Optical interferometry

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1. Introduction to high-resolution optical astronomy

2. Basics of two-aperture interferometry

3. Basics of multi-aperture interferometry

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See also “Introduction to Interferometry”, `http://xxx.lanl.gov/abs/astro-ph/9609092`

1. Introduction to high-resolution optical astronomy

Definitions:

- High (spatial) resolution: ability to see fine detail
- Optical and infrared wavelengths: 300 nm to 20 μm

What limits our ability to get high resolution?

1. Wave nature of light
2. Earth's atmosphere

Wave nature of light

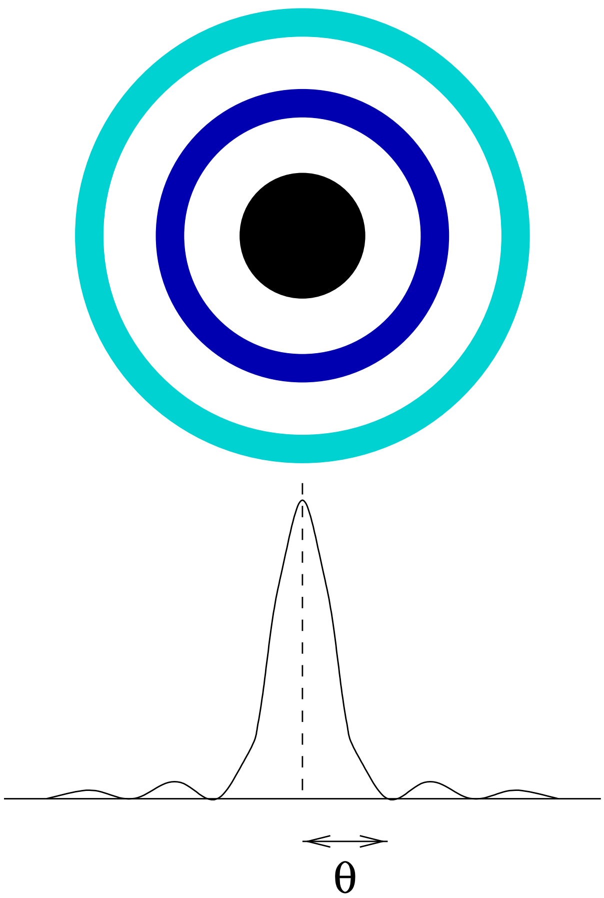
Consider a perfect space telescope:

- A point source produces an Airy pattern

$$\theta = 1.22\frac{\lambda}{D} \quad (1)$$

where

  - θ is (approximately) the width of the image, called the 'angular resolution'
  - λ is the wavelength
  - D is the diameter of the telescope aperture



- Cause of Airy pattern: interference between parts of the wavefront that arrive at different parts of the aperture (note dependence on wavelength)

- Each point on the source produces an Airy pattern. These overlap, degrading the fine detail.

- High resolution (smaller θ) requires shorter wavelengths and/or larger aperture:

	Visible (0.4–1 μm)	Near IR (1–5 μm)	Mid IR (10–20 μm)
$D = 8$ m	18 mas	77 mas	400 mas
$D = 100$ m	4 mas	6 mas	30 mas

Note: mas = milliarcsec

The Earth's atmosphere

Effects on the wavefront:

- On the ground, our perfect telescope produces stellar images 0.5–1 arcsec in diameter (seeing disk)
- Why? Wavefront gets distorted by variations in refractive index in atmosphere (c.f. crumpled piece of paper).
- 1 arcsec seeing disk at 500 nm implies $D = 13$ cm. Call this r_0.
- r_0 is (approximately) the typical size over which the wavefront is 'flat'. Note that 'flat' is measured relative to the wavelength, so $r_0 \propto \lambda$ (actually, $r_0 \propto \lambda^{6/5}$)
- To be precise, r_0 is the distance over which the rms wavefront variation is 1 radian.

The Earth’s atmosphere (cont.)

