The Mid-Infrared Nulling Beam Combiner for the Keck Interferometer

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Overview

Why build a nuller?

Scientific Objectives

Technological Rationale

Basic Principles and Design Drivers

Four-beam combination

Balancing Act

Dispersion Control

Feedforward

Modulation and Detection

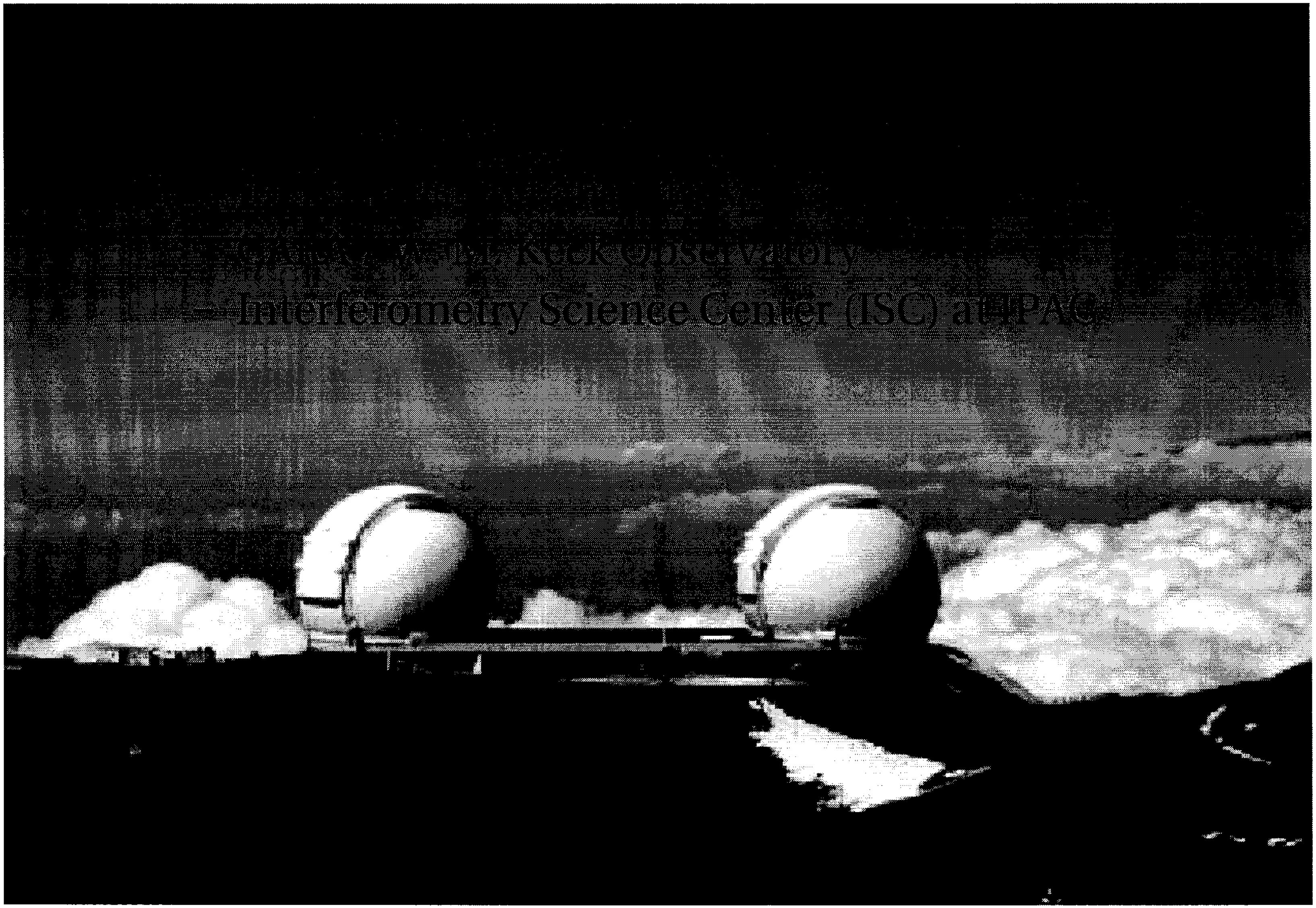
Anticipated Performance

Minimum Target brightness in the V, J, K, and N bands

Leakage Signal and Photospheric Size

Current Status

The Keck Interferometer



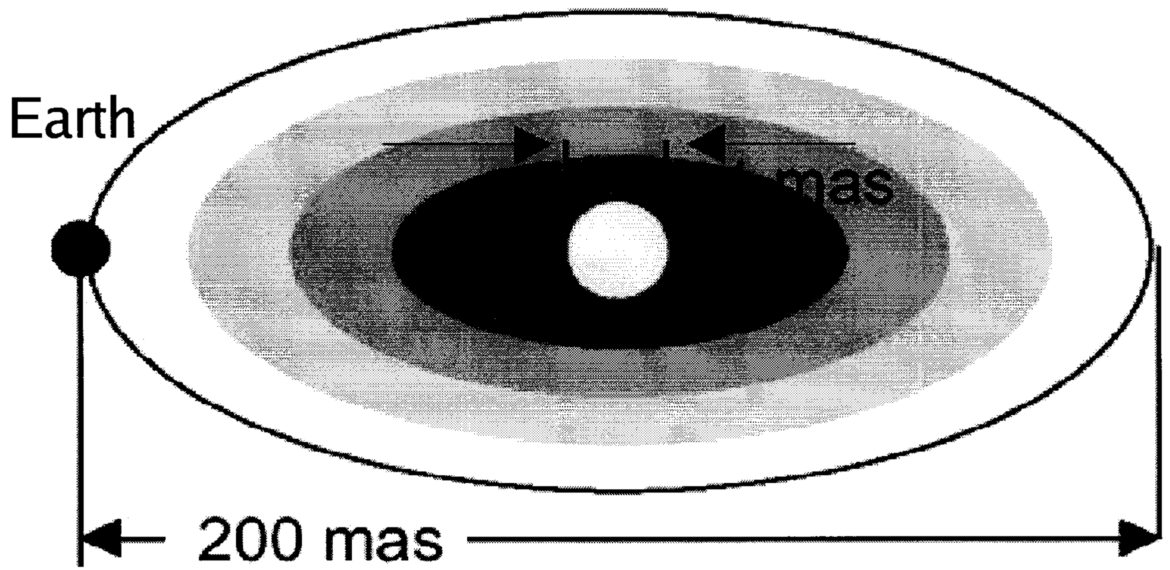
Why Build a Nuller?

