Mid-Infrared Nulling at the Keck Interferometer: How and Why

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Overview

Why build a nuller for the Keck Interferometer?

Scientific Objectives
Technological Rationale

How do we make it work?

Four-beam combination
Fringe Tracking in the Near-IR
Dispersion Control
Modulation and Detection
Spectral Dispersion
Infrared Camera

Anticipated Performance

Minimum Target brightness in the V, J, K, and N bands
Leakage Signal and Photospheric Size

Current Status

The “Why:” Science Goals

NASA Origins Program

- Terrestrial Planet Finder
  - Precursor Science: **Search for Exozodiacal Dust Disks**
  - Technology Development: Nulling Interferometry in the Mid-IR

General Science Instrument

- Disks around T Tauri and Herbig Ae/Be Stars
  - *Angular Size of Disks' Mid-IR Emitting Regions*
  - *Direct testing of disk thermal structure models*
  - ***This is the thrust of the first shared-risk science project***
- Timescales for the dissipation of pre-main sequence disks
  - *Do Young Solar Analogs retain detectable circumstellar dust?*
  - *Indirect evidence for the existence of planetary systems*
- Active Galactic Nuclei
  - *Origin of the infrared emission*
- Evolved Stars and Dusty Envelopes

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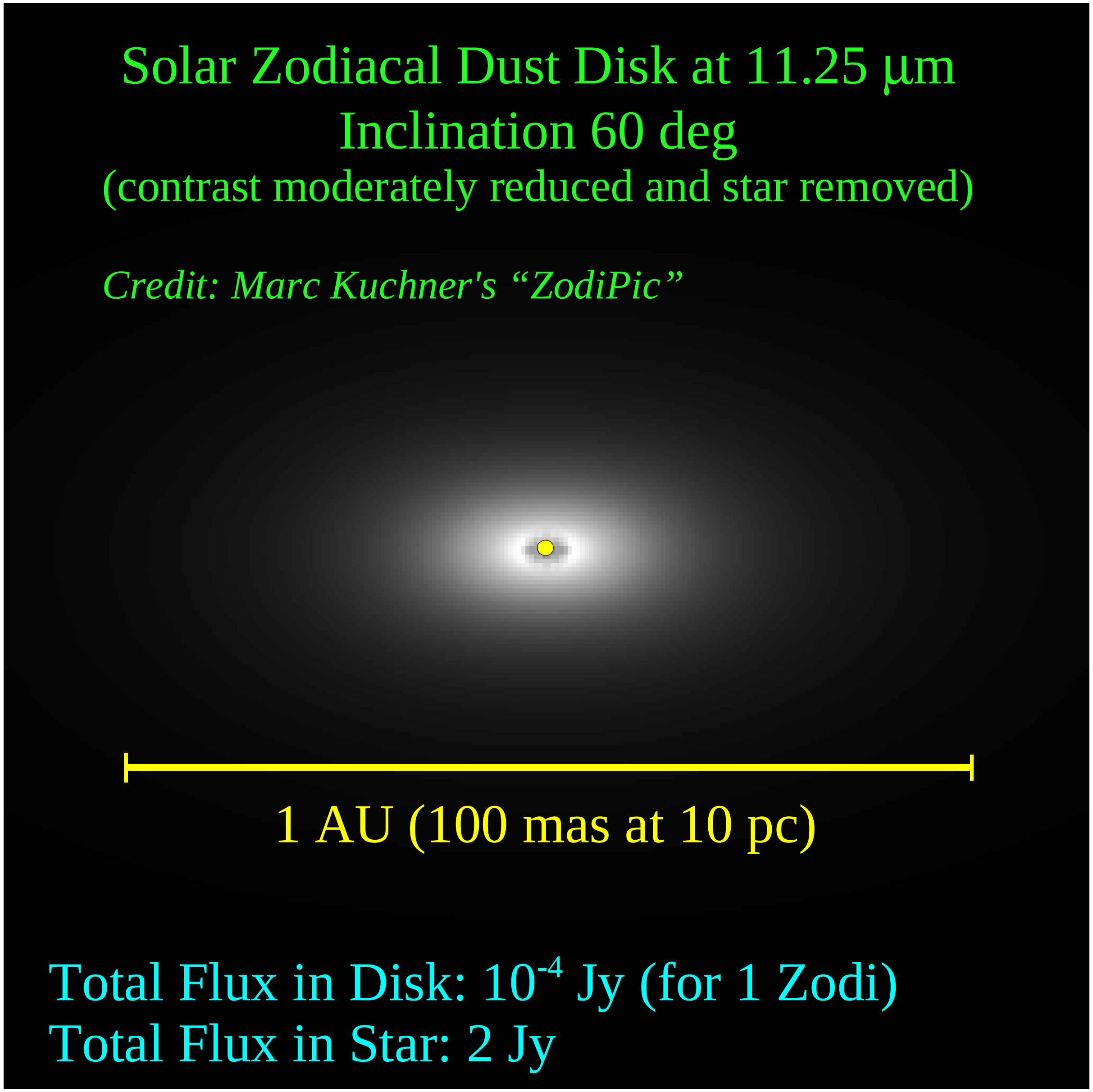
Properties of the Zodiacal Dust Cloud



In the absence of starlight, can reach SNR=1 on the 1-Zodi disk in ~50 hr with Keck/LWS

(3-sigma on a 10-Zodi disk in 5 hours)

Starlight is ~2 x10^{3} times brighter than the 10-Zodi disk

Disk-Star angular scale ~25 mas

=> *Very high contrast and angular resolution are needed, but current flux sensitivity is adequate*

NASA Origins Science Goal

Measure or put limits on emission from exozodiacal dust around a sample of nearby Solar-type stars

Preparation for Terrestrial Planet Finder (TPF)

- Dust disks may be very bright and could hamper planet detection
  - Solar-type Main Sequence stars
    - $10 < D_{pc} < 20$
    - $\theta_{phot} \sim 1$ mas (angular diameter of photosphere)
    - $\theta_{exozodi} \sim 20$ mas (angular FWHM diameter of Zodi disk)
      - *Strongly centrally concentrated with broad wings*
    - Stellar Magnitudes: V~6, K~4, N~4
    - Sensitivity Requirement: 10 x Solar Zodi emission

Also: Develop and demonstrate the technology, observing, and data-reduction techniques needed for mid-infrared nulling science.

