Nulling Interferometry

A technique for blocking the light of a bright source in order to reveal a faint source near it

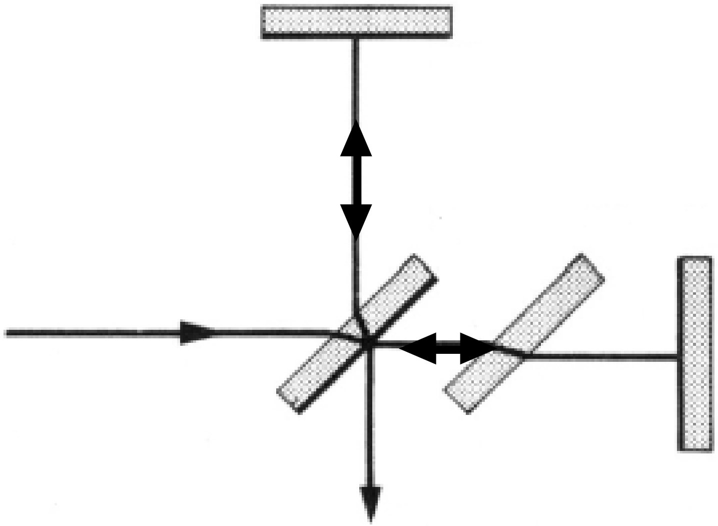
Purpose is similar to that of a coronagraph

Coronagraph: uses a physical mask to block the bright source

Nulling interferometer: uses destructive interference between two coherent beams

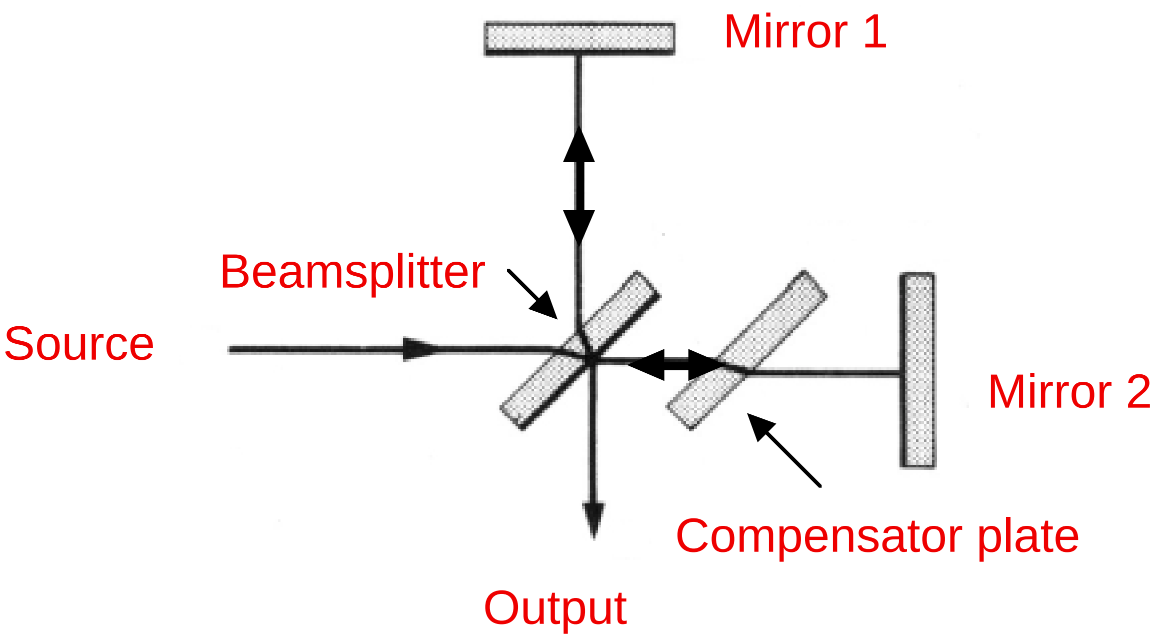
But see: "Phase Knife Coronagraph" (A&A, 400, 385) — uses destructive interference, but I hesitate to call it an interferometer

Background: the Michelson interferometer



After Rossi, *Optics* (1959, Addison-Wesley), p. 144

Background: the Michelson interferometer



When the optical path length in the two arms is identical, maximum output.

Off-axis rays traverse different optical path lengths in the two arms.