Detection of faint extended emission in the presence of a bright compact source

NASA goal (*Key Science Project)*

- Measure or put limits on emission from exo-zodiacal dust
- Preparation for Terrestrial Planet Finder (TPF)
  - Dust disks are very bright and could hamper planet detection
- Solar-type Main Sequence stars
  - $10 < D_{pc} < 20$
  - $q_{phot} \sim 1$ mas (angular diameter of photosphere)
  - $q_{exozodi} \sim 600$ mas (angular diameter of Zodi disk)
  - Stellar Magnitudes: V~7, K~5, N ~ 5

Exozodiacal Disk



Target at 10 pc

Schematic representation of an exozodiacal dust disk as seen from 10 pc. The disk actually extends well beyond 1 AU. It is 1000 times brighter at 10 microns than Earth is (and 100 times brighter than even Jupiter).

General Science Applications

Pre-Main Sequence Stars
- Herbig Ae/Be, T Tauri, FU Orionis
  - Measure angular sizes of dust disks
  - Much brighter than exozodiacal disks
  - *This is the thrust of the first shared-risk project*

Evolved Stars
- Miras and other evolved stars
  - Size and structure of dust-producing regions

Active Galactic Nuclei

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Technical Rationale

Nulling is essentially a photometric experiment with a virtual coronagraph

Goal: *Measure the flux in an extended but faint source near a bright compact source*

Typical flux ratio for 10x Solar Zodi mass is 10^{-3}

For the Keck nuller, the target null depth is 10^{-4}

Without the "coronagraph", uncertainties are dominated by the uncertain flux in the star

Isolated exozodi disk emission would be detectable by, e.g., Keck1 / LWS

Typical N-band photometry is only good to a few percent

Intrinsic N-band fluxes in most stars are not precisely known

=> ***We must suppress this noisy contribution to the total flux***

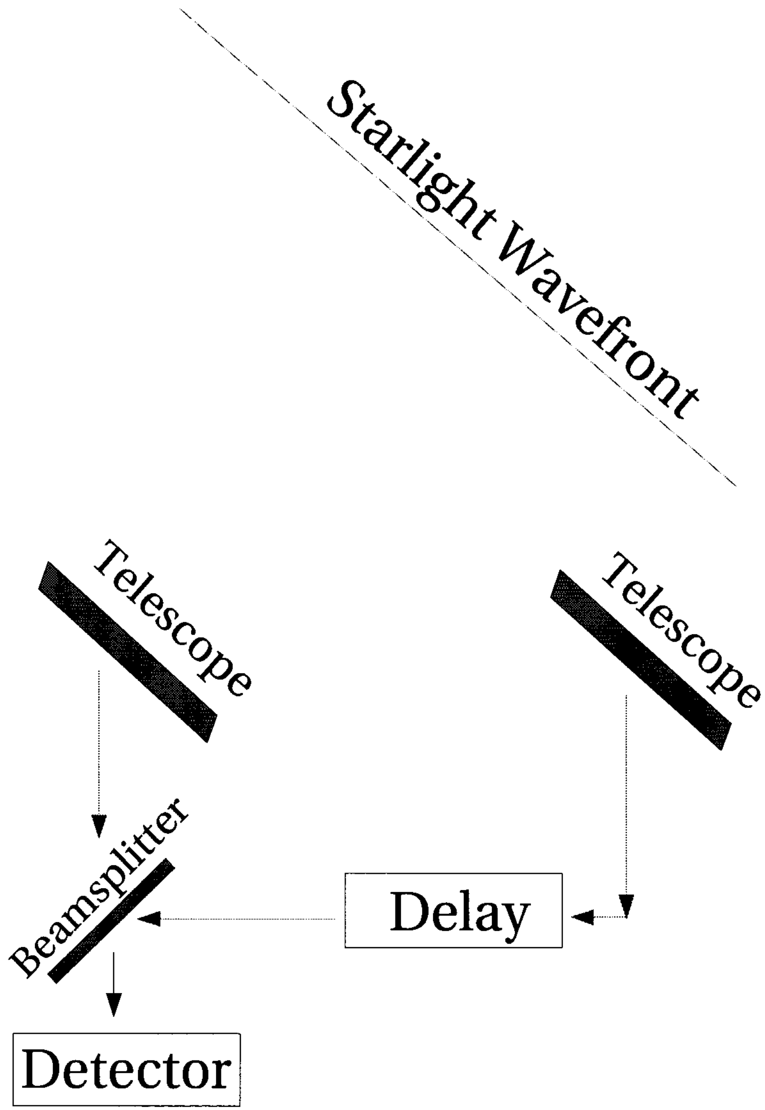
General principle: Beam combination with a useful fringe pattern on the sky

Deep null at the position of the central star

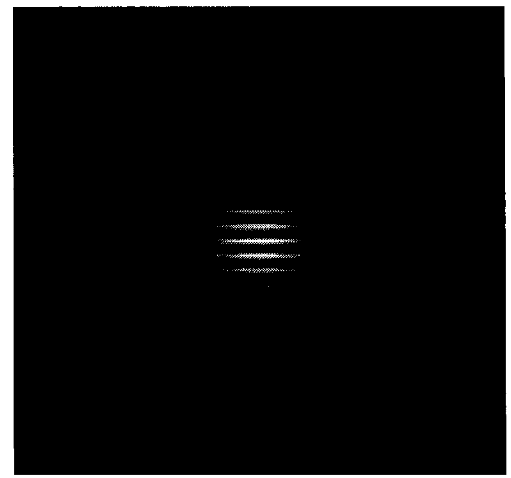
Constructive fringes present on scales comparable to dust disk radius

