

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

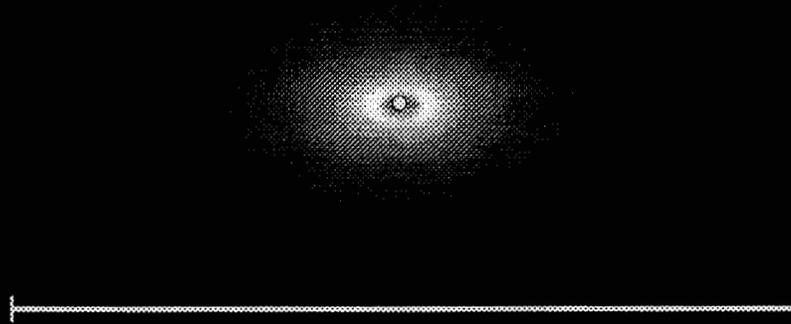
Evolved Stars and Dusty Envelopes

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Properties of the Zodiacal Dust Cloud

Solar Zodiacal Dust Disk at $11.25 \mu\text{m}$
Inclination 60°
(contrast moderately reduced and star removed)

Credit: Marc Kuchner's "ZodiPic"



1 AU (100 mas at 10 pc)

Total Flux in Disk: 7×10^3 Jy (1 Zodi)
Total Flux in Star: 2 Jy

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

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

Starlight is $\sim 2.5 \times 10^3$ 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

$$10 < D_{\text{pc}} < 20$$

$$\theta_{\text{phot}} \sim 1 \text{ mas (angular diameter of photosphere)}$$

$$\theta_{\text{exozodi}} \sim 20 \text{ mas (angular FWHM diameter of Zodi disk)}$$