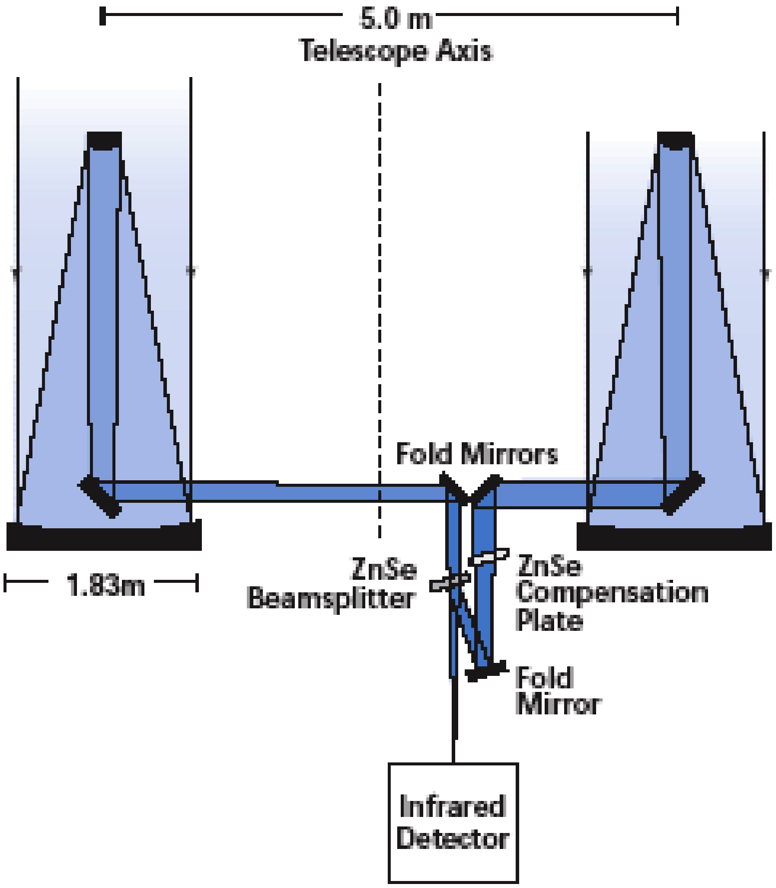
If you look into the output beam at zero path difference, you'll see circular interference fringes with a bright point at the center.

To make a nulling interferometer, just make the bright center dark by adding a half wavelength optical path to the compensator plate.

A basic nulling interferometer for infrared

(Hinz et al. 1998)

Half-wave phase shift achieved by tilting compensator; fine adjustment by moving beamsplitter, watching for null



The telescopes were two elements of the old Multiple Miror Telescope (now dismantled).

Operation is at $\lambda = 10\mu$m

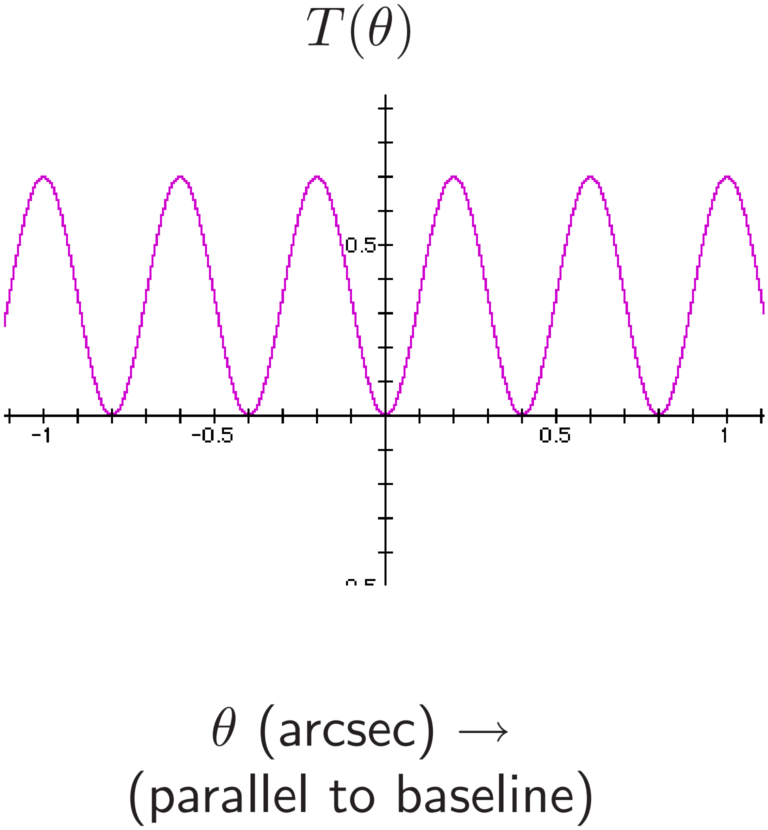
In practice, path length difference varies $\pm 5\mu$m with seeing

