The image brightness distribution of an object is related to its mutual coherence (or visibility) through an imaging system by the van-Cittert Zernike theorem. The essence of this theorem is that the brightness distribution of an object is related to its visibility by a Fourier transform.

\[
v(u, v) = \iiint \frac{I(l, m) e^{-2\pi i (ul + vm)}}{I(l, m) dl dm}
\]

The visibility is calculated for a given value of the baseline. The baseline is expressed in a coordinate system (u,v,w space) where the w-axis points at the source, the v-axis points towards the north and the u-axis points east.
To compare this complex number to the visibility as defined by Michelson we take the modulus of the complex visibility.

Relating Entrance Aperture to the PSF

Entrance Aperture/
Array Baseline

Fourier Transform

Convolution

Modulation Transfer Function/
UV-plane coverage

Multiplication

PSF/
Response Intensity

Response Amplitude

The van Cittert-Zernike theorem, applied to single aperture image formation yields the Airy pattern response for a point source.
Two Element Relation

For many interferometers $b \gg D$ so that the spatial frequencies measured within an aperture are much less than those measured between apertures. For this situation each element is treated as a point in the entrance aperture.

A four element non-redundant array

There are $n(n-1)/2$ points in the $u$-$v$ plane for an $n$ element interferometer.

For multiple element array the best choice of spacing is to create uniform sampling of the $u$-$v$ plane. The uniform sampling of spatial frequencies helps avoid degeneracies or aliasing in reconstructing an image.
LBT: an intermediate case

The LBT has a 14.4 m separation and 8.4 elements. Thus in the direction of the baseline all spatial frequencies are sampled from 0 to 22.8 m. This can be seen in the uv-plane coverage for the LBT.

Tracking a source with an interferometer

The baseline of an interferometer, as projected onto the u-v plane, is not fixed as the telescope tracks the object across the sky. For independently mounted telescopes both the baseline length and direction changes. For co-mounted (or co-moving) elements only the baseline orientation changes.

This change in baseline allows measurements over different spatial frequencies and directions, filling in the u-v plane for better image synthesis.

Animation of the LBT tracking a source at declination 20 degrees from hour angle -3 to +3
The LBT tracking a source at \( d = 20 \)

The LBT will not spend equal time at each orientation during observations. This will result in increased sidelobes in the final PSF compared to optimal sampling of the u-v plane.

The LBT tracking a source at \( d = 0 \)

At lower declinations the LBT will be unable to sample all orientations.
High Resolution Science Examples with LBTI

- High Resolution Imaging of Star/Planet Formation
  - Probe models of stellar/disk interaction and accretion
  - Protostellar companion frequency and mass
  - Protoplanetary disk structure and evolution
- Astrometry of Stellar Clusters
  - Constrain the existence of a central dark mass by precise measurements of orbits of the central stars
- Imaging of Galactic Centers
  - Kinematic determination of central mass
  - Extension of mass determination to distant galaxies
  - Search for binary supermassive black holes
- Galaxy Evolution at higher redshift
  - Formation of galactic bulges
  - Resolved studies of high redshift galaxies
- [Your idea here]

Tracking a source with separated elements

Separated-element interferometers trace out elliptical curves in the u-v plane as they track sources across the sky.

Animation of the Keck interferometer tracking a source at declination 20 degrees from hour angle -3 to +3
Spatial information for long baseline two-element interferometers is primarily in one direction.

At declination 0 the elliptical curves become straight lines in the u-v plane.
The VLT Interferometer

The European Southern Observatory has recently completed the Very Large Telescope project, with 4 large (8 m) telescopes and 3 smaller telescopes (1.8 m) capable of interferometry of various types and complexity.