Stellar Magnitudes: V~6, K~4, N~4

Sensitivity Goal: 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

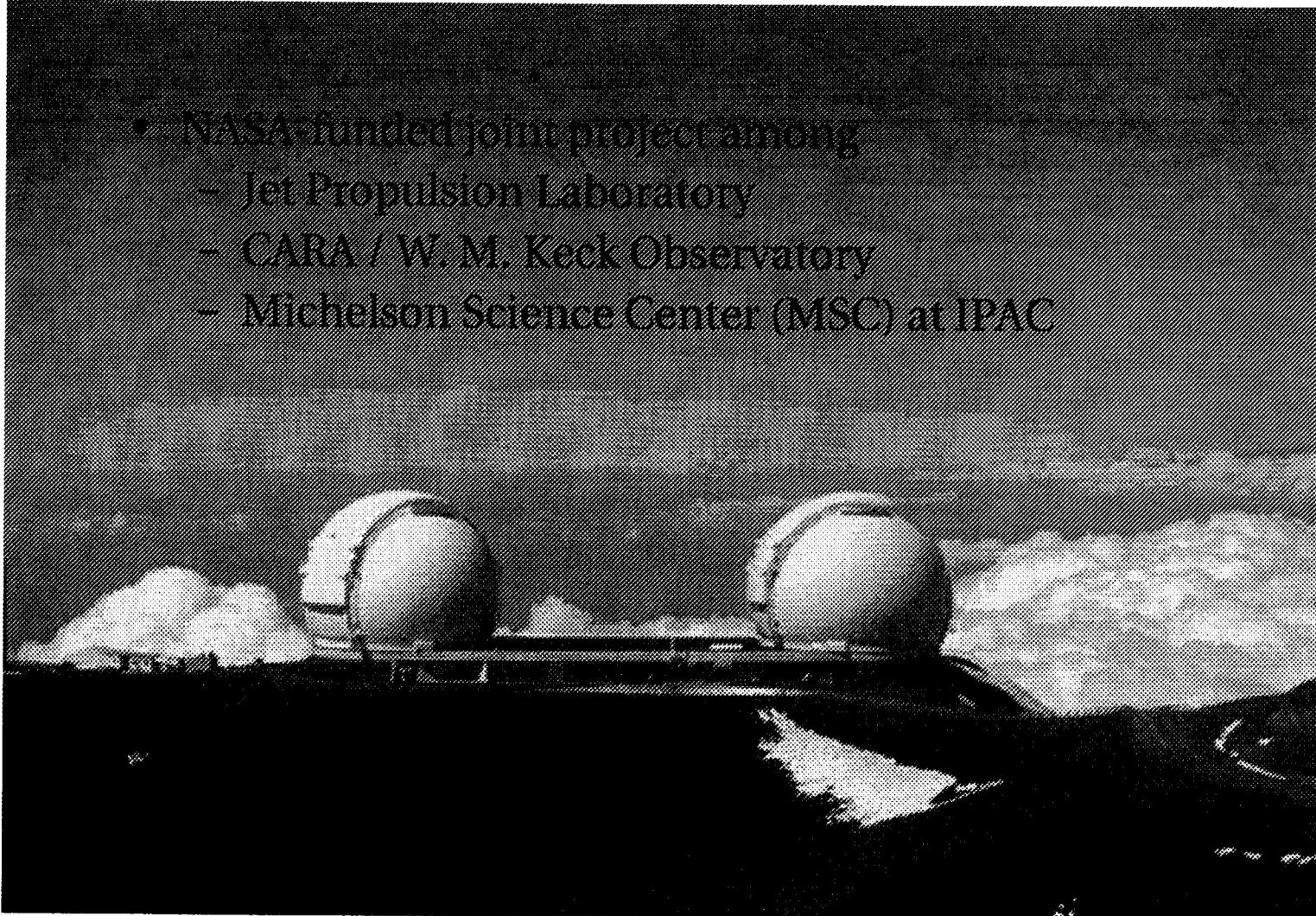
Near-IR fringe tracker

Dispersion Controllers

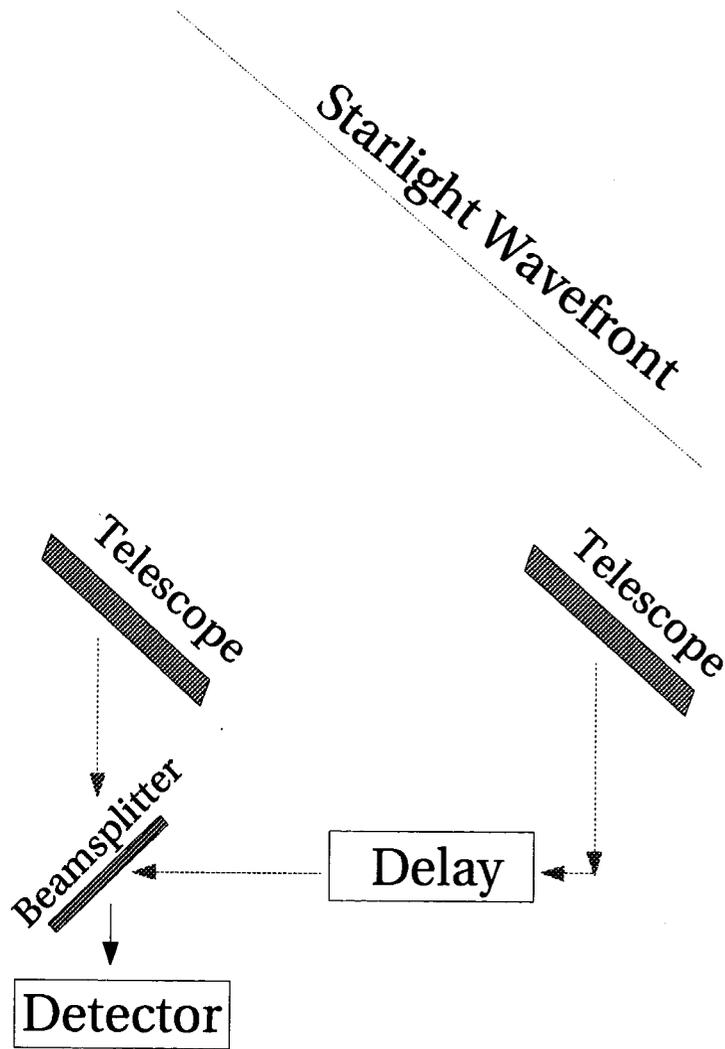
Intensity Controllers

The Keck Interferometer

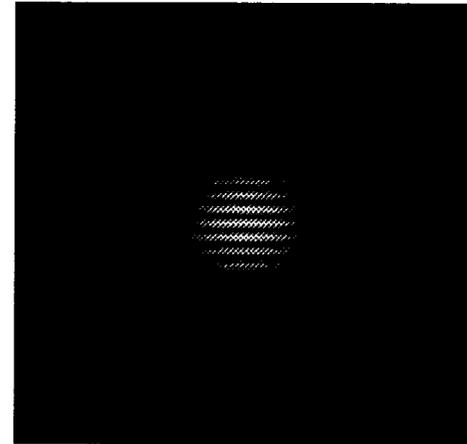
- NASA-funded joint project among
 - Jet Propulsion Laboratory
 - CARA / W. M. Keck Observatory
 - Michelson Science Center (MSC) at IPAC