Take many short exposures, select those with best null

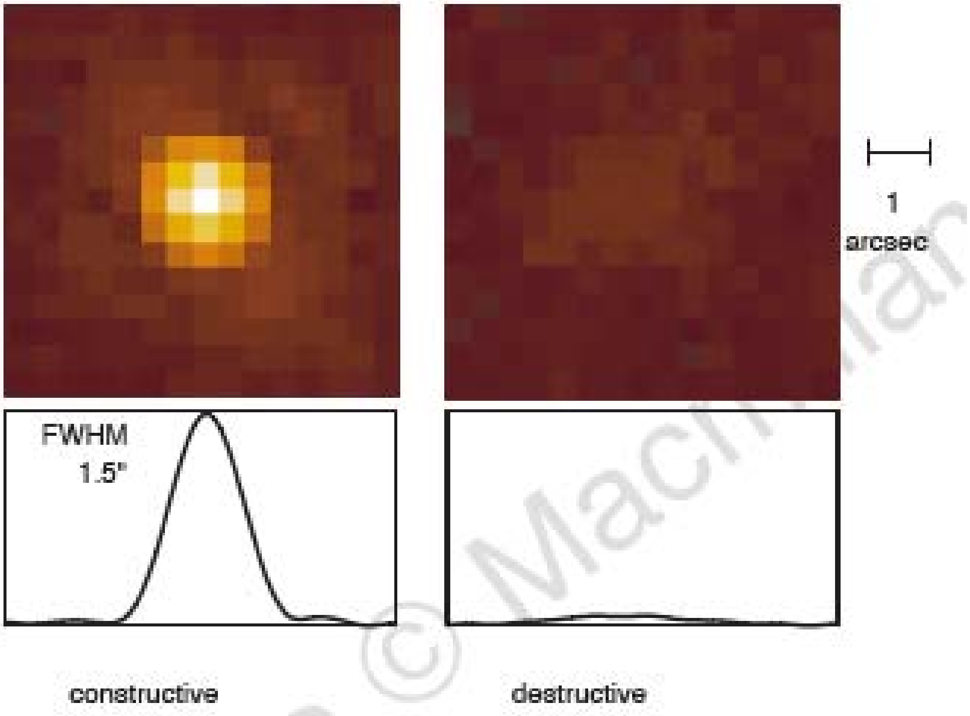
Transmission for monochromatic light

$$T(\theta) = \sin^2 \frac{\pi\theta d}{\lambda}$$

where d is the separation between the telescope mirrors



But the fringes are blurred by diffraction and seeing and are not visible in images. Nulling on α Tau:

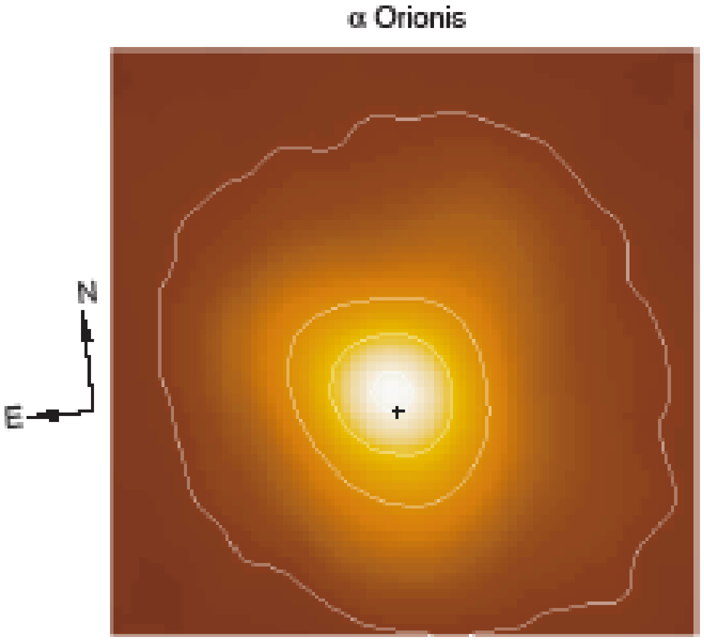


Integrated flux in nulled image is about 6% of that in constructive image.

Image of dust cloud around α Ori

- Fully resolved, FWHM 2.4 arcsec
- Definitely asymmetric

Nulled image of α Ori



Contours are at 1%,10% and 20% of the non-interfered stellar peak intensity, $+$ marks the star.

