Visible Nulling Coronagraph

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Science/Technical Objectives

1. Provide a coronagraph solution for exoplanet and debris disk discovery and characterization with a future large aperture space telescope
2. Optimize target yield by maximizing throughput
3. Achieve broadband ($>10\%$) $10^9$ raw contrasts at radial separations spanning $2.5 - 34\lambda/D$
4. Relax telescope stability requirements
VNC narrowband results - TDEM Milestone #1

Repeatability and traceability to wavefront control following telescope slew/settle demonstrated with multiple Data Collection Events (DCEs), each starting from scratch over several days.
Outline: ongoing & forthcoming VNC development

1) Broadband demo
2) Segmented stimulus
1 + 2 = 3) SAINT
**VNC broadband demo - TDEM Milestone #2**

From Clampin, Lyon, Petrone, Mallik, Bolcar, Madison, and Helmbrecht, *TDEM Milestone #1 Final Report* (2013)

![Simulated PSF (with mask overlay)](image1)

![Zoomed 4x](image2)

![Relative Intensity](image3)

Same as TDEM # 1, but at $1.0 \times 10^{-9}$ over 40 nm FWHM centered on 633 nm:

- **Left**: Dark hole region overlay on simulated PSF.
- **Center**: control modes are designed to achieve $10^{-9}$ contrast over 40 nm bandpass within the wedged region with the circle of diameter $1\lambda/D$ centered at $2\lambda/D$ showing the region over which the contrast is calculated.
- **Right**: plot from left to right along the dashed line in the central panel showing the control mask extending from $-4$ to $-1.3\lambda/D$. 
Broadband VNC Approach

Use Fresnel rhomb retarders as Achromatic Phase Shifters (APS)

- The APS consists of two pairs of symmetric Fresnel rhombs as half wave retarders
- Rhomb pairs are oriented orthogonally to one another in terms of respective s- and p-planes
- APS chromatic leakage must not exceed $10^{-7}$ rms over 613-653 nm bandpass in order to reach final $10^{-9}$ averaged over $1\lambda/D$ diameter circular dark region centered at $2\lambda/D$

Expected performance of Achromatic Phase Shifter (APS)

Uncoated Fresnel rhombs selected as a buildable approach to meeting the TDEM milestone


![Graphs showing performance metrics](image)

Plots of theoretical BK7/vacuum retardance ($\delta$) optimized for the 613-653 nm bandpass

- **Left**: Retardance as a function of total internal reflection (TIR) angle of incidence (AOI)
- **Center**: Retardance as a function of wavelength at the design AOI
- **Right**: Chromaticity of the null

Dashed lines correspond to the design AOI, dotted are +/- 15 arcsec

Parallel coronagraphs or alternative approaches needed for achieving deeper nulls over a broader instrument bandpass
Deformable mirror segment phasing: narrowband vs. broadband

- Scan delay line while recording intensity on each segment for fringe packet fitting and determining segment piston and tip/tilt offsets
- Tip/tilt on a given segment reduces fringe visibility
- 1, 40, and 80 nm bandpasses shown from left to right below

\[ \frac{\lambda^2}{\Delta \lambda} \approx 400 \mu m \approx 633 \text{ waves} \]
\[ \frac{\lambda^2}{\Delta \lambda} \approx 10 \mu m \approx 16 \text{ waves} \]
\[ \frac{\lambda^2}{\Delta \lambda} \approx 5 \mu m \approx 8 \text{ waves} \]
Deformable mirror segment phasing: group and phase delay

- Fit 3-parameter Gaussian (amplitude, FWHM, offset) to signal modulus for each segment (single scan above)
- Use offset to determine group delay for each segment relative to average (upper right)
- Shift scan data by offset and determine phase residual (lower right)
- Calculate deformable mirror correction to last state vector and iterate
“Flattened” deformable mirror state vector

- Goal is to minimize peak-to-valley of each state vector: piston, tip, tilt
- Top to bottom gradient in piston map indicative of tilt between nuller arms
- Nearest neighbor outliers restrict solution range
DM states visualized in bright pupil and dark focal outputs

- **Left to right**: DM at system startup, after setting all segment PTT values to 0, following coarse “flattening” (relative to delay arm reference), and additional flattening “by hand”

- The digital mask applied in upper right corresponds to the physical Lyot mask in the dark focal output that produces the characteristic sidelobes visible at $\sim 15\lambda / D$

- Dark outputs are the DM only and normalized to the brightest pixel value
Macro-scale actively controlled segmented mirror array

In development to demonstrate laboratory coronagraph performance in the presence of complex diffraction and instabilities.

