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Adaptive Nulling:

a new enabling technology for interferometric exo-planet detection

Muthu Jeganathan, Oliver Lay & Robert Peters

Jet Propulsion Laboratory

California Institute of Technology

TPF Expo – October 14-16, 2003

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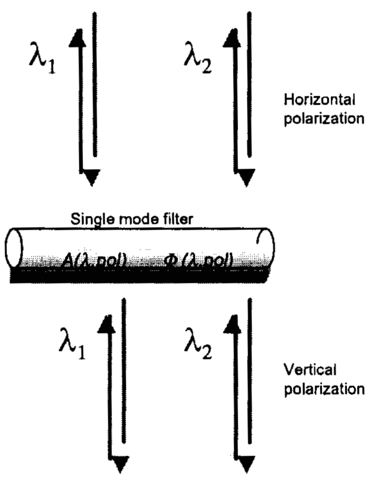
Nulling



- Deep null require electric fields with
  - equal amplitudes
  - opposite phases

  simultaneously at each wavelength and polarization
- Single-mode filter makes this simple (removes all spatial effects)

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TPF Interferometer Optical System

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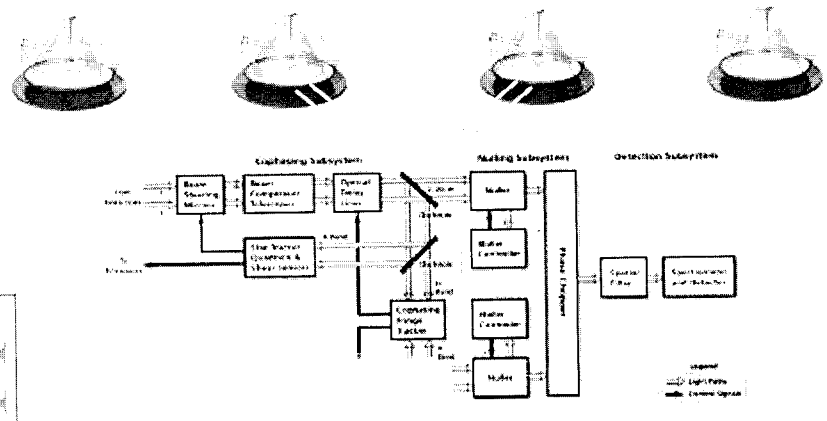

- The nuller is the *whole* instrument system, not just the nulling beam combiner
- A perturbation anywhere in the beam train will impact the null
- Focus has been on the nulling beam combiner

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Sources of Asymmetry

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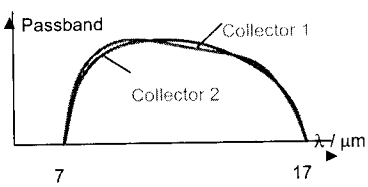

To meet nulling requirements:

- Amplitudes must be matched at 0.1% level
- Phases must be matched at 1 mrad level (λ/6000)

	Wavelength dependence	
	Amplitude	Phase
Mirror reflectivity	λ^0	?
Transmissive optics substrates	λ^0	λ^{-2}
Beamsplitter coatings	λ^0, ?	?
Dichroic coatings	λ^0	?
AR coatings	?	?
Ground contamination	?	?
Outgassing	?	?
Thruster contamination	?	?
Path offset	-	λ^{-1}
Wavefront error	λ^{-2}	λ^{-1}
Beam shear	λ^0	-
Diffraction	λ^0, λ^{-1}	λ^0, λ^{-1}

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Old Approach

[redacted]

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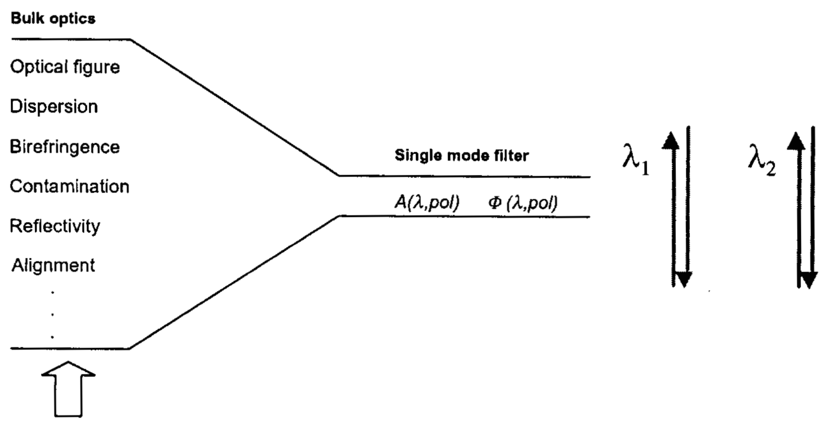

