$$

$\psi_k$: position angle of the $k^{\mathrm{th}}$ component.

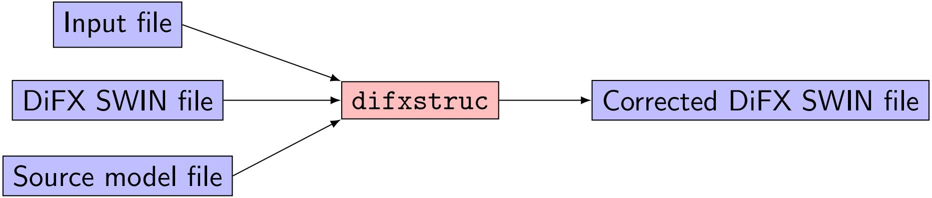
Charlot (1990, AJ, 99, 1309)


Raw data (level-0)
Observations
Deller et al. (2011, PASP, 123)
Correlation (DiFX)
Simulation (VieRDS)
Gruber et al. (2021, PASP, 131)
Visibilities (level-1) SWIN files
VieSOFT
difxstruc
Source structure models
Corrected visibilites (level-1) SWIN files
Calibration
Pérez-Díez et al. (2024, A&A, 688, A151)
Image
Fringe-Fitting (HOPS fourfit)
VGOSDB
Böhm et al. (2021, PASP, 130)
Geodetic Analysis (VieVS)
Results

## Command line tool `difxstruc`

```
difxstruc -i <DiFX input file> -d <DiFX SWIN file> -s <source model file> -o <output file>
```

| | |
|---|---|
| DiFX input file | Provides information about frequency setup. |
| DiFX SWIN file | DIFX_ file containing the *original* visibilities. Also contains $(u, v)$ coordinates for each observation. |
| Source model file | Contains information about reference points and a list of Gaussian components (one file per source). |
| Output file | Name of the SWIN file that will contain the *corrected* visibilities. |



# The source structure description file

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| DEC | $\delta$ | | | | | | | | |
| REF | $x_0$ | $y_0$ | | | | | | | |
| COMP | $\nu_{\text{min}}$ | $\nu_{\text{max}}$ | Flux | $x$ | $y$ | Maj | Min | PA | $\alpha$ |
| COMP | $\nu_{\text{min}}$ | $\nu_{\text{max}}$ | Flux | $x$ | $y$ | Maj | Min | PA | $\alpha$ |
| COMP | $\nu_{\text{min}}$ | $\nu_{\text{max}}$ | Flux | $x$ | $y$ | Maj | Min | PA | $\alpha$ |
| $\vdots$ | | | | | | | | | |

- DEC line contains the absolute declination of the source.
- All other coordinates are in units of mas and relative to some arbitrary coordinate origin.
- REF is the reference point $\mathbf{P_0} = (x_0, y_0)$.
- COMP lines contain description for one Gaussian component: Frequency range $(\nu_{\text{min}} - \nu_{\text{max}})$, Flux density, Coordinates $(x, y)$, semi-major and minor axes, position angle, and radio spectral index.

# Effect of just changing the reference point

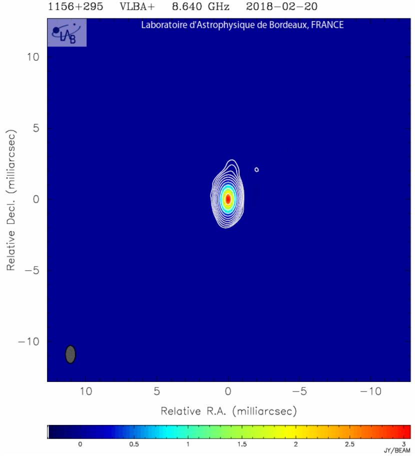
Question: If I only change the reference point, how does the estimated source position change?

