Fringe-fitting in CASA

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OPTICON RadioNet Pilot

VLBI (0)

VLBI stands for "very long baseline interferometry". But how long is "very long" and why does it matter?

VLBI (1)

"As the continuity of (u, v) coverage is improved from a few metres to more than 10^5 km [...] and fiberoptic or other advanced communications make recording unnecessary, the concept of VLBI as a distinct technique will become a matter of history."

— *Interferometry and Synthesis in Radio Astronomy*, Thomson, Moran & Swenson, 3rd Edition (2017)

VLBI (2)

The Heroic Age of VLBI (starting 50 years ago):

- Independent antennas; with independent clock and frequency standards
- Antenna position not known to cm accuracy
- Recording (on tape)
- Shipping tapes to correlator
- Limited communication during experiment
- Different skies!

A priori models used to calculate delay to shift each antenna's signal to the *phase centre*.

VLBI (3)

The Slightly Less-Heroic Age of VLBI:

- E-transfer of data typical
- Independent antennas (so still clock, frequency, position issues)
- But clock searching and fringe-tests possible!
- But still different skies: atmospheric effects not known
- a priori!

VLBI (4)

We want an *a postiori* (radio-astronomical) equivalent of adaptive optics to get the best "focus". That's what fringe-fitting is!
So one characteristation of "VLBI" might be: VLBI is the kind of interferometry where you need fringe-fitting. (But as TMS imply: this is after all just another calibration step!)

Historical context I

- CASA (née AIPS++) 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
- So while CASA's user base grew, VLBI astronomers stuck with AIPS

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 one part (of many!) 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 for the EVN and (some!) other instruments

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.

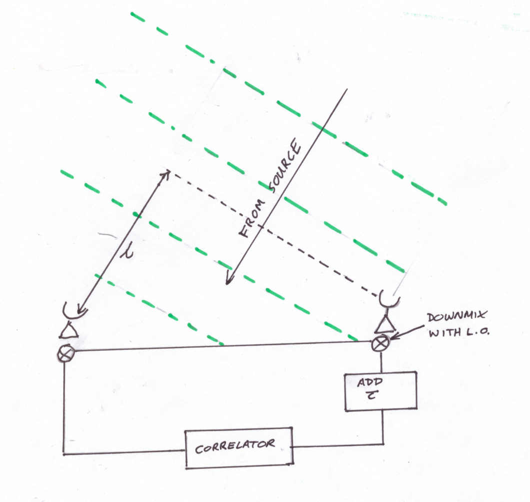
Fourier Interlude (2)

Consider a signal of finite bandwidth with constant time delay, then phase is linear in frequency.

$$\phi(f) = \Phi(t) = \exp 2\pi i f \Delta t$$

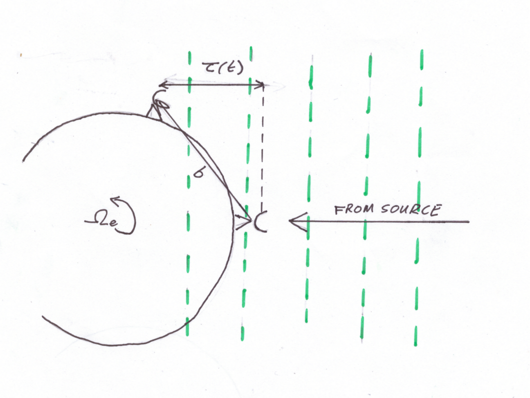
So if we Fourier transform ϕf we get a delta function at Δt!
(Note: Bracewell's Rule is very general; this Fourier pair is quite different from the u-v vs. sky coordinate transform of imaging!)

Interferometry



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 to define phase centre.

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 (Mark's talk)
- And we calibrate phase with *fringe-fitting*
- Plotting phase vs. frequency, a delay corresponds to a slope of phase $\phi \propto \tau \cdot \nu$.

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
- (The dimensions are hands of polarization; Ivan Martí-Vidal will explain more)
- 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.)

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

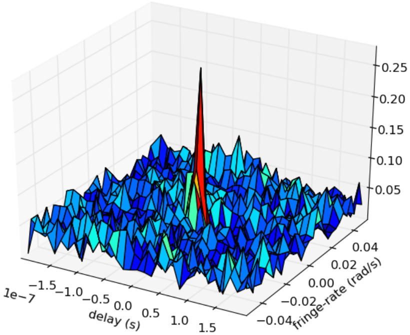
where

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

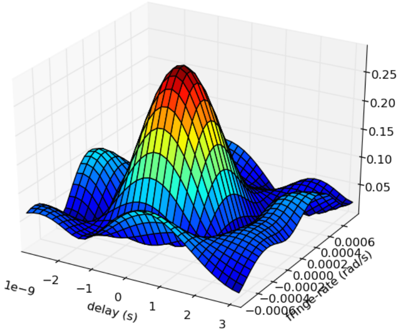
So 2D Fourier transform of $\phi(t,\nu)$ should be a δ-function at delay and fringe-rates.