Control these quantities ⇒ tight tolerances

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New Approach

[redacted]

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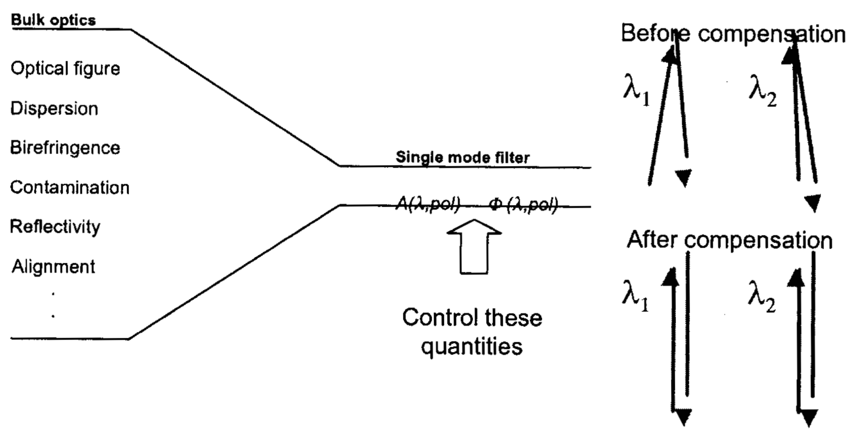

Include a compensator to actively control amplitude and phase for each polarization and wavelength

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Adaptive Nulling

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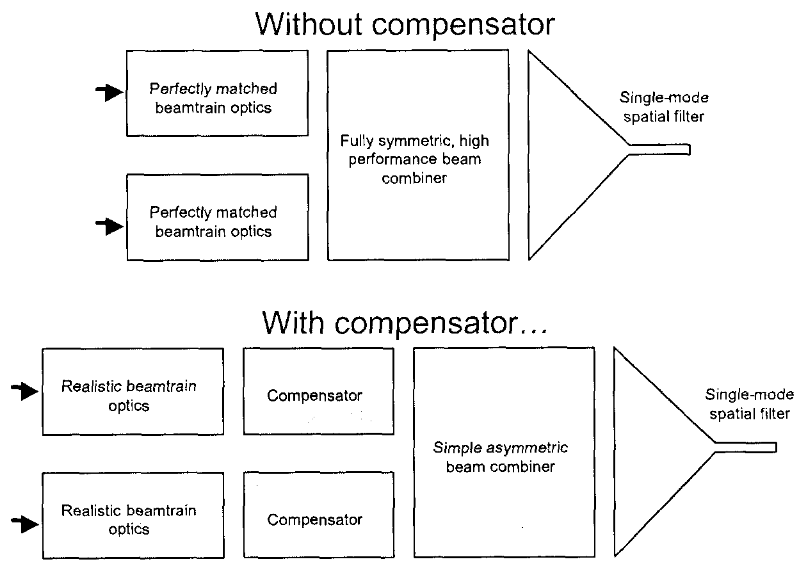

Advantages of Adaptive Nulling

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- Relax manufacturing and alignment tolerances throughout optical system
- Robust to in-flight perturbations (e.g. contamination, misalignment)
- Allows greater flexibility and simplicity in optical design (freedom from symmetry)
- Converts a system problem into a component problem, easing integration and test

“Serial Cascade” Concept

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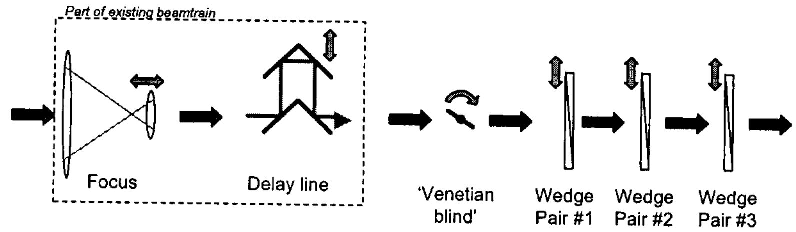

Amp	λ^{-2}		λ^{0}		λ^{-1}	
Phase		λ^{-1}		λ^{-2}		λ^{0}

- Low order spectral correction
- No control of separate polarizations

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“Parallel” compensator concept