=> ***Selective spatial filter***

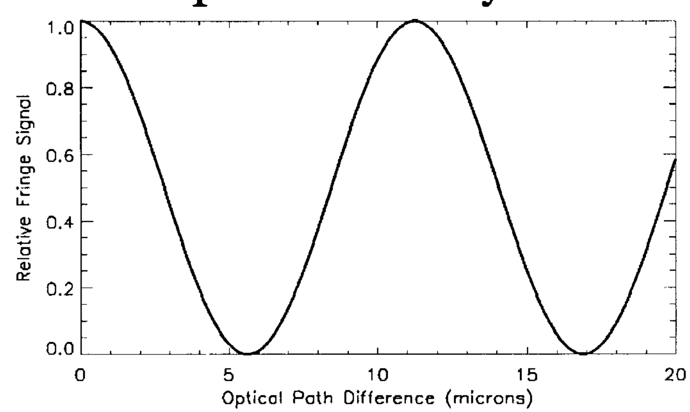
An Optical Interferometer



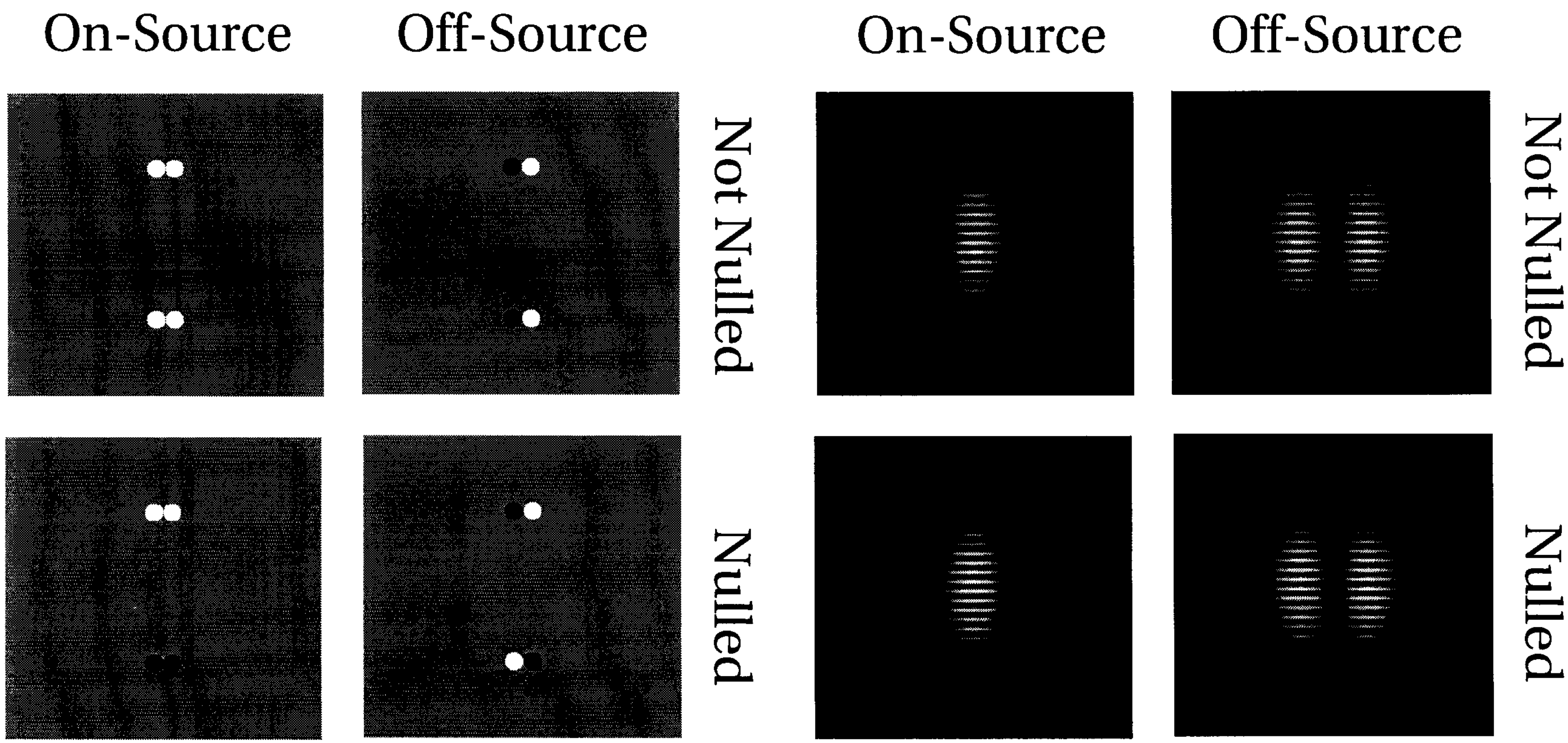
Beam Pattern on the Sky



Output Intensity vs OPD



Four-Beam Combiner



Input Apertures (phase delay color-coded)

Beam Pattern on the Sky

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

Leakage through the Null

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:

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

(A_i = wavefront amplitude in beam i)

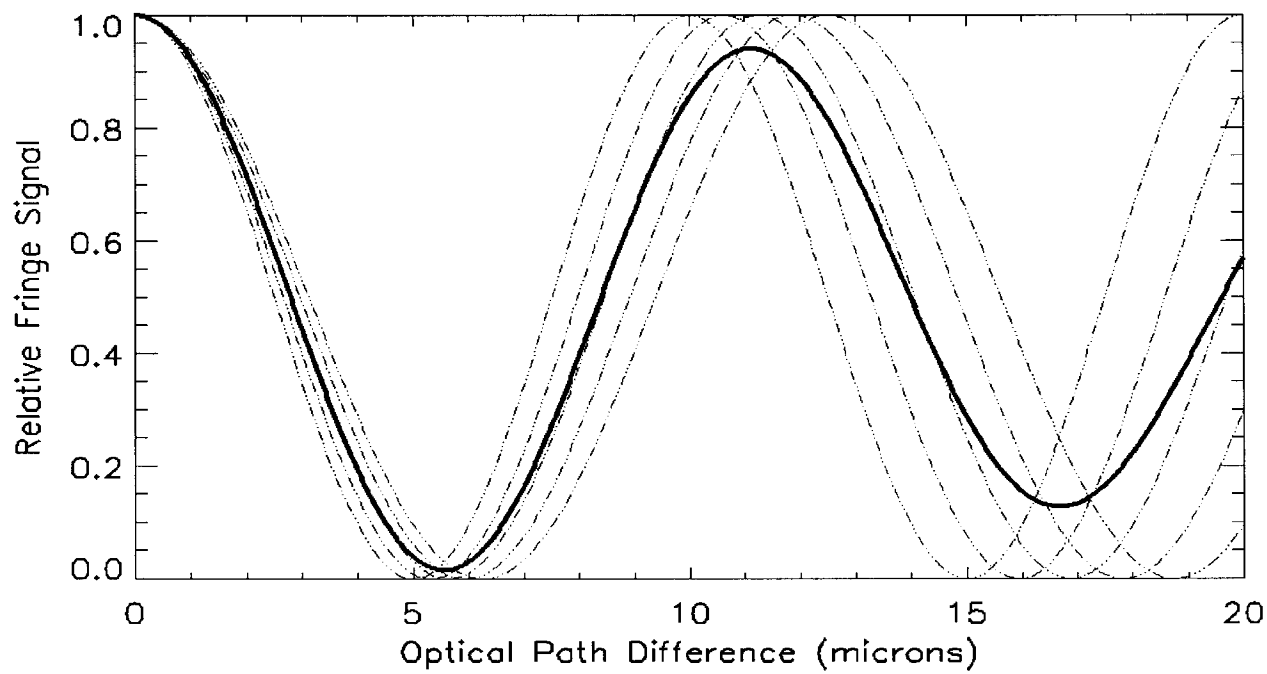
and the β_i are phase error terms.