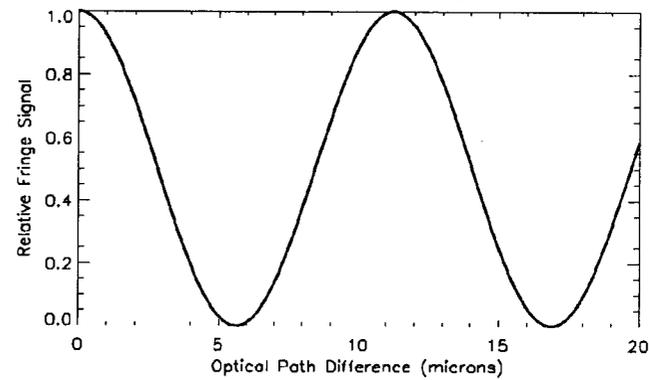
An Optical Interferometer



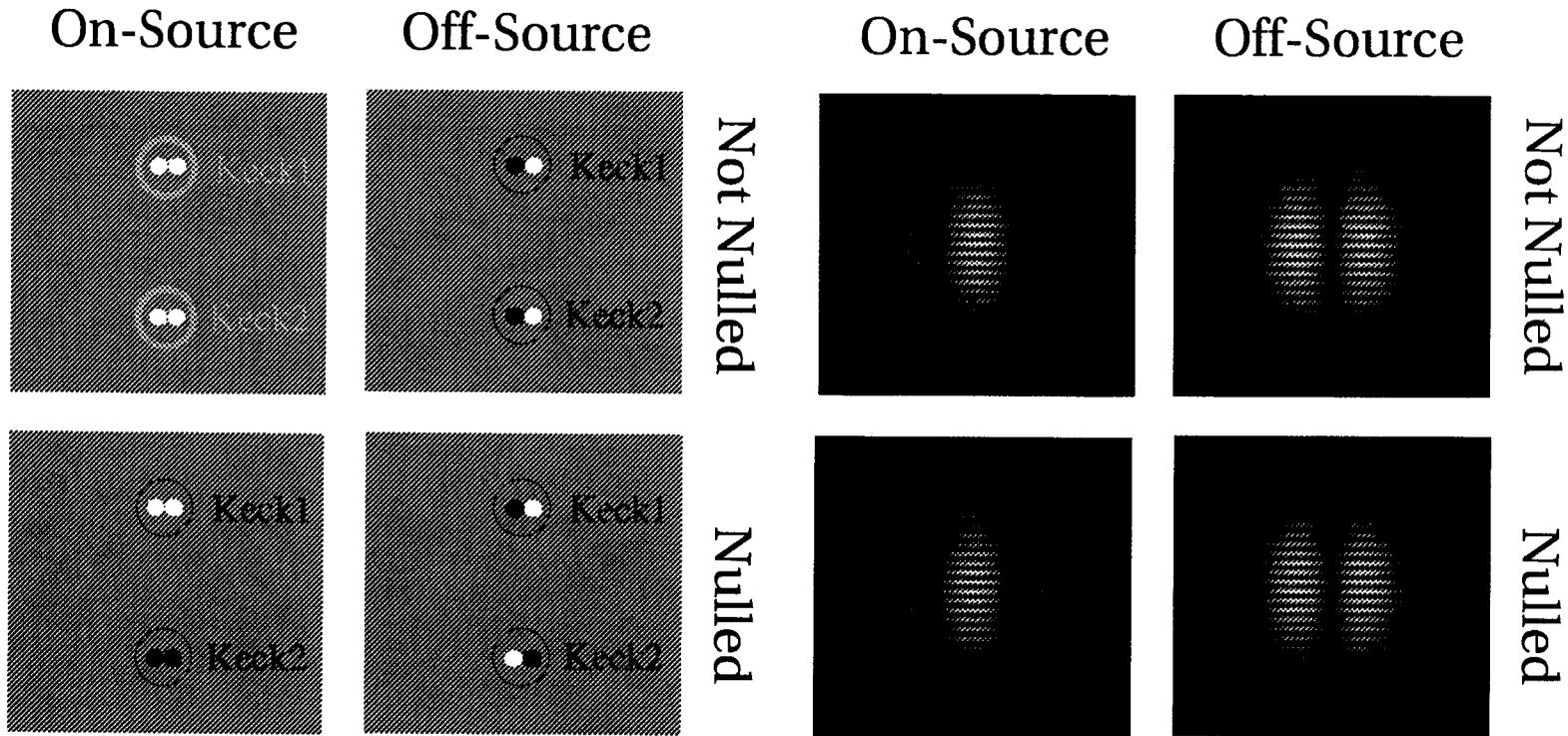
Beam Pattern on the Sky



Output Intensity vs OPD



Four-Beam Combiner



Input Apertures

Beam Pattern on the Sky

Wavefront phase: white=0, black= π

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

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

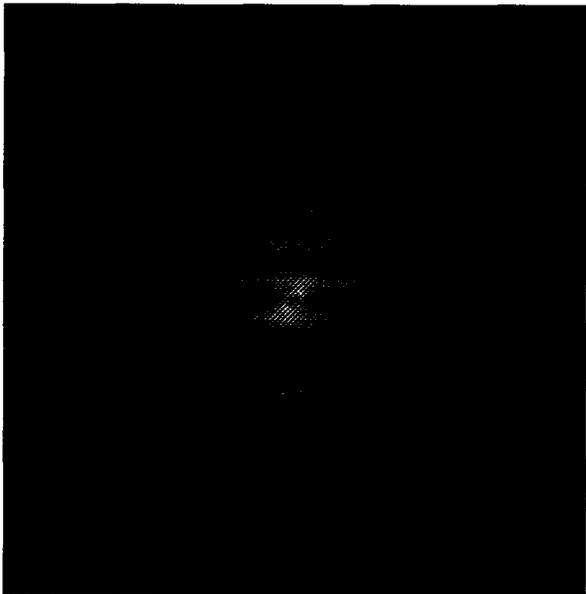
=> *does not destroy the null*

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:

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

where the α_i are amplitude imbalance terms:

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

(A_i = wavefront amplitude in beam i)

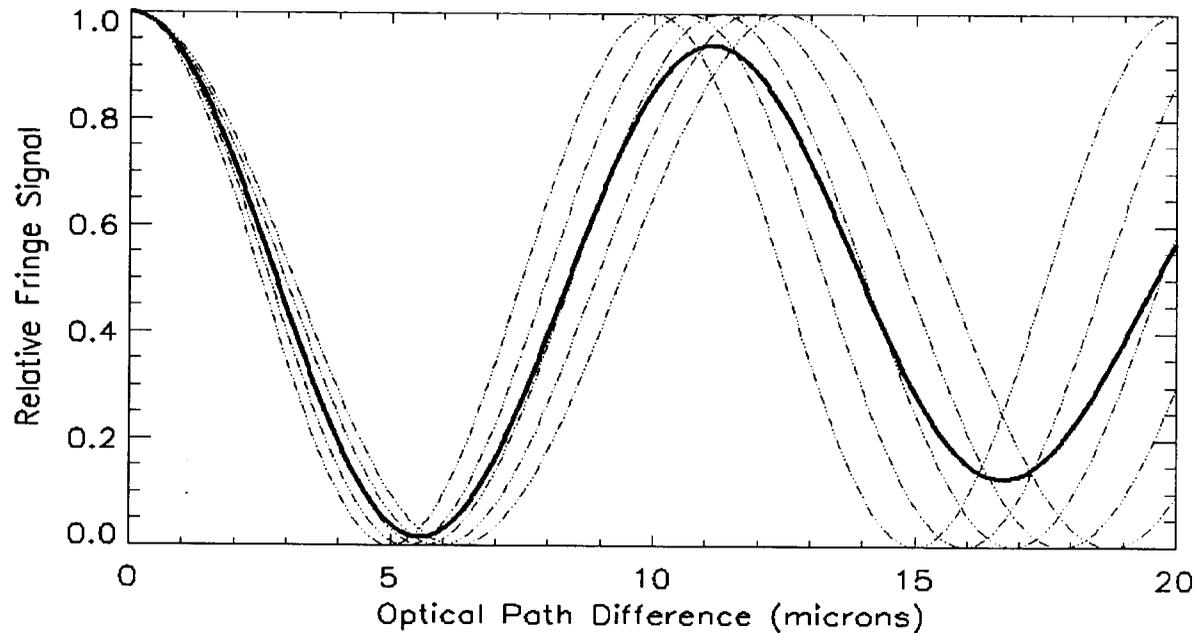
and the β_i are phase error terms.