The "How": Nulling Interferometry

Interferometry produces the required high angular resolution

- λ/D for 10 μm is 200 mas for a 10 m telescope
  - => *Unable to spatially separate the disk from the star*
  - => *Disk detection limited by precision of photometry and photospheric model*
- λ/B for 10 μm is 24 mas for a 85 m baseline
  - *Non-negligible angular size of star compared to fringe spacing limits null contrast to ~1000*

Careful choice of aperture configuration to give a useful beam pattern

- *Suppress the starlight while transmitting the disk light*
- *Interferometrically "chop" to subtract the thermal background*

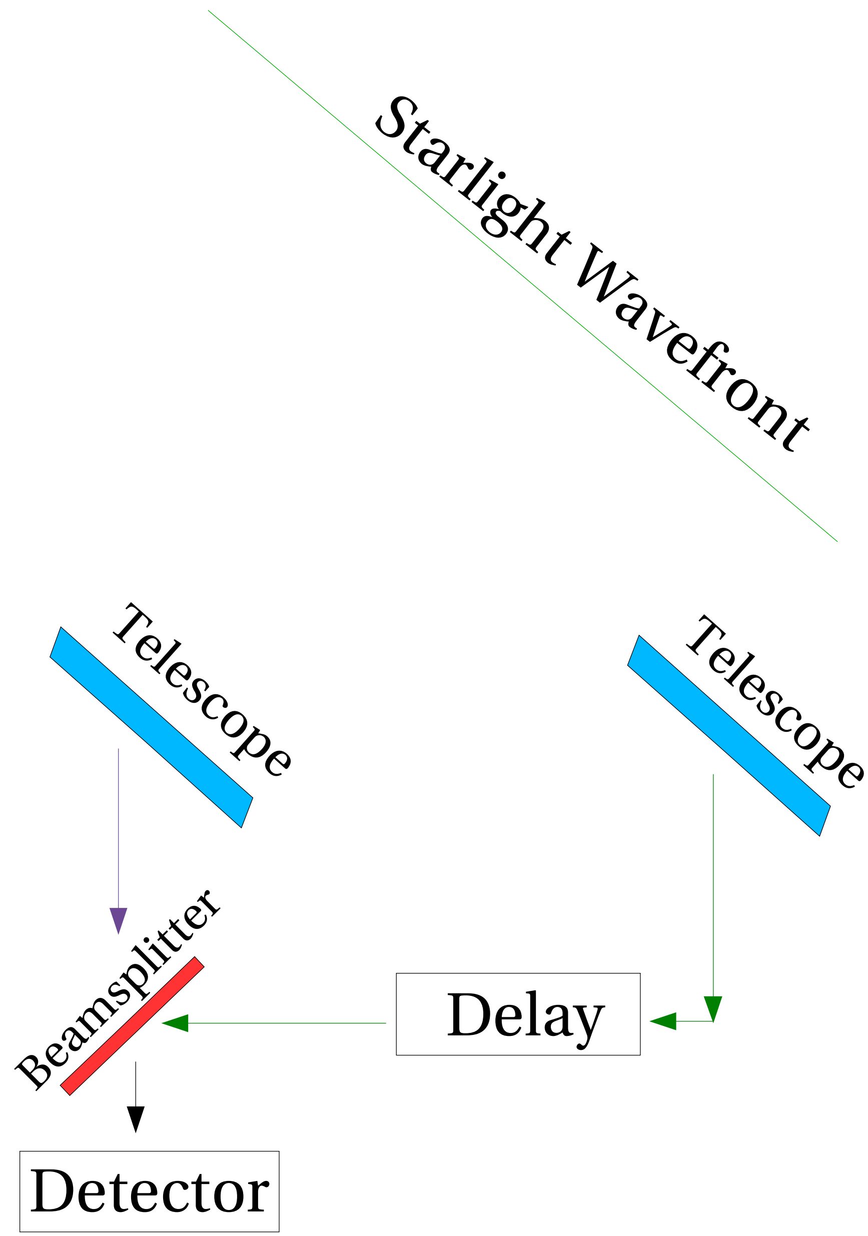
High contrast requires precise wavefront phase and amplitude stabilization

- Adaptive Optics
- Spatial Filtering
- Near-IR fringe tracker
- Dispersion Controllers
- Intensity Controllers

The Keck Interferometer

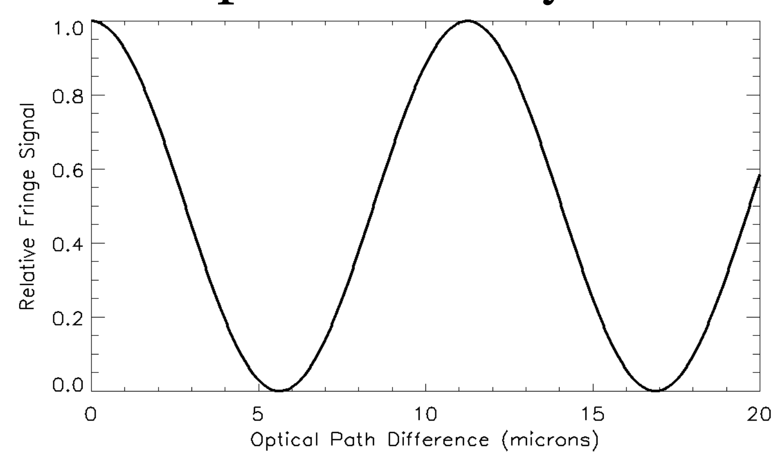
- NASA-funded joint project among
  - Jet Propulsion Laboratory
  - CARA / W. M. Keck Observatory
  - Michelson Science Center (MSC) at IPAC