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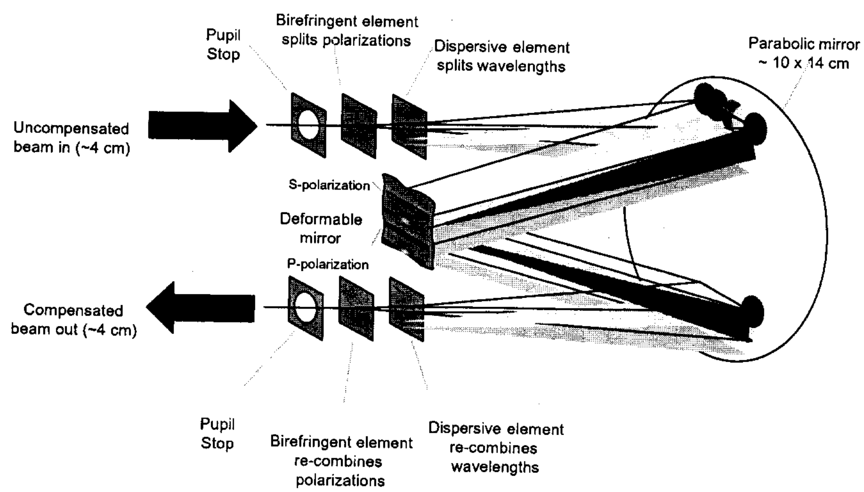

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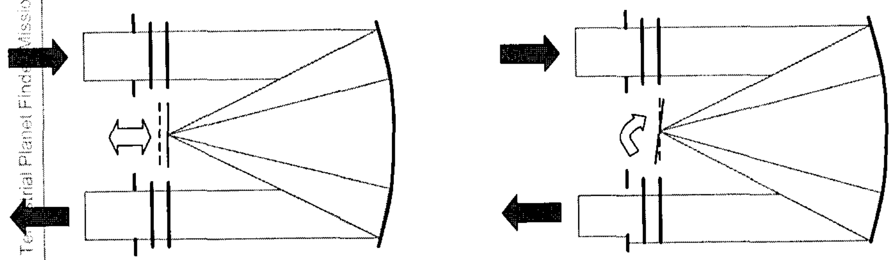
Phase and Amplitude Control

Phase control with piston*:

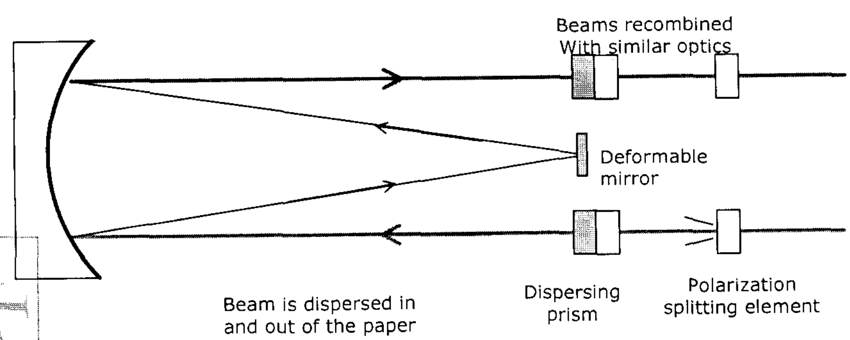
Amplitude control with tilt*:



* Side view, shown for single wavelength & polarization

- Deformable mirror allows independent control of piston and tilt at each wavelength and polarization
- Measure amplitude and phase for each spectral channel directly at science back end
- Quasi-static correction
- High-order spectral compensation

Mid-IR Lab Demo Schematic



Side view

Mid-IR Lab Demo Schematic

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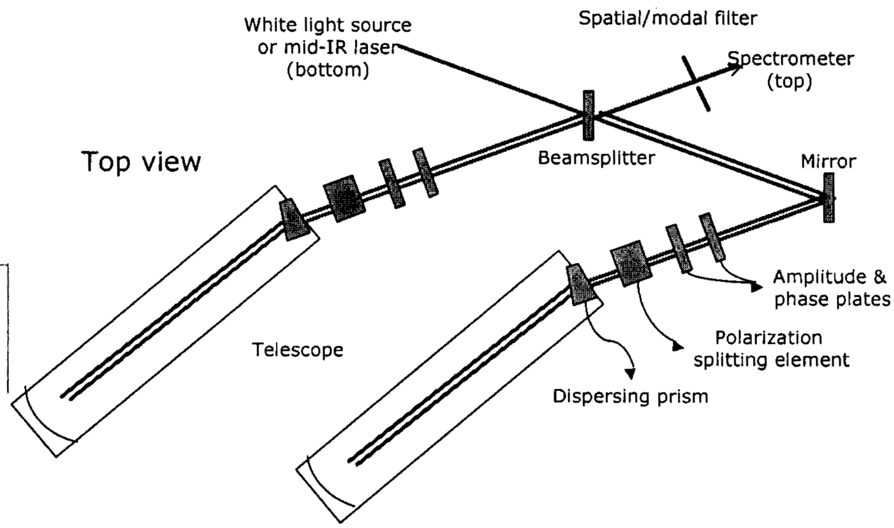

