Applying the Experiences of Radio Astronomy to Mid-IR Interferometry

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Outline:

- Similarities between mid-IR and radio interferometry.
- Differences between mid-IR and radio interferometry.
- Useful techniques/experience from radio interferometry

Similarities between radio and mid-IR

- Physics of optics the same (coherence fn)

$$V(u,v) \approx \int\int B(x,y)\, e^{-2i\pi(ux+vy)}\, dx\, dy$$

- Signals background dominated.
- Atmospheric phase fluctuations worst problem.

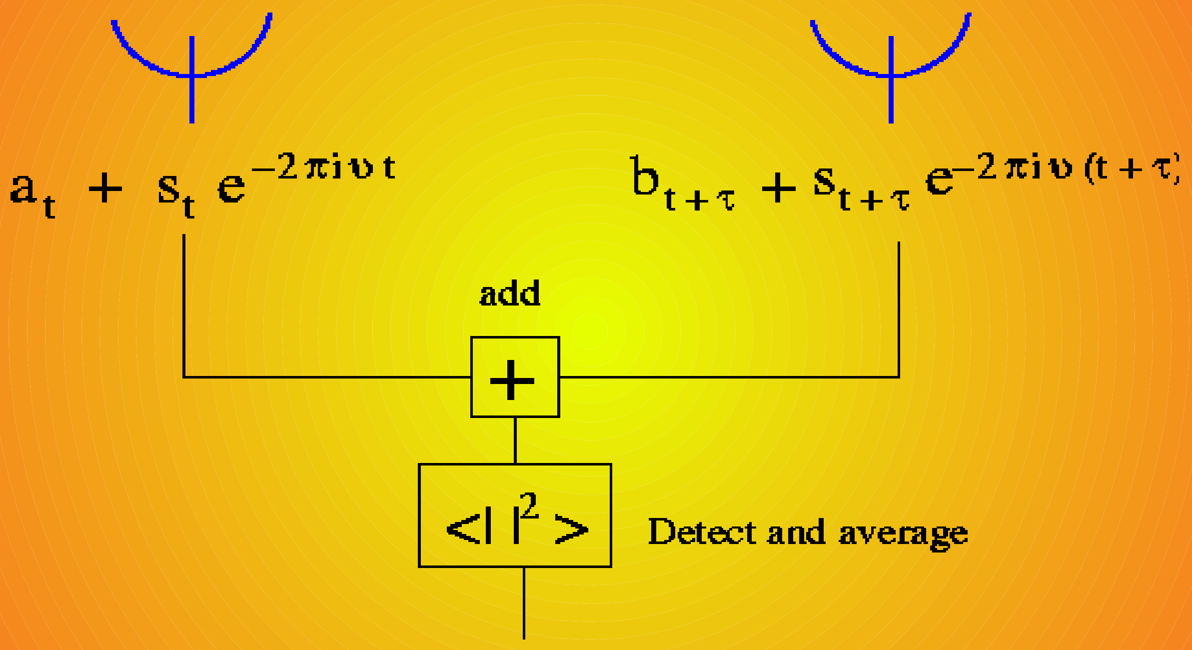
Differences between radio and mid-IR 1

- Hardware:
  - Mid-IR it's all done with mirrors
  - Radio uses analog and digital electronics.
- Time and size scales of atmospheric fluctuation are very different
  - Mid-IF few to hundreds of msec, few m
  - Radio seconds to hours, 100s – 1000s m

Differences between radio and mid-IR 2

- Heterodyne vs Direct
  - Mid-IR (usually) uses direct interferometer
    - Detect interferometer power (not phase)
    - Wide bandwidth, many THz
    - Few baselines/delays
    - Adding interferometer
  - Radio (usually) uses heterodyne interferometer
    - Bandwidth limited to few Ghz
    - Many baselines/delays
    - Correlation interferometer

