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

**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

- **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

\[ a_t + s_t e^{-2\pi i v t} + b_{t+\tau} + s_{t+\tau} e^{-2\pi i v (t+\tau)} \]

\[ \langle 1^2 \rangle \]

Detect and average

\[ \langle a^2 \rangle + \langle b^2 \rangle + 2s^2(1 + \cos 2\pi iv\tau) \]
Correlation interferometer

\[ a_t + s_t e^{-2\pi i v t} \]

\[ b_{t+\tau} + s_{t+\tau} e^{-2\pi i v (t+\tau)} \]

Correlate (multiply)

\[ \langle s^2 \cos 2\pi i v \tau \rangle \]

\[ \langle s^2 \sin 2\pi i v \tau \rangle \]
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 \( V(\nu) \) is in frequency space and \( S(\tau) \) 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:

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

\[ \phi_{\text{Closure}} = \phi_{12} + \phi_{23} - \phi_{13} \]

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.
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:

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

Where:

- \( \nu \) is frequency of observations (Hz),
- \( \Delta \nu \) bandwidth (Hz),
- \( \theta \) 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:

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

Where:
\( \nu \) is frequency of observations (Hz),
\( \tau \) is averaging time (sec),
\( \theta \) is the synthesized beam size (rad),
\( \delta \) 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.