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TECHNOLOGY DEVELOPMENT FOR EXOPLANET MISSIONS

Technology Milestone Whitepaper

Compact Achromatic Visible Nulling Coronagraph Technology Maturation

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1. Objective

In support of NASA's Exoplanet Exploration Program and the Technology Development for Exoplanet Missions (TDEM) component of NASA's Strategic Astrophysics Technology (SAT) solicitation, we propose to demonstrate broadband performance of the GSFC laboratory visible nulling coronagraph (VNC). This is accomplished by using a new technology developed under this SAT and GSFC IRAD known as an *achromatic phase shifter* (APS) (Figure-1). Herein we describe the milestone, its data collection, and the success criteria against which the milestone will be evaluated.

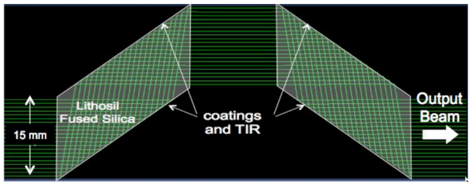

Figure-1 *Double Rhomb Achromatic Phase Shifter.* A pair of double rhomb prisms are inserted in each VNC. The pair in the DM arm are rotated by 90° about the optical axis relative to the pair in the opposing arm. Light enters from the left on the side of height of 15 mm and experiences total internal reflection (TIR) twice in the 1st prism and twice in 2^{nd}. A 4-layer coating stack with the TIR gives a π/4 achromatic phase retardance between the 2 polarization states of π.

2. Milestone Description

The technology milestone developed herein serves to gauge the developmental progress of technology for a space-based mission and the mission's readiness to proceed from pre-formulation to formulation. The completion of the milestone described here is to be documented in a report by the Principal Investigator and reviewed by NASA HQ.

The milestone addresses broadband starlight suppression at small inner working angles using a VNC coronagraph. This is a high-efficiency nulling coronagraph that enables high-contrast imaging at small inner working angles of 2 λ/D. The milestone will be demonstrated using the NASA/GSFC VNC testbed[1] at the Goddard Space Flight Center.

The milestone is succinctly stated as:

> "Demonstrate with the VNC an average contrast of 10^{-9} at 2.0 λ/D inner working angle as averaged over a circular region of diameter 1 λ/D extending (Fig-1 red-circle) from 1.5 to 2.5 λ/D, in light of spectral bandwidth of Δλ=40 nm (FWHM) at a central wavelength of λ=633 nm."

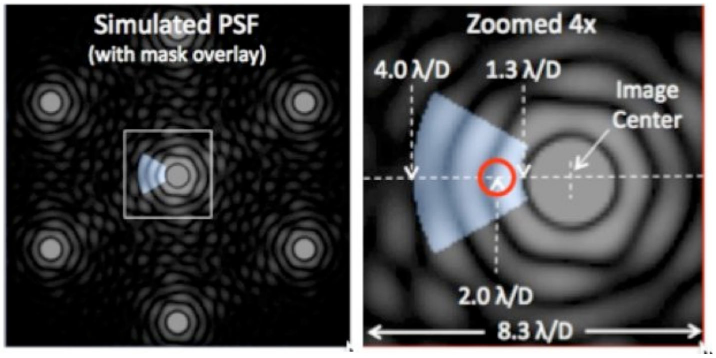

Figure-2 *High-Contrast Focal Plane.* Left panel shows VNC focal plane on log-scale where blue shows regions of highest contrast. Right panel shows high contrast region over which milestone is to be assessed, which is shown as the red circle in right panel.

This is an improvement over the previous VNC SAT milestone in that the high contrast spectral bandpass of the VNC will be increased from the previous milestone of 1.2 nm (SAT #1 footnote below) to 40 nm (this SAT). The improvement is not an improvement on the focal plane area since this is limited by the number of DM segments. The current SAT uses a DM with the same number of segments as the pre-

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[1] M. Clampin, R. Lyon, P. Petrone, U. Mallik, M. Bolcar, T. Madison, and M. Helmbrecht, *Technology Milestone #1 Final Report: Visible Nulling Coronagraph Technology Maturation: High Contrast Imaging and Characterization of Exoplanets, JPL Document #* D-80950 (2013)

vious SAT.

The VNC and the experiment is the same as the previous SAT[1] except for the development and introduction of one new technology known as the *achromatic phase shifter* (APS). The APS modifies the optical path lengths to set the phase retardance between the two arms to π for both polarizations simultaneously over the specified bandpass. The APS risk is that the angular and coating tolerances on the double rhomb prisms are not achievable within the confines of this SAT. Zygo Corporation believes that the tolerances can be met for 10^{-9} contrast.