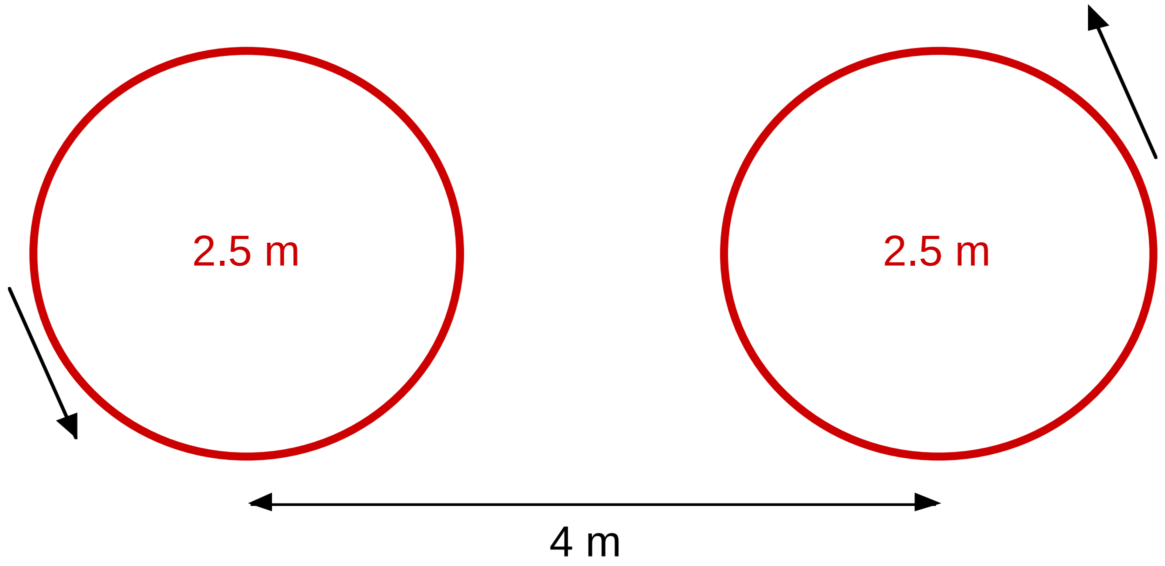
The next generation

Nulling interferometry is defined as achieving destructive interference between “the pupils of two telescopes or the subapertures of a single telescope” for a star on the optical axis (Hinz et al. 2001)

On the newer 6.5-m Multiple Mirror Telescope (now a single mirror), the Bracewell Infrared Nulling Cryostat (BLINC)

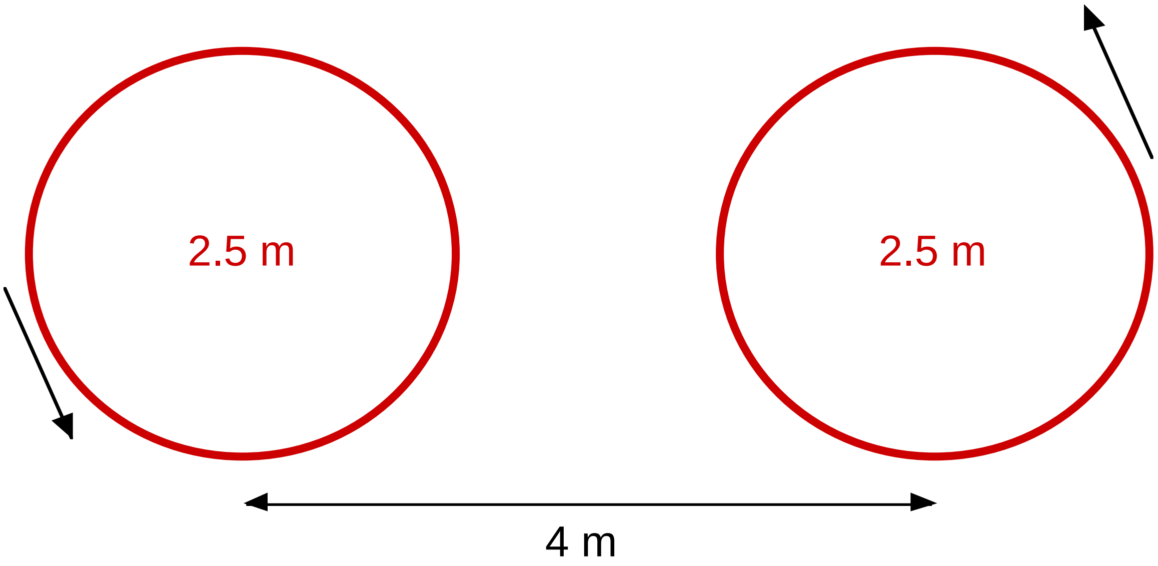
Divides the pupil of the telescope into two halves and overlaps them on a 50% transmissive beam splitter

Defines two 2.5-m apertures with centers 4 m apart; fringe period 0.544 arcsec



Map focal plane by rotating telescope

Defines two 2.5-m apertures with centers 4 m apart; fringe period 0.544 arcsec



Map focal plane by rotating telescope

Telescope is alt-azimuth; image rotates as telescope tracks.

