CASA VLBI

WORKSHOP 2020

2-6 NOVEMBER 2020

LATEST VLBI TASKS IN CASA

Des Small, JIVE

CASA Common Astronomy Software Applications

JIVE Joint Institute for VLBI ERIC

RadioNet

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Latest VLBI tasks in CASA

Des Small

CASA-VLBI Workshop, 3 November 20202

A note on the title

Mark Kettenis' lecture on "The CASA calibration model" discussed importing *a priori* gain calibration and system temperature; the only other task needed to make CASA complete for VLBI as well as connected-element interferomety was a fringe-fitting task. This lecture will cover the how, why, what, when and (a bit of the) theory of fringe-fitting in CASA.

Historical context I

- CASA was developed by NRAO starting in the 1990s
- It is the standard program for VLA data reduction
- It has long been planned to make it also suitable for VBLI
- But it lacked among other things a fringe-fitting task
- I will mostly discuss fringe-fitting here

Historical context II

- The Black Hole Cam project provided funding for JIVE to work on CASA
- JIVE developed a CASA fringe fitter, with support from NRAO
- CASA was used as part of the EHT project to image the shadow of the supermassive black hole at the centre of M87
- CASA is now a viable choice for VLBI data reduction

Bracewell's Rule of Fourier Transforms

If you are dealing with phase, everything looks locally like a Fourier transform pair.

Suppose

$$f(\xi) = \exp i\phi(\xi).$$

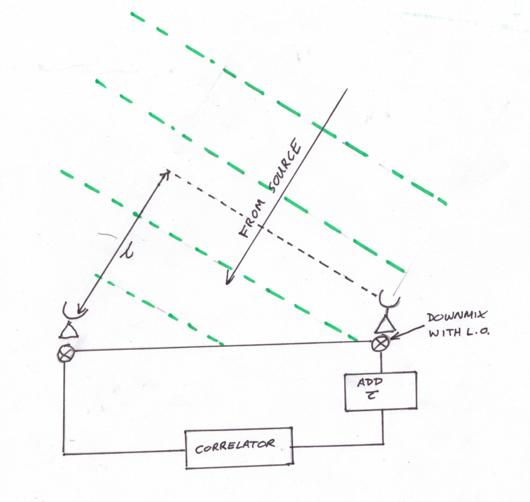
Expand $\phi(\xi)$ to first order:

$$\phi(\xi) \approx \phi(\xi_0) + \frac{\partial \phi}{\partial \xi} \cdot \Delta\xi$$

Define $r = \frac{\partial \phi}{\partial \xi}$, then

$$f(\xi) \approx e^{i\phi_0} \cdot e^{ir \cdot \Delta\xi}$$

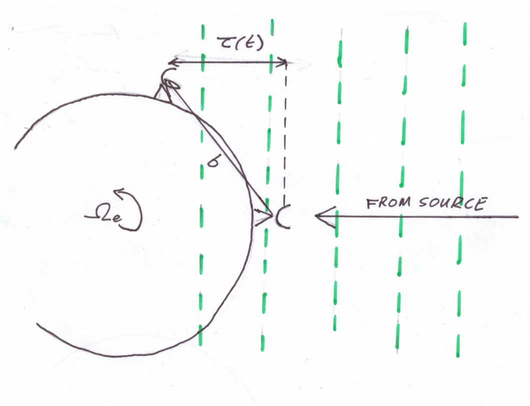
so r and $\Delta\xi$ are a Fourier transform pair.



Coherence at antennas equals the absolute value of the normalized Fourier transform of the brightness distribution of the source. (Van Cittert-Zernike Theorem.)

Geometric delay, τ to align wavefronts is crucial!

VLBI problems



- Heterogeneous antennae hundreds or thousands of km apart
- Geometric delays calculated using software (e.g. CALC); but
  - Different view of atmosphere
  - Different clocks
  - Different frequency standards (LOs)
- Adds up to unknown delays, and limits phase coherence

VLBI solutions

- We measure T_{sys} for each antenna, to get a handle on amplitude
- And we calibrate phase with *fringe-fitting*
- Plotting phase vs. frequency, a delay corresponds to a slope of phase $\phi \propto \tau \cdot \nu$.

