Nulling Coronagraph

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- A coronagraph based on nulling interferometry, architecture of a nulling coronagraph
- Deep nulls, Contrast ≠ starlight suppression
- Post coronagraph wavefront sensing and PSF subtraction
High Contrast imaging with a Nulling Interferometer

Nulling interferometer when the Shear (baseline) > D (dia of telescope) (eg $\lambda = 10$um)

Nulling coronagraph when the Shear (baseline) < D (dia of telescope) (eg $\lambda = 0.5$ um)
2-arm vs. 4-arm Nulling Interferometers

2 arm:
\[ I = \left| A_0 e^{i\phi_x} - A_0 e^{-i\phi_x} \right|^2 \]
\[ \approx I_0 \left( kb \cos \phi \right)^2 \theta^2 \]

4 arm:
\[ I = \left| A_0 e^{i\phi_x} - A_0 e^{-i\phi_x} + A_0 e^{i\phi_y} - A_0 e^{-i\phi_y} \right|^2 \]
\[ \approx I_0 \left( \frac{kb}{2} \right)^4 \cos^2(2\phi)\theta^4 \]
• At ~4 \( \lambda/D \) the airy function is ~ \( 10^{-3} \) of the peak
• At ~2 \( \lambda/D \) the airy function is ~ \( 10^{-2} \) of the peak

• Starlight suppression of \( 10^{-7} \) will yield a contrast of \( 10^{-10} \) at 4 \( \lambda/D \)
Symmetric nuller
    equal # mirror reflections, BS ref, and AR transmission in two arms.
    Polarization and spectrally balanced

Single mode fiber output
    Inside a single mode fiber a perfect null can be obtained by controlling just two parameters, phase and amplitude
Monochromatic (635nm) Light Nulling

- Laser data:
  - Optical path error of 90 picometer will cause $2 \times 10^{-10}$/airy spot null leakage
  - rms vibration and drift over ~15 sec is ~60pm
- $1.2 \times 10^{-7}$ suppression $\sim 1.2 \times 10^{-10}$ contrast @ $4 \lambda/D$

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<table>
<thead>
<tr>
<th>Source Null</th>
<th>Pupil Rotation</th>
<th>Intensity Mismatch</th>
<th>Pathlength Fluctuations</th>
<th>Birefringence</th>
<th>Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value achieved</strong></td>
<td>0.01 Deg</td>
<td>0.03%</td>
<td>0.06 nm, rms</td>
<td>0.04 nm</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Contribution to Null</strong></td>
<td>7.6E-9</td>
<td>2.25E-8</td>
<td>8.73E-8</td>
<td>9.7E-9</td>
<td></td>
</tr>
<tr>
<td><strong>Net Null:</strong></td>
<td><strong>1.27E-7</strong> (7.9M:1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>% Contribution</strong></td>
<td>6.0%</td>
<td>17.7%</td>
<td>68.7%</td>
<td>7.6%</td>
<td></td>
</tr>
</tbody>
</table>
Achromatic Nulling Interferometer

- Single pupil input
- Symmetric design
- Preserves pupil orientation and polarization
- Pupil shear adjustable—variable null baseline
- Dielectric plates provide achromatic null

Dispersive Components For Achromatic Null

Null output

Symmetric Beam Splitters

Variable shear, s

Variable delay

Bright output

Pupil Input
Broadband Light Nulling Summary

- **Tungsten lamp** (and filter)
- **White light data**
  - null over 60 sec \([-1.1 \times 10^{-9}]\) Contrast
    - Control of dispersive effect to \(~1 \times 10^{-9}\)
    - \(~16\%\) bandwidth around 650nm.
- 1st order approx null \((-\Delta \lambda)^2\) at 2% bandwidth, potentially 64 times better

Data taken @ 10 Hz
\(~20\) photons/sample @ null
\(~8\) of those photons are dark photons

The deep white light null illustrates a 2nd property of nulling interferometry, the ability to **sense and control** optical path to \(10^{-9}\) contrast using literally a **handful** of detected **photons** at null.

**Nulling interferometry has demonstrated deeper white light suppression than any other coronagraphic approach**
Beam with double shear, $\theta^4$ null output

Turning Mirrors

X shear MMZ

Telescope Pupil

$\theta^4$ Null in Pupil Overlap Areas

Visible Nulling System Concept

Lenslet and fiber-optic array spatial filter

Image plane (real image) ~$(64 \times 64)$

Diffraction limited imaging system ($\lambda/10$)
Self Assembly of Fibers in (2\textsuperscript{nd} Generation) Coherent Array

- **Fiber Array:**
  - 3 Dove prisms on rectangular slab
  - Prism 2 corner is cut flat to accommodate Fibers
  - New Technology Report filed

- **Lens Array**
  - Monolithic Lens Array on thin substrate
  - Spacer bonded with thickness = focal length
  - Coating (and pinhole) at focal plane of lenslets, \textbf{blocks cladding modes} in fiber
BU DM + JPL Electronics

- 61 channel pathfinder DM
  - Boston University

- 128-channel D/A board
PSF Calibration: Separating the Starlight Speckles from the Planets

- Even with fibers and deformable mirrors, the starlight suppression will not be perfect.
  - How can you tell the difference between starlight speckles and planet light?
- Spectral subtraction
- Angular subtraction
- **Coherence of starlight** and property that the star light and planet light are incoherent with each other.