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Wavelength Separation

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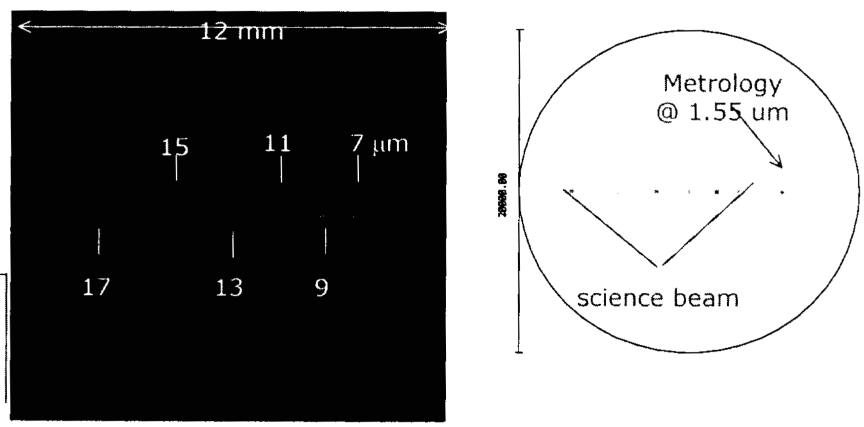

- 20 degree KBr wedge
- 0.75 m focal length parabolic mirror
- Metrology through compensator possible

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Polarization Separation

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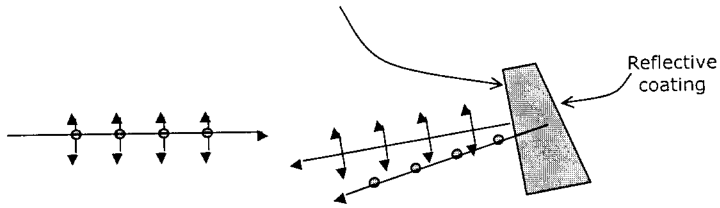
- Option I – birefringent material
  - Cadmium Selenide (CdSe) is the only birefringent crystal in Handbook of Optics that is transparent from 1 - 20 microns
- Option II – wire-grid polarizer



- Will pursue both options

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Proof-of-concept Visible Experiment

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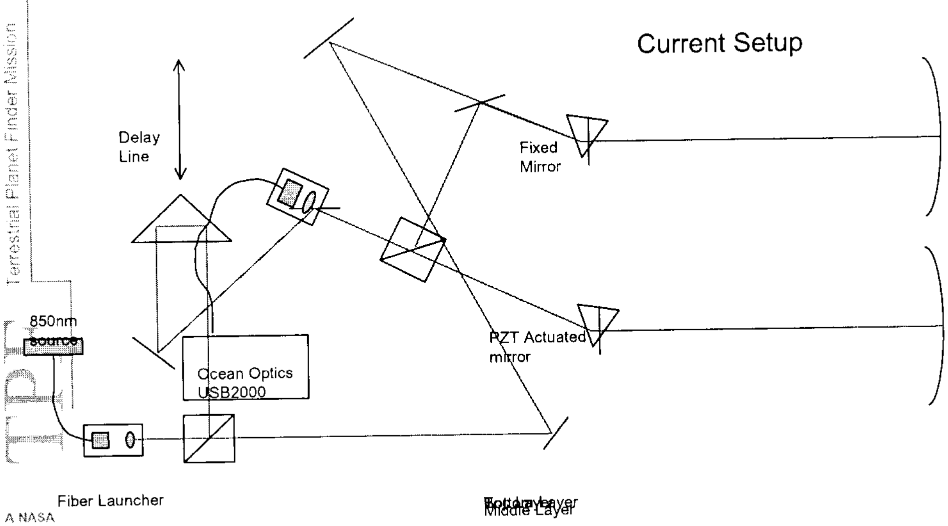

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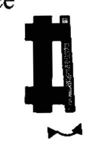
Progress to Date [redacted]

- Interfacing (LabVIEW enviroment)
  - Computer to PZT driver (through NI DAQ)
    - Tip and piston independently controlled with 3/5 2/5 split between phase and amplitude.
  - Spectrometer to computer (through USB)
- Phase control (with piston on PZT actuated mirror)
  - Better than 10nm stability with simple proportional-integral control algorithm.
  - 4um phase correction range with PZT actuators used.
  - Dominated by air-path disturbances.