Variations with time:

- The wavefront shape changes, but the dominant effect is that the whole pattern blows past the telescope with windspeed v.
- The ‘coherence time’ τ_0 is (approximately) the time for the pattern to move sideways by distance r_0. For example:

  $v = 10$ m/s and $r_0 = 10$ cm gives $\tau_0 = 10$ ms.
- **High-resolution astronomy demands sampling faster than τ_0.**

Methods of overcoming the atmosphere for single telescope:

- Adaptive optics: correct wavefront in real time
- Fast imaging: rapid sampling of the image, followed by post-processing to extract high-resolution information ('speckle interferometry')

But we are still limited by the wave nature of light (Airy diffraction pattern).

To reach even higher resolution, we use interferometry:

- To make D very big, we combine light from separate telescopes.
- Do not get real images directly, but we do get information on spatial scales corresponding to λ/B (where B = baseline length).

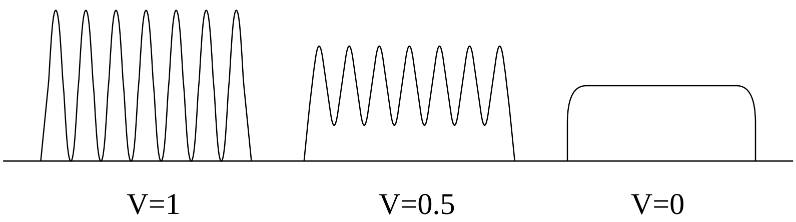
2. Basics of two-aperture interferometry

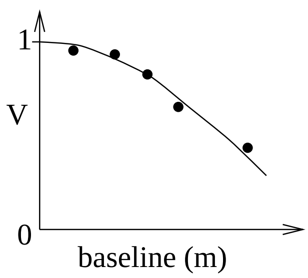
- Combining light from two separate apertures produces fringes (Young's double-slit experiment).

- The fringe visibility is defined as

$$V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}. \tag{2}$$

  Note that V measures the fringe contrast, and lies between zero (no fringes) and one (full contrast).





- The measured V is usually divided by V from a point source to calibrate atmospheric and instrumental effects.

- The calibrated fringe visibility contains information about the source: low V means the source is partially resolved.

- The reason is that each part of the source produces its own fringe pattern, but these all have slightly different phases and tend to wash out.

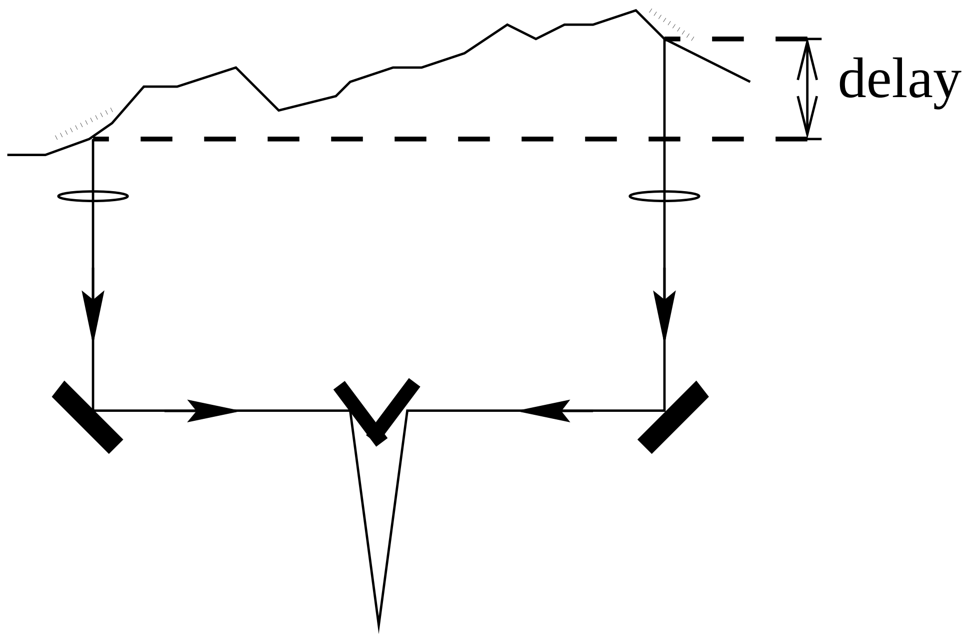
- To be precise, V measures the amplitude of the Fourier component of the source at the spatial frequency being sampled by the interferometer (B/λ).

- In other words, the visibility curve (V versus baseline) is the amplitude of the Fourier Transform of the source (the van Cittert–Zernike Theorem).