VLTI u-v plane coverage

The uv-plane

This is the uv-plane:

Note: This is the uv-plane for an object at zenith. In general, the projected baselines have to be used.
VLTI u-v plane coverage

The uv-plane with the UTs

- uv coverage for object at -15°
- 8 hour observation with all UTs
- Resulting PSF is the Fourier transform of the visibilities
- \( \lambda = 2.2 \mu m \) (K-band)

Nulling: Why?
The fundamental limit to suppression for a perfect nulling interferometer is set by the size of the stellar disk, relative to the fringe spacing. The effect limits nulling to $2\times10^{-5}$ for typical stars at the LBT. This effect scales as the baseline squared.

Fizeau interferometry is well-suited for high spatial resolution studies, while pupil-plane interferometry is well-suited for suppression of starlight.
Nulling Measurements

Nulling interferometry measures the total flux transmitted by the interference pattern of the two elements, convolved with the PSF of a single element.

Subtlety 1: Chromaticity of Null

Fraction of light remaining in nulled output is given by

\[ N(\lambda) = \frac{1 + \cos(\Phi(\lambda))}{2} \]

where

\[ \Phi(\lambda) = \frac{\lambda}{4\lambda} + \frac{1}{4} \]

Level of suppression is good over only a narrow bandwidth.

Three fixes:
- Rotate one beam 180 degrees (Shao and Colavita)
- Send one beam through focus (Gay and Rabbia)
- Balance dispersion in air by dispersion in glass (Angel, Burge and Woolf)

Dispersion Compensation allows out-of-band light to be used to sense phase (Angel and Woolf 1997)
Subtlety 2: True Image Formation

In Bracewell’s original nulling concept (1978) the beams form images which are mirror versions of one another.

Rotation nulls create images which are rotated versions of one another.

It is only possible to create a true image of the field using dispersion compensation for the suppression and an interferometer which has an equal number of reflections in each beam.

First Telescope Demonstration of Nulling

Nulling at the MMT

For unresolved stars, destructive/constructive peak ratio = 0.94

For α Ori, peak ratio = 0.18

Residual flux is a direct thermal image of the extended dust nebula
Phase Compensation of the Null

Calculation of phase versus wavelength for a null introduced by path-length alone (solid line) and by path-length combined with an appropriate thickness of glass (ZnSe).

To achieve a good null over a wide bandpass glass compensation is necessary.

Beam-splitter Performance

The beam-"splitter" is the key component in a nulling interferometer, introducing the correct phase difference between the beams and mixing the light with equal intensity to create optimal suppression. Light at shorter wavelengths is used for sensing errors in phase.
The Bracewell Infrared Nulling Cryostat

Phase sensing at 2 microns
Laboratory Null

Constructive image  Scanning pathlength

0.5% of peak  2% of peak  White=5% of peak

Expected Sensitivity

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>MMT (µJy/√hour)</th>
<th>LBT (µJy/√hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-12.2 µm</td>
<td>660</td>
<td>45</td>
</tr>
<tr>
<td>M band</td>
<td>190</td>
<td>21</td>
</tr>
<tr>
<td>L' band</td>
<td>18</td>
<td>2.1</td>
</tr>
</tbody>
</table>
A Nulling Infrared survey of Extra-solar Systems for TPF (NIREST)

The LBTI is being built to survey nearby stars for direct evidence of exo-solar planetary systems. The survey is called the nulling infrared survey of exo-solar systems for TPF (NIREST, as in the nearest systems)

The LBTI NIREST survey will be an important scientific step in understanding what exists around potential candidate stars for the Terrestrial Planet Finder Mission (TPF). Do they have zodiacal dust disks? Gas giant planets?

- Zodiacal dust disks signal the existence of planetary systems and provide information about their placement.
- Giant planets, similar to Jupiter, dominate the dynamical environment of potential terrestrial planets. As such, their existence and placement in a planetary system are important for determining the habitability of a system.
- The sample size is set at 80 stars due to the need to understand what the zodiacal dust strength is for stars as a function of their spectral type and age.