An Optical Interferometer

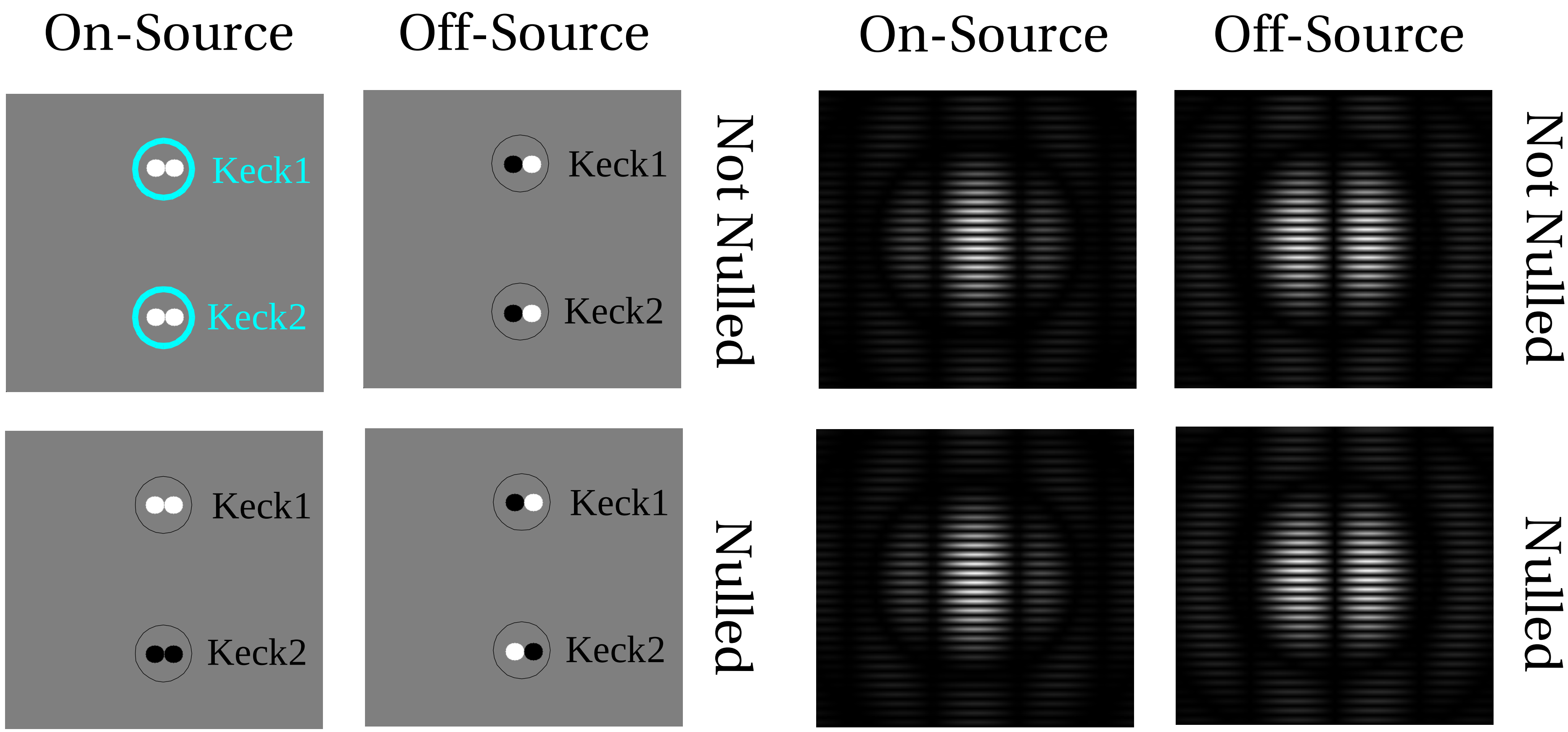


Beam Pattern on the Sky

Output Intensity vs OPD



Four-Beam Combiner



Input Apertures
Wavefront phase: white=0, black=π

Beam Pattern on the Sky

Interferometrically "chop out" the sky background
Other nice properties (more on that later!)

Chopping out the Thermal Background

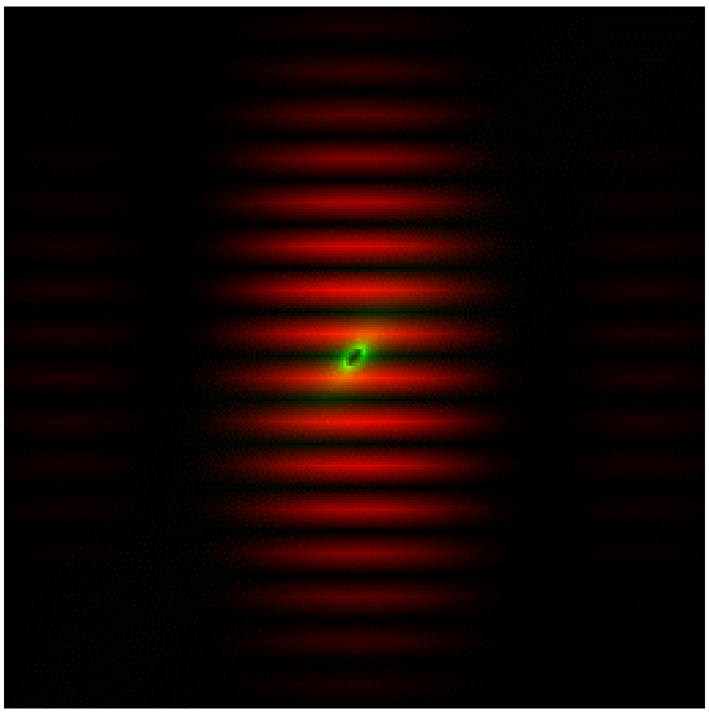
Ground-based Mid-IR instruments must "chop" on and off the source

Thermal background is vastly brighter than most stars

=> *Subtract off-source measurement from on-source measurement*

Typical power spectrum for sky background falls off at ~10 Hz

=> *Do this frequently and fast*



Keck Nuller does this interferometrically

No need to build large chopping secondaries

Secondaries would need high precision

Precise control of pathlengths possible

=> *does not destroy the null*

Small motions of small optics

=> *High speed chopping possible*

Chopping optics downstream of AO system

=> *No loss of AO lock*

Costs:

Less efficient use of apertures

More optics to handle split pupils

Demodulated Null Leakage Signal

The Null Leakage Signal (demodulated) is:

$$I_{leak} \sim \alpha_{12}\alpha_{34} + \beta_{12}\beta_{34}$$

where the α_i are amplitude imbalance terms:

$A_2 = (1+\alpha_{12})\,A_1$ $\quad\quad$ $A_4=(1+\alpha_{34})A_3$

(A_i = wavefront amplitude in beam i)