- Spatially filter the starlight from the bright output of the nuller.
- Interfere it with the output from the nuller (after fiber bundle).
  - This measures the amplitude and phase of the light in the speckle pattern.
- The PSF (starlight speckle pattern) is estimated by the Fourier transform of the measured amplitude and phase.
Importance of Post Coronagraph Calibration Interferometer

• Post coronagraph wavefront sensor that can produce $10^{-9}$ contrast with detection of a few dozen photons (per subaperture) that leaks through the coronagraph.

• PSF subtraction based on coherence of light (as opposed to telescope rotation, spectral features, or polarization of source)
  – In space, relaxes the wavefront stability by a few orders of magnitude (over angle diff imaging)
  – Through the atmosphere, can measure quasi-static telescope and non-common path AO errors.
    • Extend contrast from $10^{-3} \sim 10^{-4}$ to $10^{-7} \sim 10^{-8}$
    • Offer the possibility of atmospheric speckle subtraction
Projects Using these Concepts

• PICTURE (nulling coronagraph and calibration interferometer on a sounding rocket)
• TPF-C Instrument concept study
• EPIC (discovery proposal)
• Gemini Planet Imager (calibration interferometer)
• TMT extreme AO coronagraph concept study. (nuller and calibrator)
Summary

• Nulling interferometry (with single mode fiber) has demonstrated the largest amount of starlight suppression, in laser light, and in white light.
  – White light suppression using realistic photon fluxes. (~100 detected photons/second (16% bandpass) at 10^{-9} contrast)

• Post coronagraph interferometer is a key subsystem for both ground and space based coronagraphs.
  – In space, relaxes stability requirement by orders of magnitude (replace angular differential imaging) for speckle subtraction
  – Through the atmosphere, the calibration system measures the quasistatic AO/telescope errors that produce “pinned speckles” and also offers the possibility of removing residual atmospheric speckles.
Backup slides
2-arm vs. 4-arm Nulling Interferometers

2 arm:
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Nuller Architecture for Planet Imaging

- Telescope Pupil
- Nuller #1
- Nuller #2
- Fiber Array
- Calibration Wavefront Sensor
- Spectrometer
- Science Camera

- Yields $\theta^4$ null
SNR comparison

- Canonical Earth @ 10pc
- Wavelength = 055µm
- ∆λ=20% band pass

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Nuller SNR</th>
<th>Lyot SNR</th>
</tr>
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<tbody>
<tr>
<td>8.3 x 3m</td>
<td>9.6</td>
<td>5.2</td>
</tr>
<tr>
<td>4m</td>
<td>5.9</td>
<td>Not det.</td>
</tr>
</tbody>
</table>
# Targets for Characterization

- Spectroscopy @ 0.8\(\mu\)m (limitation of \(2\lambda/D\) vs. \(4 \lambda/D\))
- Spectroscopy @ 1.6\(\mu\)m
- The target list for spectroscopy will be smaller than detection/discovery because \(\lambda\) is bigger
Post Starlight suppression wavefront sensing

- \( \theta^4 \text{ nuller} \)
- Shot noise, Detector noise, pixelization included
- Contrast improvement \( \alpha \) integration time\(^{-1/3} \)
Future Work

• Near Term
  – Advanced Automation of Nuller Experiment
  – Design and Modification of Nuller Test Bed

• Long Term Experiments:
  – Integration of Nuller and SMF Array in Test Bed System Demonstration on Test Bed

• Integrated nuller and calibration wavefront sensor design
• Design suitable for a future sounding rocket experiment
Status of Nulling Experiments

• Prior to 2005, experiment was conducted on an optical table
• Since May nuller moved into the vacuum chamber
• To date, experiments have been run at 1 atm, with the door shut
Boston University MEMS Pathfinder
Deformable Mirror

- Current development is for a 361 segment device
- Future development path is for a 1000 segment DM
Preliminary Fiber Array Placement Accuracy
500 (331) Fiber Array

• Measurements show:
  – 125.75μm fiber spacing
  – 2.8μm rms position error

• Lens arrays to be integrated with Fiber Array