- Amplitude control (with tilt on the PZT actuated mirror, reference beam blocked)
  - Achieved ~12% amplitude reduction with sheer.
  - Less than 1% amplitude variation over 10 minute timescale.



Boston MicroMachines MEMS DM [redacted]

- 12 x 12 (140) actuators on a 3.3mm square gold coated aperture.
- 2um Stroke
- 7kHz bandwidth
- System includes deformable mirror, driver electronics, control computer, software, power supply, mirror mount, and all cables and assemblies.

Spectrometer Outputs

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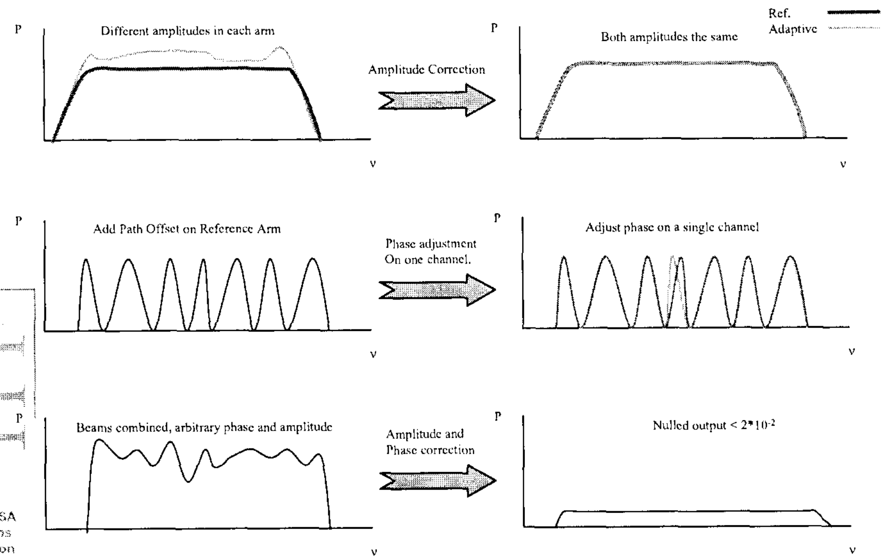

Technology Development Plans

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- Full Visible/near-IR proof-of-concept demonstration (Sept 2004)
  - 820-980 nm
  - Amplitude control (5%)
  - Phase control (15 nm)
  - Nulling (0.02)

- Mid-IR demonstration (February 2006)
  - 8-12 micron band
  - Amplitude control (0.1%)
  - Phase control (1 nm)
  - Nulling (10^{-5})

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Summary

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- Adaptive Nulling gives us full control of the spectrum

- A successful mid-IR demonstration would lead to TPF interferometer designs that are
  - Simpler (asymmetric beam combiners)
  - Cheaper (relaxed tolerances, less analysis needed)
  - More robust
  - More flexible
  - Easier to integrate and test

- Established feasibility of an Adaptive Nulling compensator with current technology
  - remaining concerns are cryogenic operation of DM & its stability

- 2-year tech development and demonstration program underway

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Challenges for current approach

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- Nulling is a system-wide issue, driving tight tolerances...
  - primary mirror
  - beam transport
  - coatings
  - beam combiners

- ...and challenging Integration & Test

- Difficult to achieve deep null over broad bandwidth (7-20 um) with single nuller

- Null is sensitive to in-flight perturbations, e.g.
  - Contamination on optical surfaces
  - Mis-alignment