R = 4000 mm, k = 0 surface allows multiple approaches to generating array using parent segmentation or blocking.

Rendering provided by C. Koca (NASA GSFC)
Finite element analysis of gravity sag, thermal, and bond stress

Including mounted segment surface measurements (+ environment dynamics) will allow scalable STOP model study and tuning of end-to-end active primary + DM wavefront control (forthcoming slides)

Slide content courtesy of J. Bolognese (NASA GSFC)
Surface residual measurements

Preliminary analysis of unblocked segment quality assurance data

- **Left**: Stitched segment data
- **Center, Right**: Piston/tip/tilt removed and 5, 10 pixel guard band, respectively
- Blocking stress corresponding to asymmetries in blank dimensions – needs more forensics
### Surface errors binned by spatial frequency

Charts and table generated from vendor measurements of unblocked segment

<table>
<thead>
<tr>
<th>bin</th>
<th>wavelengths (mm)</th>
<th>spatial frequencies (cpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0–8.0</td>
<td>5-10</td>
</tr>
<tr>
<td>2</td>
<td>8.0–10.0</td>
<td>4-5</td>
</tr>
<tr>
<td>3</td>
<td>10.0–13.3</td>
<td>3-4</td>
</tr>
<tr>
<td>4</td>
<td>13.3–20.0</td>
<td>2-3</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 20.0*</td>
<td>&lt; 2*</td>
</tr>
<tr>
<td>6</td>
<td>total*</td>
<td>&lt; 10*</td>
</tr>
</tbody>
</table>

*a*piston, tip, tilt, and power removed

- Surface data taken with 100 mm Zygo and bandpass filtered
- Excellent results surpassing mid–high spatial frequency requirements
- Only a single out of spec point measured in the < 2 cpa bin, likely due to springing
Assembled mechanisms and fit-checking the array

- Design (optics, mounts, fixtures) completed early spring 2015, PO submitted 6/5/2015, mirrors received 11/3/2015, bonding process underway
- Tolerancing of segments and jig to achieve < 0.25 mm segment centration and < 0.5°clocking
- Coarse (manual) and fine (active) actuation stages tested
- Combined mirror + pedestal mass less than half recommended actuator load limit
Segmented Aperture Interferometric Nulling Testbed (SAINT)

- PI: R. Lyon - Awarded in 2014; Funding initiated 2015
- Demonstrate and quantify high contrast imaging capability with an actively controlled segmented aperture by modifying an existing reconfigurable sparse aperture
- Maintain single mode fiber source option currently used with the VNC
- Fast steering mirror to be added between the segmented aperture telescope and VNC
- Continue incremental improvements to control routines, as well as hardware including detectors, deformable mirror(s), and nuller mechanisms
Adapting the Fizeau Interferometry Testbed (FIT) to SAINT

- Filled hexagonal array is a drop-in replacement for sparse array
- Additional hyperbolic mirror before reaching relay collimator
- Periscope relay through baffled vacuum chamber window (not shown)
- Relay reimages segmented primary to fast steering mirror at existing VNC breadboard aperture stop location

A tool for studying end-to-end controls in the presence of dynamic instabilities

- Refine wavefront control offloading of non-common vs. common mode dynamic perturbations
- Study contrast control authority in the presence of diffraction from a complex aperture
- Mapping of primary segments to deformable mirror segments and Lyot mask
A 100% yield Iris, AO PTT489 DM is available for use with SAINT

- *Left and center:* APS-equipped 1 nm and 40 nm bandpass VNC bright output pupil images recorded June 2015 using a fully active PTT DM prior to flattening (shown without digital mask)

- *Right:* Broadband PSF of the reference (delay) arm showing the six sidelobes spaced at 60° characteristic of the 7-ring hexagonal array of circular subapertures in the physical Lyot mask
Summary of ongoing and forthcoming VNC development