Adding interferometer



$a_t + s_t e^{-2\pi i \nu t}$

$b_{t+\tau} + s_{t+\tau} e^{-2\pi i \nu (t+\tau)}$

add

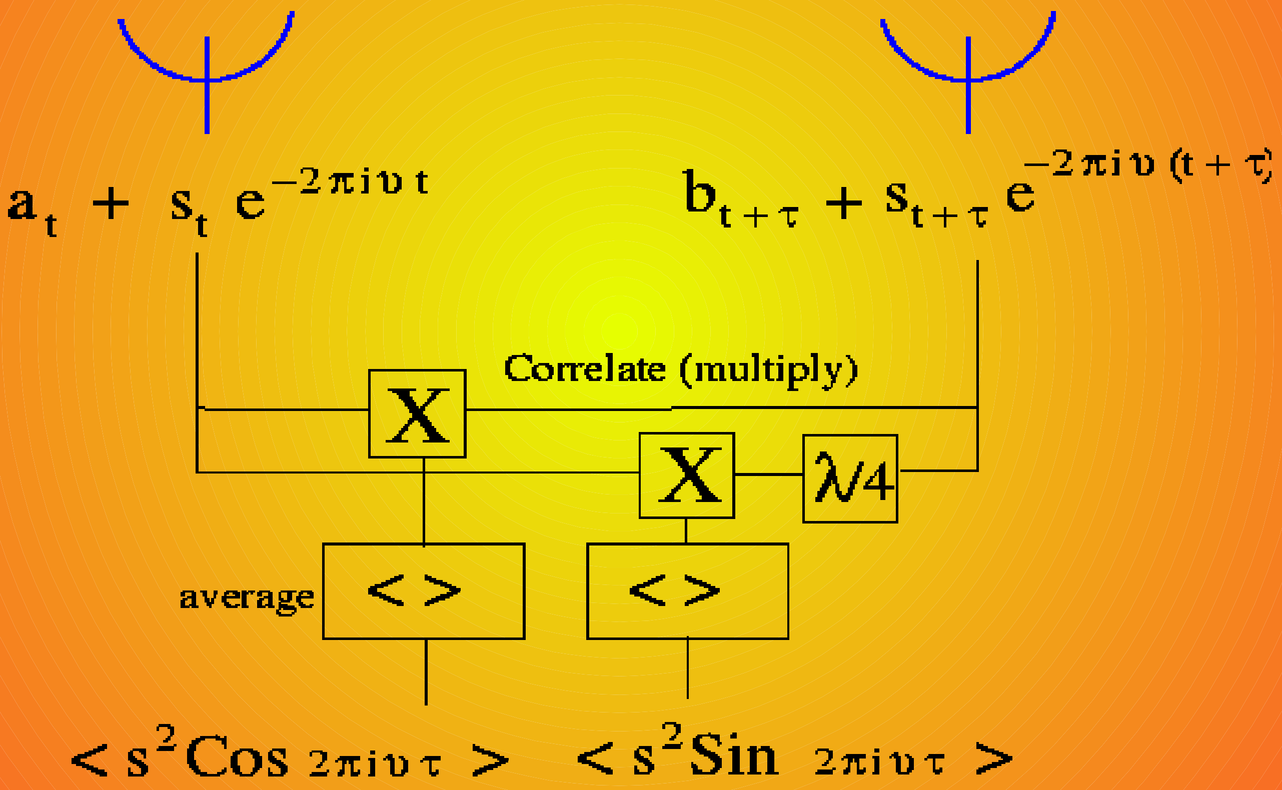
$+$

$<|\ |^2>$

Detect and average

$$<a^2>+<b^2>+<2 s^2(1 + \mathrm{Cos}_{2\pi i \nu \tau})>$$

Correlation interferometer



$a_t + s_t\, e^{-2\pi i \upsilon t}$

$b_{t+\tau} + s_{t+\tau}\, e^{-2\pi i \upsilon (t+\tau)}$

Correlate (multiply)