![NIREST dust limits for stars at 10 pc](chart.png)

NIREST will dramatically improve our understanding of dust disks around stars with planetary systems.
Planet Limits at 3.8 µm

Future Interferometers
How do you preserve wide-field imaging interferometry in a non-comounded telescope?

Put them on a circular track.

The 20/20 telescope

21 m telescope design

Short focal length primaries are used for the individual 21 m telescopes. The resulting compact structure minimizes wind buffeting, simplifies control of track motion and reduces enclosure cost.
Mechanical design similar to LBT

A preliminary design for the steel supporting structure has been made by Warren Davison. It is based on the LBT structure, an alt-azimuth concept pioneered by Davison in which the optical assembly is supported by two large diameter (14 m) wheels that turn on hydrostatic bearings to provide the elevation motion. The azimuth motion is provided by a simple, squat carriage that transmits the load from the rings directly to a 14 m diameter azimuth track.

The two LBT 8.4 m mirrors and their cells, which include flotation support and thermal systems, weigh 100 tons; the entire moving mass including all other optics and instruments is 400 tons. The optical assembly of a 20/20 telescope will be similarly supported by two elevation wheels, in fact the same 14 m diameter suffices.

20-20 is optimized for low scattered light

The 21 m primary mirror will be made from just seven large segments, so as to minimize contrast-reducing scatter from gaps and phase steps at mirror boundaries. There will be a central hexagonal segment surrounded by six petals. In this way we can take advantage of the established technology developed at the Mirror Lab for the 6.5 m Magellan and MMT mirrors, and the two 8.4 m LBT mirrors. These mirrors are of honeycomb sandwich construction, nearly a meter thick and extremely stiff. They also are ventilated for short thermal time constant, in order to eliminate mirror seeing. The supports and thermal stabilization will be essentially identical to those in the LBT.

The secondary mirror will be adaptive, made as seven segments as a slightly undersized 1/10 scale model of the primary.
Enclosures and beam combining station

The cryogenic beam-combiner moves in sync. with the two telescopes, holding a position midway between. We show it in brown mounted on a 50 m radial beam, shown in blue.

The telescope enclosures could be moved on a separate track, as shown, or they could remain fixed with the telescopes operating in the open or with separately driven wind shields.

20/20 compared to the Celt 30m and the LBT

The CELT design is as currently shown of the web. It shows the C-ring support pioneered by the LBT, and also adopted in the 20/20 design.
nulling interferometry sensitivity of 20/20 to extra-solar planets

<table>
<thead>
<tr>
<th>Telescope Parameters</th>
<th>Integration time:</th>
<th>Bandwidth</th>
<th>Sky</th>
<th>Flux leak, sun @ 10 pc</th>
<th>5σ limit (dominated by telescope emission)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope separation</td>
<td>21 m</td>
<td></td>
<td></td>
<td></td>
<td>2 hrs</td>
</tr>
<tr>
<td>Telescope diameter</td>
<td>20 m</td>
<td></td>
<td></td>
<td></td>
<td>8-13 microns</td>
</tr>
<tr>
<td>Temp. of Telescope</td>
<td>0 deg C</td>
<td></td>
<td></td>
<td></td>
<td>0.75 mag/arcsec</td>
</tr>
<tr>
<td>Emissivity of Optics</td>
<td>5%</td>
<td></td>
<td></td>
<td></td>
<td>29 µJy</td>
</tr>
<tr>
<td>Throughput of Instrument</td>
<td>80%</td>
<td></td>
<td></td>
<td></td>
<td>3.1 µJy</td>
</tr>
</tbody>
</table>

The short, 21 m baseline allows strong suppression (~20,000 for sun’s disc @ 10 pc) while still being sensitive to planets as close as 0.5 AU from their star. 20/20’s sensitivity will be an order of magnitude better than the LBT, opening up two exciting areas of planet detection: searching for Earths around the nearest several stars, and spectroscopy of gas giant exo-planets.