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 the input beams
Adjust the Delay Line to compensate for the added optical path difference

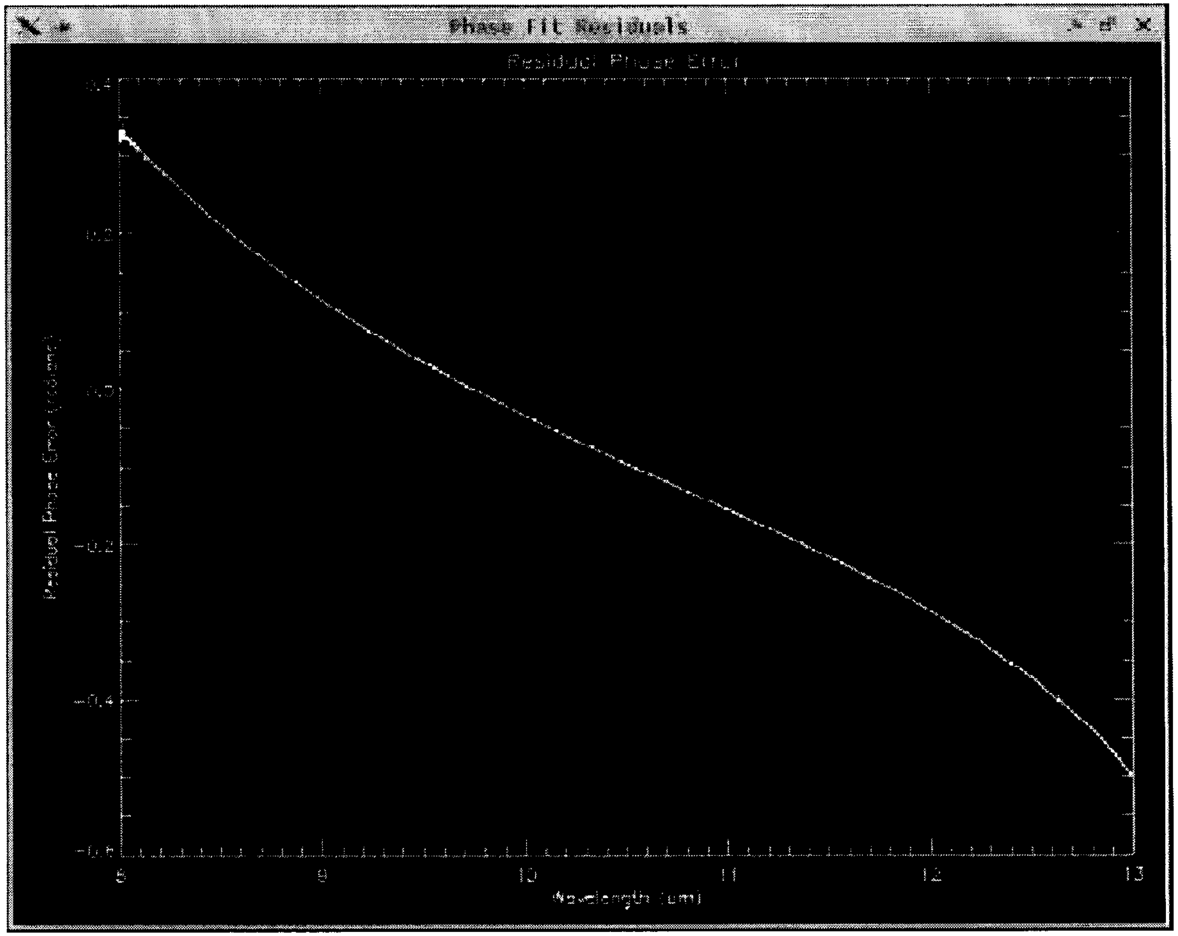
Dispersion due to Air and Water

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*

Dispersion due to 60 m of Dry Air



Dry air contributes:

~1 cm of OPD

~0.2 radians of phase per micron of wavelength

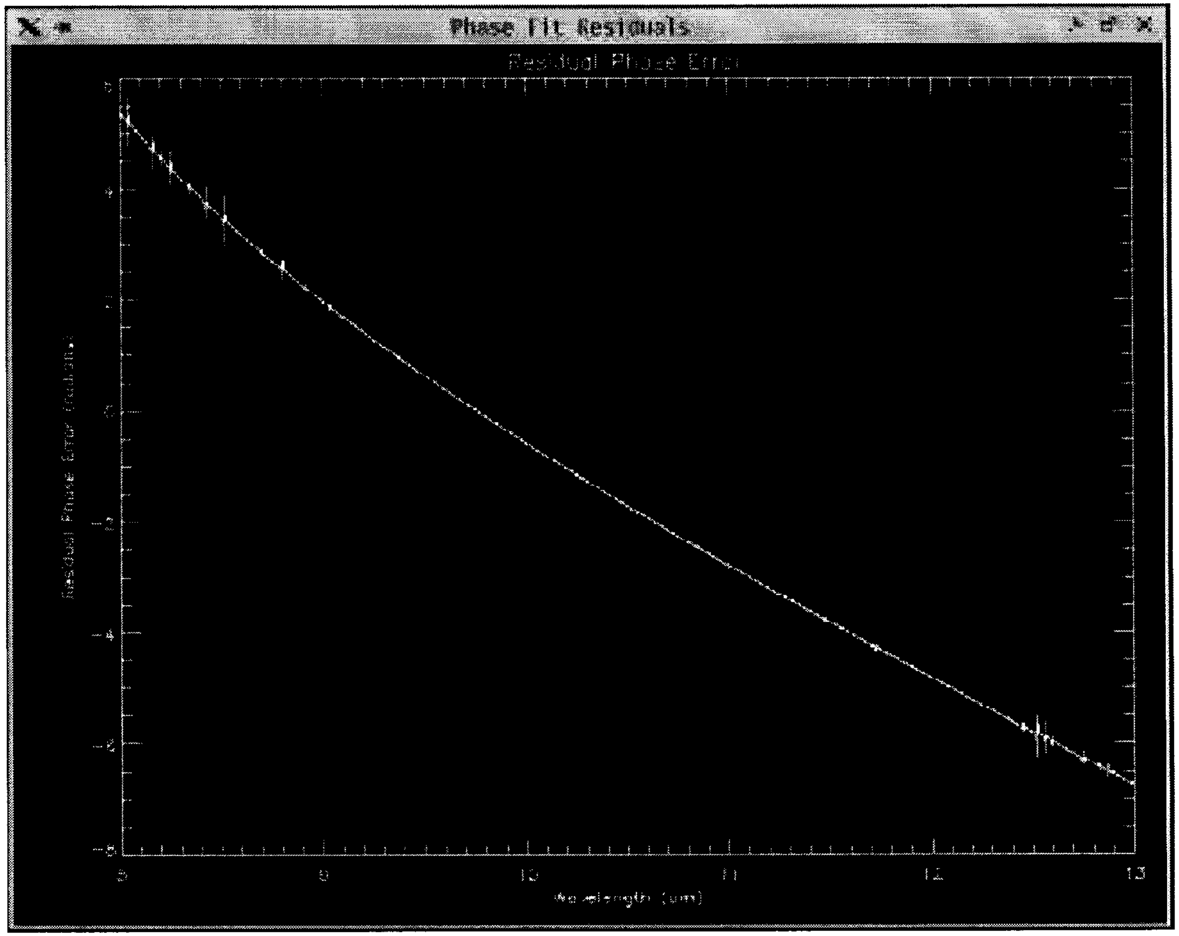
~ 0.3 μm OPD per micron of wavelength

No strong spectral features

Nonlinear with inflection

Dispersion for 60 m of dry air at 0.6 atmosphere pressure

Dispersion due to 60 m of H2O Vapor



H2O contributes:

Dispersion is ~2.4 radians of phase per micron of wavelength

Varies with humidity and projected baseline

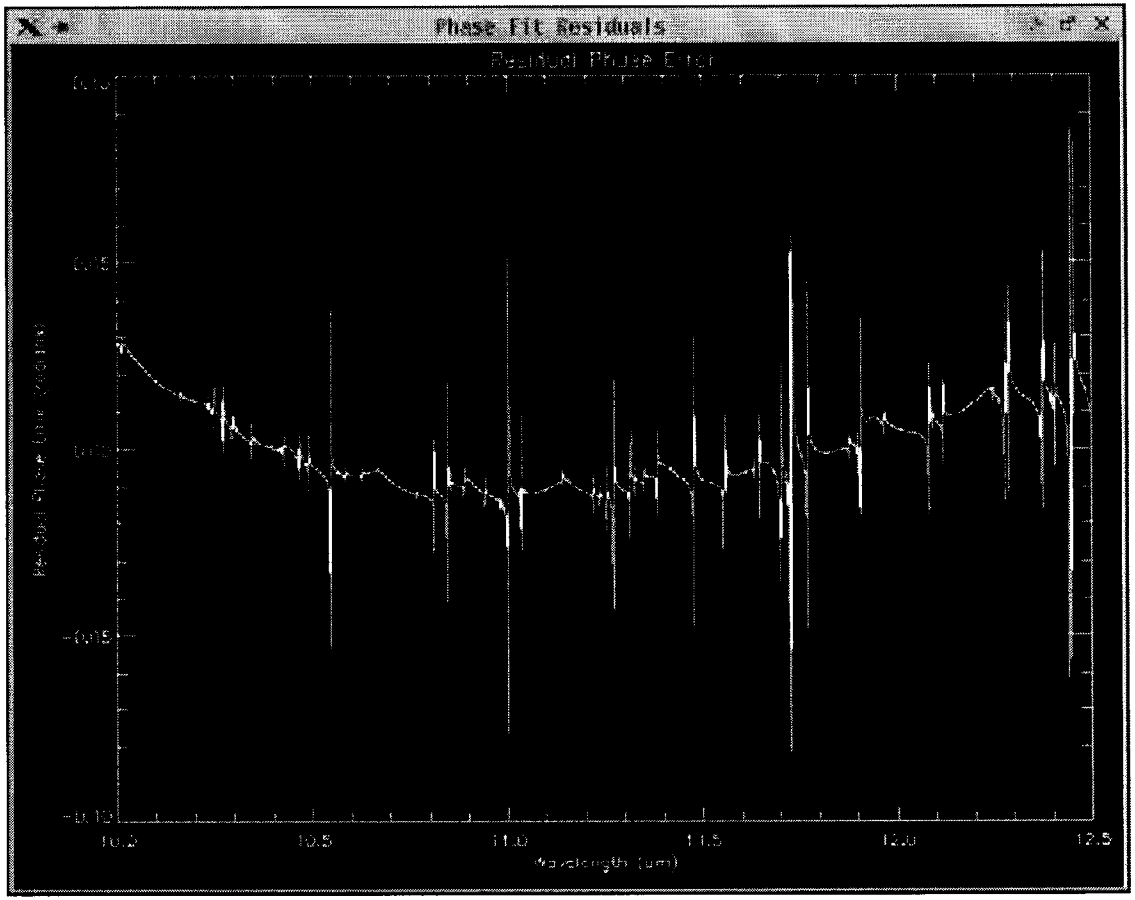
Water-vapor "seeing"

Strong spectral features (especially toward band edges)

Dominant source of dispersion

Dispersion for 60 m of H2O vapor with density 10^{17} cm^{-3} (32% RH)

Fitting the Dispersion with ZnSe

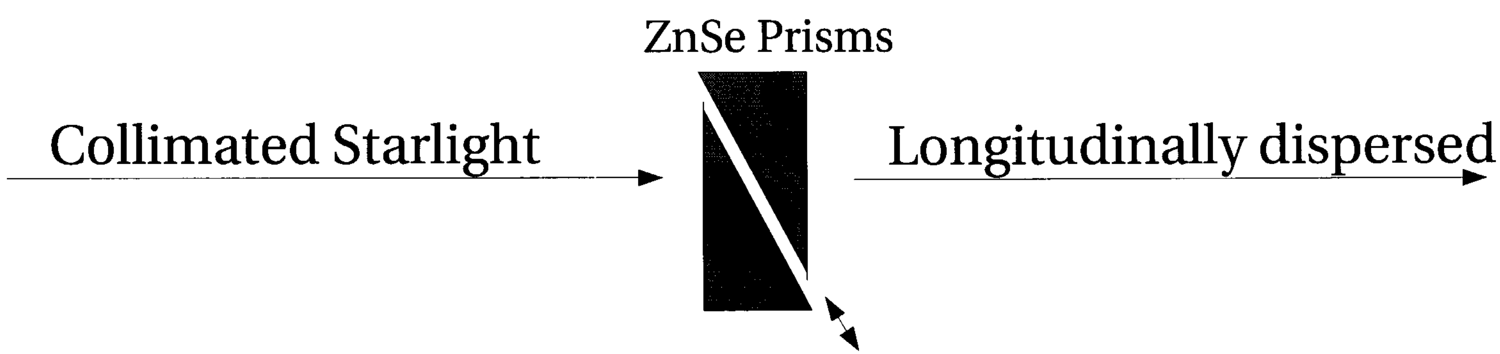


RMS phase error 0.012 radians (more than adequate for the Keck system)
0.6 mm ZnSe and 1.4 mm DL motion
Significant contribution from lines