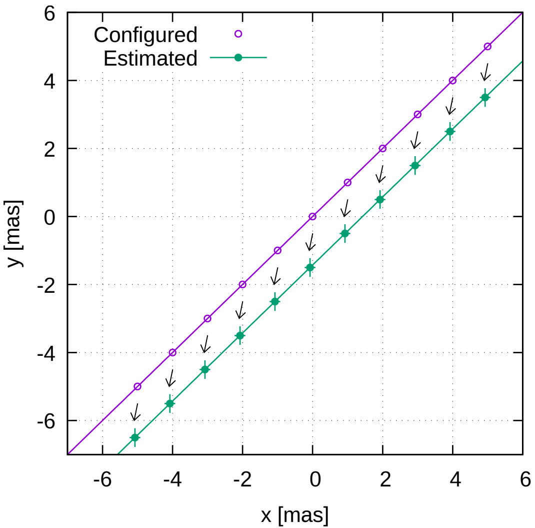
To answer this questions

- Well-behaved VGOS session: vo3012
- Compact source with many observations: 1156+295
- Systematically change reference point coordinates
- Apply visibility phase corrections
- Run fringe-fitting, export VGOSDB
- Geodetic analysis with the VLBI module of VieVS

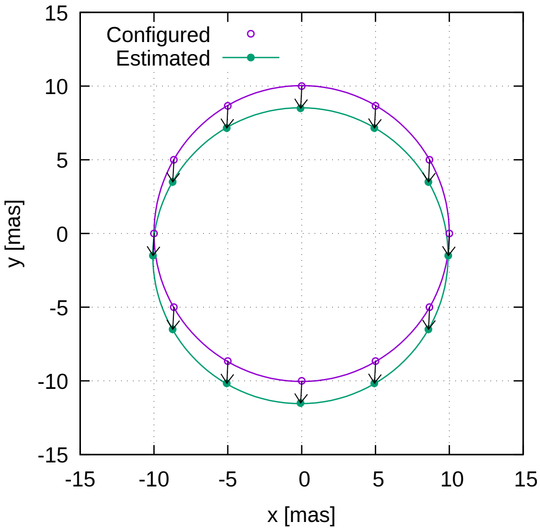
0 (for this test)

