What the experience of radio-interferometry tells us

Bill Cotton

Abstract

Topics discussed during this lecture :

- Brief description of heterodyne interferometry esp. VLBI
- Comparison of heterodyne and direct interferometry
- Phase closure: keeping coherent in an incoherent world
- Resolution: too much of a good thing?
- Delay - frequency relationship
- Imaging versus modeling
- Demonstration of VLBI data analysis and results

Related publications :

- "Very Long Baseline Interferometry", eds. M. Felli and R. E. Spencer, (1989), (NATO) ASI Series C, no. 283, Kluwer Academic Publishers.
- "Synthesis Imaging in Radio Astronomy", eds. R. A. Perley, F. R. Schwab, and A. H. Bridle, (1989) ASP Conference Series, vol. 6, pp. 233-245.
- "Very Long Baseline Interferometry and the VLBA", A.Zensus, P. Napier and P. Diamond eds. (1995) ASP Conference series ASP, vol. 82, pp. 190 - 207.
- "Synthesis Imaging in Radio Astronomy II", Volume 180 of the ASP Conference Series Proceedings, eds. G.B. Taylor, C.L. Carilli, and R.A. Perley (NRAO) A Collection of Lectures from the Sixth NRAO/NMIMT Synthesis Imaging Summer School held at Socorro, New Mexico, USA June 17-23, 1998 Published July 1999, 688 pgs., ISBN 1-58381-005-6

A more technically oriented work is:

- "Interferometry and Synthesis in Radio Astronomy", by A. Richard Thompson, James M. Moran and George W. Swenson, Jr, (1986), John Wiley and Sons, New York. The authors of this last book are revising it. The previous edition is out of print.

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What the experience of Radio Interferometry tells us

Bill Cotton, NRAO

- Radio astronomers have over 50 years of experience with interferometry
- Optical/IR technology very different from radio
- But, the fundamentals are the same
- Difficulties for Optical/IR astronomers in applying radio experience:
  - hardware technology differences
  - different jargon

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Brief History of Radio Interferometry

1946 − Sea Cliff Interferometer (Aust.)
1958 − Jodrell Bank Interferometer (UK)
1963 − One Mile Telescope (UK)
1964 − Green Bank Interferometer (US)
1967 − VLBI (US, Can.)
1974 − Westerbork Array (NL)
1974 − CLEAN
1978 − Self calibration
1978 − Very Large Array (VLA) (US)
1989 − ATCA (Aust.)
1990 − Very Long Baseline Array (VLBA) (US)
1997 − GMRT (India)
1997 − Halca orbiting VLBI (Japan)

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Radio (heterodyne) interferometers

- Telescopes sample wavefront
  - convert to electrical signals
  - may also digitize
  - signal may be replicated as needed
- Once sampled, signals may be transported by wire, fiber optics cable, tape ...
- Multiple baselines cost $ not sensitivity
- Signal combination
  - Adding interferometer (not used for decades)
  - Correlation Interferometer
- Simplified radio interferometer