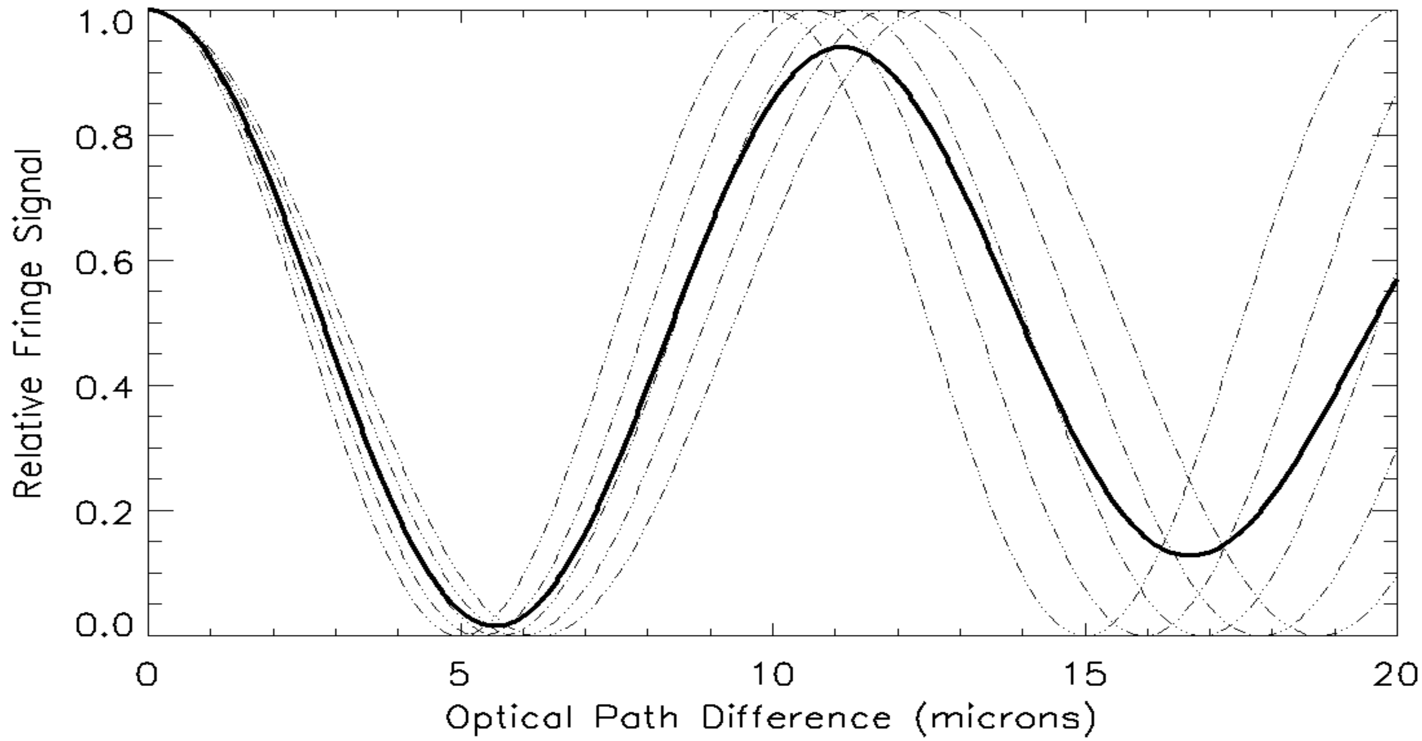
and the β_i are phase error terms.

Note that the indices are defined as follows:

{1,2,3,4} => {Keck 1 Left, Keck 2 Left, Keck 1 Right, Keck 2 Right}

The terms that determine the leakage through the null in the demodulated signal are the products of the imbalances within the individual MMZs

Chromatic Null



A "normal" beam combiner produces a constructive fringe at zero OPD.
Offsetting to a dark fringe ("Null") works only at a single wavelength,
so the broadband null is not very deep.
We say that the null is "Chromatic"
=> An achromatic null is needed to achieve good contrast

More Chromatic Effects

The intrinsic chromaticity of the null produced by a constructive beam combiner is just one source of longitudinal dispersion…

Unbalanced paths through optics
glass is dispersive!

Unbalanced airpath (dry air and H2O)
these have terms which fluctuate with seeing
large compared to intrinsic chromaticity

=> Measure the position of the fringe as a function of wavelength
Insert a suitable thickness of dispersive glass in each input beam
Adjust the Delay Line to compensate for the added optical path difference

Dispersion due to Air and Water

Two major sources: "static" and "dynamic"

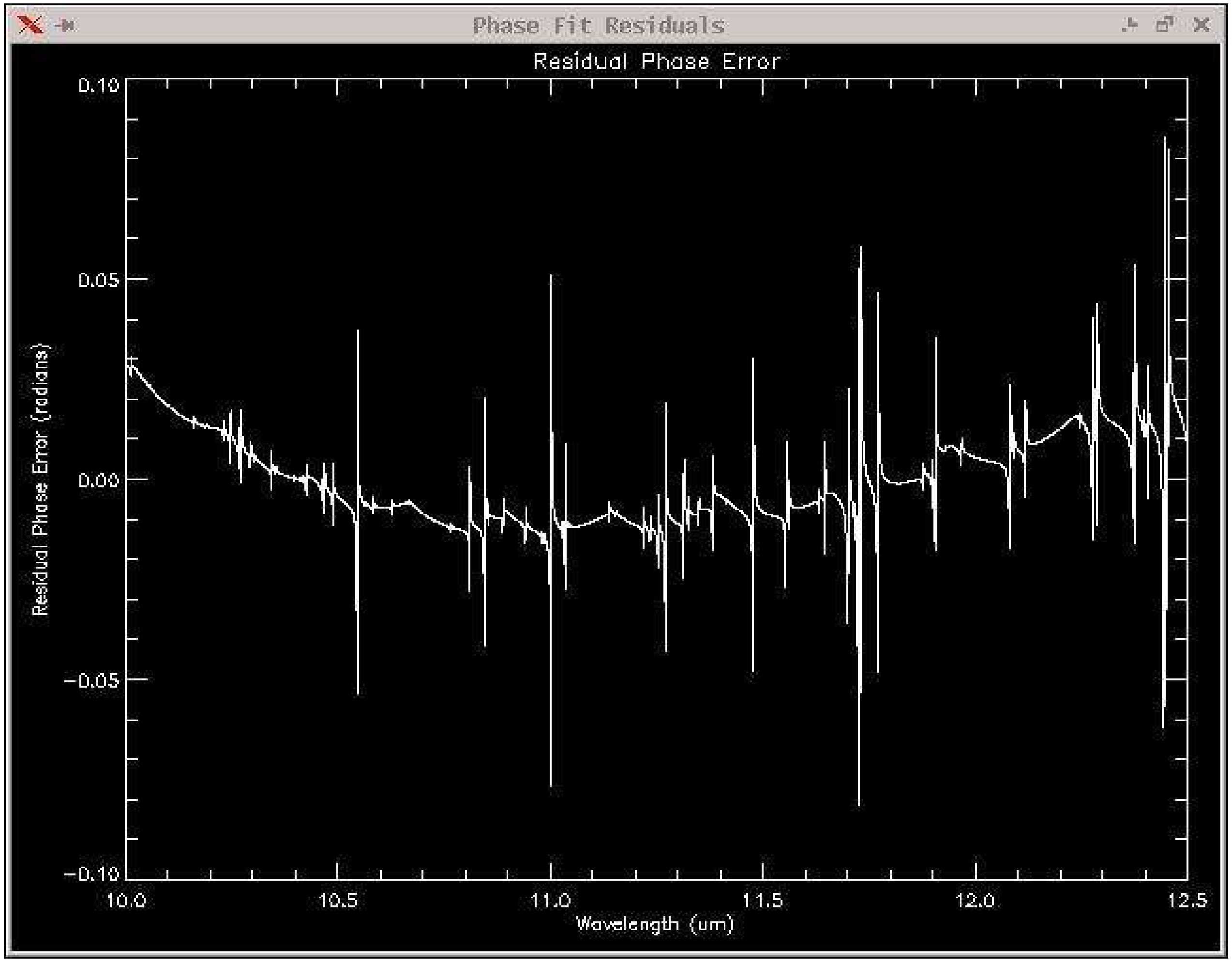
"Static":
- Air path in the delay-lines compensates vacuum path above telescopes
- Unbalanced pathlength
  - Up to ~60 m
  - Changes on sidereal timescales