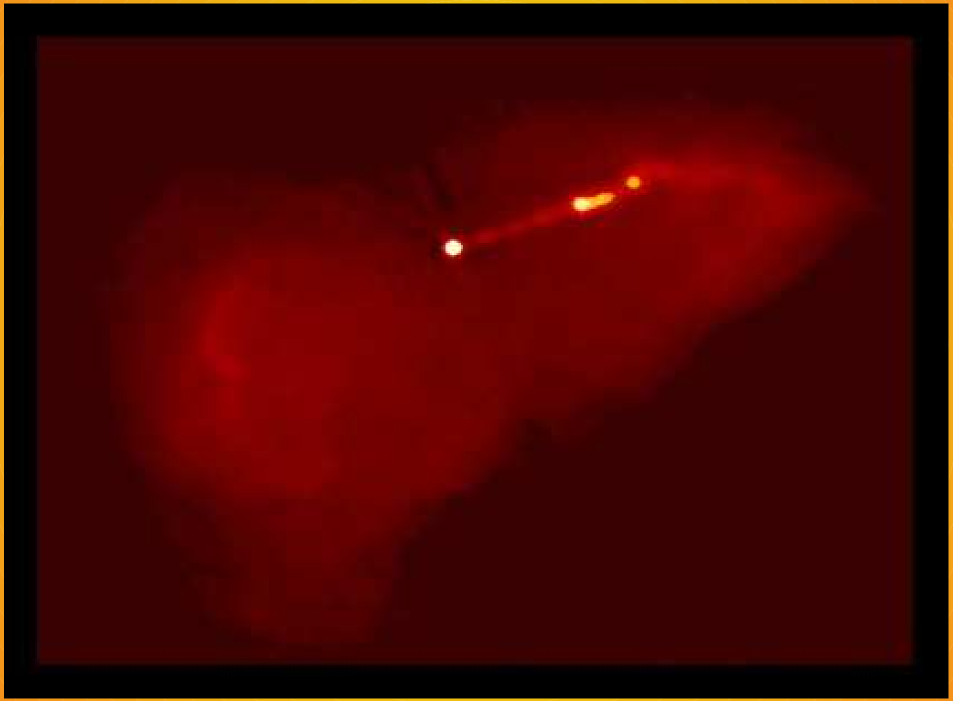
$< s^2 \mathrm{Cos}\ 2\pi i \upsilon \tau >$ $< s^2 \mathrm{Sin}\ 2\pi i \upsilon \tau >$

- Why not always a heterodyne system?
  - Bandwidth, max. correlator few 10s Ghz, direct interferometry can obtain many THz.
  - Heisenberg. Quantum effects add noise if phase measured:
    - @ 2mm add 7.2 K noise
    - @ 20μ add 720 K noise
    - @ 10μ add 1450 K noise
    - @ 5μ add 2900 K noise
    - @ 1μ add 14500 K noise

Experience from Radio Interferometry

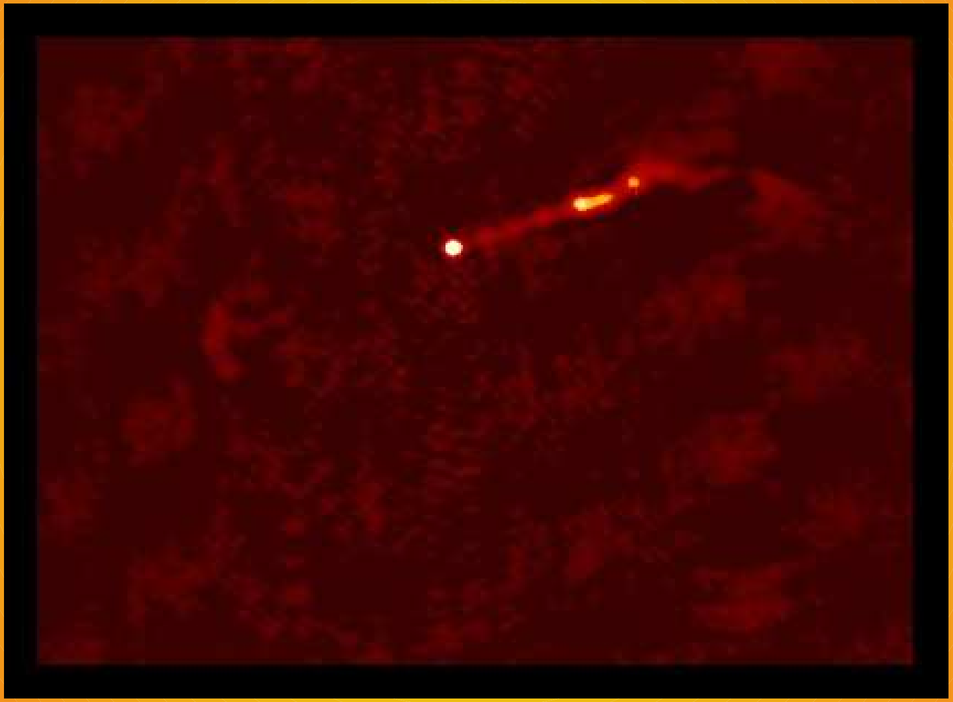
- Imaging issues:
  - Short baselines are important.
  - It takes many baselines to make a good image.
  - Sparse uv coverage requires modeling rather than imaging
  - Self calibration works much better with increasing number of simultaneous telescopes.

