Early interferometers

Michelson in 1881

Wikipedia: Michelson Morley experiment
Early interferometers
Measurement of the diameter of Betelgeuse
(by ‘resolving out’ the source - see later)

Michelson & Pease 1921
Optical interferometry

Capella binary at two epochs

Cambridge!

Baldwin et al 1996
Mid-IR interferometry
Radio interferometry
Gravitational waves

Abbott et al 2016
Why do interferometry?

- Resolution \( 1.22 \frac{\lambda}{D} \rightarrow \frac{\lambda}{(2b)} \)
- Dishes can only be so big
Windows for astronomy
Interferometry
Jansky Very Large Array, New Mexico
Basic interferometer
response to a monochromatic source

\[ R_C = \frac{V^2}{2} \cos (\omega \tau_g) \]

\[ = \frac{V^2}{2} \cos \left( 2\pi \frac{b \cdot \hat{s}}{\lambda} \right) \]

(i.e. a number)
Basic interferometer

finite bandwidth - add delay to “point” phase center

(i.e. fringe spacing varies with frequency)
Astrometry

milli-arcsec precision - basis of ICRF

\[ \phi = 2\pi \frac{b \cos \theta}{\lambda} \]
\[ \frac{d\phi}{d\theta} = 2\pi \frac{b \sin \theta}{\lambda} \]
\[ b \sin \theta \gg \lambda \]

Fey et al. 1996
When is a source resolved?

Point source at infinity

Point sources at infinity separated by 1/2 the fringe spacing

Incoming plane waves

\[ \text{Baseline} = b \]

2 slits

\[ \Delta \theta = \frac{\lambda}{b} \text{ radians} \]

Interference pattern (Visibility = 1)

2 sine waves destructively interfere (Visibility = 0)

\[ \Delta \theta = \frac{\lambda}{(2b)} \]
Basic interferometer

signal = sum of \((\text{sky image } \times \text{fringe pattern on sky})\)

\[ R_C = \int I(s) \cos \left(2\pi b \cdot \hat{s}/\lambda \right) d\Omega \quad \text{(i.e. a number)} \]
Basic interferometer

signal = sum of (sky image x fringe pattern on sky)

\[ R_C = \int I(s) \cos \left(2\pi b \cdot \hat{s}/\lambda\right) d\Omega \]  (i.e. a number)

one point source: \( R_C = 1 \)

one point source: \( R_C = -1 \)
Basic interferometer

signal = sum of (sky image × fringe pattern on sky)

\[ R_C = \int I(s) \cos (2\pi b \cdot \hat{s}/\lambda) d\Omega \] (i.e. a number)

two point sources: \( R_C = 0 \)
Basic interferometer

but odd component of a signal is invisible:
second correlator with 90deg phase shift

\[ R_S = \int I(s) \sin (2\pi b \cdot \hat{s}/\lambda) d\Omega \]

now define complex visibility

\[ V = R_C - iR_S = Ae^{-i\phi} \]

\[ A = \left( R_C^2 + R_S^2 \right)^{1/2} \]

visibility amplitude

\[ \phi = \tan^{-1} \left( \frac{R_S}{R_C} \right) \]

visibility phase
Basic interferometer

\[ V = R_C - i R_S = A e^{-i\phi} \]

\[ V = \int I(s) \exp\left(-i2\pi b \cdot \hat{s} / \lambda\right) d\Omega \]

Van Cittert-Zernike theorem:
Fourier transform of a far source is equal to its complex visibility

image

\[ u = b / \lambda \]

‘uv’ plane

i.e. sample \( V \) at a given \( u,v \) (which is set by baseline)
Basic interferometer

i.e. sample $V$ at a given $u,v$ (which is set by baseline)

image

‘uv’ plane

$u = b/\lambda$

(+ phase)

each point corresponds to a baseline separation and orientation
Visibility curves

This figure shows simple one-dimensional images and their corresponding visibility curves. The left panels are the images while the right panels correspond to the Fourier amplitudes, i.e. the visibility amplitudes. Note that 'large' structure in image-space result in 'small' structure in visibility-space.

Most astronomical objects are not one-dimensional, and the two-dimensional space of spatial frequencies is called the Fourier Plane, or the \((u,v)\) plane, named after the \((u,v)\) coordinates defined in equation (7). Further, in general we must consider both the visibility amplitude and the visibility phase. For example, consider the equal binary system depicted in figure 3. The complex visibility can be easily written by choosing the origin midway between the two components. Note the abrupt phase jump when the visibility amplitude goes through a null. These discontinuities are smoothed out when the two components are not precisely equal.

2.2. Atmospheric problems

An incoming plane wave from a stellar source is corrupted as it propagates through the turbulent atmosphere. Variations in the column density of air along different paths cause the effective pathlength to vary, introducing wavefront distortion. If these distortions become a significant factor, the visibility can be degraded. The baseline \((b/\lambda)\) is a measure of the pathlength in terms of the wavelength, where \(b\) is the baseline length and \(\lambda\) is the wavelength.
Resolving out ‘extended’ flux

Figure 2. This figure shows simple one-dimensional images and their corresponding visibility curves. The left panels are the images while the right panels correspond to the Fourier amplitudes, i.e. the visibility amplitudes. Note that ‘large’ structure in image-space result in ‘small’ structure in visibility-space.

While the point-source remains unresolved out to the highest spatial frequency. Note that the visibility plateaus at 0.10, corresponding to the fraction of the total flux which is left unresolved. This is easy to understand since the Fourier Transform is linear; that is, the (complex) visibility of a point-source and extended structure is equal to the visibility of the point-source plus the visibility of the extended structure separately. This property of linearity is very helpful in interpreting simple visibility curves.