Observations at 10μm of three Herbig Ae/Be stars:
HD 150193, HD 163296, HD 179218
Fringe patterns do not differ from those of point sources

Constrains thermally emitting circumstellar dust disks to less than 20 AU diameter (90% of 10-μm flux)

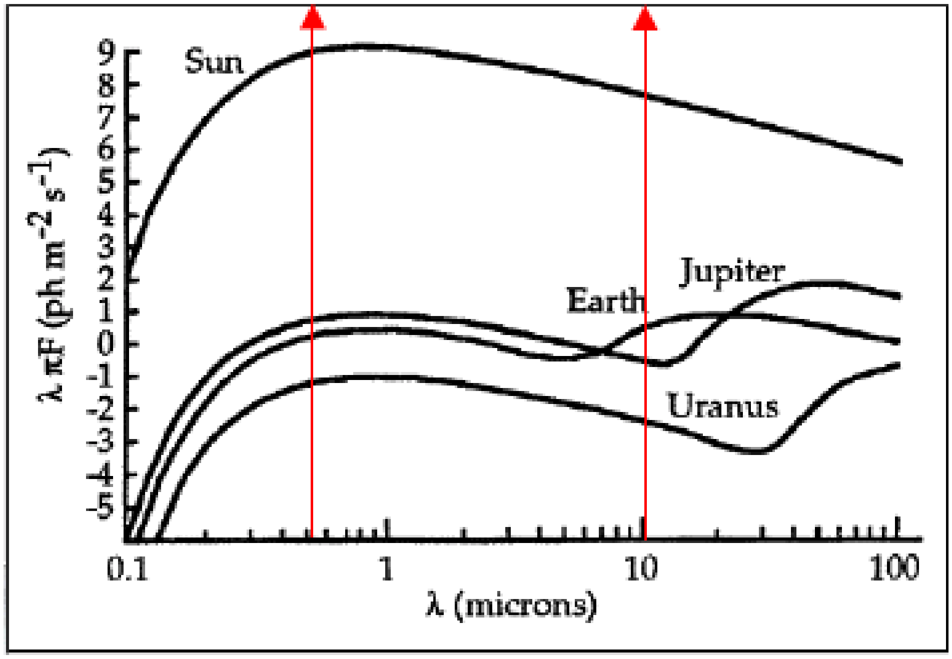
But disk of HD 163296 previously observed in visible (scattered) light to have diameter of 100 AU

Result contradicts standard dust disk models

Precision nulling not achieved; requires adaptive optics.

Goal: find extrasolar terrestrial planets

Requires starlight rejection factor of 10^6 at 10μm



(Creech-Eakman 2002)

Requirement relaxes to longer wavelengths; ∼20,000 at 20μm

For a 3.5-m telescope:

Error source	Requirement
Optical path errors	$<$ 70 nm
Transmission asymmetries between beams	$<$ 1.4%
Pointing jitter	$<$ 75 mas
Differential polarization rotation	$< 0.7^{\circ}$
Differential polarization phase delay	$< 1.4^{\circ}$

From the TPF Book, chapter 10

Approaches to precision nulling interferometry: Rotational shearing interferometer (Wallace, Hardy, and Serabyn, 2000)