- The ‘phase’ of the fringes (can be thought of as the sideways position on the detector) contains information about the source (the Fourier phase), but the measurement is dominated by atmospheric fluctuations.

- To measure all spatial scales on the source, use various baselines plus Earth rotation to cover the so-called (u, v) plane.

- *Interferometers measure fringes!*
- To get good fringes:
  - the path lengths must be (nearly) equal.
  - the wavefronts must be (nearly) flat
  - the spectral resolution must be high enough
  - temporal sampling must be fast enough
  - the source must be (nearly) unresolved
- Main elements of an interferometer:
  - apertures
  - tip-tilt correction on each aperture (or higher-order adaptive optics)
  - delay line (with optional fringe tracking)
  - fringe detection and measurement


delay

3 Basics of multi-aperture interferometry

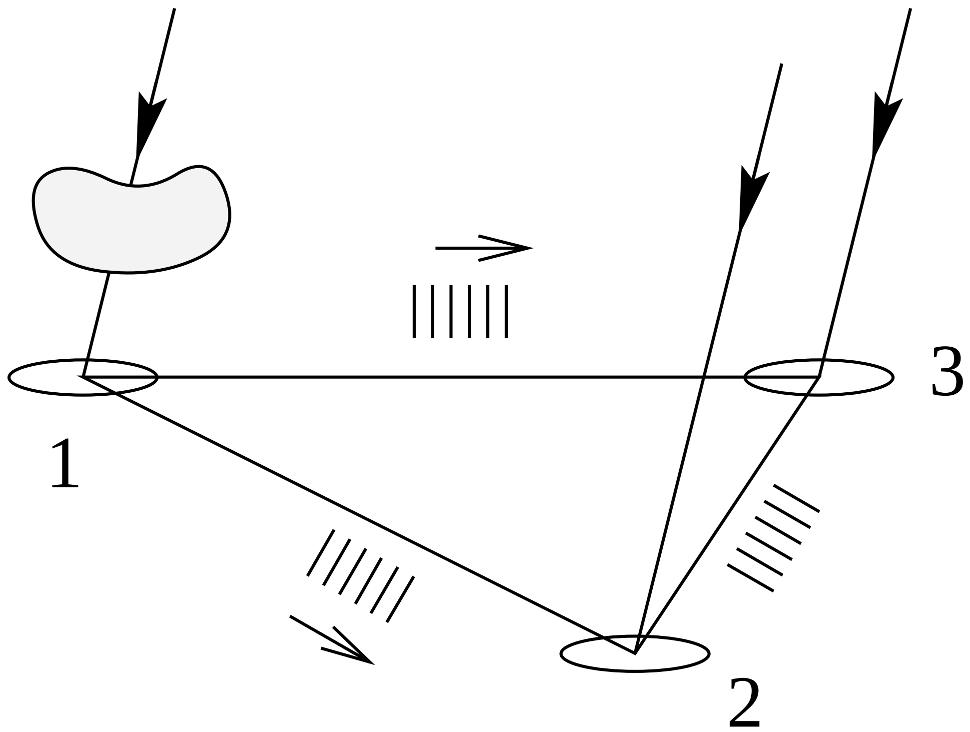
Why use more than two apertures?

- Faster coverage of different baselines (called (u, v) coverage). Several baselines can be measured simultaneously, and N apertures form $N(N-1)/2$ baselines.
- The ability to measure closure phases (see below).
- The possibility of baseline bootstrapping (see later).

Closure phases

How can we construct an image?

- Recall that fringe visibility (V) gives the amplitude of the Fourier transform of the source.
- To reconstruct an image using the inverse Fourier transform, we also need phases. In principle, the phase (position) of the fringes gives this information, but the measured phase is badly corrupted by the atmosphere.
- With three apertures, the three sets of fringes move due to the atmosphere, but their *relative* positions contain information about the source phase.



Closure phases (cont.)

- The algebraic sum $\phi_{12} + \phi_{23} + \phi_{31}$ is called the closure phase. It is completely unaffected by atmospheric fluctuations and therefore is a property of the source.
- For example, the closure phase of a symmetric source is always either 0° or 180°.
- By measuring closure phases of the source on various baseline triangles, we can use 'self-calibration' methods to reconstruct an image.