Earth-like planets would be detectable around the 3-4 nearby solar type stars at ~3 au, as bright as 4 µJy and appearing at 0.3 arcsec separation.

The detectability of Jupiter-like planets in wide orbits is a strong function of their age. A 3 µJy survey would allow detection of a 1 Gyr old Jupiter mass planet out to 30 pc.

Fizeau interferometry

High resolution from multiple images at different baselines

The lower figures show examples of images of the target top left that would be recorded at the combined focus, for different baseline lengths and orientations.

20/20 images equivalent to 120 m filled aperture are shown at upper right, a reconstruction from 20 images with baselines up to 100 m, made by Keith Hege. For imaging in the 2.2 µm K band, the image shown would correspond to a field of 1 arcsec. The actual field at 2.2 µm would be ~30 arcsec, 1000 times larger area.

For fixed 32 m baseline, just three exposures at 60 degree orientations will yield elongated images from which an image with the resolution of a 50 m filled aperture can be reconstructed.
Nulling Interferometry: Space-based
Why from space?

Space-based telescope gives >10^6 reduction in background light. => Collecting area can be <10^{-3} of ground based system.

Why an interferometer?

- Need resolution < 0.1 arcsec to spatially resolve a planetary system. (10 m at 10 µm)
- Only need a couple of meters^2 collecting area for cooled space-based system to get detectable flux from planet (1 photon/s/micron, in the presence of 100 photons/s of background).

Why more than two elements?

- Multiple nulling pairs provide flexible modulation of the signal, suppression of exo-solar zodiacal emission and a broader null over the star, if needed.

Why in the thermal infrared?

- The contrast between an exo-earth and star is much more favorable than in the visible. The thermal infrared also has suitable spectral absorption lines for investigating whether a planet has an atmosphere (CO_2 at 15 microns), is habitable (H_2O at 8 microns) and has signs of life (O_3 at 10 microns).
TPF Transmission Pattern

Interferometer rotates about its pointing center to rotate the beam pattern about the star.

Planet Signals are modulated by rotation.

Detected Signal is the sum of all the light transmitted through the beam pattern.

Signal from an Earth-like Planet

Detected signal in TPF beam-combiner.
Signal from a system of planets

Signal of Earth, Venus and Jupiter.

Reconstruction of the Image

- Intensity of a given position is the sum of the signal as a function of rotation times the beam pattern transmission for that rotation.
- Raw image shows the prominent sources plus artifacts.
- Algorithm similar to CLEAN can be used to form a higher fidelity image.
- Image for each channel of the instrument spectrometer gives a spectrum for each point source.
Extracting the Spectra

- Each wavelength channel allows a similar image reconstruction, and a measurement of the flux in that channel. The spectrometer will have a resolution of $R=20$. 

![Graph showing flux vs. wavelength](image)

Which planet does it resemble (if any)?

![Graph showing brightness temperature vs. wavelength](image)
Telescope Nulling (no AO)
First demonstration of telescope nulling

Lab demonstration of high precision infrared nulling

Telescope demonstration of high precision infrared nulling

Development of cryogenic nulling interferometer (BLINC)

Telescope use of BLINC to detect protoplanetary disks

First prototype nulling interferometer

Closed loop 2 micron control of null

Nulling interferometry with the LBT

Lab demonstration of nulling with LBTI

Development of the LBTI

- complete
- current work
- to be accomplished

NIREST planet limits for stars at 10 pc

Flux models for objects at 10 pc from Burrows et al. 1997

GJ 229B

LBTI sensitivity limit

NI REST will also be sensitive to young giant planets in these systems.

mass (M_J)

11 µm flux (mJy)

0.01 0.1 1

0 5 10 15 20 25 30 35 40 45 50

flux of 0.5 Gyr old planet

1 Gyr

5 Gyr

NIREST will also be sensitive to young giant planets in these systems.