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Resolving out ‘extended’ flux

sky

uv

small b

large b

uv, both
Resolving out ‘extended’ flux

signal = sum of (sky image x fringe pattern on sky)

\[ R_C = \int I(s) \cos \left( 2\pi \mathbf{b} \cdot \mathbf{\hat{s}} / \lambda \right) d\Omega \]  (i.e. a number)

\[ R_C \sim 0 \]

large source - averaging over many fringes
Resolving out ‘extended’ flux

application to ‘exo-Zodi’ with CHARA

34m baseline

Absil et al 2006
Resolving out ‘extended’ flux

application to ‘exo-Zodi’ with CHARA

$$V^2 \approx (1 - 2f) \left( \frac{2J_1(\pi b \theta/\lambda)}{\pi b \theta/\lambda} \right)^2$$
Resolving out ‘extended’ flux
Basic interferometer

antenna has directional response ("primary beam")

ERA: Fig 3.41

\[ V_1 = V \cos(\omega(t - \tau_g)) \]
\[ V_2 = V \cos(\omega t) \]
\[ \Delta t \gg 1/\omega \]

\[ R = (V^2/2) \cos(\omega \tau_g) \]
Aperture synthesis

- Two element interferometer - imaging degenerate
- But, N antennas means N(N-1) baselines
- Goal: sample visibility at enough u,v points with many small antennas to “synthesise” an aperture of size $u_{\text{max}},v_{\text{max}}$
- Result: response to point source (“dirty beam”) is the average of the fringes for all baselines (more baselines, more Gaussian beam).
Multiple baselines

point-source response = synthesised ("dirty") beam

- single baseline
- three baselines
- six baselines

ERA: Fig 3.42
Multiple baselines

what is the dirty beam?

dirty beam reality image obtained

\[ b(x, y) \otimes I(x, y) = O(x, y) \]

\[ \text{convolution theorem} \]

\[ FT^{-1}\{B(u, v)V(u, v)\} = O(x, y) \]

sampled visibilities
Multiple baselines

\[ B(u, v) = \sum_i (u_i, v_i) \]

\[ \text{FT}^{-1}\{B(u, v)\} = b(x, y) \]

i.e. sample all spatial scales, and \( \text{FT}(\text{constant}) = \text{delta function} \)
Aperture synthesis
use Earth rotation to fill in uv plane
Aperture synthesis

sky rotation makes all the difference

5 antennas

baselines

sum of fringes
Aperture synthesis

ALMA: 2.5km max baseline, 3h, 43 antennas: 861 baselines

(for ALMA integration time the main consideration)

http://almaost.jb.man.ac.uk/
Imaging visibilities

incomplete uv coverage results in spatial filtering

\[ FT \{ \text{me} \} \]
CLEAN
turning visibility data into images

- Initialise residual image to dirty image
- Identify strongest source in residual image
  - subtract fraction of this peak from residual image
  - add it to clean component list
- Repeat until residual image maximum less than some threshold
CLEAN
turning visibility data into images

• Make restored image:
  • make image with all clean components
  • convolve with Gaussian fit to main lobe of dirty beam
  • add residual map
CLEAN

turning visibility data into images

• Main options:
  • Continuum vs. spectral cube
  • Choose how to weight baselines (e.g. ‘natural’)
  • Choose where clean components are (‘mask’)
CLEAN
turning visibility data into images
ALMA
ALMA

$4 \times 12\,\text{m} + 12 \times 7\,\text{m}$ compact array, the ‘ACA’ acts as a ‘single dish’ to recover large scale structure
Spectral line observations

different ‘slices’ through a data cube

Maercker et al 2012

Pinte et al 2017
Spectral line observations

Pinte et al. 2018
ALMA…

…will do a lot of the hard stuff for you
ALMA

...and packages exist to deal with visibility modelling

• Modelling example:

  • https://github.com/drgmk/alma/blob/master/examples/vis_model.ipynb
Nulling interferometry
~as before, but 180deg phase shift and no correlator
(i.e. photons on an IR detector)
Nulling interferometry

as before, but 180deg phase shift and no correlator (i.e. photons on an IR detector)

Kennedy et al 2015

Defrere et al 2015
LBTI - early results

\[ \text{signal} = \frac{\text{transmitted disk flux}}{\text{stellar flux}} \]
Sparse Aperture Masking

21 unique baselines - ‘sparse’

Cheetham et al 2016
Summary

• Interferometry is a valuable and flexible tool

• Using ALMA is relatively easy - don’t think it’s too hard*

*getting your proposal accepted is the hard part
Resources


• https://science.nrao.edu/opportunities/courses/era/

• John D Monnier, 2003, Rep. Prog. Phys. 66 789

• http://almaost.jb.man.ac.uk/

• http://www.jb.man.ac.uk/pynterferometer/index.html

• https://launchpad.net/apsynsim

• https://github.com/griffinfoster/fundamentals_of_interferometry
Radio astronomy

M87

• Dust obscures optical light
• Not all emission is thermal
Radio astronomy

- Interstellar dust smaller than wavelength - e.g. Sgr A*
- Cold emission negligible in optical - e.g. CMB
- Free-free radiation - e.g. (ionised) HII regions
- Spectral lines - e.g. 21cm HI line, CO rotational transitions
- Synchrotron emission - e- accelerated in SN remnants

Sky at 408MHz