4. Summary of interferometer projects*

No longer operating (incomplete list):

- Intensity Interferometer (1964-1976)
- I2T (Interféromètre à 2 Télescopes; 1974–1987)
- Mark III (1986–1993)

Operating:

- GI2T (Grand Interféromètre à 2 Télescopes).
- SUSI (Sydney University Stellar Interferometer)
- COAST (Cambridge Optical Aperture Synthesis Telescope)
- ISI (Infrared Spatial Interferometer)
- FLUOR (Fiber Linked Unit for Optical Recombination)
- IOTA (Infrared-Optical Telescope Array)
- NPOI (Navy Prototype Optical Interferometer)

*`http://huey.jpl.nasa.gov/olbin/`

- PTI (Palomar Testbed Interferometer)
- CHARA (Center for High Angular Resolution Astronomy)

Under Construction:

- Keck Interferometer
- VLTI (Very Large Telescope Interferometer)
- LBT (Large Binocular Telescope)
- MIRA-II (Mitaka IR Array)

5. Main science targets for optical/IR interferometry

Visibility measurements and imaging:

- Stellar angular diameters and effective temperatures
- Binary star orbits
- Stellar surface structure
- Star formation and early stellar evolution
- Be stars (B stars with excretion disks)
- AGB stars (red giants)
- The Galactic Centre
- Active Galactic Nuclei

Narrow-angle astrometry (dual-feed interferometer):

- Parallaxes and proper motions
- Indirect detection of low mass stars, brown dwarfs and extra-solar planets
- Direct detection of brown dwarfs and ‘hot’ Jupiters (two-colour)

Nulling:

- Characterization of exo-zodiacal dust.
- Direct imaging of extra-solar planets (space missions)

6. Special topics

6.1 Thermal infrared

6.2 Wide-angle astrometry

6.3 Narrow-angle astrometry

6.4 Nulling

6.5 Adaptive optics and laser guide stars in interferometers

6.6 Space interferometry projects

6.1 Thermal infrared (5–20 μm):

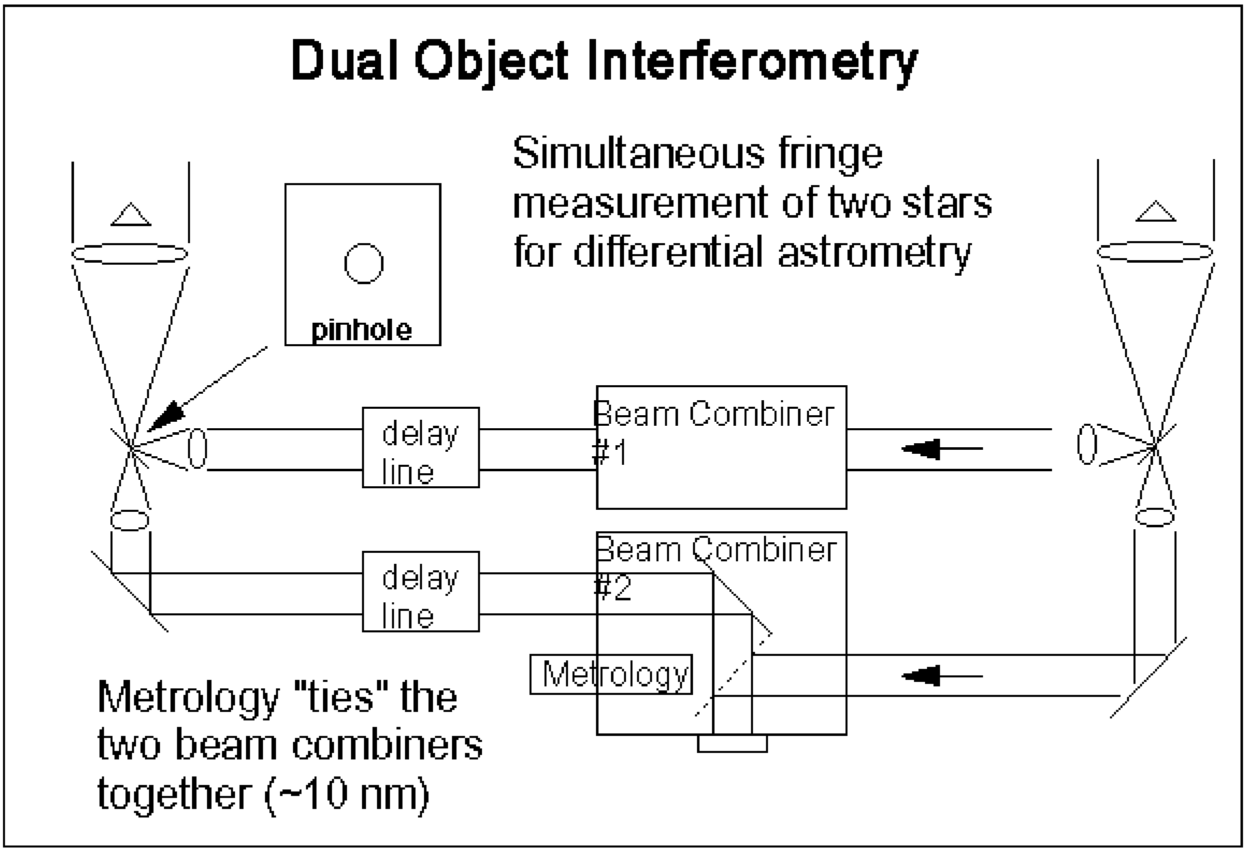
- The dominant noise source is thermal emission from the instrument and sky.
- So far, ISI has done heterodyne interferometry at 11 μm with two apertures.
- Signal-to-noise scales as D^2, so big telescopes have a huge advantage: VLTI (MIDI) will combine four 8-m telescopes; Keck will combine two 10-m telescopes.
- Science targets are: AGB stars; AGN; direct detection of brown dwarfs and hot Jupiters; exo-zodiacal light