"Dynamic"
- Dry-air column fluctuations are mostly tracked out in the near-IR
- H2O column fluctuations due to "H2O seeing" are important
  - *These set the maximum integration time between phase resets*

	Dry Air	**H2O Vapor**
Optical Pathlength	1 cm	0.004 cm
Dispersion (per μm)	0.2 radians	2 radians
Spectral	No strong features	Strong features

Assumptions: 60 m pathlength at 0.6 atm with 10^{17} molecules/cm^3 of H_2O

Fitting the Dispersion with ZnSe



RMS phase error 0.012 radians (more than adequate for the Keck system)
0.6 mm ZnSe and 1.4 mm DL motion
Significant contribution from lines

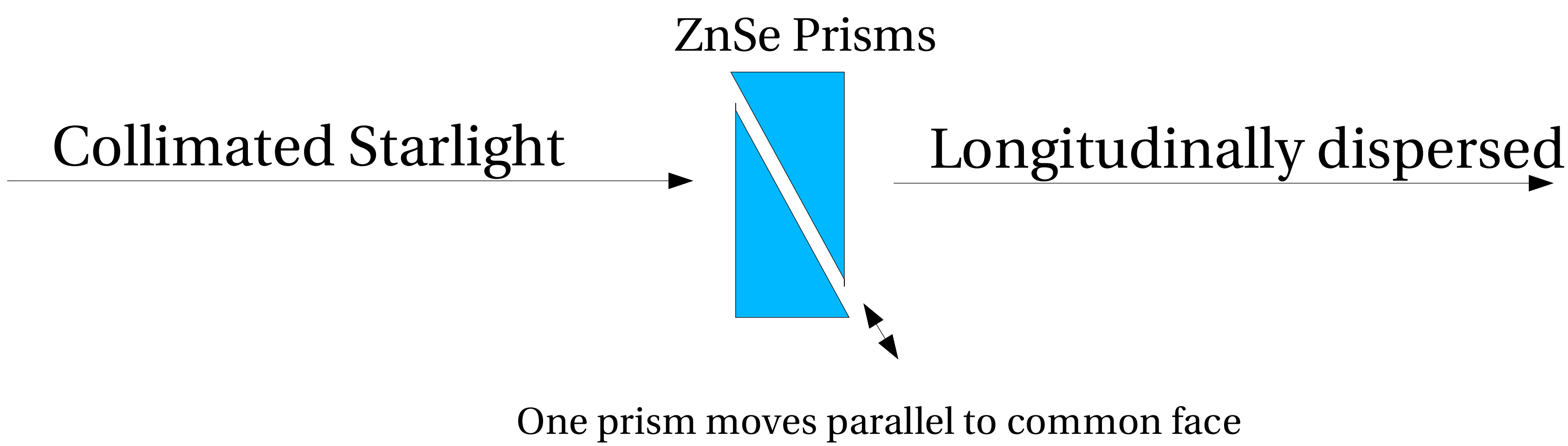
Dispersion Controllers

Correct dispersion with an adjustable thickness of ZnSe

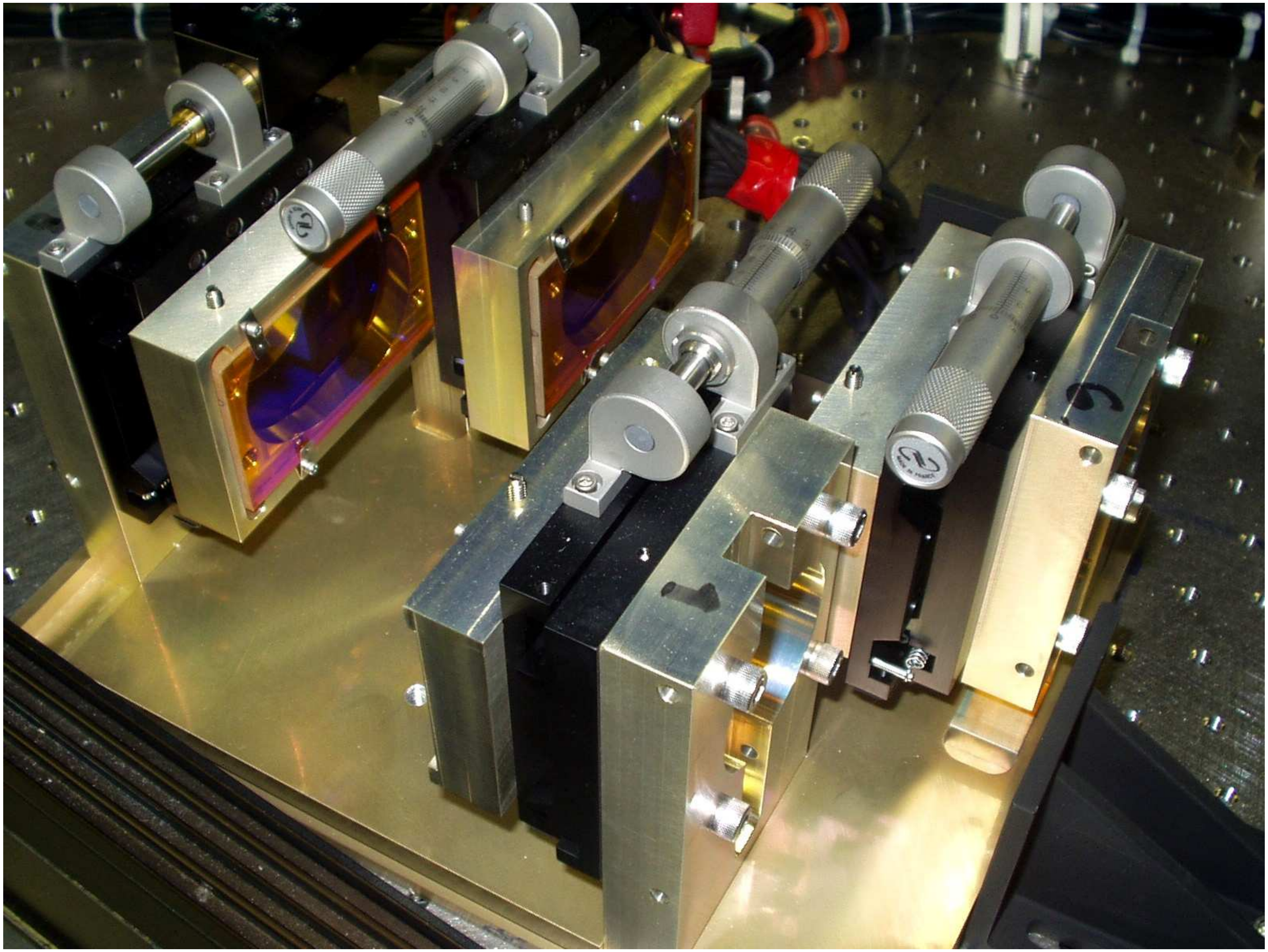
- Need one Dispersion Corrector (DC) per input beam
- Changing the DC setting introduces pathlength as well as chromaticity
  - -> Must adjust the corresponding delay-line as well