Dispersion Correctors

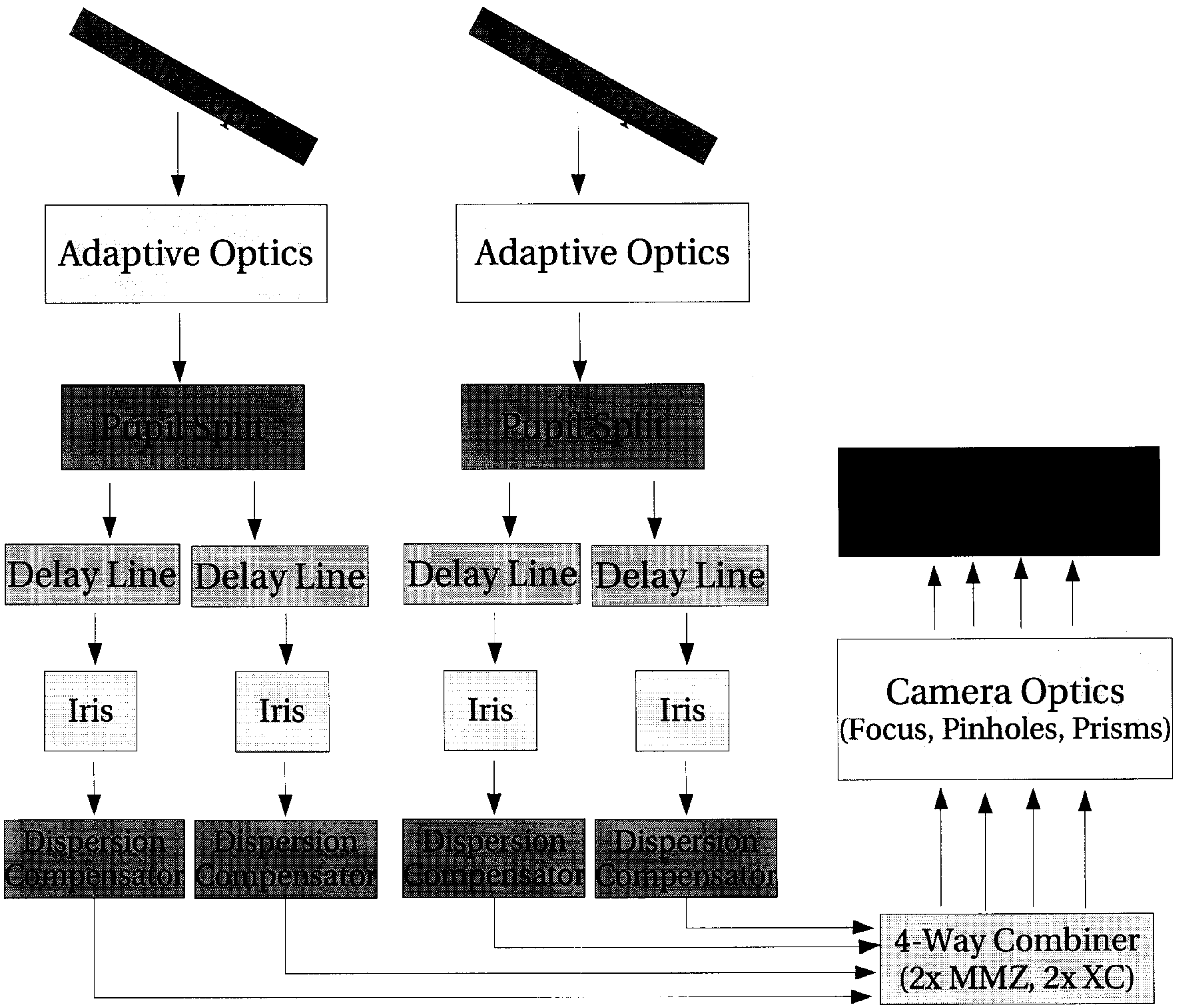
Correct dispersion with an adjustable thickness of ZnSe
- Need one Dispersion Corrector (DC) per input beam
- Changing the DC setting introduces pathlength as well as chromaticity
  - -> Must adjust the corresponding delay-line as well

Performance: (For a perfectly-adjusted DC)
- Expect RMS phase errors ~0.02 radians from 10.0-12.5 microns
  - -> Null depth limited to $\sim 10^{-4}$
  - (assuming 60 m unbalanced airpath with humidity ~30%)

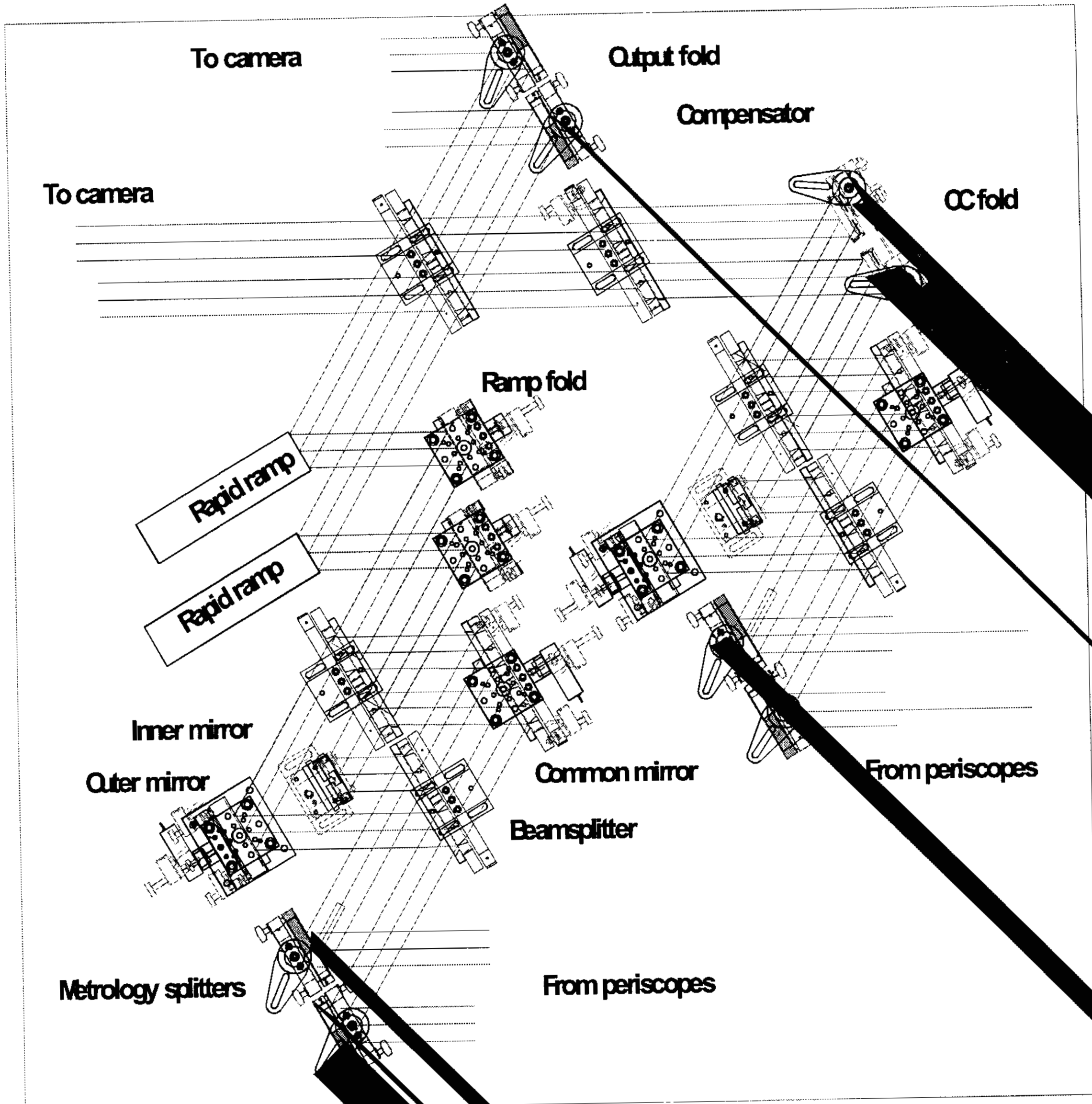


One prism moves parallel to common face

Hardware Overview



Beam Combiner Schematic



Input Beams
"From Periscopes"