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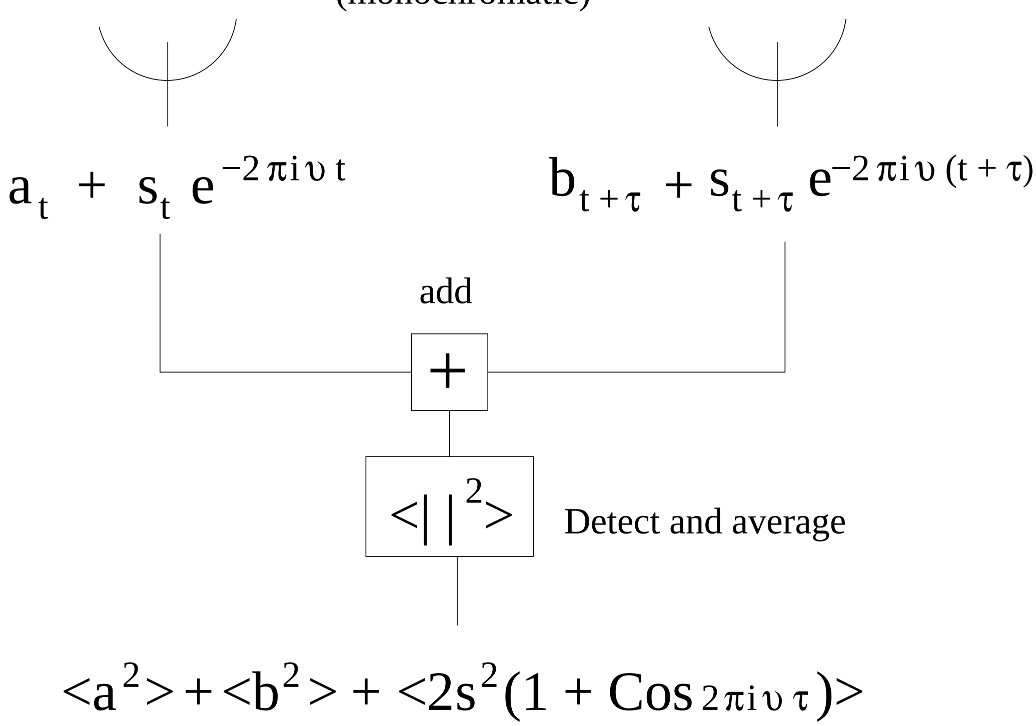
Adding Interferometer

(monochromatic)



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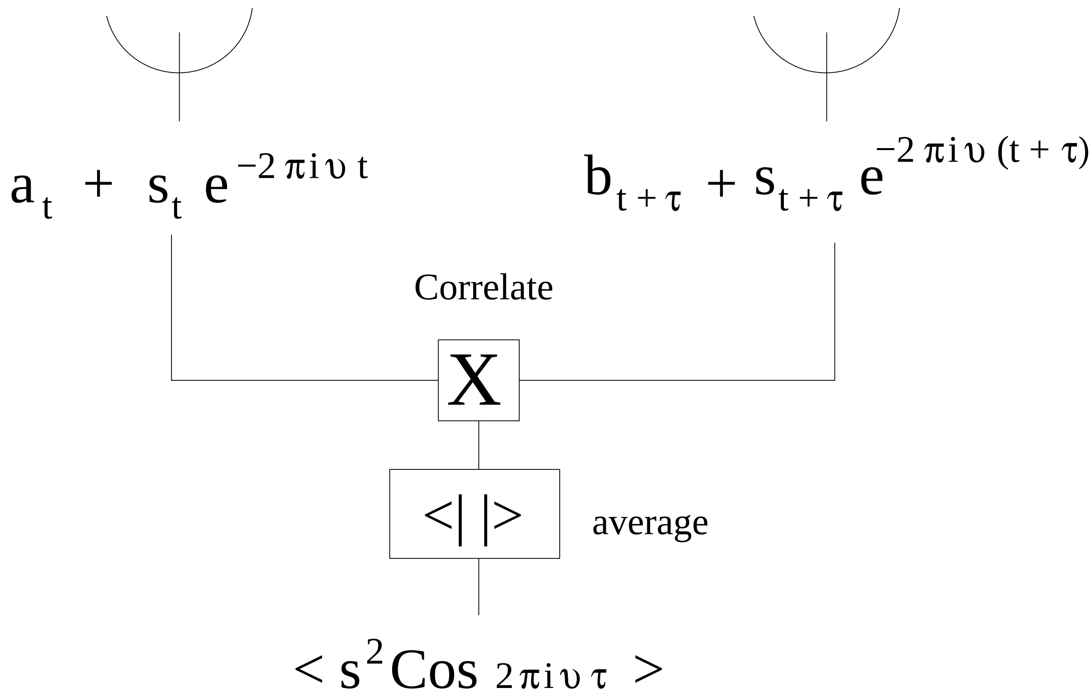
Correlation Interferometer

(monochromatic)