Performance: (For a perfectly-adjusted DC)

- Expect RMS phase errors ~0.02 radians from 10.0-12.5 microns
  - -> Null depth limited to ~10^{-4}
  - (assuming 60 m unbalanced airpath with humidity ~30%)

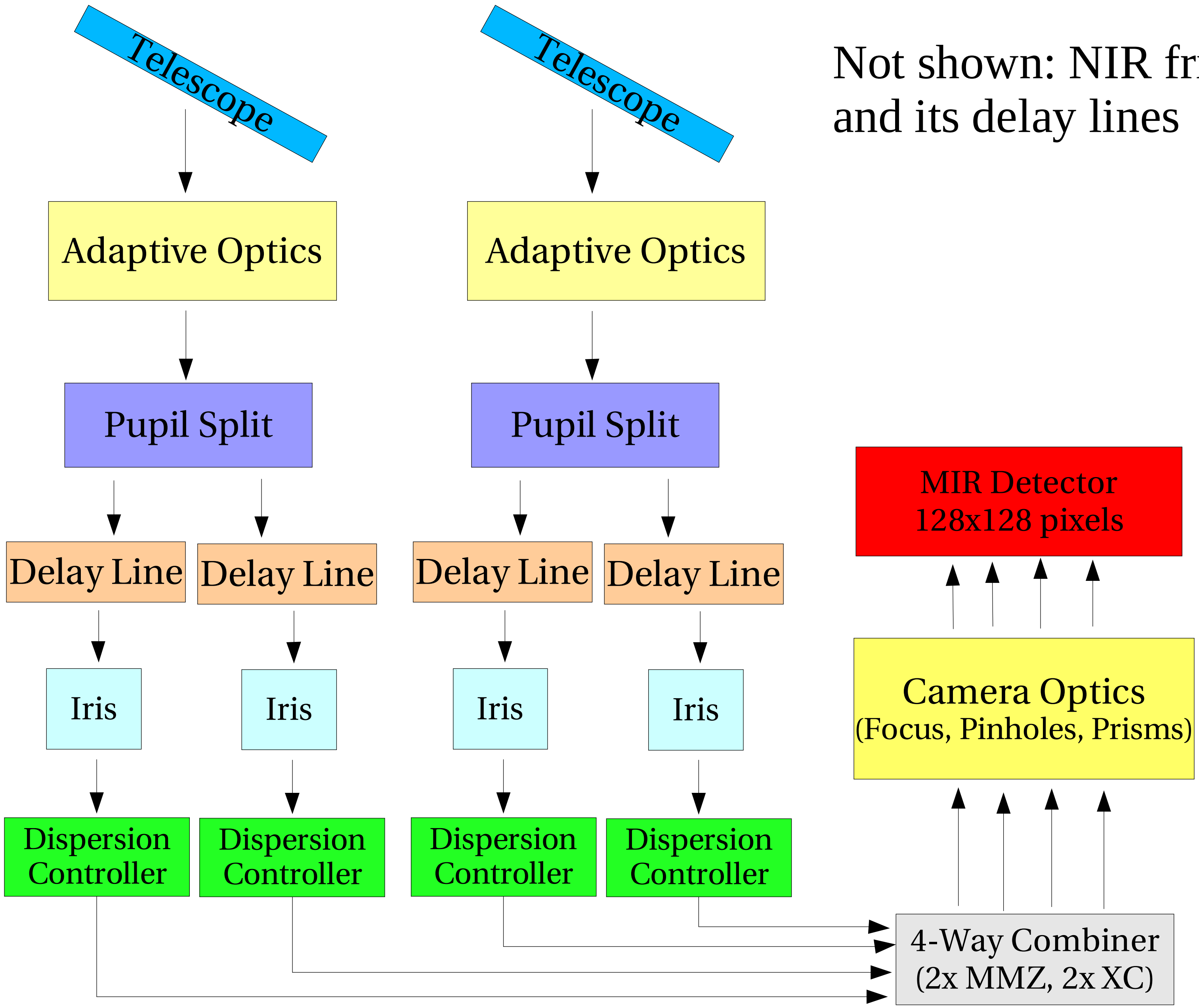


Dispersion Controllers (two beams)

