Lecture 1

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- Interferometry Measurements
- Scientific Motivation
- Optical vs. Radio Interferometry
- Fizeau and Michelson Interferometry
- Sensitivity
- Field-of-View
- Astrometry Limit
- Suppression Limit

Lecture 2

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  - Narrow-angle astrometry
  - Nulling
  - Image synthesis
  - Fizeau Imaging
- Michelson Interferometers
  - IOTA, PTI, GI2T
  - Keck and VLT
- Fizeau Interferometers
  - MMT
  - LBT
- The Future
  - 20-20
  - TPF

History of Astronomical Interferometry

- 1868 Fizeau first suggested stellar diameters could be measured interferometrically.
- Michelson independently develops stellar interferometry. He uses it to measure the satellites of Jupiter (1891) and Betelgeuse (1921).
- Further development not significant until the 1970s. Separated interferometers were developed as well as common-mount systems.
- Currently there are approximately 7 small-aperture optical interferometers, and three large aperture interferometers (Keck, VLT, and LBT).
Interferometry Measurements

Interferometers can be thought of in terms of the Young’s two slit setup. Light impinging on two apertures and subsequently imaged form an Airy disk of angular width $\lambda/D$ modulated by interference fringes of angular frequency $\lambda/B$. The contrast of these fringes is the key parameter for characterizing the brightness distribution (or “size”) of the light source. The fringe contrast is also called the visibility, given by

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

Visibility is also measured in practice by changing path-length and detecting the maximum and minimum value recorded.

Motivations for Interferometry

- **High Spatial Resolution**
  - Measure Stellar Diameters
  - Calibrate Cepheid distance scale
  - Size of Accretion Disks around Supermassive black holes (SBH)

- **Precise Position**
  - Detect stellar “wobble” due to planets
  - Track stellar orbits around SBHs

- **Stellar Suppression**
  - Detect zodiacal dust disks around stars
  - Direct detection of exosolar planets
Optical vs. Radio Interferometry

Radio interferometry functions in a fundamentally different way from optical interferometry.

Radio Telescope arrays are heterodyne, meaning incoming radiation is interfered with a local oscillator signal before detection. The signal can then be amplified and correlated with signals from other telescopes to extract visibility measurements.

Optical interferometers are homodyne, meaning incoming radiation is interfered only with light from other telescope. This requires transport of the light to a central station, without the benefit of being able to amplify the signal. However, homodyne interferometry allows large bandwidths to be used since the interfered light is detected directly.

(One heterodyne optical interferometer (ISI) has been built to operate at 10 microns. The technique is feasible but limited to bright sources.)

Types of Interferometers

Pupil-plane interferometry is used in long-baseline interferometry. Bracewell (1978) first suggested using this technique to null a stellar point source for detection of planets. This is the basis for NASA’s Terrestrial Planet Finder.

Imaging interferometry is more typically implemented on a common-mount interferometer. An imaging interferometer can be designed to create high resolution images over a wide field of view.
The Sine Condition

Properly designed imaging systems obey the sine condition for the relation of the object plane to the image plane. For imaging systems with the object at infinity the relation becomes

\[ \sin \alpha = \frac{h}{f} \]

where \( h \) is the height of the ray from the optical axis and \( f \) is the focal length of the system.

For interferometers, obeying this design constraint results in interference fringes for a source anywhere in the focal plane. For interferometers not obeying this constraint the field is much smaller.

Types of interferometers

Pupil-Plane

The Keck Interferometer is made up of two independent telescopes. Beam transfer optics and delay lines allow it to maintain equal path-length between the telescope as the object is tracked across the sky. Since the baseline pupil geometry changes no attempt is made to preserve the sine condition.

Image-Plane

The LBT is a single-mount structure resulting in a fixed entrance pupil. This allows straightforward implementation of wide-field imaging.
The atmosphere limits interferometer performance in several distinct ways. While adaptive optics is helpful in improving performance, atmospheric effects still define the limit for most measurements.

**Field of view:** Limited by isoplanatic patch for imaging interferometry

**Guide Star:** Coherence time requires guide star of $V \approx 13$.

**Astrometry**
Precision limited by anisoplanicity of beams.

**Nulling**
AO performance determines suppression level.
Field-of-View Limits

Pupil-Plane
For pupil plan combination, the phase difference between the two apertures depends on the sources position on the sky. So a source $\lambda/2B$ away from the main source would have $\frac{1}{2}$ wave phase difference from the main source. Once the source has introduced a phase difference equivalent to the coherence length, the source does not create fringes.

Path difference $\Phi = \frac{\theta}{\lambda} \text{ microns}$
FOV $\theta = \frac{\lambda}{B \Delta \lambda} \text{ radians}$

This is $\sim 0.03^\circ$ for Keck at 2.2 microns

Image-Plane
If the sine condition is preserved for image-plane interferometry the FOV is set by the parameters of the atmospheric correction. Stars within the isoplanatic patch will have similar atmospheric phase errors, allowing tracking of phase on a bright star in the field and measurement of fringe contrast for fainter stars anywhere within the isoplanatic patch.

$\theta = 0.31 \frac{r_0}{h}$

This is approximately 20" for 2.2 microns

Phase Tracking
For both types of interferometers the phase between the apertures must be sensed and corrected at a rate well above the coherence time of the atmosphere. This typically requires 500-1kHz rates for detection of the phase. If we assume phase sensing is done in K band (2.0-2.4 microns) an 8 m aperture receives ~150 photons from a K=15 star in 1 ms. Roughly, phase can be determined to a precision of

$\delta \kappa = \frac{\lambda}{B \sqrt{SNR}}$.