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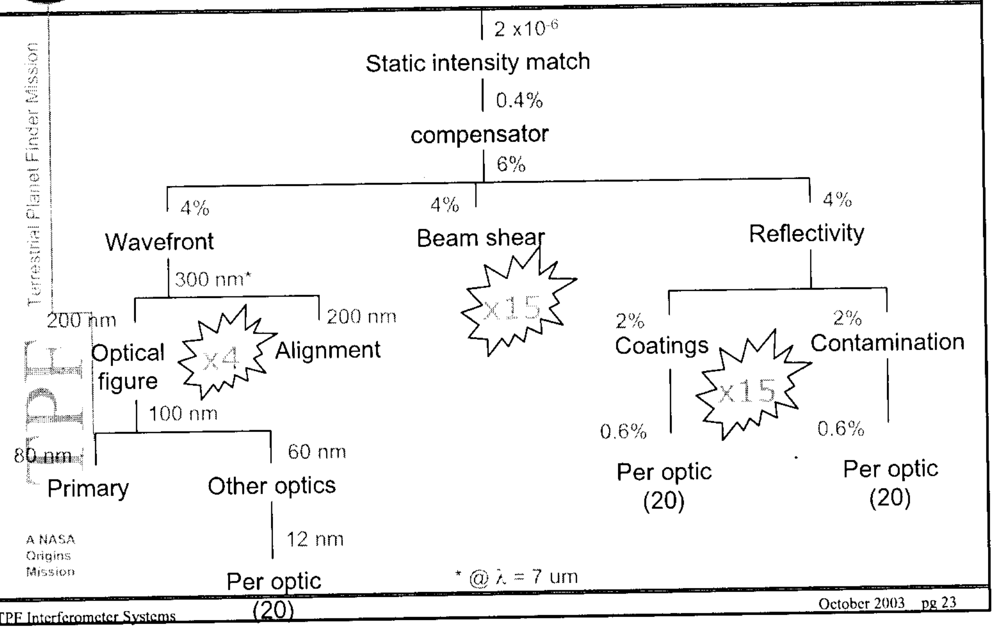
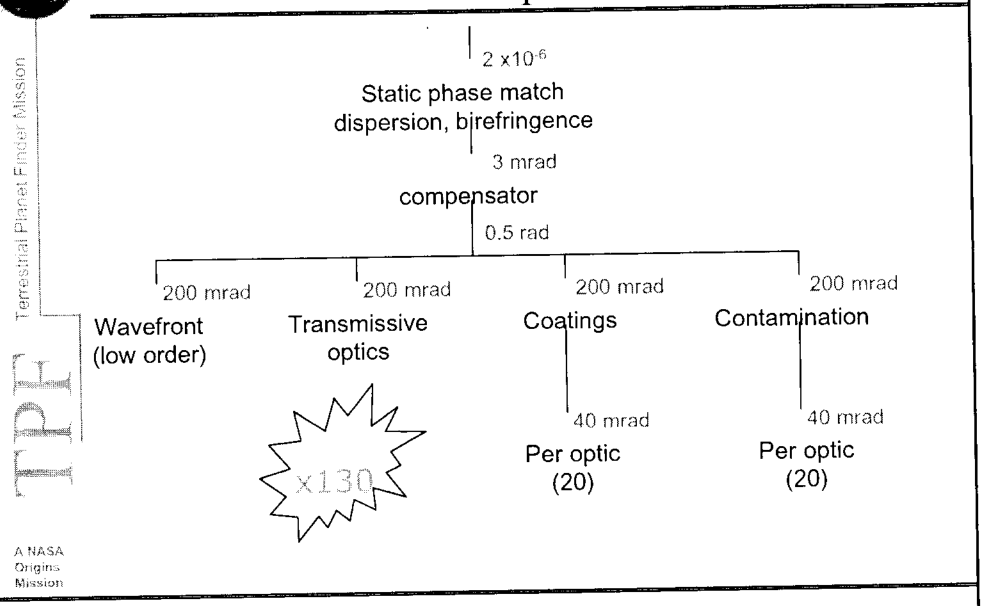
Intensity Match Requirements



Phase Match Requirements



Abstract

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Deep, stable nulling of starlight requires careful control of the amplitudes and phases of the beams that are being combined. The detection of earth-like planets using the interferometer architectures currently being considered require that the electric field amplitudes are balanced at the level of ~ 0.1%, and the phases are controlled at the level of 1 mrad (corresponding to ~ 1.5 nm for a wavelength of 10 microns). These conditions must be met simultaneously at all wavelengths across the science band, and for both polarization states, imposing unrealistic tolerances on the symmetry between the optical beamtrains. We introduce the concept of a compensator that is inserted into the beamtrain, which can adaptively correct for the mismatches across the spectrum, enabling deep nulls with realistic, imperfect optics. The design presented uses a deformable mirror to adjust the amplitude and phase of each beam as an arbitrary function of wavelength and polarization. Preliminary results from a proof-of-concept visible/near-IR experiment as well as plans for an mid-IR demonstation will be presented.

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