$$\phi_s = 2\pi(ux_0 + vy_0) + \cancel{\mathrm{atan2}(-Z_s, Z_c)}$$



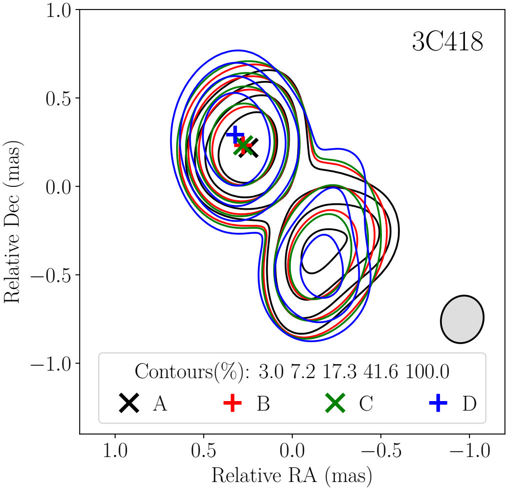



Line → Line ✓

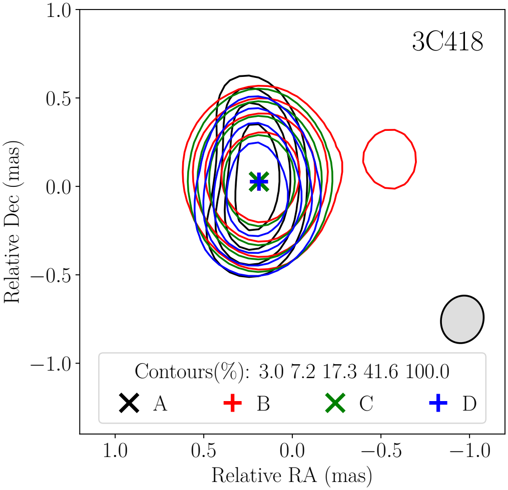



Circle → Circle ✓

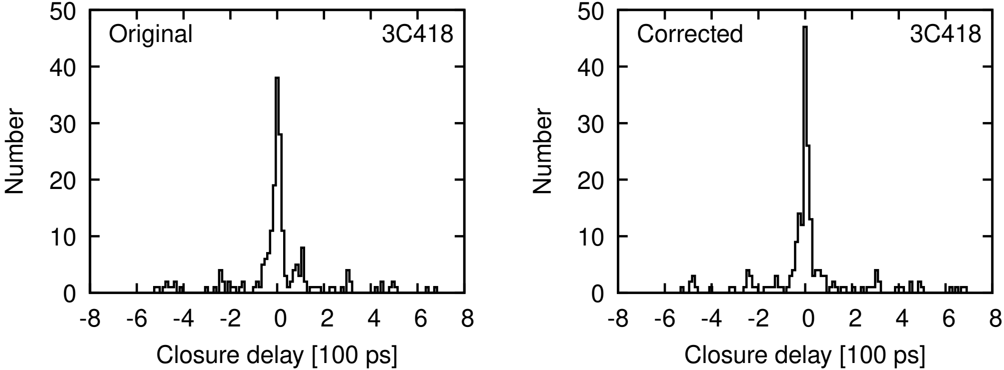
Original:




After visibility correction:




Credit: Victor Pérez-Díez, applying the method of Pérez-Díez et al. (2024) to vo2187.



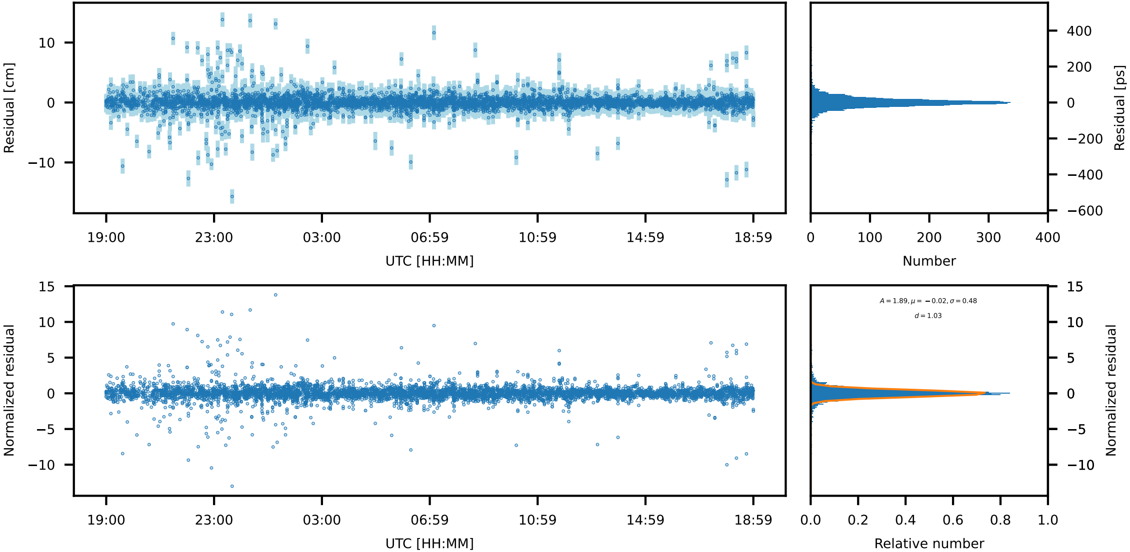

$$\tau_{\mathrm{ABC}} = \tau_{\mathrm{AB}} + \tau_{\mathrm{BC}} + \tau_{\mathrm{CA}}$$

- All three delays have to refer to the same wavefront (e.g., geocentric delays).
- Without any baseline specific systematics: $\tau_{\mathrm{ABC}} = 0$
- Observational results from vo3012.