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

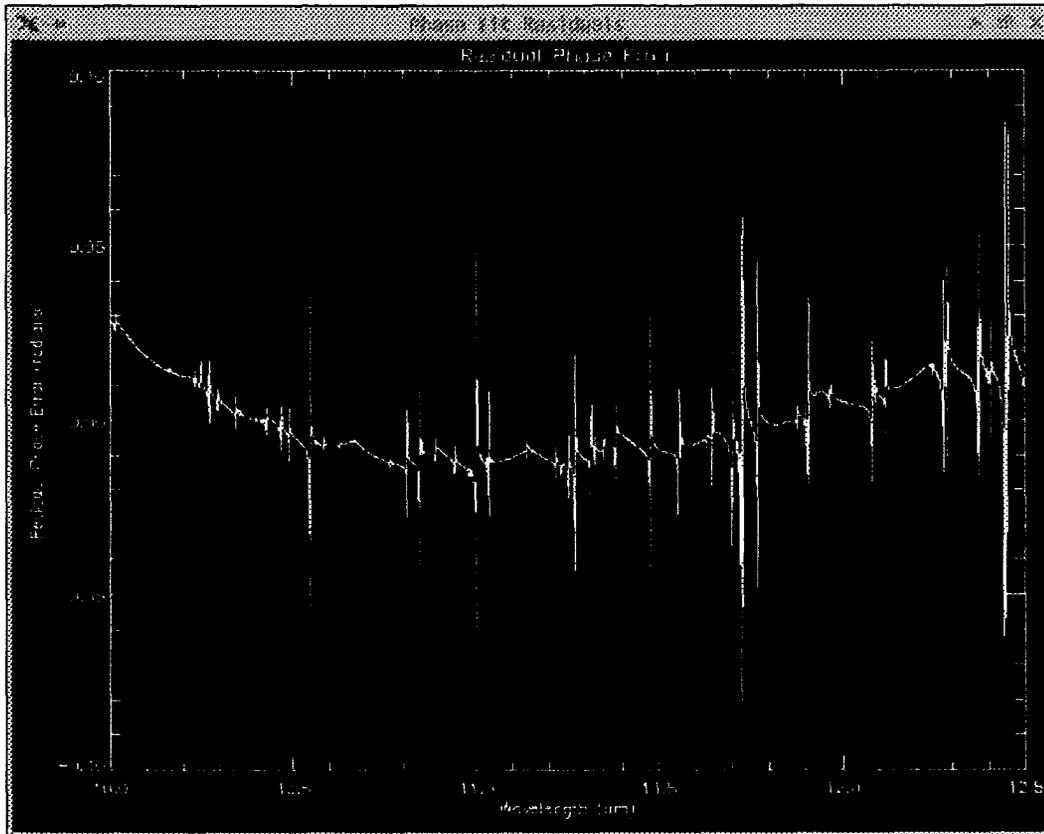
H₂O column fluctuations due to “H₂O seeing” are important

These set the maximum integration time between phase resets

	Dry Air	H ₂ O 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/cm³ of H₂O

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

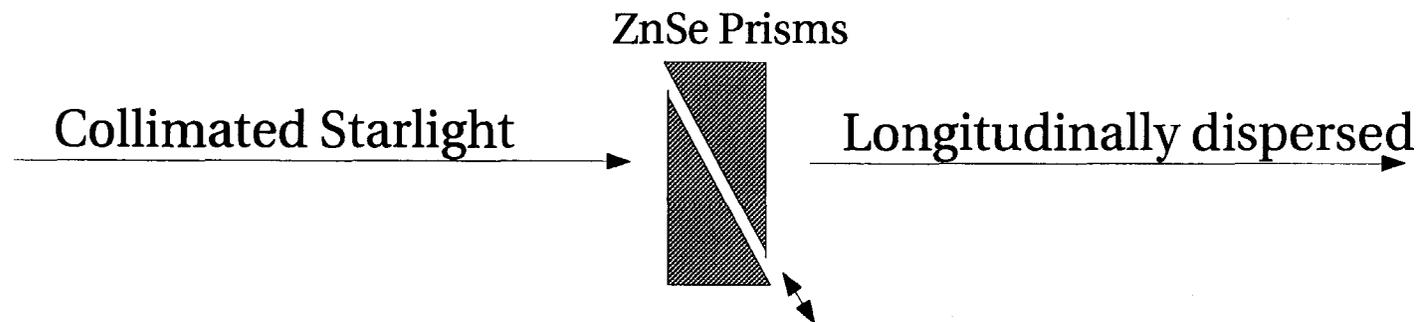
-> Must adjust the corresponding delay-line as well

Performance: (For a perfectly-adjusted DC)