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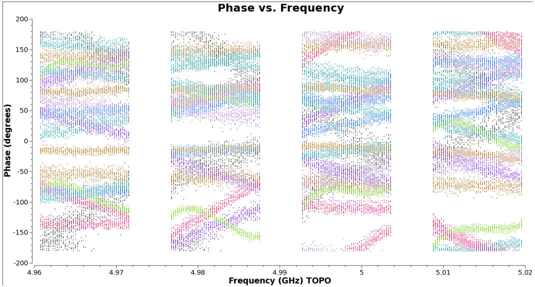
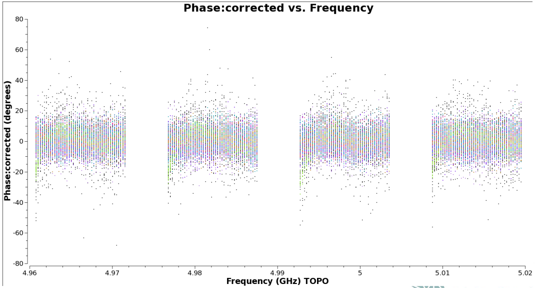
VLBI procedures 1: "Manual Phase Cal"

- There can also be instrumental delays due to different signal paths between bands
- Fringe fit with a short interval on a bright source
- Bands are then aligned for the whole experiment
- This can be done with phase calibration tones, hence the name
- Don't forget to zero rate term – we're extrapolating!



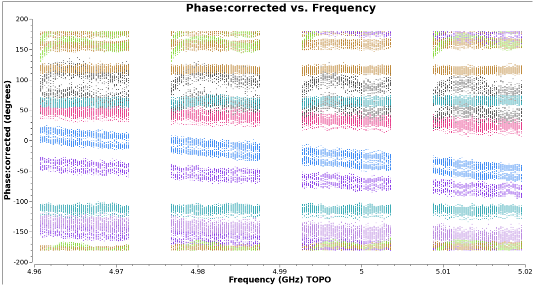
Before fringe-fitting



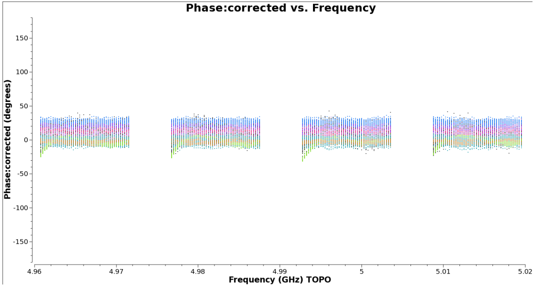
After fringe-fitting

VLBI procedures 2: "Wide band fringe fit on strong source"

- Once bands are aligned, use full frequency width for fringefit
- Higher signal-to-noise that way
- Fringe-fit all of the data on good sources that way



After "manual phase cal"



After "multi-band" fringe fitting

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VLBI procedures 4: Wide and multiband remarks

Multiband solving:

```
fringefit(vis="n14c3.ms", caltable="n14c3-1848.mbd",
          solint='60', combine='spw', field='1848+283',
          refant='EF', minsnr=50,
          gaintable=['n14c3.gcal', 'n14c3.tsys', 'n14c3.sbd'],
          parang=True)
```

Multiband application:

```
applycal(vis="n14c3.ms",field="1848+283,J1849+3024",
         gaintable=['n14c3.tsys', 'n14c3.gcal',
                    'n14c3.sbd', 'n14c3-1848.mbd'],
         interp=[],spwmap=[[], [], [], 8*[0]], parang=True)
```

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VLBI procedures 5: Gaps between bands

For multiple spectral windows, all data is regridded to a single wide frequency grid. This does work for S/X data, but is very inefficient.
Nearest neighbour interpolation is used for quirky inter-band spacing like like ALMA.
A new more efficient method for these cases is currently in test, but the existing code does work.

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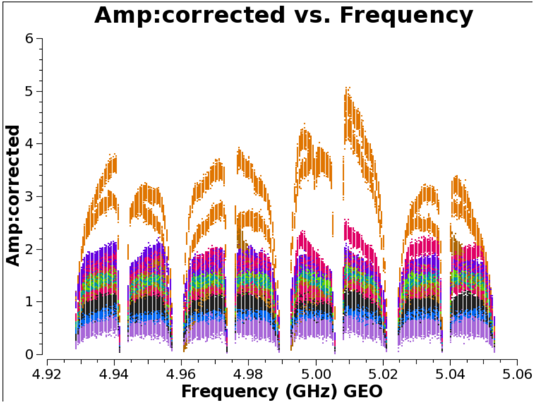
VLBI procedures 5: "Phase transfer"

- The target source is too weak to fringe fit directly
- But there is a nice strong calibrater near it on the sky
- Schedule alternating scans on this *phase calibrater* and *target source*.
- A common idiom, but not the only way.
- Does not preserve absolute astrometry!
- All of this is discussed in the EVN tutorial

VLBI procedures 6: Final tips

- Flag channel edges: low amplitude, untrustworthy phase
- Reference station should be biggest antenna (Effelsberg or ALMA)
- For homogenous arrays like VLBI, pick a central antenna
- Don't forget to plot calibrated data to check!