Will omit details of instrument; similar to what follows

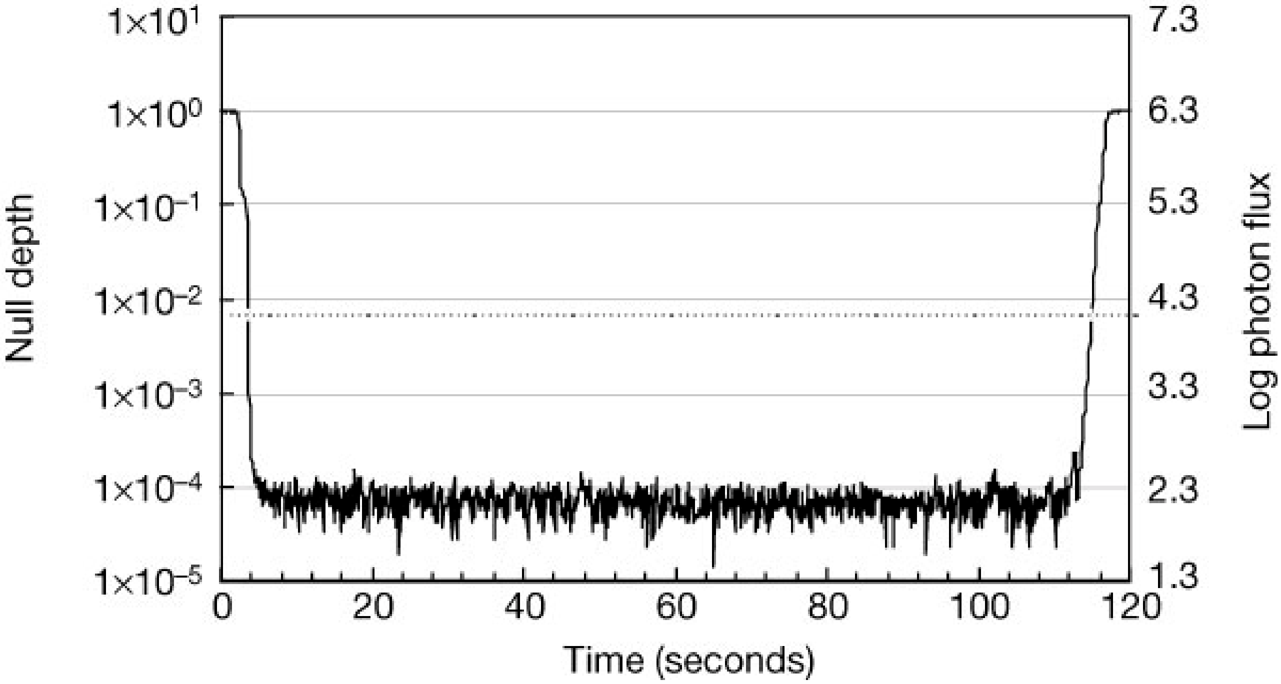
Main features

- Phase inversion is achromatic (geometrical design)
- Beamsplitter is used in double pass; provides symmetry between interferometer arms
- Output beam passes through optical fiber so only core of output point spread function detected

Lab demonstration

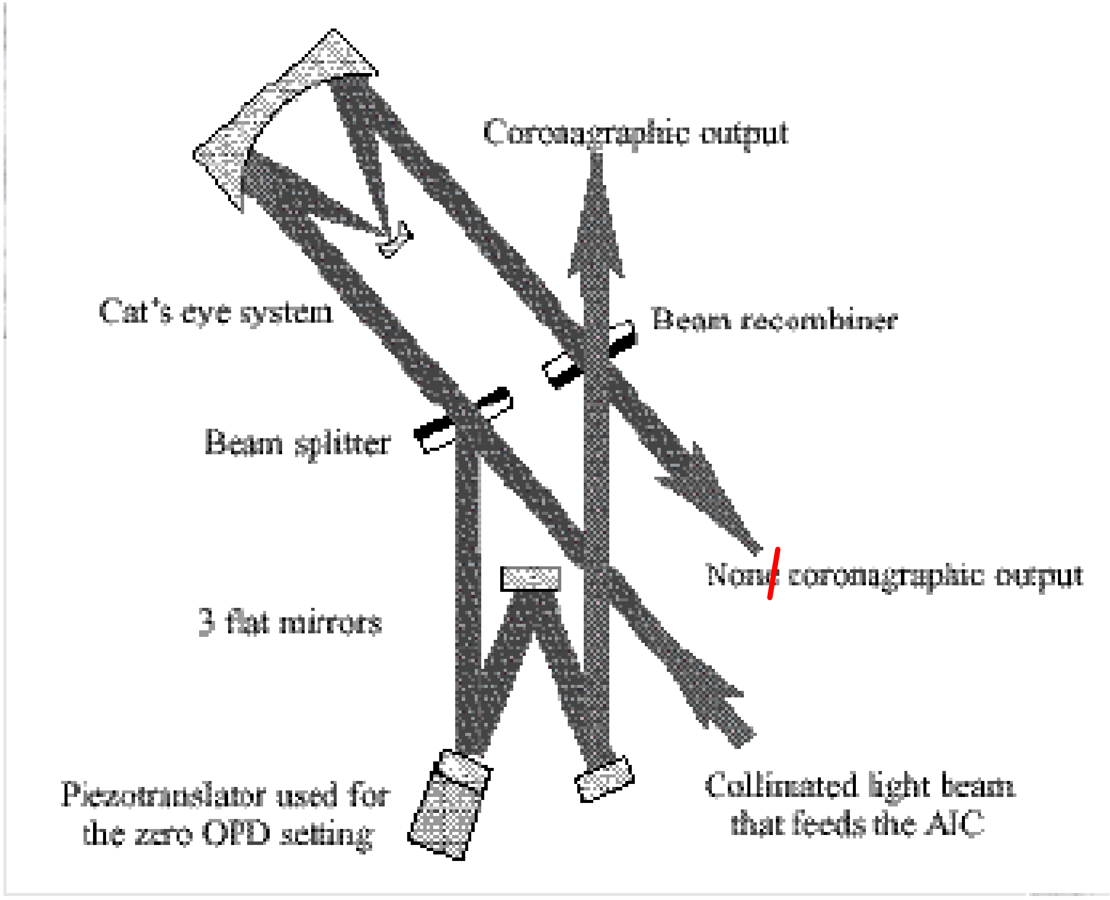
- Light source linearly polarized, 590 to 710 nm
- Highly stable instrument mount
- Active control of path length