Expect RMS phase errors ~ 0.02 radians from 10.0-12.5 microns

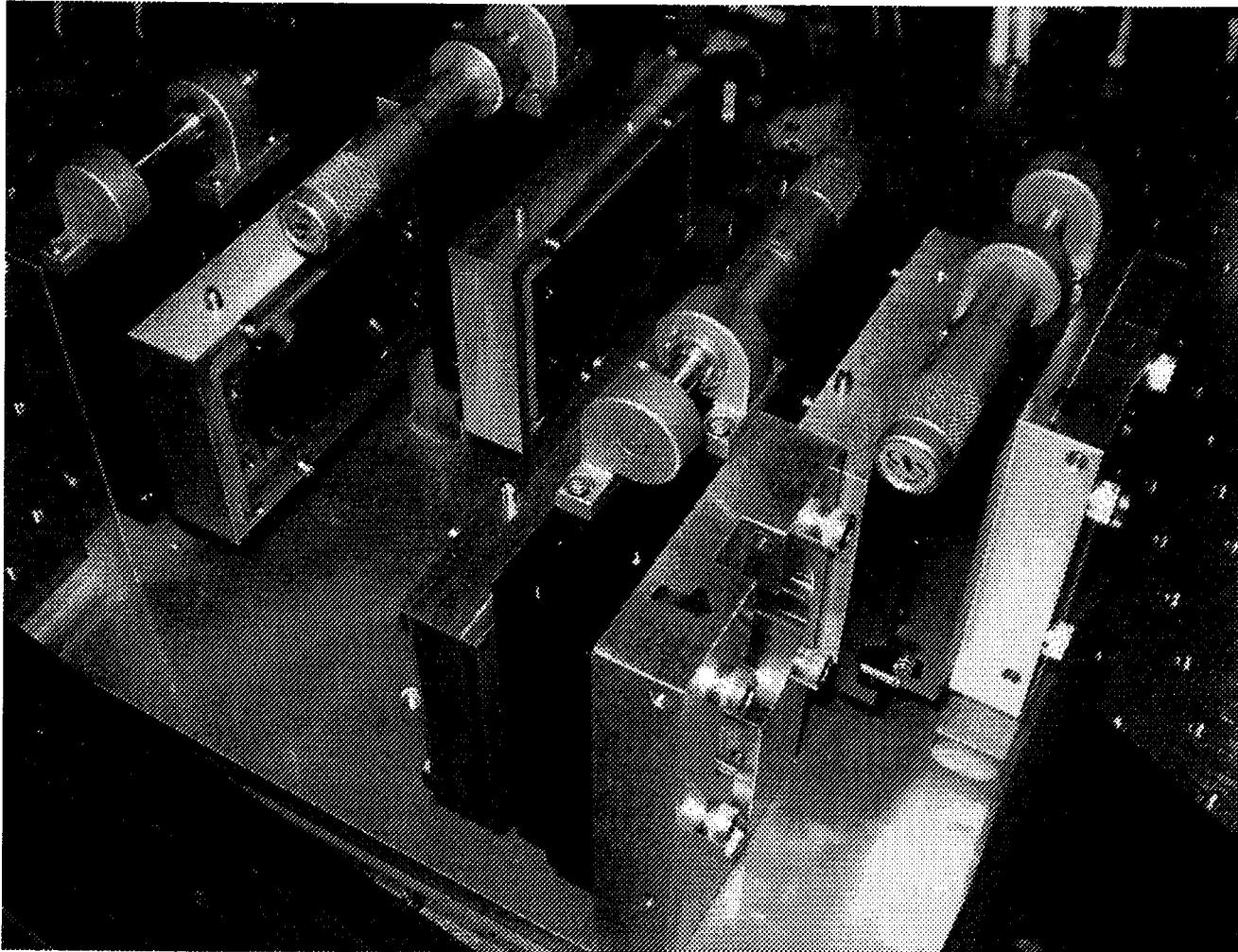
-> Null depth limited to $\sim 10^{-4}$

(assuming 60 m unbalanced airpath with humidity $\sim 30\%$)