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



Unpadded FFT



Padded FFT (close-up)

VLBI Theory 3.5: Signal to noise

The *idea* of signal to noise ratio for the FFT stage is simple: we compare the height of the highest peak to an average of the noise floor.
The *use* of the signal to noise ratio for the FFT stage is also simple! Stations for which the SNR is below a threshold are excluded from the second, global stage.
The *details* of the SNR calculations in CASA are Deep Arcana, which I stole straight from the AIPS code.

VLBI Theory 4: Global method

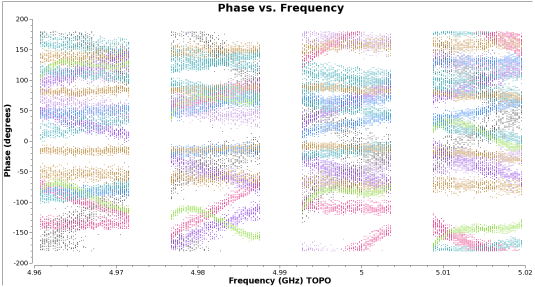
- Still following Schwab and Cotton (1983)!
- So far, only using N of N(N-1)/2 baselines!
- Use a per-station model of ϕ
- Choose a reference station
- Use FFT method for initial guess
- Eliminate low SNR antennas
- Apply least-squares optimisation in regular t-ν space for *all* valid baseline data.
- Minimize weighted sum $||W_{ij}\left[\phi_{ij}(\nu,t) - \exp\left(i\left\{\phi_{0,ij} + \tau_{ij}\Delta\nu + r_{ij}\Delta t\right\}\right)\right]||$
- Uses all the (good) data!
- With good estimates non-linear least squares converges fast
- Used in AIPS; current industry standard for non-geodetic VLBI

VLBI Theory 4: Source models

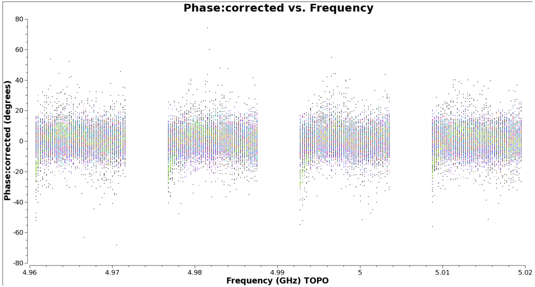
- Without explicit model, fringe-fitting implicitly assumes a point source
- This is often good enough anyway for a phase calibrator
- And it is usually good enough to bootstrap self-calibration!
- CASA supports sky models, but
- If your models are from AIPS it is fiddly to import them
- (But it is possible!)

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!



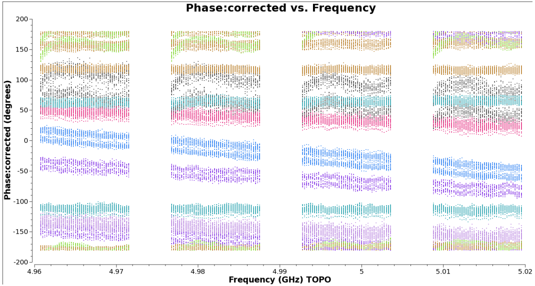
Before fringe-fitting



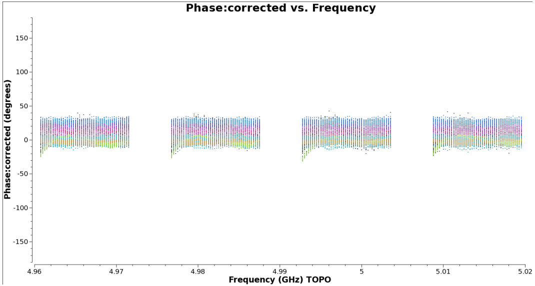
After fringe-fitting

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

VLBI procedures 3: 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)
```

VLBI procedures 4: Gaps between bands

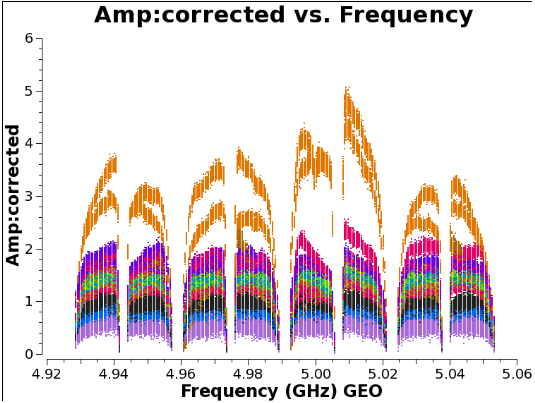
For multiple spectral windows, all data is regridded to a single wide frequency grid.
This does work for S/X data, but is very inefficient.
Nearest neighbour interpolation is used for quirky inter-band spacing like like ALMA.
A new method for these cases is available as an option, but still being road-tested.

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!



Some miscellaneous remarks specific to CASA

- We do now support merging the two polarizations!
- We *do* now support data with only one hand of polarization on some antennas!
- Ionospheric dispersion term is now supported
  - Useful at P-band
  - Important for LOFAR Long Baseline
  - Will be required for broad band receivers
- We now support uvranges!

Final remarks

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