Nuller output intensity under active path control



Approaches to precision nulling interferometry: Achromatic interfero coronagraphy (Baudoz et al. 2000)

- Reflection from cat's eye mirror introduces achromatic half-wave phase shift ($n_2 > n_1$)
- Beamsplitters are ~~aer~~ symmetric
- Off-axis source yields double image
- Tested at telescope (OHP 1.8-m) with adaptive optics
- Best nulls 5–10%


Coronagraphic output
Cat's eye system
Beam recombiner
Beam splitter
None coronagraphic output
3 flat mirrors
Piezotranslator used for
the zero OPD setting
Collimated light beam
that feeds the AIC

Approaches to precision nulling interferometry: Fully symmetric beam combiners (Serabyn and Colavita 2001)

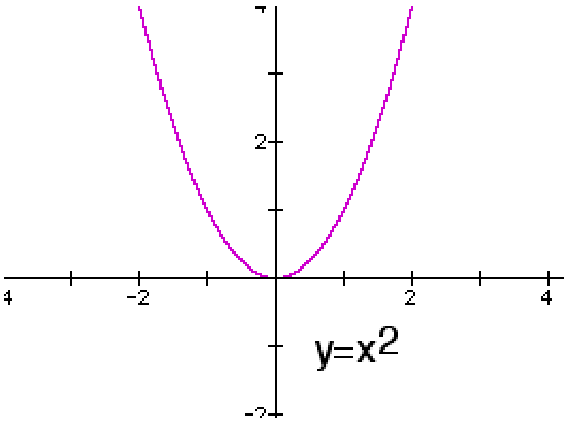
To be used in mid-IR on Keck interferometer

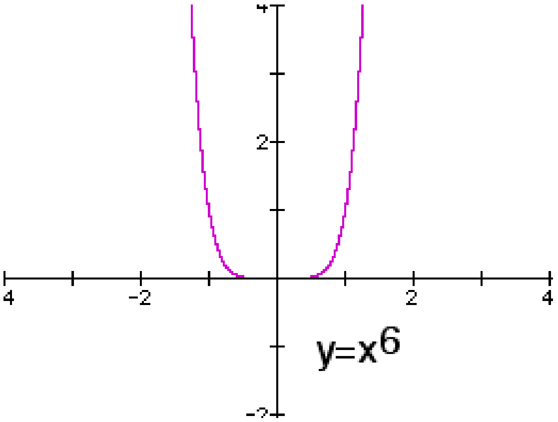
Input phase flipping is by reflection, completely achromatic; each “periscope” has two right-angle reflections, one “upside down” with respect to the other.

Interferometer uses Mach-Zehnder concept, which has two beamsplitters and is more symmetrical than the Michelson.

Approaches to precision nulling interferometry: larger arrays (Mieremet and Braat 2003)

For N input apertures, $T \propto \theta^{2(N-1)}$. Therefore, the central minimum is broader, the larger N is.





References

- Hinz, P. M., et al. 1998, *Nature*, 395, 251, "Imaging circumstellar environments with a nulling interferometer"
- Hinz, P. M., Hoffmann, W. F., and Hora, J. L. 2001, *Ap. J.*, 561, L131, "Constraints on Disk Sizes around Young Intermediate-Mass Stars: Nulling Interferometric Observations of Herbig Ae Objects"
- Serabyn, E. and Colavita, M. M. 2001, *Appl. Opt.*, 40, 1668, "Fully symmetric nulling beam combiners"

- Wallace, K., Hardy, G., and Serabyn, E. 2000, *Nature*, 406, 700, "Deep and stable interferometric nulling of broadband light with implications for observing planets around nearby stars"
- Baudoz, P. et al. 2000, *A&A Suppl. Ser.*, 145, 341, "Achromatic interfero coronagraphy"

Useful review: Mieremet, A. L. and Braat, J. J. M. 2003, *Appl. Opt.*, 42, 1867, "Deep nulling by means of multiple-beam recombination"