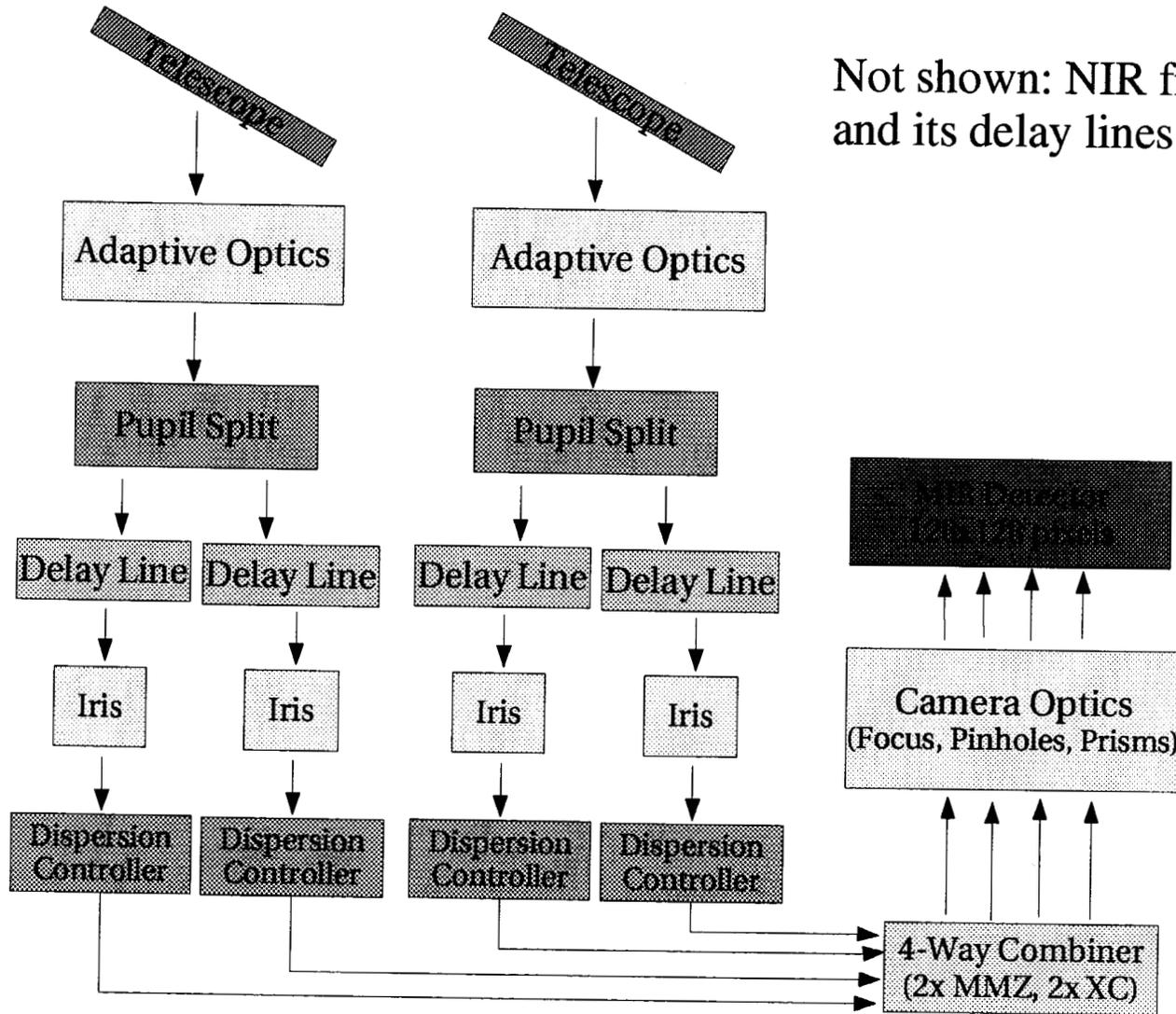


One prism moves parallel to common face

Dispersion Controllers (two beams)

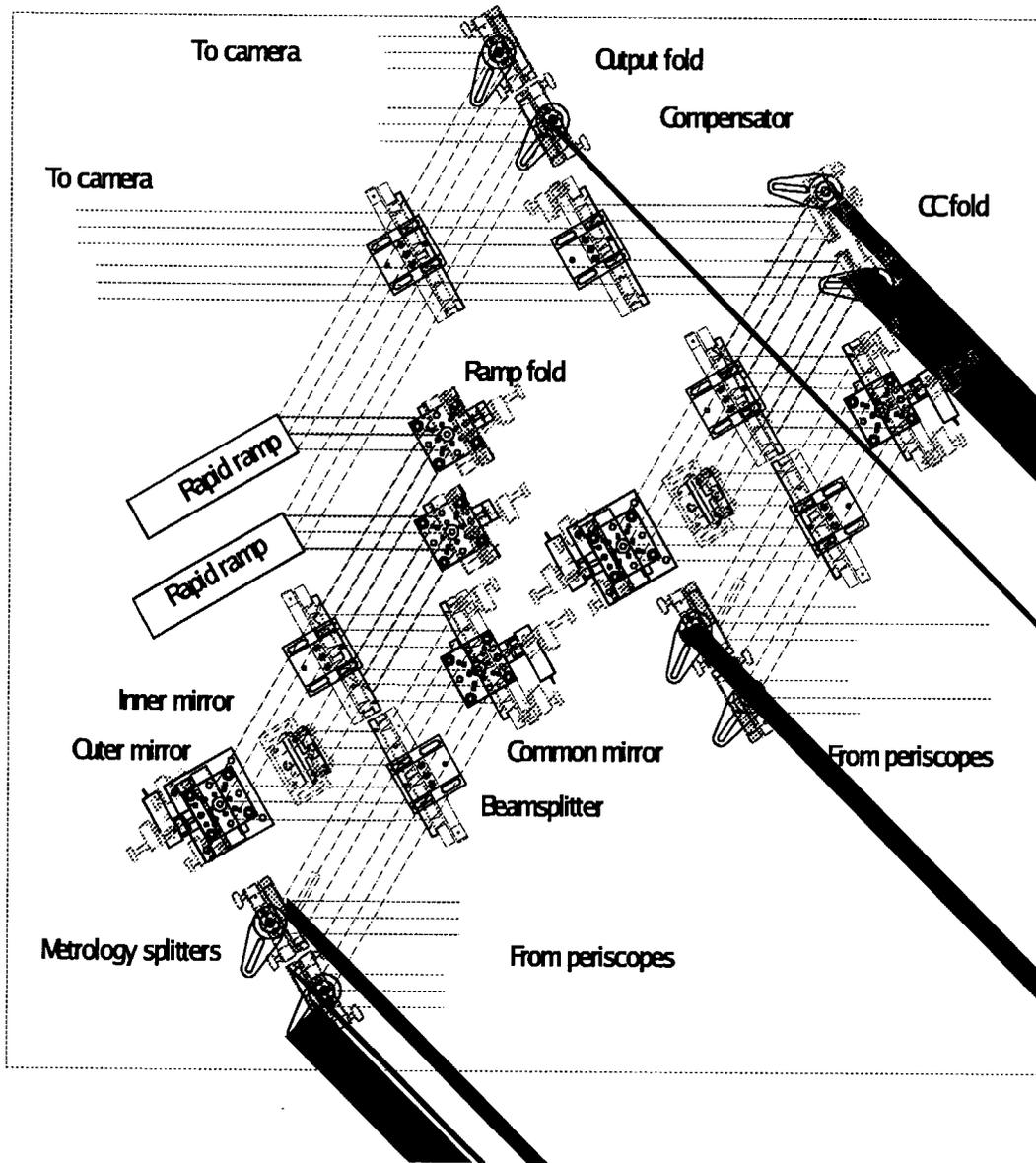


Hardware Overview



Not shown: NIR fringe tracker and its delay lines

Beam Combiner Schematic



Input Beams
"From Periscopes"