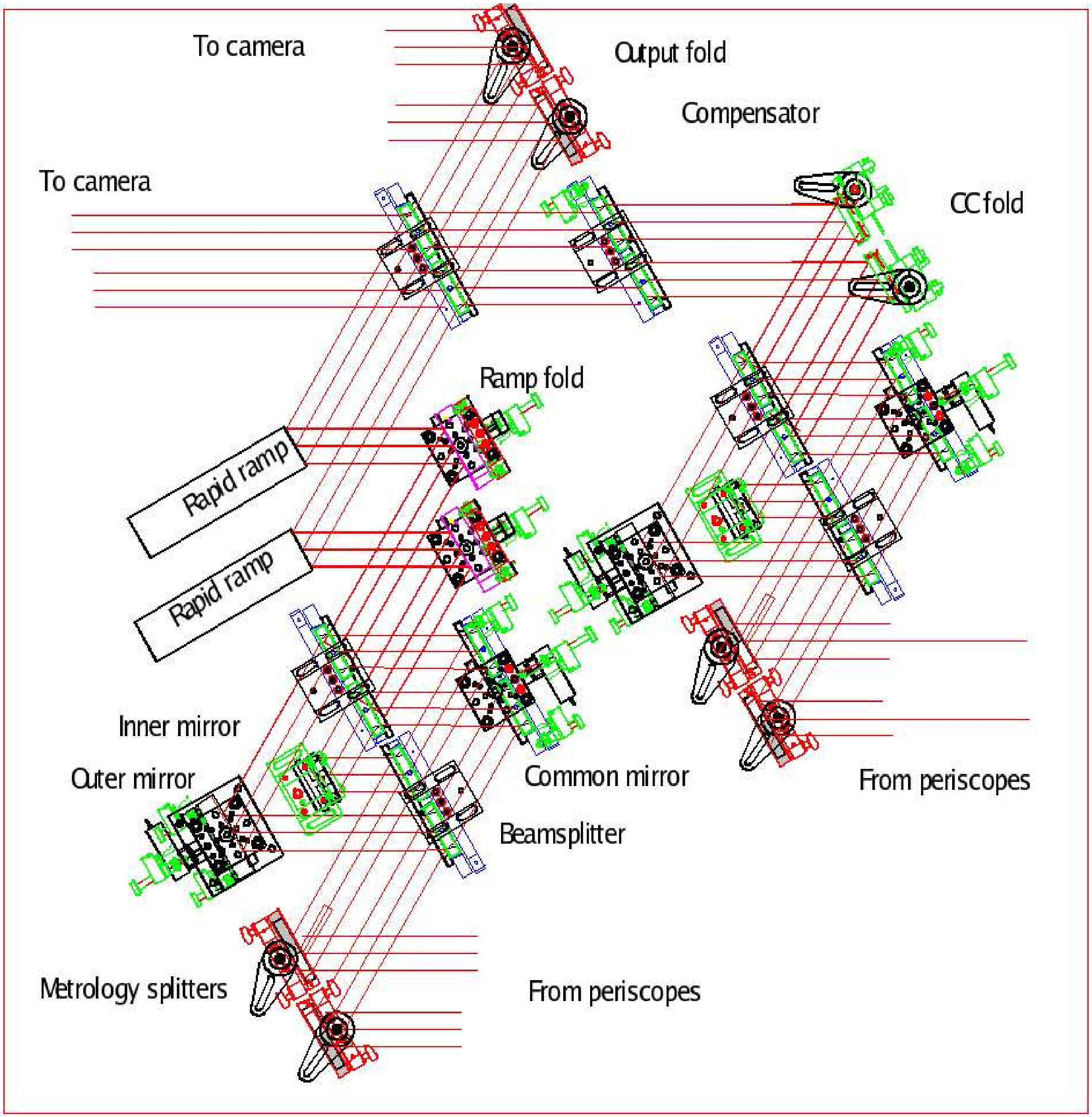


Hardware Overview

Not shown: NIR fringe tracker and its delay lines



Beam Combiner Schematic



Input Beams
"From Periscopes"

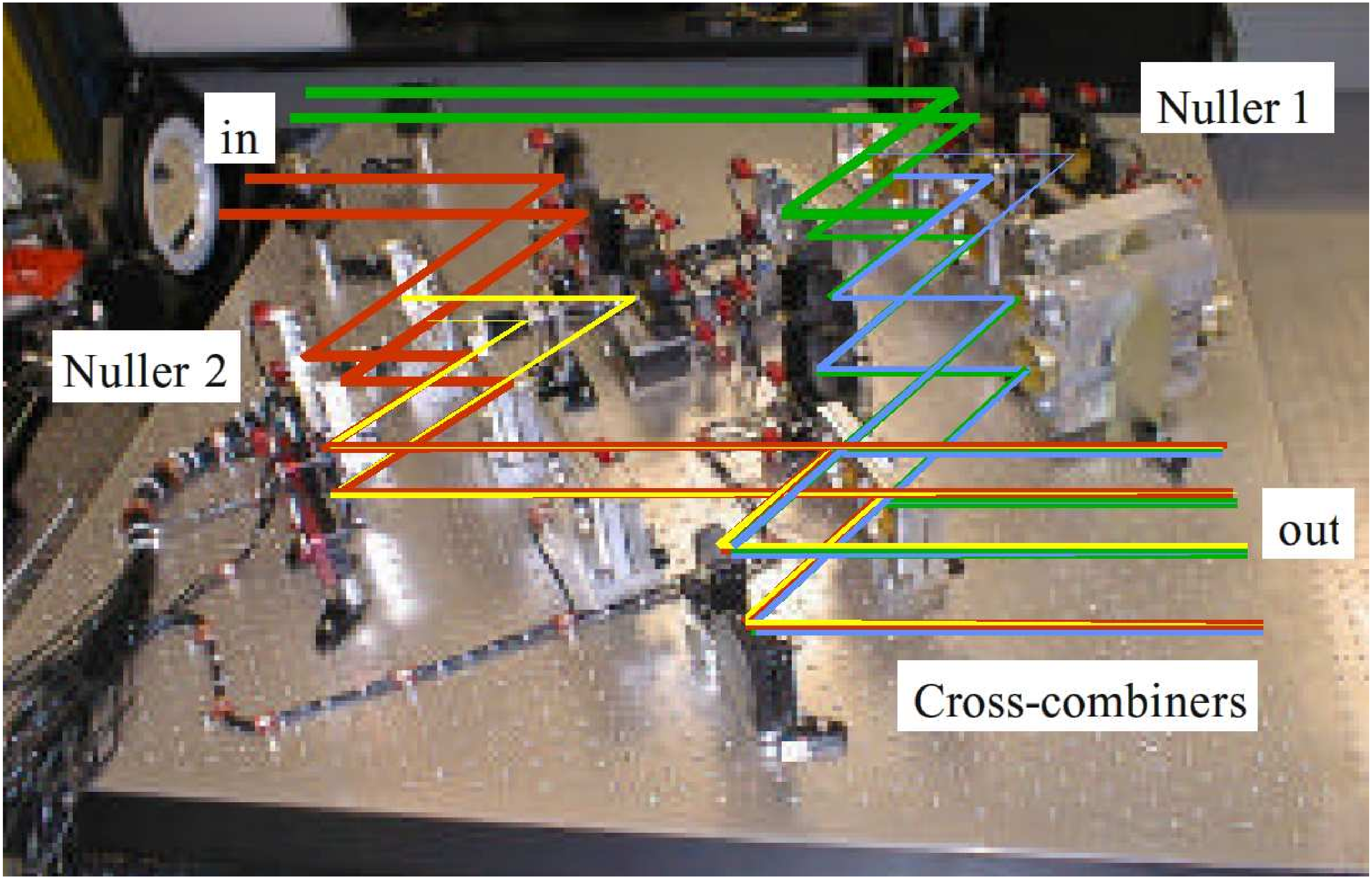
Modified Mach-Zehnder (MMZ) combiners for long baselines (one for the Left sides of both Kecks, and one for the Right sides).