Radio image with 27 antennas (353 baselines)



Radio image with 6 antennas (30 baselines)

(and no short baselines)



Frequency - Time relationship 1

- Frequency and time (delay) related by Fourier Transform:

$$V(\nu) = c \int S(\tau) e^{-2\pi i \nu \tau} d\tau$$

$$S(\tau) = \frac{1}{c} \int V(\nu) e^{2\pi i \nu \tau} d\nu$$

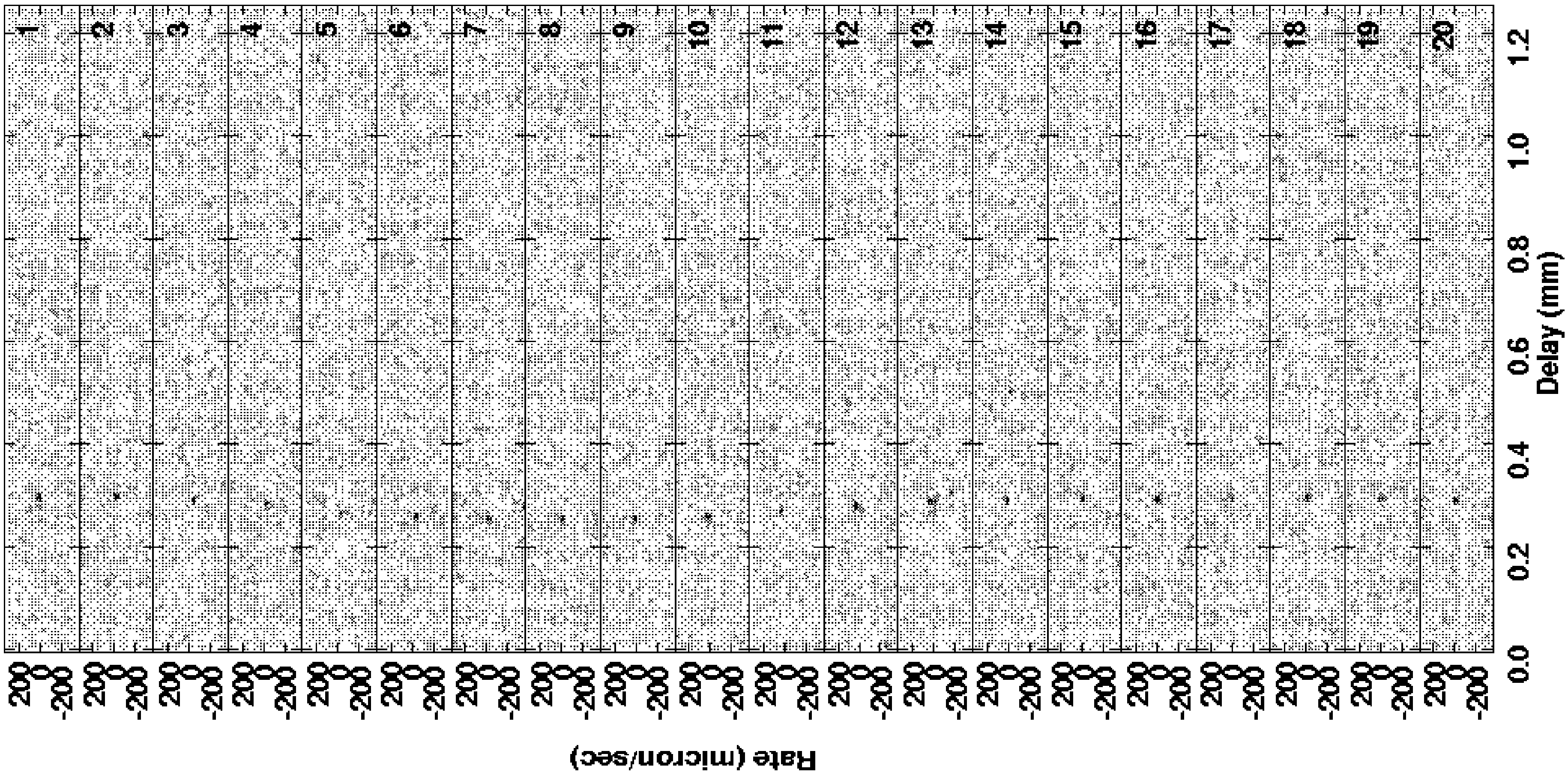
Where V(ν) is in frequency space
and S(τ) is in delay space.