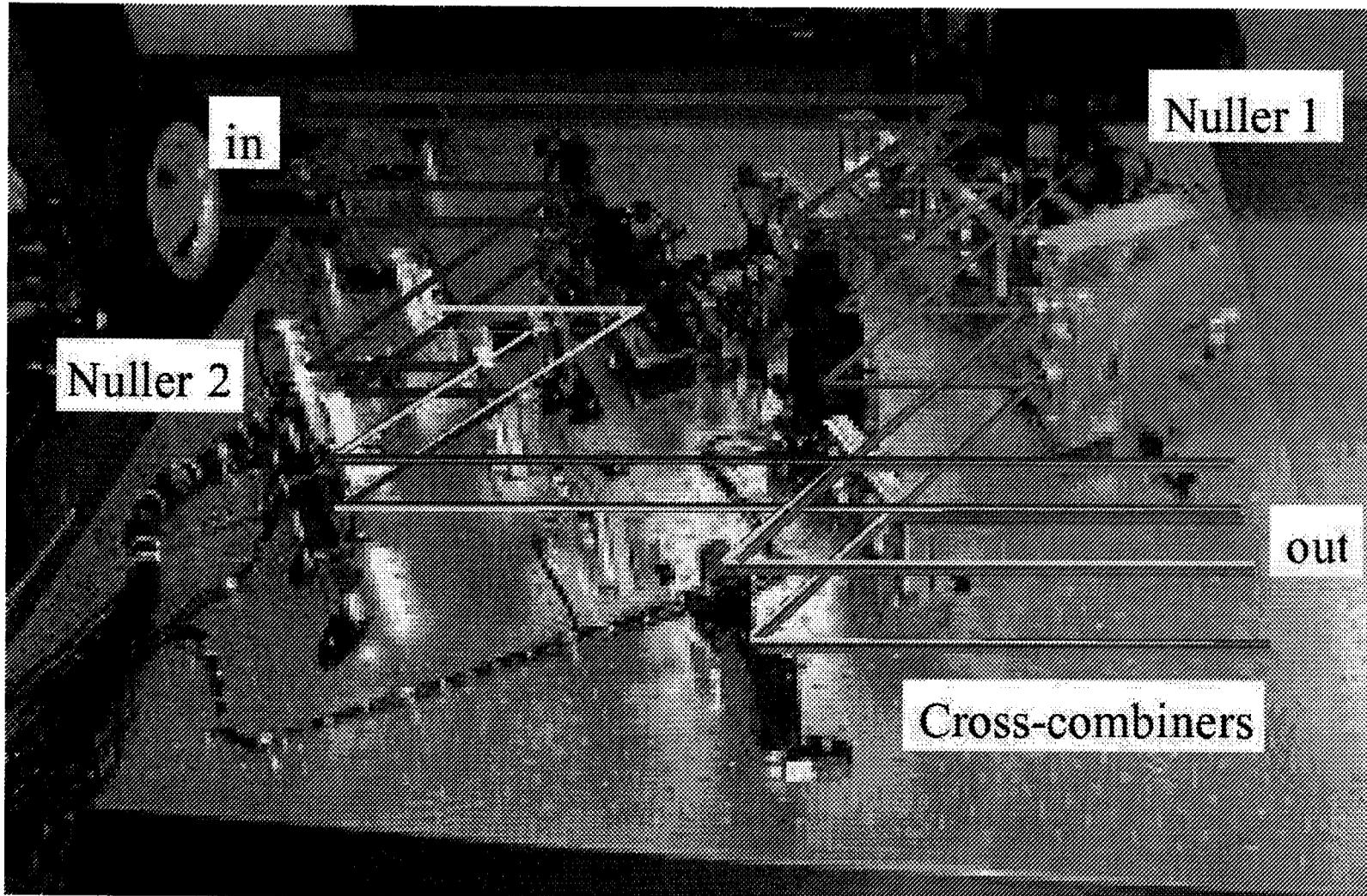
Modified Mach-Zehnder (MMZ) combiners for long baselines (one for the Left sides of both Kecks, and one for the Right sides).

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.



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 (baseline)

Dry Air: Static Term

4 Dispersion Correctors (one for each input beam):

ZnSe plates with adjustable thickness

Noise Sources

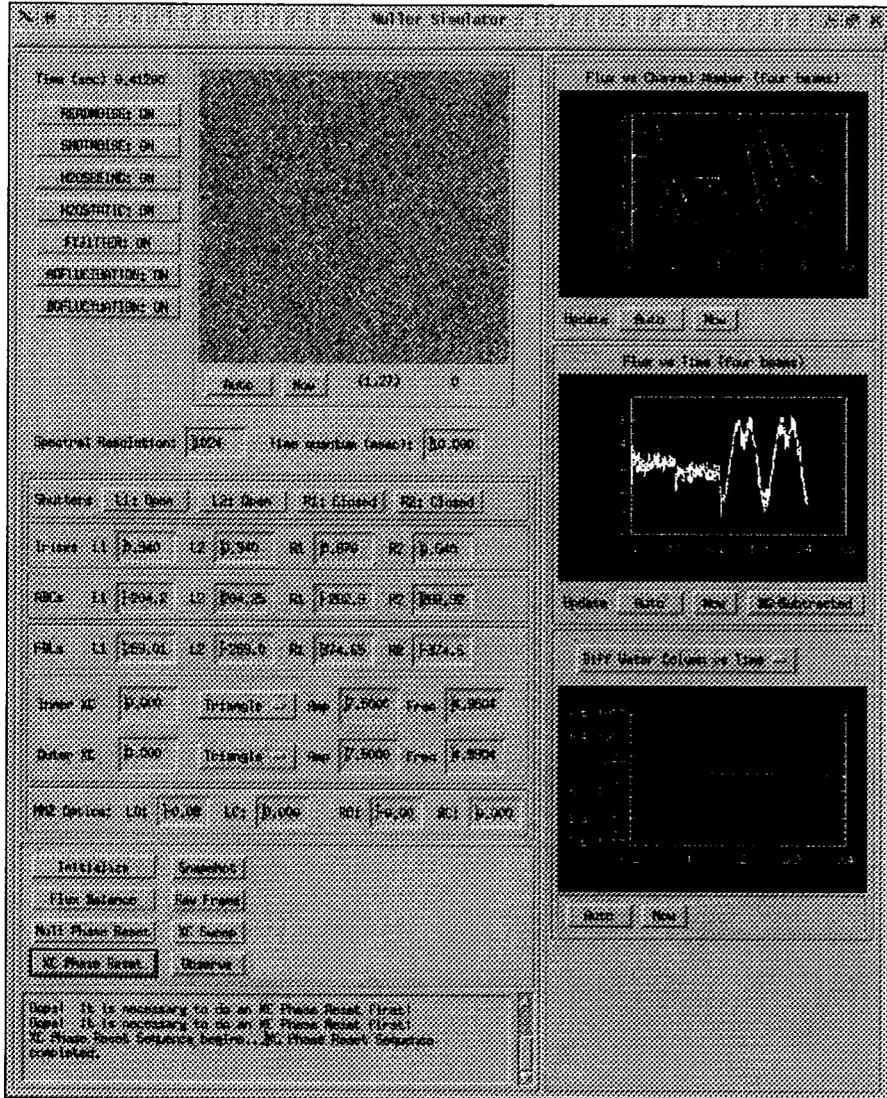
Detector readnoise (assume 1000 electrons)