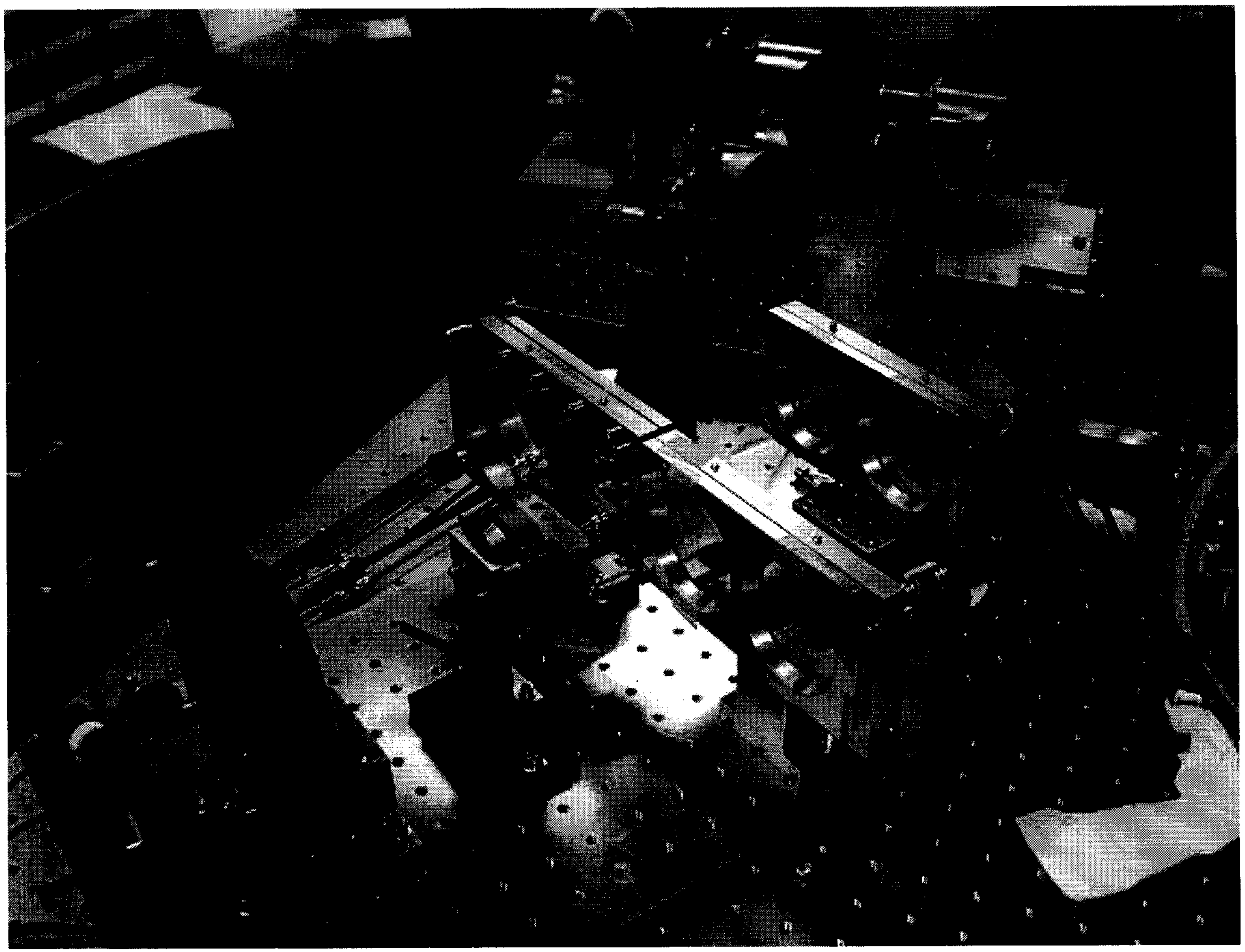
Modified Mach-Zehnder (MMZ) combiners for long baselines (one for the Left sides of both Kecks, and one for the Right sides).

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)

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.

A Nuller Simulator

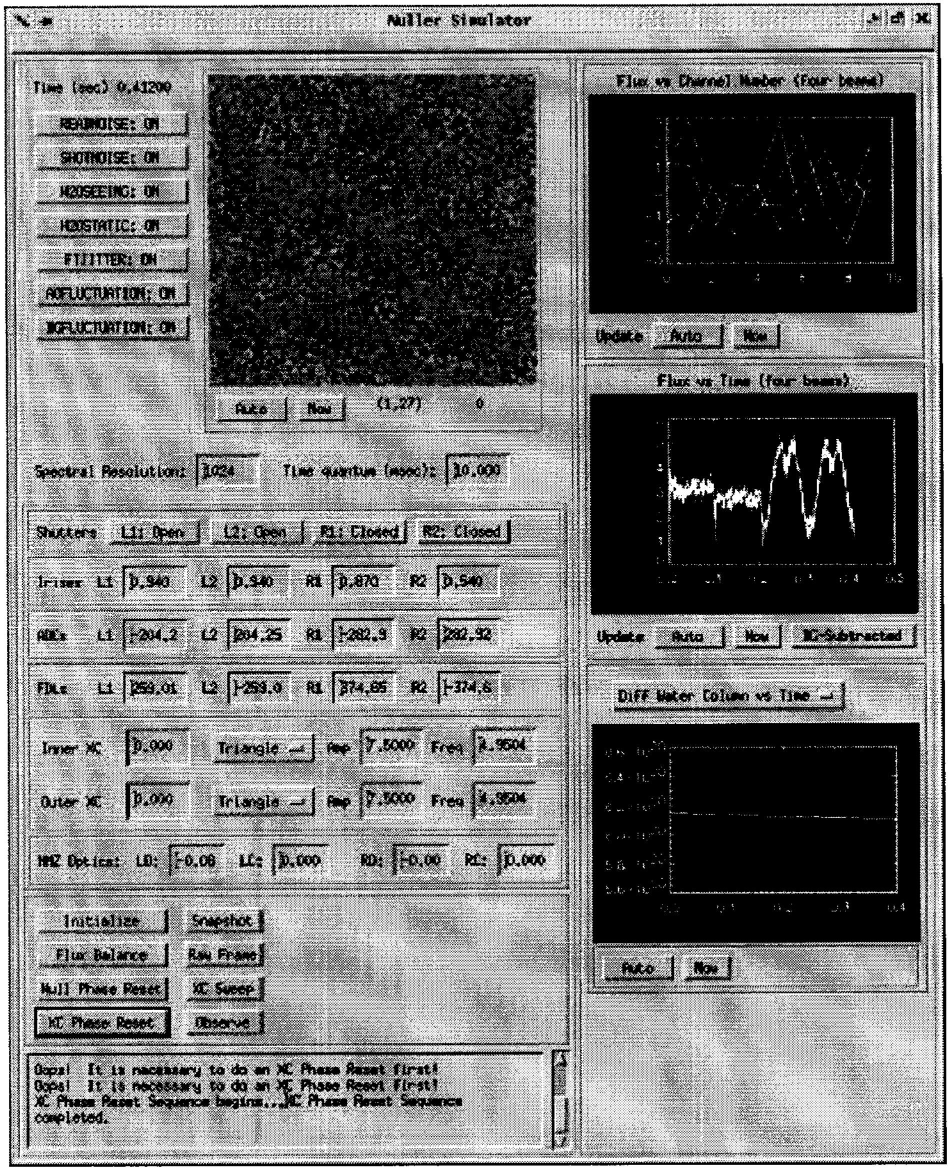
Longitudinal effects only; no aberrations or polarization