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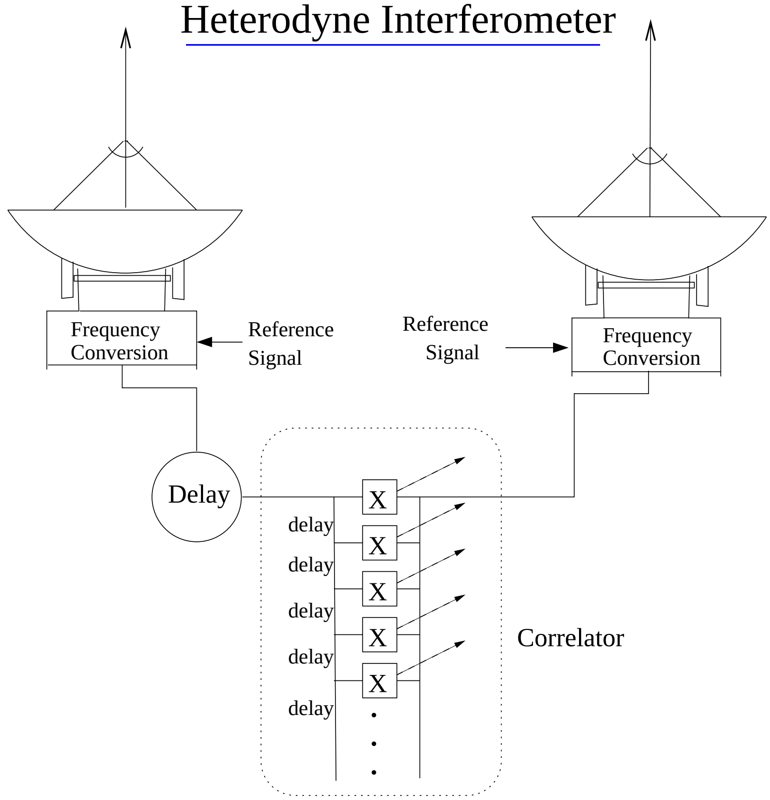
Heterodyne Interferometer



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Direct vs Hetrodyne interferometers

differences

direct (optical)	heterodyne (radio)
interference in free space then detection	detection then interference
bandwidths many THz	bandwidths few GHz
adding interferometer	correlation interferometer
must sweep delay or disperse	measure lag function
more baselines cost sensitivity	more baselines cost $
aperature variable coherence	aperature coherent
coherence time msec	coherence time sec to hours

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Direct vs Hetrodyne interferometers

Similarities

Atmospheric decorrelation/delay drift fundamental limitation
Measure coherence function to derive spatial structure
Delay − sky frequency Fourier relationship
Sometimes must use sparse arrays (few telescopes)
Data processing converges away from hardware
Many calibration errors are telescope based

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Tourist Guide to Interferometry Jargon

Optical/IR speak	Radio speak
Optical path difference (OPD)	Delay, lag
Differential piston	Delay residual
Strehl ratio	Antenna gain
Background level	System temperature
Fringe tracking	Phase referencing
Telescope	Antenna
Detector	Feed
Point spread function (PSF)	Dirty (or CLEAN) beam
Magnitudes	log (flux density)
Obscure band designations	Confusing band designations

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Phase Closure: keeping coherent in an incoherent world

– If aperature coherent, phase errors mostly telescope based (this is not so true if the aperatures are partially coherent)

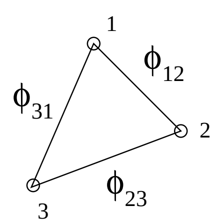
– Summing phase around a closed loop cancels tel. phase.

"Closure" phase: $\Phi^{cl}_{123} = \phi_{12} + \phi_{23} + \phi_{31}$

but $\phi_{ij} = \phi^s_{ij} + \phi^e_i - \phi^e_j$

where ϕ^s_{ij} = source structure phase

ϕ^e_i = phase error for telescope i



so $\Phi^{cl}_{123} = \phi^s_{12} + \phi^e_1 - \phi^e_2 + \phi^s_{23} + \phi^e_2 - \phi^e_3 + \phi^s_{31} + \phi^e_3 - \phi^e_1$

$= \phi^s_{12} + \phi^s_{23} + \phi^s_{31}$

is only a function of source phase.