Frequency - Time relationship 2

- Frequency and delay relationship forms the basis of Fourier Spectroscopy.
- Relationship can be used to track OPD for dispersed interferometry.
  - Dispersed fringes can be transformed to OPD
  - Allows tracking atmospheric OPD without observing ``off fringe".

Dispersed Fringe Tracking

MIDI High Dispersion Simulation



Closure relationships 1

- Many, but not all, atmospheric and instrumental phase errors close when summed around a closed set of baselines:

$$\phi_{Closure} = (\phi_{12} + \phi_2 - \phi_1) + (\phi_{23} + \phi_3 - \phi_2) - (\phi_{13} + \phi_3 - \phi_1)$$

$$\phi_{Closure} = \phi_{12} + \phi_{23} - \phi_{13}$$

- These can be used as constrains when solving for calibration phase and source structure or in fitting models.
- Number of closure phases goes up rapidly with the number of simultaneous telescopes.

Closure relationships 2

- Differences in phase screen across apertures may introduce non closing errors, need:
  - Sufficiently good adaptive optics, or
  - Spatial filtering, or
  - A small aperture.
- A similar relationship exist for amplitudes and 4 or more telescopes.

Wide Field Considerations

- Time and wavelength averaging average over uv plane.
- If visibility function changes in averaging interval, the results will be distorted.

Frequency Averaging 1

- Causes chromatic aberration
- Reduction in point source response:

$$R = \frac{1}{\sqrt{[1 + (0.939\, r\, \Delta\nu / \theta\nu)^2]}}$$

Where:
ν is frequency of observations (Hz),
$\Delta\nu$ bandwidth (Hz),
θ is the synthesized beam size (rad),
r is distance from center,
Thompson, Moran, Swenson, 2001

Frequency Averaging 2

- Objects will be smeared in the radial direction.
- Can be reduced by observing in dispersed mode.

Time Averaging

- Reduction in point source response:

$$R \sim 1 - \frac{1}{3}\left(\frac{0.8326\,\nu\,\tau}{2\pi\theta}\right)^2 \left(l^2 + m^2 \sin^2(\delta)\right)$$

Where:

ν is frequency of observations (Hz),

τ is averaging time (sec),

θ is the synthesized beam size (rad),

δ is source declination,

l ,m are the direction cosines from the center,

Thompson, Moran, Swenson, 2001

- Effects depend on details of observation

Conclusions

- Much commonality in Radio and Mid-IR interferometry.
- Some serious technical differences.
- Similarities increase away from the hardware.
- Much potential for sharing technology.