6.2 Wide-angle astrometry:

- Done by Mark III (closed down), NPOI and SIM
- Aim is to maintain the Hipparcos reference frame
- Accuracy is 2 mas over large angles, but requires a very stable baseline (accurate laser metrology)

6.3 Narrow-angle astrometry:

- Requires a dual-feed system to observe two stars simultaneously, plus an extra delay line (PTI; VLTI/PRIMA; Keck).
- Use the differential delay to measure the phase difference between the two stars. This gives their separation on the sky to about 20 μarcsec.



A dual-feed system can also be used for phase-referenced interferometry:

- Measure the atmospheric delay on the brighter star, and use this to track fringes on the fainter star (‘co-phasing’).
- This allows extended coherent integration of fringes on the fainter star.

Another trick is two-colour phase-referenced interferometry:

- Observe one star at two wavelengths and use narrow-angle astrometry to measure the shift in photo-centre as a function of wavelength.
- This method will be used with the Keck Interferometer to detect hot Jupiters.

6.4 Nulling:

- Proposed by Bracewell (1979) as a means of detecting extrasolar planets
- Demonstrated with the MMT by Hinz et al. (1998).
- In SIM, the beam combiners will introduce an achromatic 180 phase shift in one of the interferometer arms by polarization inversion, thus eliminating the light from a point source that is located at the phase center.
- Science applications: direct detection of exo-planets; determining the spatial extent of stars, supernova shells, etc., by measuring the light leakage around the phase centre.

6.5 Adaptive optics and laser guide stars in interferometers:

- AO can be used to flatten the wavefront across individual apertures (e.g., big telescopes of VLTI and Keck).
- This AO correction can be helped by laser guide stars.
- A conventional laser guide star is too big for use as an interferometer reference source (about 1 arcsec).
- Two interfering laser beams would produce fine fringes on the sky. These could be used as an interferometer reference source. The interferometer could track fringes on the laser source, allowing long integration on a faint target.

6.6 Space interferometry projects

- Main difference from ground-based is the absence of atmosphere. Thus, r_0 and τ_0 become very large. There will still be slow variations from vibrations, etc.

- The NASA Origins Program (through the Jet Propulsion Laboratory) includes a series of space interferometers:
  - Space Technology 3 (ST3)
  - Space Interferometry Mission (SIM)
  - Terrestrial Planet Finder (TPF)
  - Planetary Imager (PI)

- There is an ESA proposal for 'InfraRed Space Interferometry Mission' DARWIN.