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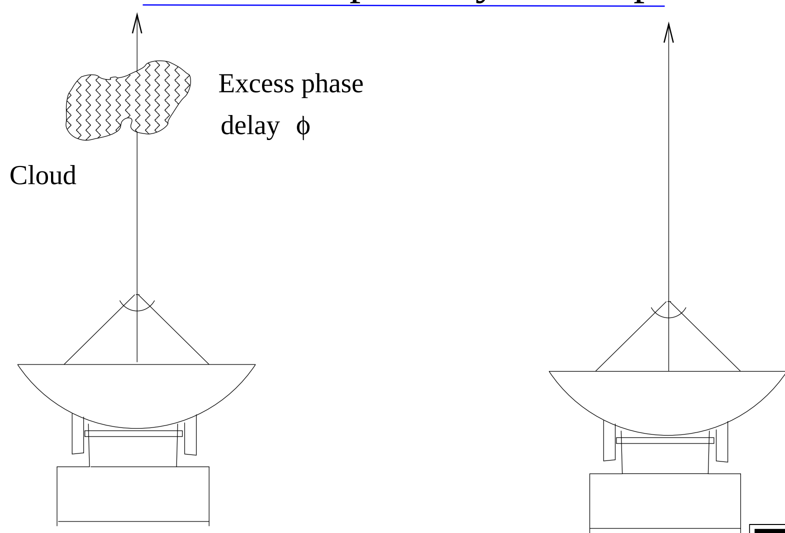
Phase corruption by telescope



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Phase Closure: continued

− In practice usually solve for telescope phases

$$\phi_{ij}^{obs} = \phi_{ij}^{mod} + \phi_i^e - \phi_j^e$$

− Geometric errors are also telescope based and close

− All astrometric information is lost using closure

− Using closure relations called "self calibration"

− Self calibration can produce spurious results
if SNR is low.

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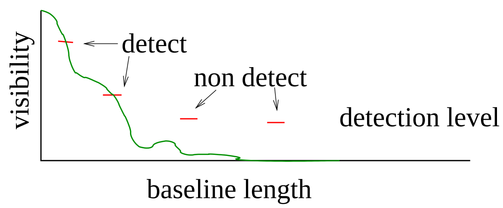
Resolution: too much of a good thing?

− Source detectability drops quickly with resolution once the object is resolved.

− Interferometers are spatial frequency filters



− Large scale structure lost

− Need detectable flux density in synthesized beam

− Want array "matched" to source structure

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Delay − Frequency Relationship

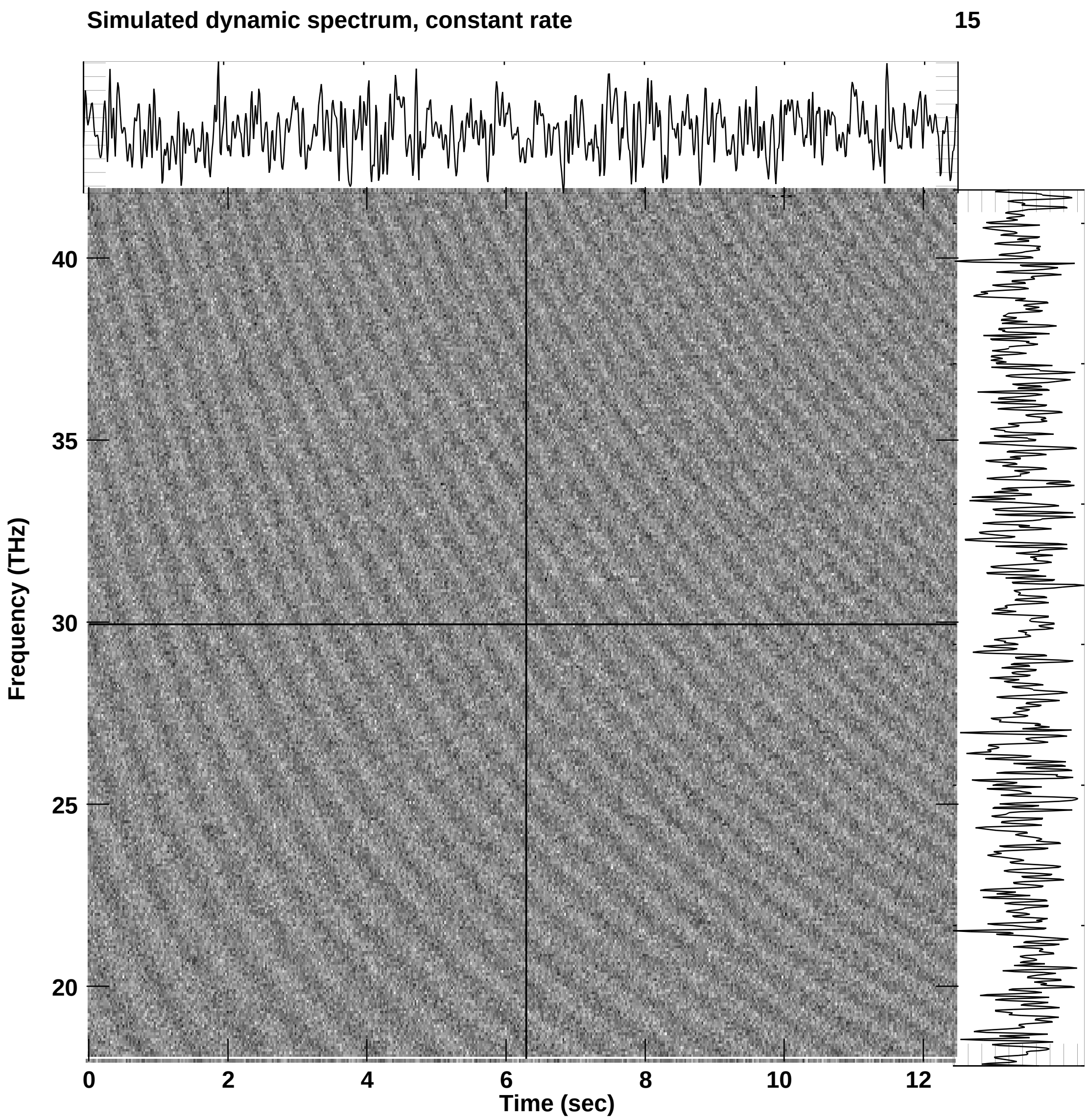
− Delay function and sky frequency spectrum are related by a Fourier transform