Mirror Optics (treated as achromatic pathlength contributors)
- 4 Irises (one for each input beam)
- 4 Shutters (one for each input beam)
- 4 FDLs (one for each input beam)
- 2 MMZs, each with:
  - Inner, Outer, and Common Mirrors
  - (beamsplitters are fixed)
- 2 XCs, each with a Ramp Mirror

Chromatic Optics (treated as chromatic pathlength contributors)
- H2O: Dynamic Term (seeing) + Static Term (basement)
- Dry Air: Static Term
- 4 Dispersion Correctors (one for each input beam):
  - ZnSe plates with adjustable thickness

Noise Sources
- Detector readnoise (assume 1000 electrons)
- Background level (thermal static + sky variability)
- Variable throughput (due to imperfect AO correction)
- H2O Seeing (realistic model based on measured power spectrum)

Simulator GUI

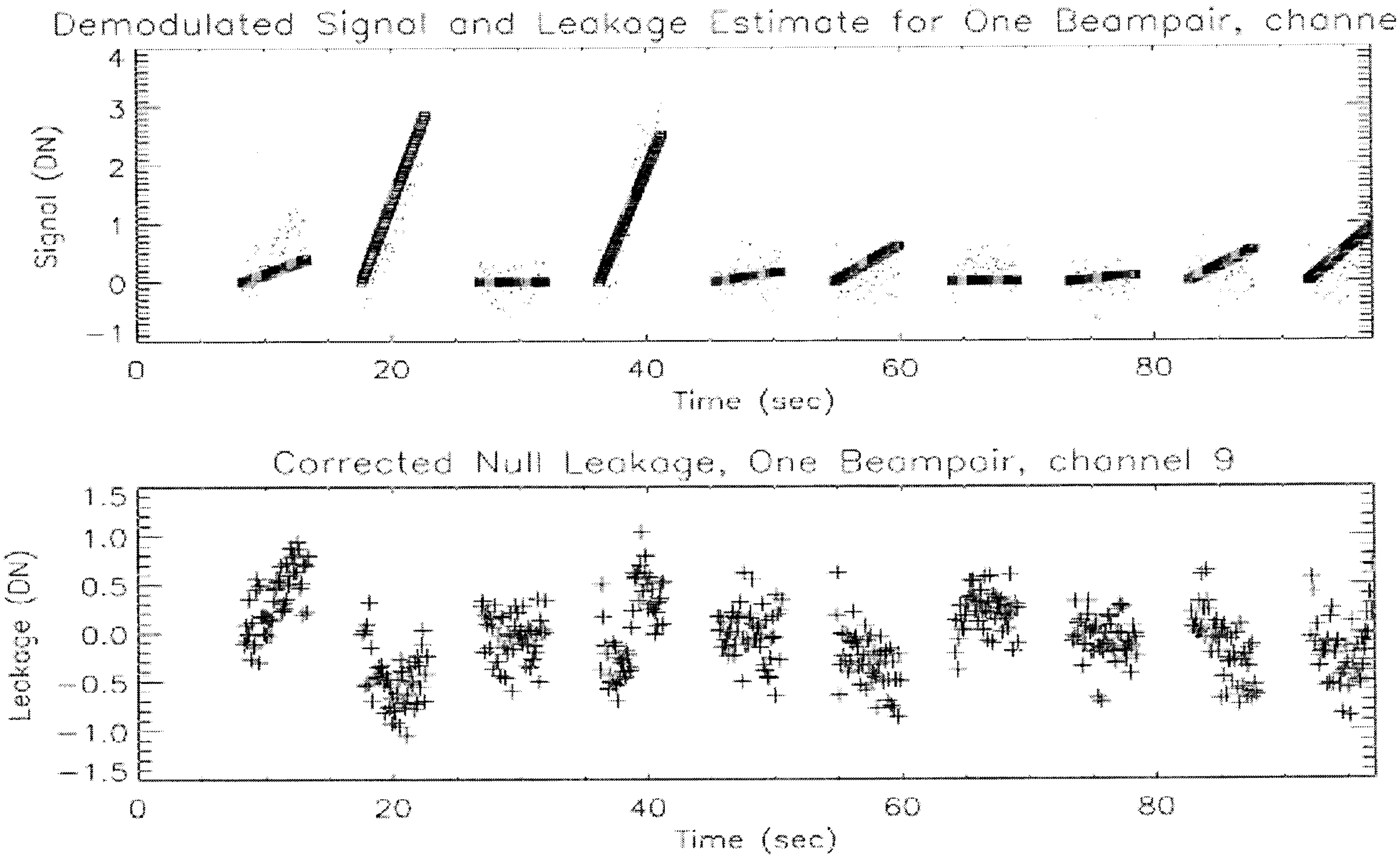


Displays:
- Camera Frame
- Flux vs Channel (plot)
- Flux vs Time (plot)
- Multifunction (plot)
  - H2O Seeing
  - Background
  - AO Throughput
  - Null Phase
- Shutters
- Irises
- ADCs
- FDLs
- XCs
- Outer and Common Mirrors

Controls
- Set optic positions
- Invoke Sequences

Status info

Simulated Data



Average over all 10 spectral channels and over the full experiment time

-> **Null depth = -7.6e-5 +/- 9.7e-5**

Nuller Status

Adaptive Optics working on both Kecks

Keck Interferometer First Fringes (in the 2.2 mm K band) March 12, 2001

Target star: HD 61249
Fringe tracker sensitivity now K~9

Single MMZ beam combiner assembled and tested at JPL

Narrowband (9-micron laser) null depth ~$2x10^{-4}$
Uses rotational shear instead of dispersion corrector

4-Way beam combiner assembly in progress

Dispersion Compensators

Prisms ordered
To be tested with MMZ in lab

Nuller Camera

Detector has arrived
Mechanical design being finalized (with Infrared Labs)
Electronics by Russell Wallace

Will it Work?

Yeah.