MMZ outputs are combined using simple beamsplitters

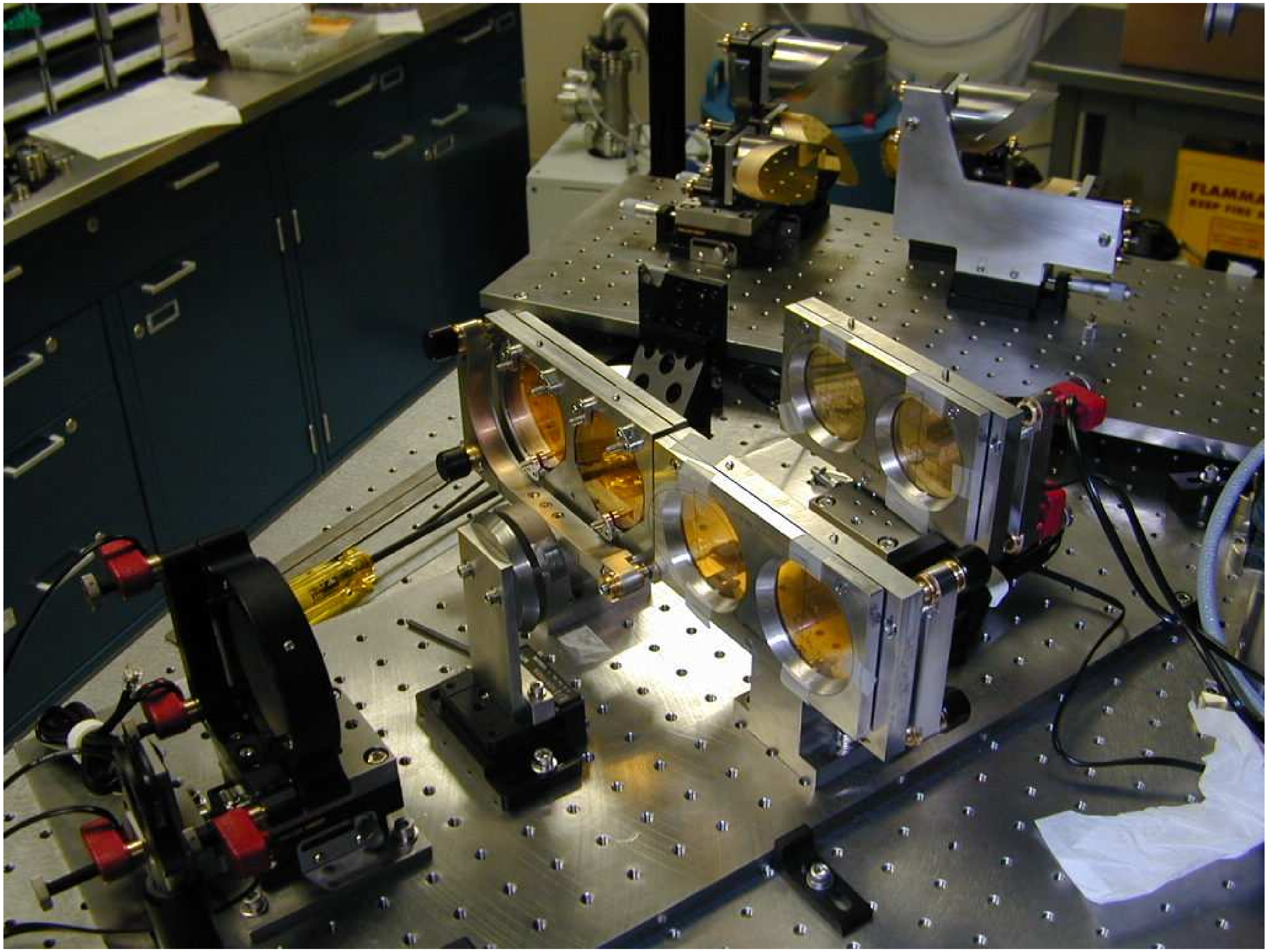
Rapid Ramp mirrors are PZT actuated and can modulate the OPD between the MMZ outputs at ~200 Hz

Mid-IR Camera with
- 4 input beams
- 10 spectral channels
- (10.0 – 12.5 microns)

Beam-Combiner Breadboard



Modified Mach-Zehnder Combiner



A single MMZ in the lab at JPL.

The Keck Nuller has two of these, and a pair of simpler combiners (called “Cross Combiners” or “XCs”) which add their outputs to produce 4 output beams for the camera.

The actuators are for adjusting the alignment and internal pathlengths.

Nuller Status

Adaptive Optics working on both Kecks

Keck Interferometer NIR fringe tracker working

First fringes March 2001

Fringe tracker sensitivity now K~9

Two Science Papers accepted so far (on DG Tauri and NGC 4151)

Four-input beam combiner assembled and tested at JPL

Narrowband (10.6-micron laser) null depth 10^{-6}

Broadband (thermal source with ~20% filter) null depth 10^{-4}

Nuller Camera

Detector, Electronics, Dewar, and Mechanical Components in hand

Assembly and testing in progress at JPL

Integration of the Beam Combiner, Nuller Camera, and Delay Lines in progress at JPL

Shipment to Keck scheduled for late 2003

Will it Work?

Yeah.