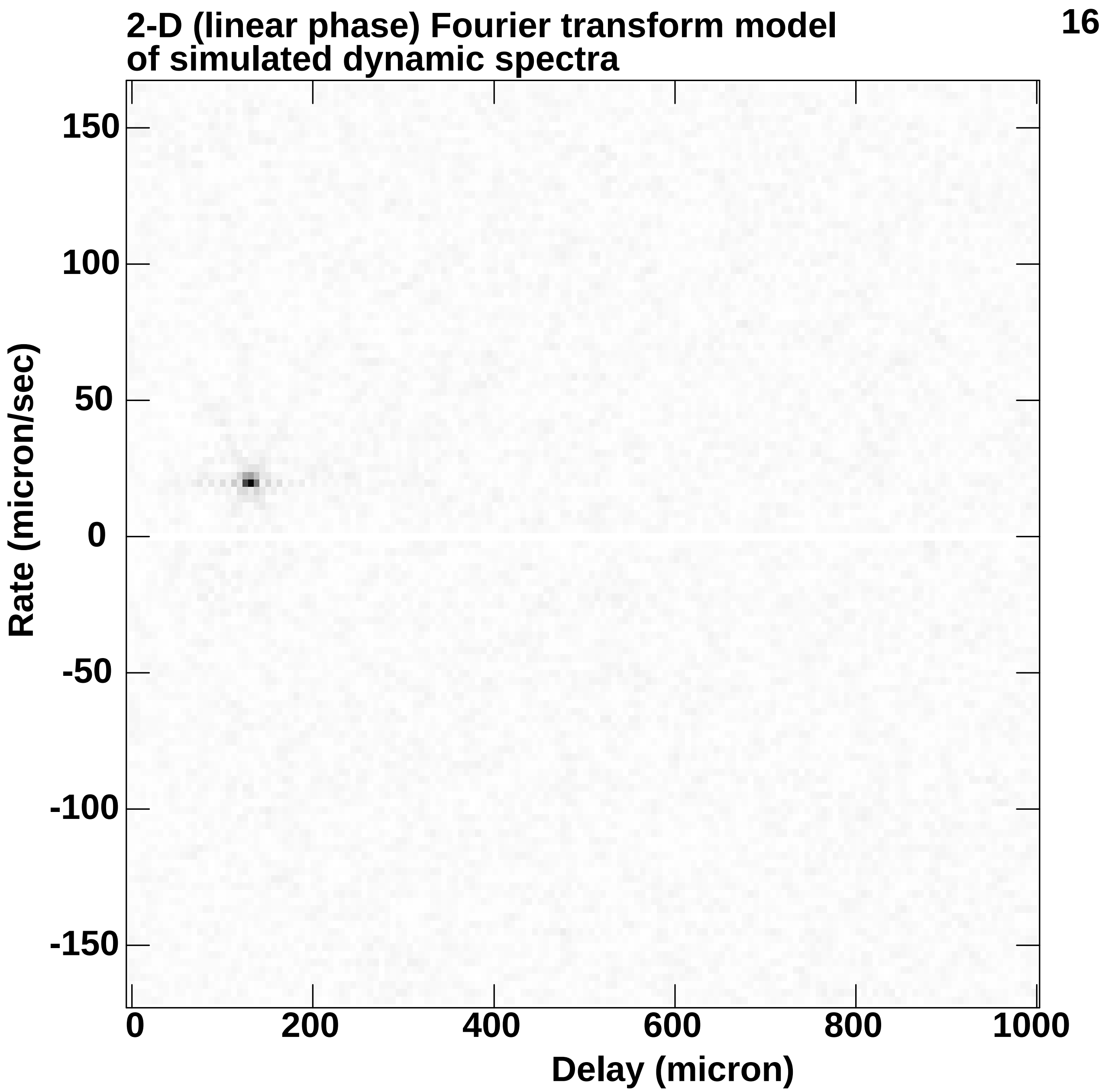
− Can measure spectrum with a delay scan
Fourier transform spectrometer

