Prospects with the Crossed Cube Nuller

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Plan of presentation

• General view of the Crossed-Cubes Nuller
• Design
• Cubes polarization model
• Use as a nulling combiner
• Preliminary manufacturing requirements
• Experiment and test results
• Discussion / Main advantages
• Integration into a Fully achromatic nulling interferometer (FANI)
  – Principle
  – Simulated fringe patterns
  – Potential SNR gain
• Conclusion
Prospects with the Crossed Cube Nuller

General view of the Crossed-Cubes Nuller (CCN)

- Two “crossed” beamsplitter cubes generate four parallel beams, recombined axially. Only two of them are used to create a “null” at the focal plane centre.
- It is independent of wavelength, **chromatic flux unbalance** and polarization orientation.
Prospects with the Crossed Cube Nuller

Principle

- Both cubes have their semi-reflective (SR) planes perpendicular one to the other
- The input beams propagates parallel to both cubes SR layers
- It is splitted into four parallel beams, being recombined axially
- A null is created at the focal plane centre between the two diagonal, intensity symmetric outputs
- It is independent wavelength, **chromatic flux unbalance** and polarization orientation
- When used in reverse sense, this is actually an Achromatic phase shifter (APS)

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Prospects with the Crossed Cube Nuller

Cubes polarization model

- Shown in coronagraph mode (interferometric mode is in reverse sense)
- Only the two diagonal symmetric ports are usable for nulling

Modified Mach-Zehnder (MMZ):

\[ N = T_{C1}(\lambda)T_{C2}(\lambda) - R_{C1}(\lambda)R_{C2}(\lambda) \]

CCN:

\[ N = R_{C1}(\lambda)T_{C2}(\lambda) - T_{C1}(\lambda)R_{C2}(\lambda) \]
Use as a nulling combiner

Prospects with the Crossed Cube Nuller

From collecting telescopes

Metrology beam 1

Metrology beam 2

Crossed-cubes nuller

Fringe tracker

Other option

Metrology beam 2

Metrology beam 1

Crossed-cubes nuller

Focal plane

Z

O''

(P')

O'

B'

F'

B

Telescope 1

Relay optics 1

Telescope 2

Relay optics 2

Telescope 1

Relay optics 1

Telescope 2

Relay optics 2

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Use as a nulling combiner – polarization model

Cube 2
Cube 1

Output ports
Entrance telescopes
Use as a nulling combiner – polarization model
### Preliminary manufacturing requirements

- If OPDs are compensated for by optical delay lines, there remains one tight specification: Flux balance $< 0.1 \%$

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>REQUIRED VALUE</th>
<th>EQUIVALENT NULLING RATE</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating wavelength</td>
<td>$\lambda = 10 \mu m$</td>
<td></td>
<td>Depending on science requirements</td>
</tr>
<tr>
<td>Spectral range</td>
<td>8-12 µm</td>
<td></td>
<td>Depending on science requirements</td>
</tr>
<tr>
<td>Semi-reflective layer (SR)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission factor</td>
<td>$50 \pm 0.1 %$</td>
<td></td>
<td>On full spectral band</td>
</tr>
<tr>
<td>Reflection factor</td>
<td>$50 \pm 0.1 %$</td>
<td></td>
<td>On full spectral band</td>
</tr>
<tr>
<td>Flux mismatch</td>
<td>$&lt; 0.1 %$</td>
<td>1.0E-06</td>
<td>On full spectral band</td>
</tr>
<tr>
<td>Anti-reflective coating (AR)</td>
<td>Standard</td>
<td></td>
<td>$\lambda/4$ AR coating</td>
</tr>
<tr>
<td>Geometrical parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cube hypotenuse</td>
<td>$75.5 \pm 0.1 \text{ mm}$</td>
<td></td>
<td>Case of ZnSe material</td>
</tr>
<tr>
<td>Transmitted pathlength in glass</td>
<td>$21.4 \pm 0.1 \text{ mm}$</td>
<td></td>
<td>Case of ZnSe material</td>
</tr>
<tr>
<td>Reflected pathlength in glass</td>
<td>$21.4 \pm 0.1 \text{ mm}$</td>
<td></td>
<td>Case of ZnSe material</td>
</tr>
<tr>
<td>Pathlength difference in glass</td>
<td>$&lt; 0.005 \mu m$</td>
<td>9.8E-06</td>
<td>Only applicable to coronagraph</td>
</tr>
<tr>
<td>Angular errors</td>
<td>$&lt; 3 \text{ arcmin}$</td>
<td>7.6E-07</td>
<td>For both SR/AR faces, including pyramid</td>
</tr>
<tr>
<td>Wavefront error</td>
<td>$&lt; \lambda/4$ PTV</td>
<td>0.0E+00</td>
<td>For both transmitted and reflected beams, on each sub-pupil</td>
</tr>
</tbody>
</table>

| Total Null (RMS sum)                         | 4.6E-06        |                         |                                              |
Prospects with the Crossed Cube Nuller