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

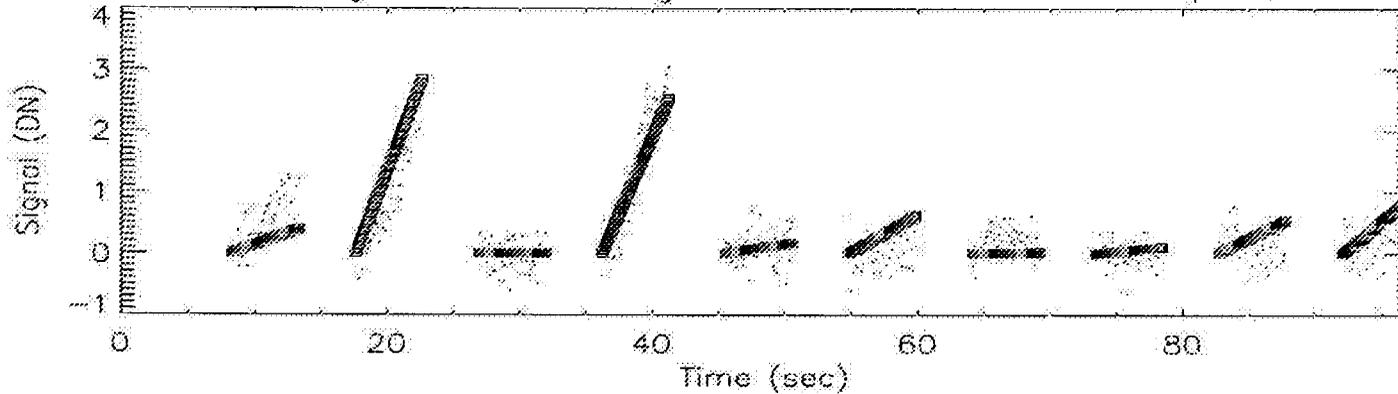
Controls

- Set optic positions
- Invoke Sequences

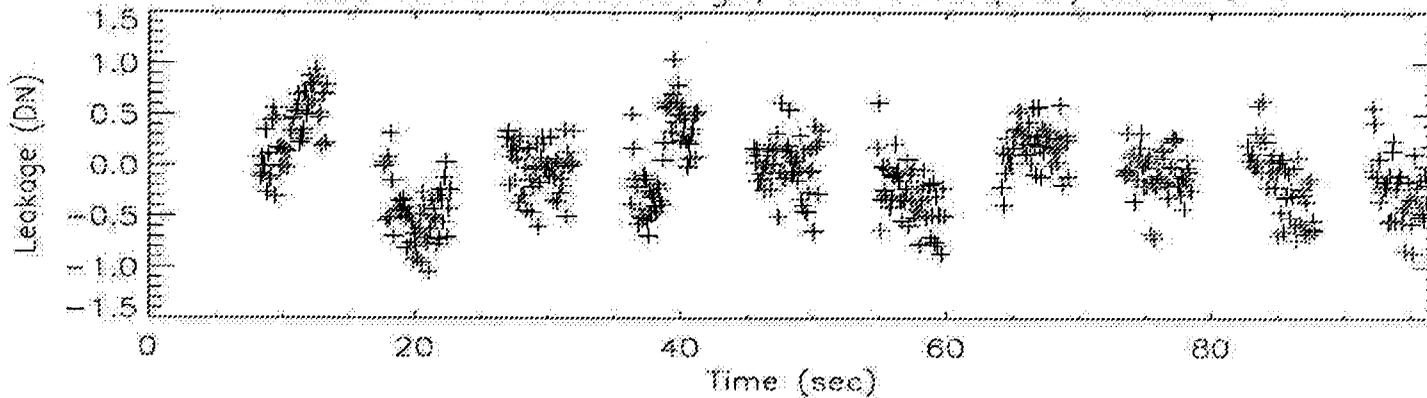
Status info

Simulated Data

Demodulated Signal and Leakage Estimate for One Beampair, channel



Corrected Null Leakage, One Beampair, channel 9



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

-> **Null depth = $-7.6e-5 \pm 9.7e-5$**

Nuller Status

Adaptive Optics working on both Kecks

Keck Interferometer NIR fringe tracker working

First fringes March 2001

Fringe tracker sensitivity now $K \sim 9$

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.