If we require knowledge of phase to 1/10 the fringe width we require an SNR~10 which is roughly what we have for a perfect detector in K band after 1 ms. In reality we probably lose a couple magnitudes to detector noise, and throughput losses. So we require a star similar in brightness to that needed for AO correction of the individual apertures.
Astrometric Measurements

Shao and Colavita (1992) analyze astrometric precision in the presence of turbulence. They derive that for measuring the position relative to a reference star, distance $\theta$ away, using an interferometer with baseline $B$

$$\delta r \propto \frac{\theta}{B^{\frac{1}{2}}}$$

- Want baseline as long as possible without resolving the star
- Need reference stars as close as possible
- Results in expected precisions of $10-30$ uas in an hour (capable of detecting planets down to the mass of Uranus for nearby stars)

Suppression Level

The suppression level for an interferometer used as a nulling instrument is governed largely by the performance of the adaptive optics system. Residual aberrations in the wavefronts causes some of the light to not interfere exactly out of phase. The level and distribution of this light can be estimated by estimating what the wavefront errors are in the presence of atmospheric turbulence and adaptive optics correction.
Fitting Error Contribution to Residual Intensity

Kolmogorov turbulence predicts an RMS phase variation of:

\[ \sigma_{fit} = \sqrt{2} \cdot 0.55 \left( \frac{\Delta x}{r_0} \right)^{5/6} \]

Residual Intensity (N) from these phase variations:

\[ N_{fit} = 1 - S_{fit} \left( \frac{\Delta x}{D} \right)^2 \]

For \( r_0 = 6 \) m, a spacing of 0.5 m gives \( N_{fit} = 1.8 \times 10^{-5} \)

LBT: 0.28 m actuator spacing, planned high resolution WFS

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Temporal Lag Contribution to Residual Intensity

Kolmogorov turbulence predicts an RMS phase variation of:

\[ \sigma_{time} = \sqrt{2} \cdot \left( \frac{\Delta t}{t_0} \right)^{5/6} \]

Residual Intensity (N) from these phase variations:

\[ N_{time} = 1 - S_{time} \left( \frac{r_0}{D} \right)^2 \]

For \( v = 10 \) m/s, and a lag of 2 ms, \( N_{time} = 4.2 \times 10^{-5} \)
LBT Status

- Telescope structure being assembled on Mt. Graham
- Both primaries are cast. LBT 1 has been polished in the Mirror Lab in Tucson, AZ.
- Telescope enclosure on Mt. Graham is complete.
- Second light planned for late 2005.

LBT Structure Acceptance in Italy, November 2000.

Strengths of the LBT Interferometer

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<th>Characteristic</th>
<th>Imaging Interferometry</th>
<th>Nulling Interferometry</th>
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<tr>
<td>Fixed-Pupil</td>
<td>Simple wide-field beam combination</td>
<td>Small number of reflections (low emissivity)</td>
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<tr>
<td>Modest Baseline</td>
<td>Complete uv-plane coverage</td>
<td>High suppression of starlight (stellar disk not resolved)</td>
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<tr>
<td>Deformable Secondary</td>
<td>Simple beam train</td>
<td>Keeps warm elements to a minimum.</td>
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<td>8.4 m apertures</td>
<td>Sensitive to faint objects</td>
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The LBTI on the Telescope

The Main Components

UBC = Universal Beam Combiner
NIL = Nulling Interferometer for the LBT
NOMIC = Nulling Optimized Mid-Infrared Camera

UBC, Fizeau Imager Platforms, NIL, NOMIC, LBTI on the telescope
UBC Design Requirements

UBC-Universal Beam Combiner

- Provide “perfect” imaging on-axis for minimum degradation of suppression
- Provide a reflective solution for 0.5-20 micron operation
- Provide capability to have a cold pupil stop for optimum IR sensitivity
- Maximize the combined field of view for wide-field operation
- Have design accommodate multiple cameras
- f/15 final envelope for convenient plate scale

The UBC Optical Design

- 40 arcsec field
- 3.8 m pupil image for cold baffling
- PZT mounted mirror for fast tip, tilt, and phase compensation
- Adjustable mirror for tip, tilt, and path adjustment
- Combined focal plane
- f/15 envelope, f/41.2
- Individual beams
UBC Optical Performance

Interferometric Performance analyzed by a custom ray trace code (developed by C. Peng)

- “Perfect” on-axis imaging
- Design delivers >80% Strehl over a 40” diameter field at 2.2 microns.
- Pupil image at fold mirror allows precise cold stops
- Design study determined this was the optimum three mirror design

LBTI Imaging Sensitivity

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<tr>
<th>Band</th>
<th>1 hour, 5σ detection limit µJy (mag.)</th>
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<tbody>
<tr>
<td>K (2.2 µm)</td>
<td>0.06 (25)</td>
</tr>
<tr>
<td>L' (3.8 µm)</td>
<td>1.7 (20.5)</td>
</tr>
<tr>
<td>M (4.8 µm)</td>
<td>18 (17.3)</td>
</tr>
<tr>
<td>N (10.6 µm)</td>
<td>70 (14.3)</td>
</tr>
<tr>
<td>K' (18.0 µm)</td>
<td>350</td>
</tr>
</tbody>
</table>

Sky Background
Telescope Background
LBTI Fizeau Imaging Capabilities

Fizeau imaging snapshot of Io

Reconstruction from three images formed at 60 degree intervals

resolution appropriate for I, J, & H bands

(simulation by Keith Hege)