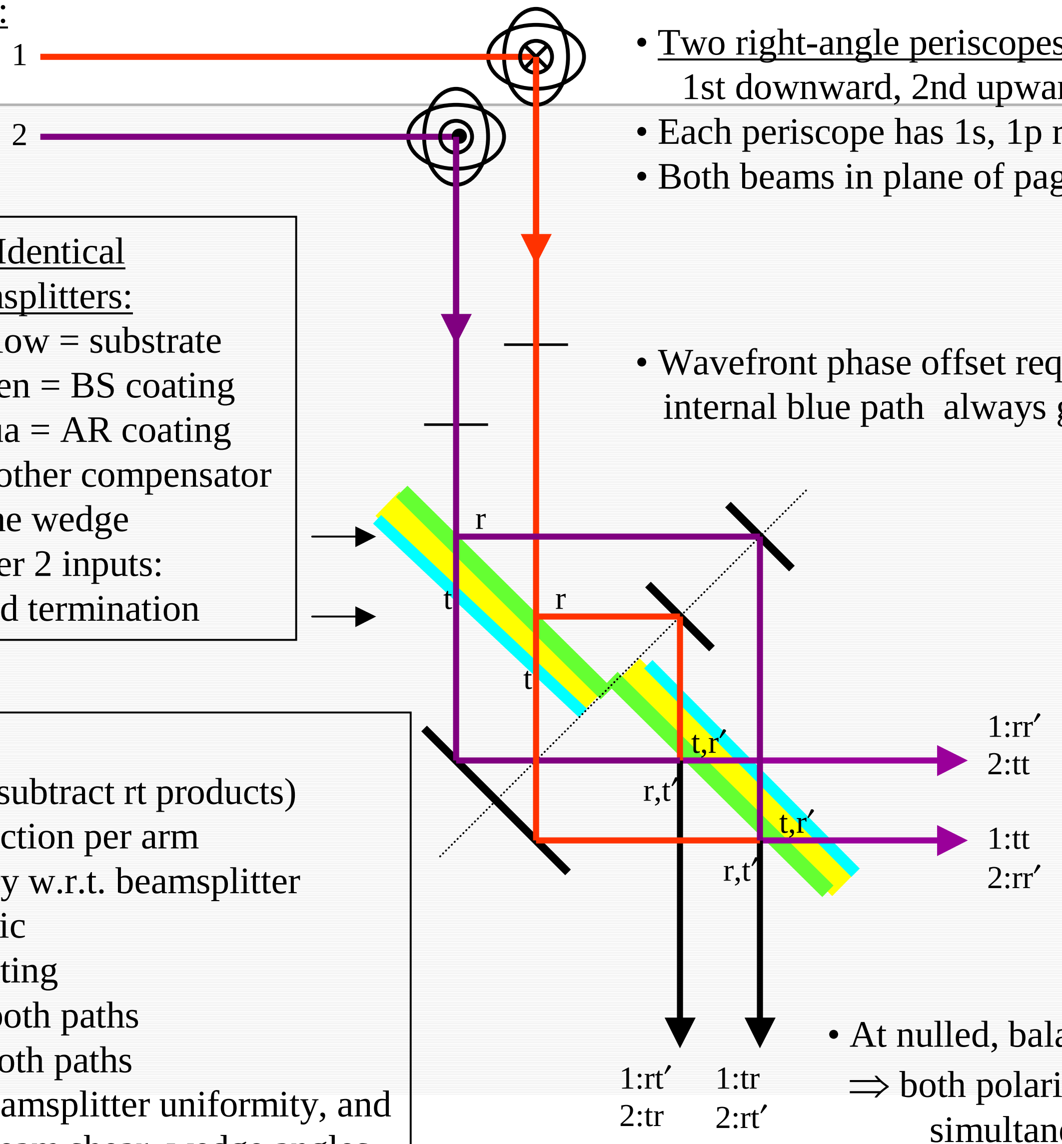
Web pages:

- Terrestrial Planet Finder Book Chapter 10
- Review presentation by M.J. Creech-Eakman (Jet Propulsion Laboratory) at the 2002 Michelson Interferometry Summer School, Smithsonian Astrophysical Observatory, Cambridge, Massachusetts June 24–28, 2002

New Nulling Configuration:

Field-flip prior to beam combiner, followed by modified Mach-Zehnder interferometer

Non-coplanar inputs:
1st input beam
above page,
2nd input below



- Two right-angle periscopes perform field-flip:
  1st downward, 2nd upward
- Each periscope has 1s, 1p reflection
- Both beams in plane of page after periscopes

- Wavefront phase offset required at input:
  internal blue path always greater by offset shown

Two Identical Beamsplitters:
- Yellow = substrate
- Green = BS coating
- Aqua = AR coating
- No other compensator
- Same wedge
- Other 2 inputs:
  cold termination

- Bright (unbalanced) outputs: t^2+rr'

Nulling Outputs:
- Balanced outputs (subtract rt products)
- Only 1 mirror reflection per arm
- Complete symmetry w.r.t. beamsplitter
- 1 pass thru dielectric
- 1 pass thru AR coating
- Common r, Φ_r in both paths
- Common t, Φ_t in both paths
- Limited only by beamsplitter uniformity, and alignment issues: beam shear, wedge angles

- At nulled, balanced outputs, $r(t - t') = 0$
  $\Rightarrow$ both polarizations can be nulled simultaneously at any AOI