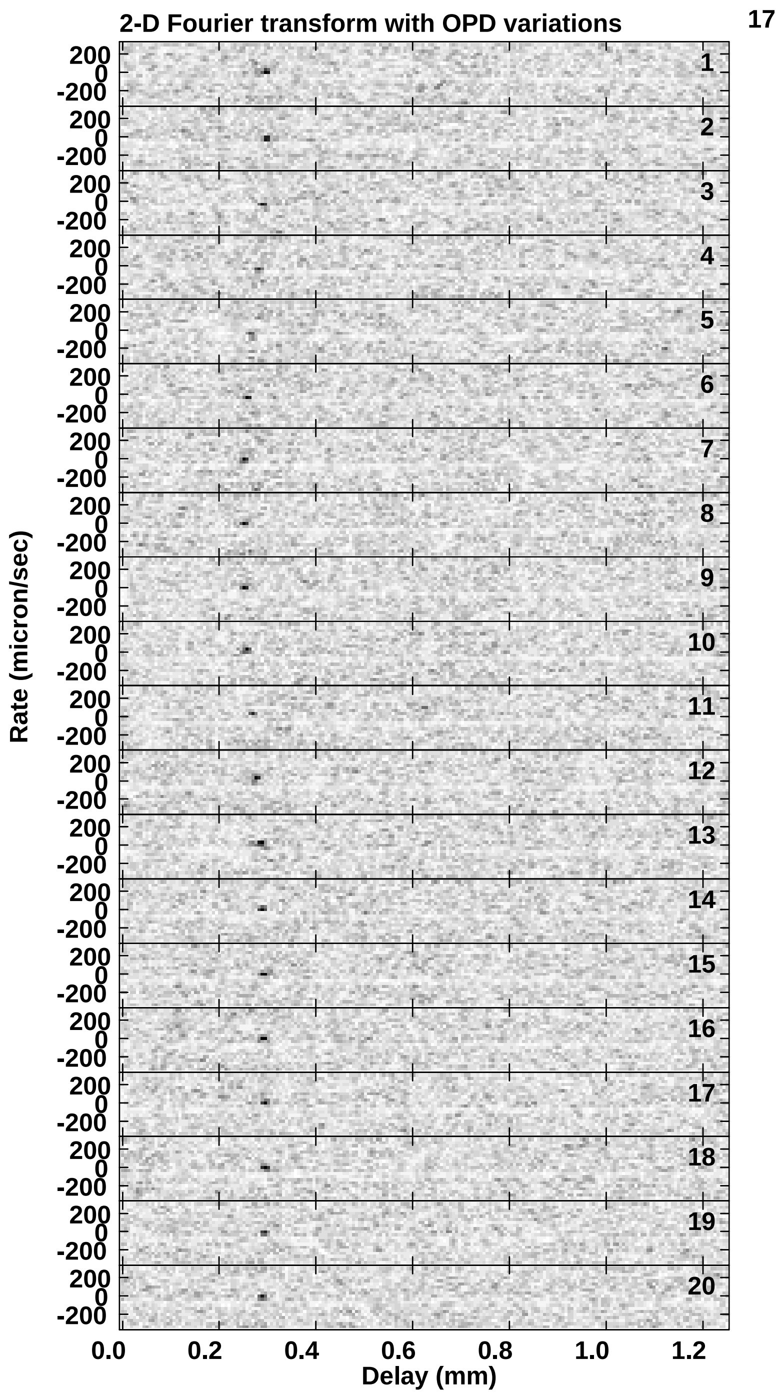
− Can measure delay function from spectrum