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VLBI Theory 1: The "Measurement Equation"

- The Radio Interferometric Measurement Equation (RIME) is a formalism for describing calibration
- The RIME is central to CASA's calibration framework
- All effects described by 2×2 complex matrices, known as Jones matrices
- Fringe-fitting calibration is no exception!
- This is all transparent to the user, though

VLBI Theory 2: Baseline approach to Fringe-fitting

Following Schwab and Cotton (1983). Ignore amplitude, related observed phase $\tilde{\phi}$ to true phase ϕ. (This is like a tiny fragment of the Measurement Equation.)

$$\tilde{\phi}_{pq} = \phi_{pq} + (\psi_p - \psi_q)\big|_{t_o,\nu_o} + r_{pq}(t_k - t_0) + \tau_{pq}(\nu_l - \nu_0)$$

where

$$r_{pq} = \left.\frac{\partial(\psi_p - \psi_q + \phi_{pq})}{\partial t}\right|_{t_o,\nu_o}$$

$$\tau_{pq} = \left.\frac{\partial(\psi_p - \psi_q + \phi_{pq})}{\partial \nu}\right|_{t_o,\nu_o}$$

So 2D Fourier transform of $\phi(t,\nu)$ should be a δ-function at delay and fringe-rates.

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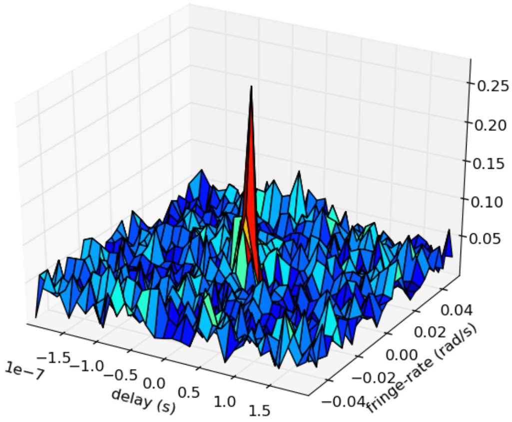
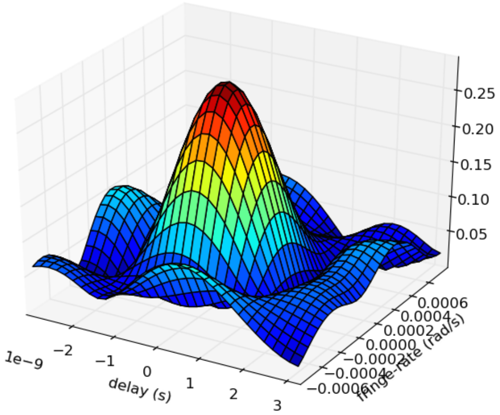
VLBI Theory 3: More on baseline approach

- Instead of interpolating *after* FFT, pad data with zeros
- A zero-padding factor of eight is a good balance between accuracy and computational effort





VLBI Theory 4: Global method

- Still following Schwab and Cotton (1983)!
- Use a per-station model of ϕ
- Choose a reference station
- Use FFT method for initial guess
- Eliminate low SNR antennas
- Apply least-squares optimisation in regular t-ν space for *all* valid baseline data.
- Minimize $||W_{ij}\left[\phi_{ij}(\nu, t) - \exp\left(i\left\{\phi_{0,ij} + \tau_{ij}\Delta\nu + r_{ij}\Delta t\right\}\right)\right]||$
- Uses all the (good) data!
- With good estimates non-linear least squares converges fast
- Used in AIPS; current industry standard for non-geodetic VLBI

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VLBI Theory 4: Source models

- Without explicit model, fringe-fitting implicitly assumes a point source
- This is usually good enough anyway!
- And it is usually good enough to bootstrap self-calibration!
- CASA supports sky models, but
- If your models are from AIPS it is fiddly to import them
- (I've given NRAO the code to do this; they plan to support it)

Some miscellaneous remarks specific to CASA

- Currently we don't support merging the two polarizations
- Also don't support use of cross-hand polarization data
- We *do* now support data with only one hand of polarization on some antennas!
- Conversion from XY to RL polarizations is possible
- Ionospheric dispersion term is now supported
  - Useful at P-band
  - Important for LOFAR Long Baseline
  - Will be required for broad band receivers

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Final remarks

- CASA for VLBI is here to stay!
- More features are being added
- We work with NRAO to provide support through their ticket system
- Plot you data after calibrating to check it did what you want!

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