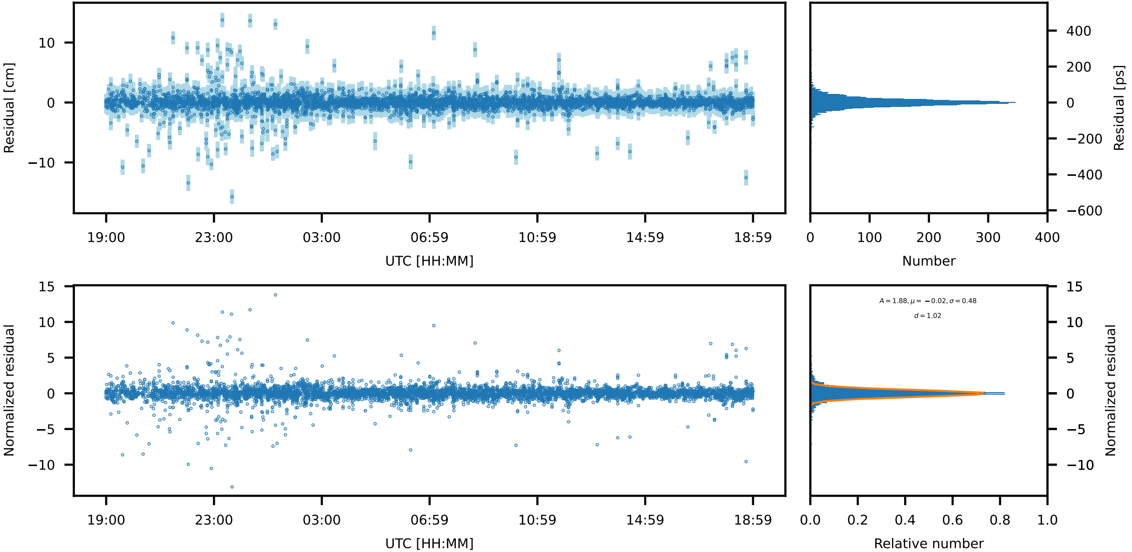
# Geodetic analysis

- Full geodetic analysis on the session vo3012.
- Vienna VLBI and Satellite Software (VieVS, Böhm et al. 2021).
- Estimated:
  - Source coordinates
  - UT1-UTC
  - Tropospheric zenith delays.
- Compare post-fit residuals before and after the source structure correction.