− Narrow frequency channels have wide delay response

− With sufficient spectral resolution, long delay scans are not needed.


Simulated dynamic spectrum, constant rate
15
Frequency (THz)
40
35
30
25
20
0
2
4
6
8
10
12
Time (sec)


2-D (linear phase) Fourier transform model
of simulated dynamic spectra
16
150
100
50
0
-50
-100
-150
Rate (micron/sec)
0
200
400
600
800
1000
Delay (micron)


2-D Fourier transform with OPD variations
17
Rate (micron/sec)
200
0
-200
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Delay (mm)

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Imaging vs. Model Fitting

- Imaging requires a large quantity of calibrated data
  - but requires little a priori knowledge of source
  - need both amplitude and phase
  - frequently model fit image to extract physics
- Model fitting works with few data
  - requires considerable a priori knowledge
  - need parameterized model
  - generally nonlinear (unstable) fitting
  - can work with only amplitude / closure phase
- For marginally resolved objects model fitting (before or after imaging) is usually needed.

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Incomplete Sampling (deconvolution)

- Cannot measure everywhere in u,v (aperature) plane
- Define sampling function

$$S(u,v) = \begin{cases} 1 & \text{where measured} \\ 0 & \text{elsewhere} \end{cases}$$

- Measured visibilities are (ignoring noise, calibration):

$$V^{meas}(u,v) = V^{true}(u,v)\ S(u,v)$$

- Can image the sky ("dirty" image)

$$D(x,y) = FT(V^{meas}) = FT(V^{true}) \star FS(S)$$

$$= I(x,y) \star B(x,y) \quad \text{(convolution)}$$

I = Sky brightness distribution
B = "Dirty" beam

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Deconvolution (CLEAN)

− Need nonlinear deconvolution to recover I(x,y)

− CLEAN deconvolution
Decompose image into δ functions
1) find peak
2) subtract fraction of dirty beam centered on peak
3) repeat until converged
4) convolve δ functions with "CLEAN" beam and restore

− CLEAN is very robust
− but can produce artifacts in extended emission

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Self Calibration

− Atmosphere corrupts even phase referenced data

− Can phase reference source to itself

− Lose geometric information

− Use closure relations (error enters by telescope)
Have more baselines than telescopes
- need n−1 phases
- have n(n−1)/2 baselines

− Use source (CLEAN) model to correct data for structure

$$V^{Pt} = V^{Obs} / V^{Model}$$

− Phase errors factorizable (per telescope)

$$V^{Obs} = V^{true}\, e^{i\phi_i}\, e^{-i\phi_j}$$

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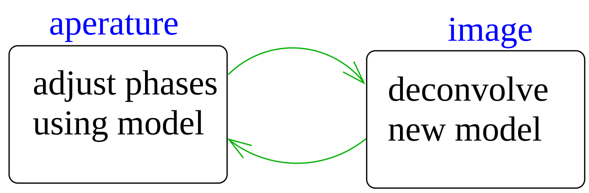
Self Calibration Continued

– Iterate with deconvolution



– With many telescopes an initial point model OK

– With few (<10) telescopes do model fitting first.