- Complete the broadband VNC demonstration (imminent)
- Align segmented mirror and generate surface map of phased array (end of calendar 2015)
- Install 100% yield deformable mirror (early 2016 or sooner)
- Finish SAINT telescope, telescope to VNC relay design, and procure components (spring 2016)
- Design the Next Generation Visible Nulling Coronagraph (summer 2016)
- Couple active segmented telescope to VNC, demonstrate SAINT (fall 2016)
- Continue testing of single mode fiber bundle arrays for full field complex wavefront control
- Continue work towards integrating photon counting CCDs and developing detector electronics [Mallik+ *Proc. SPIE* (2015)] using real-time Linux
Polarization Nulling: *generalized* beamsplitters and retarders

\[ E_0 = E_0 \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix}, \quad E_t = E_0 \begin{pmatrix} t_{\perp} e^{i\psi} \cos \theta \\ t_{\parallel} \sin \theta \end{pmatrix}, \quad E_r = E_0 \begin{pmatrix} r_{\perp} e^{i\xi_{\perp}} \cos \theta \\ r_{\parallel} e^{i(\psi + \xi_{\parallel})} \sin \theta \end{pmatrix} \]

\[ E_{tt} = E_0 \begin{pmatrix} t_{\perp}^2 e^{i\psi} \cos \theta \\ t_{\parallel}^2 \sin \theta \end{pmatrix}, \quad E_{rr} = E_0 \begin{pmatrix} r_{\perp}^2 e^{i2\xi_{\perp}} \cos \theta \\ r_{\parallel}^2 e^{i(\psi + 2\xi_{\parallel})} \sin \theta \end{pmatrix} \]

\[ l_b = |E_{tt} + E_{rr}|^2, \quad l_d = |E_{tr} + E_{rt}|^2 \]
### APS specifications and measurements

<table>
<thead>
<tr>
<th>Specification</th>
<th>Measurement</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thickness</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>12.3+00/-0.05 ±20 nm precision</td>
<td>12.28323</td>
<td>12.28323</td>
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<tr>
<td><strong>Length</strong> (unchamfered)</td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>35.24+0.0/-0.1 ±50 nm precision</td>
<td>35.20</td>
<td>35.20</td>
</tr>
<tr>
<td><strong>Entrance/exit edge length</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>15.0+0.0/-0.1</td>
<td>14.95±0.01</td>
<td></td>
</tr>
<tr>
<td><strong>Angle</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>55°4’48″±1.0″; ±0.1 precision</td>
<td>55°4’48.5″±0.5″</td>
<td>Measurement performed optically contacted to machining reference chuck</td>
</tr>
<tr>
<td><strong>TIR surface parallelism</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>&lt; 0.5; ±0.1 precision</td>
<td>0.12</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Entrance/exit parallelism</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>&lt; 0.5; ±0.1 precision</td>
<td>1.6</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Right angle errors</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>±1.0′ from 90°</td>
<td>&lt; 0.5′</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td><strong>P-V WFE</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>&lt; 43 (&lt; λ/15 at 633 nm)</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td><strong>RMS WFE</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>&lt; 13 (&lt; λ/50 at 633 nm)</td>
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<td>4</td>
</tr>
<tr>
<td><strong>P-V WFE</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>&lt; 159 (&lt; λ/4 at 633 nm)</td>
<td>103</td>
<td>114</td>
</tr>
<tr>
<td><strong>RMS surface roughness</strong></td>
<td>FR1</td>
<td>FR3</td>
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<tr>
<td>&lt; 1</td>
<td>0.8 (F)</td>
<td>0.9 (F), 0.8 (B)</td>
</tr>
<tr>
<td><strong>Scratch/Dig</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>10/5</td>
<td>10/5</td>
<td></td>
</tr>
<tr>
<td><strong>Entrance/exit reflectance</strong></td>
<td>FR1</td>
<td>FR3</td>
</tr>
<tr>
<td>Ra &lt; 0.1%, 613-653 nm</td>
<td>&lt; 0.1%</td>
<td></td>
</tr>
</tbody>
</table>

- Dimensions in mm, angles in arcseconds, and surfaces in nm unless specified
Rhomb anti-reflection coatings

- Require $R < 0.1\%$ over design bandpass
- Reflectance can be enhanced to aid in alignment
The Visible Nulling Coronagraph (VNC) laboratory

Optics and detectors, control software and electronics, and vacuum isolation chamber
WFC sequence

1. Dark frame Pol Balance
2. Flatten MMA Lookup Table
3. Coarse/Fine Delay Line Locate & center fringe packet
4. Global MMA Zernikes Piston, tip, tilt, AST, FOC, CMA
5. Tune MMA Drive pupil dark, < 20 nm rms
6. Dark Channel Control
7. Hi Contrast Image