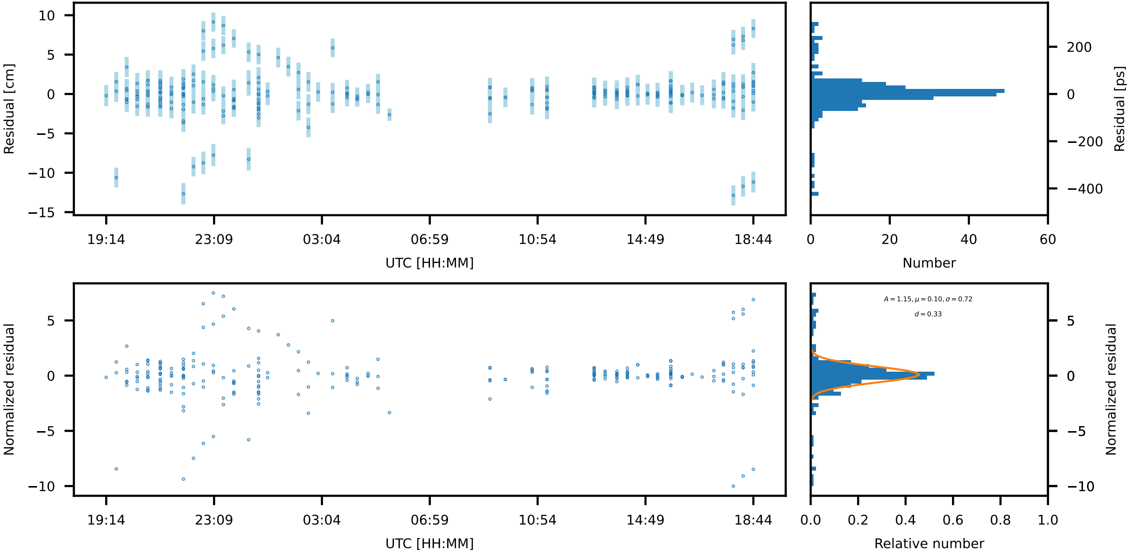
Correction: No -- Observations: All



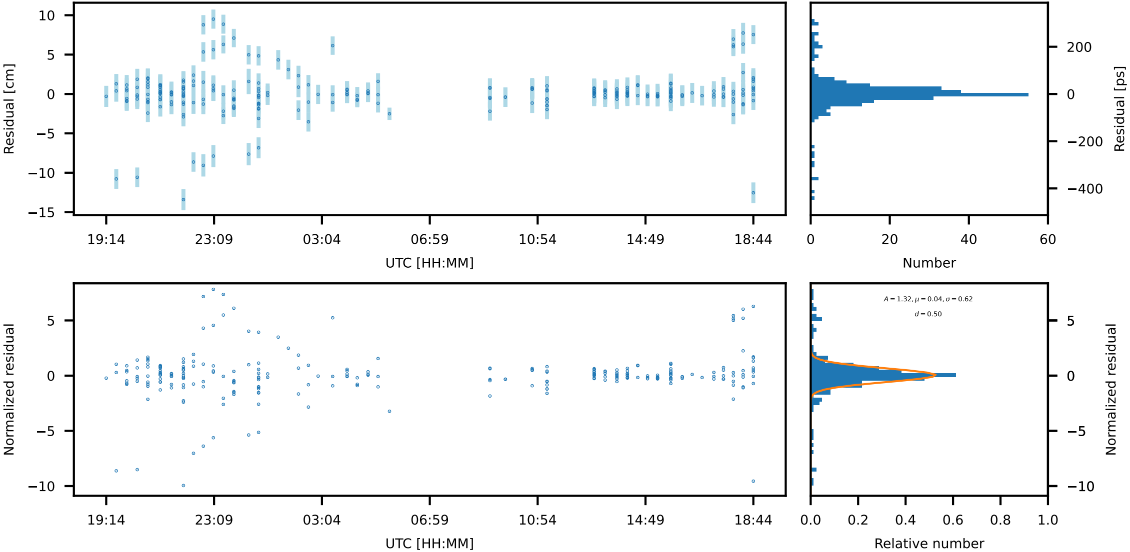
# Correction: Yes -- Observations: All

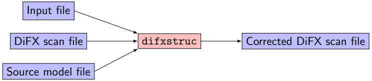


Correction: No -- Observations: 3C418

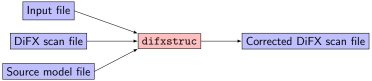


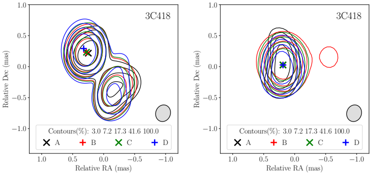
Correction: Yes -- Observations: 3C418





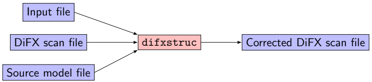

We have developed a tool to remove source structure from DiFX visibility data.

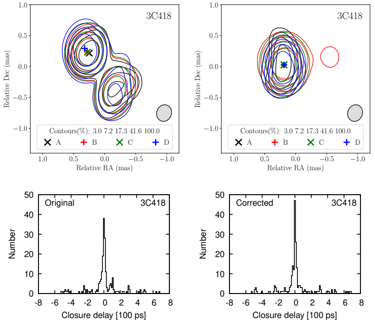



We have developed a tool to remove source structure from DiFX visibility data.

Images obtained from structure-corrected visibilities indeed appear more compact.

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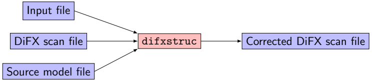
Images obtained from structure-corrected visibilities indeed appear more compact.

Closure delays show a more compact distribution, but not all misclosures are removed.

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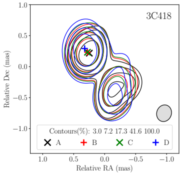


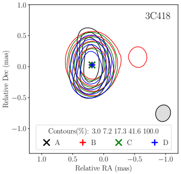


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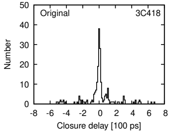


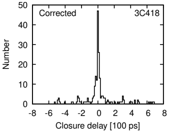


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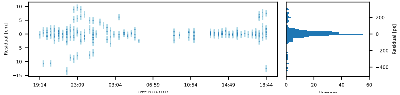


After a geodetic analysis post-fit residuals seem slightly improved.