Adaptive Nulling for the Terrestrial Planet Finder Interferometer

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Outline

• Background
• How it works
• Development activities
• Summary
Nulling in TPF-I

- For deep null require electric fields with
  - equal amplitudes
  - opposite phases

- simultaneously at each wavelength and polarization

- Single-mode filter makes it easier
  - Removes all spatial effects
Why Do Adaptive Nulling

Include a compensator to actively control amplitude and phase for each polarization and wavelength at low bandwidth.
Parallel high-order compensator design

Uncompensated beam in (~4 cm)

Parabolic mirror
~ 10 x 14 cm

Dispersive element splits wavelengths

Birefringent element splits polarizations

Pupil Stop

Compensated beam out (~4 cm)

Pupil Stop

Dispersive element re-combines wavelengths

Birefringent element re-combines polarizations

Deformable mirror

S-polarization

P-polarization
Phase and Amplitude Control

- Deformable mirror allows independent control of piston and tilt at each wavelength and polarization

* Side view, shown for single wavelength & polarization
Development activates

- **Proof-of-concept experiment** ($\lambda = 0.8$ to $0.9$ µm)
  - Less expensive optics and detectors
  - Relaxed/scaled requirements
  - Demonstrate feasibility of the design
  - Gain experience with the control system
  - Status: Complete – all requirements met/exceeded.
    - Results presented at SPIE 05 Annual Meeting, San Diego.

- **Mid-IR experiment** ($\lambda = 8$ to $12$ µm)
  - Requirements traceable to flight needs for phase and intensity control
  - Demonstrate the functionality of the design
## Requirements

<table>
<thead>
<tr>
<th>#</th>
<th>Requirement</th>
<th>mid IR</th>
<th>Flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wavelength range of operation</td>
<td>8 – 12 µm</td>
<td>7-17µm</td>
</tr>
<tr>
<td>2</td>
<td>Metrology wavelength</td>
<td>1.319 µm</td>
<td>0.5 - 2 µm</td>
</tr>
<tr>
<td>3</td>
<td># independent spectral degrees of freedom</td>
<td>&gt; 5</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>4</td>
<td># independent polarization states</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Null depth across the band</td>
<td>&lt; 10^{-5}</td>
<td>&lt; 10^{-5}</td>
</tr>
<tr>
<td>6</td>
<td>Amplitude correction range</td>
<td>&gt; 5%</td>
<td>&gt; 5%</td>
</tr>
<tr>
<td>7</td>
<td>Amplitude precision / stability (1 σ)</td>
<td>&lt; 0.12%</td>
<td>&lt; 0.1%</td>
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<tr>
<td>8</td>
<td>Phase correction range</td>
<td>&gt; 1 µm</td>
<td>&gt; 2 µm</td>
</tr>
<tr>
<td>9</td>
<td>Phase precision / stability (1 σ)</td>
<td>&lt; 5 nm</td>
<td>&lt; 1 nm</td>
</tr>
<tr>
<td>10</td>
<td>Throughput reduction</td>
<td>&lt; 50 %</td>
<td>&lt; 50 %</td>
</tr>
<tr>
<td>11</td>
<td>Polarization isolation</td>
<td>NA</td>
<td>&gt; 50 dB</td>
</tr>
</tbody>
</table>
Simplified Experimental Setup

- Mach-Zehnder type interferometer
- Reference is a “fixed” version of the adaptive nuller.
- Laser metrology to maintain a stable difference between the two arms.
Intensity Correction

- Block each arm and measure the spectrum
- Calculate the difference/sum = % difference
- Positive = more light in the adaptive nuller arm

![Graph showing intensity correction](image)
TPF plans to use the adaptive nuller in a “quasi-static” mode.
- Once adjusted, it will need to hold through the measurement without drifting.
- Correction is made once at T=0, RMS of intensity dispersion is measured over time.
Things left to do

- Phase dispersion adjustment.
  - Phase dispersion is measured with spectral fringes
  - Optical path difference needs to be stabilized during spectral measurement.
  - Fine-tuning optical metrology, we expect results soon.
- Cross-coupling effects
  - Intensity causes phase error, and vise versa.
  - Would converge after 4-5 iterations in the near-IR.
- Measure null improvement.
  - Also requires the optical path difference be stabilized during measurement
- Improvements to spectrometer
  - Linear mercury-cadmium-telluride array.
    - Much faster than single pixel scanning spectrometer
  - All reflective optics (Remove germanium lens)
    - More throughput
  - New single mode fiber
    - Even more throughput.
Summary

- Adaptive nulling eases requirements on optics and beam combiner
  - Realistic manufacturing tolerances
  - Does not require a highly symmetric beam combiner
- Design for a parallel high-order compensator
  - Based on a deformable mirror actuator
- Mid-IR experiments in progress
  - Intensity correction working well.
  - Metrology to stabilize path for phase correction.
  - Examine the cross-coupling effects, make null measurements.
BACKUP

SLIDES
Near-IR Intensity dispersion

- Due to difference in coated optics.
- Still need to generate intensity dispersion in mid-IR
Deformable Mirror

- MEMS deformable mirror from Boston Micromachines.
- 140 actuators (12x12 – 4 corners)
- 3mm square continuous membrane
- ~1.8µm travel per actuator

- Tilting every other actuator
- 8 actuators to control the spectrum
Phase Measurement

- Based on a Hilbert transform.
- Measure spectrum with path offset from null
  - Fourier transform
  - Filtering
  - Inverse Fourier transform
  - Remove linear part (OPD)

- Final output is residual phase versus wavelength
- Measured residual agreed with calculated residual for a BK7 window in one arm.
Long term stability – near-IR

- TPF plans to use the adaptive nuller in a “quasi-static” mode.
- Once adjusted, it will need to hold through the measurement without drifting.
- Mean and peak/valley of each spectral measurement is plotted over time to show stability.
Mid-IR components

• Using ceramic heater as source
• Transmissive optics replaced with appropriate materials (ZnSe)
• Wollaston prism tested separately.
  – CdSe is the only birefringent material
  – Manufactured by Cleveland Crystals
  – Cost ~ $27k each.
  – Test sample had good agreement with our Zemax model.
• Built a mid-IR spectrometer
  – Grating and single pixel mercury cadmium telluride detector on a computer controlled translation stage