Experiment and test results

- At Institut de Planétologie et d’Astrophysique de Grenoble (June 2016)

First fringes

\[ N \approx 1.8 \times 10^{-3} \]

- At Laboratoire Lagrange (Observatoire de la Côte d’Azur): New tests in preparation
Prospects with the Crossed Cube Nuller

Experiment and test results

Two beams \((A_T A_R - A_R A_T)\)

Two beams \((A_T A_T - A_R A_R)\)

Four beams

Interference fringes

Spectral power density

256 pixels of 5.2 µm

Destructive and symmetric (balanced) \(N \approx 1.8 \times 10^{-3}\)

Constructive and not symmetric \(N \approx 2.2 \times 10^{-3}\)

Unlike Mach-Zehnder interferometer!
Prospects with the Crossed Cube Nuller

Discussion / Main advantages

• Simple, compact, low mass and volume
• Reasonable manufacturing tolerances
• Potentially not expensive
• High throughput, close to maximum
• Good candidate for future space missions characterizing extra-solar planets atmospheres
  – Can also be implemented into a nulling coronagraph telescope
Prospects with the Crossed Cube Nuller

The Crossed Cube Nuller could also be integrated into a

**Fully achromatic nulling interferometer (FANI) for high SNR exoplanet characterization**

Prospects with the Crossed Cube Nuller

Classical interferometer

- Beam relaying optics
- Beam collimating optics
- Multi-axial combining stage
- Entrance baseline
- Focal plane
- Telescope 1
- Telescope 2
Prospects with the Crossed Cube Nuller

Fully achromatic nulling interferometer

Beam relaying optics

Entrance baseline B

Telescope 1

L1 L2 M1 L3

Beam dispersing optics

Grism lens L4 L5

Grism mirrors

Multi-axial combining optics

Exit pupil plane

Focal plane
Prospects with the Crossed Cube Nuller

Fully achromatic nulling interferometer

Entrance pupil

Dispersed exit pupil

\( \lambda_0 \)

\( B \)

\( O \)

\( Y \)

\( X \)
**Specifications**

- **Spectral range**: 7-14 µm
- **Entrance baseline**: B = 20 m
- **Telescope diameter**: D = 5 m
- **Compression factor**: \( m = 1/500 \)
- **Dispersive material**: ZnSe
- **Fizeau interferometer at \( \lambda = 10.5 \) µm**
Also covered in the original paper

- Mathematical analysis
- Dimensioning the dispersive element
- Preliminary optical design
- Preliminary tolerancing (no critical alignment)

<table>
<thead>
<tr>
<th>Geometrical parameter</th>
<th>Tolerance</th>
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<tbody>
<tr>
<td>Grism mirror translation along Z-axis</td>
<td>≤ 0.1 mm</td>
</tr>
<tr>
<td>Grism mirror decenter (along X’ and Y’ axes)</td>
<td>≤ 1 mm</td>
</tr>
<tr>
<td>Grism mirror tilt around X’-axis</td>
<td>≤ 5 degs.</td>
</tr>
<tr>
<td>Grism mirror tilt around Y’-axis</td>
<td>≤ 1 deg.</td>
</tr>
<tr>
<td>Grism mirror roll angle(around Z-axis)</td>
<td>≤ 5 degs.</td>
</tr>
<tr>
<td>Grism thickness at centre</td>
<td>≤ 0.1 mm</td>
</tr>
<tr>
<td>Grism angle $\alpha$</td>
<td>≤ 1 deg.</td>
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</table>
Prospects with the Crossed Cube Nuller

Potential SNR gain

- Planet detection possible on \textit{all} bright fringes $\rightarrow$ Higher Signal
- If used as a imaging stellar interferometer, SNR gain $\approx \sqrt{n}$ for read noise
- \textbf{But:}
  - No quantitative study has been done so far
  - May not be useful for all types of spectrographs (IFS ?)
Where should we put the CCN?

Beam relaying optics

Telescope 1

F

L1

L2

M1

Telescope 2

F

O

B

F_C

O’

Multi-axial combining optics

Exit pupil plane

Focal plane

X”

O’

Z

Beam dispersing optics

O

Grism lens

L3

L4

L5

F

Probable here
Conclusion

- CCN could have been used to build “PERSEE interferometer in a nutshell”
- Quick and dirty experiment in coronagraph configuration shows extinction below 1/256 bits
  - Next step: Measurements with higher dynamic range (Lagrange)
  - Demonstration in interferometer configuration (reverse) remains to be done
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Questions?