Figure

A pointwise focal plane contrast map results in a value for contrast at each sample point within the focal plane. A simulation of the VNC focal plane is shown in the left panel, and zoomed by a factor of 4x in right panel, of -1. For this milestone we are interested in the contrast within a region centered on 2 λ/D

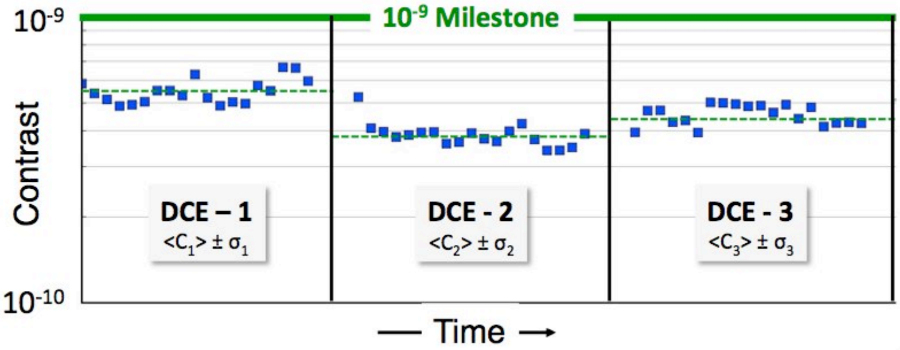

Figure-3: *Contrasts for each Realization for each DCE*. Each DCE consists of 19 realizations; the contrasts averaged over the 1 -λ/D mask centered on 2 λ/D are shown as blue boxes. The mask is the circular region shown as the open red circle on Figure-2. There are 154 samples with this region. The average over the set of 19 is shown as the dashed green line for each DCE and the average contrast value is shown as <C> with error bars. The error bars are the population standard deviations over square root of 19. *The average contrasts, with error bars, are used to assess the milestone.*

as defined by the red circle shown in the right panel of Figure-2. The red-circle extends from 1.5 to 2.5 λ/D in the direction radially away from the core (peak, center) of the image and is circular. The focal plane sampling is ~ λ/14D yielding ~154 contrast values within the red circle and at each time step. The temporal sampling is 40 fps (frames per second) with a 4 Hz integrator for controls. The integrated images, collected at 4 Hz, are herein referred to as "realizations". A single image at 40 Hz appears noisy due to few photon counts within the dark-hole region. Each of these 19 realizations per data collection event (DCE) actually consists of 38,000 control frames at 40 fps, thus the standard deviation of the noise is lower by ~1/200 per realization. The source and throughput are such that the brightest pixel is at a contrast of 10^{-4} yielding 80% of full well, or 52,428 analog to digital units (ADUs or detector counts) at the brightest detector pixel. The camera gain is 3 photons per 1 electron and thus the image peak corresponds to ~160,000 photons, or an effective contrast dynamic range of 1×10^{-4} to 0.6×10^{-9} per realization. The 0.6×10^{-9} is the camera limited noise floor for a single realization, however multiple realizations are used to lower this to $\sim 10^{-10}$. The first 46,200 images are part of initial wavefront control to achieve the final contrast, and the last 3,800 images (950 seconds/DCE) for holding the contrast and is the data used for assessing the contrast milestone. Each of the 19 realizations for 3 simulated DCEs are shown as a function of time in Figure-3. The dotted green line in Figure-3 is the mean over the 19 realizations for each DCE.

Each set of realizations is averaged to produce one contrast value and its standard error at each point within the red-circle. The 154 numbers are not strictly independent since they can be part of the same speckle. Subsequent averaging over the area subtended by the red-circle yields one contrast and one standard error such that this contrast is random variable. This complete process is repeated 3, or more, times separated by 24 hrs or longer, to ensure that the contrast is not a one-time spurious result. Each complete repetition is known as a DCE.

3. Success Criteria

Listed are the required elements of the milestone demonstration with its rationale.

3.1. A baseline filter of 40 nm FWHM centered on 633 nm will be used. This filter will be calibrated with a lab spectrophotometer to measure its transmittance at 1 nm resolution. The baseline filter shall serve as the reference filter for future measurements.

Rationale: This filter will correct for spectral variations in the source's supercontinuum light. This is an issue that will not be encountered with real stars in a space mission.

3.2. A mean contrast metric of 1 x 10^{-9} or smaller shall be achieved in a region extending from 1.5 to 2.5 λ/D, centered on 2 λ/D in the focal plane for a spectral filter of 40 nm FWHM.

Rationale: This provides evidence that the high contrast field is sufficiently dark (10^{-9} *expected exozodi level) to be useful for searching planets, and test whether there is a fundamental limitation at the inner working angle.*

3.3. Criterion 3.2, averaged over each of the three data sets (DCEs), shall be met with a confidence of 90% or better. Sufficient data will be taken to justify this statistical confidence.

Rationale: Assuming the contrast values have a Gaussian distribution about the mean contrast, this demonstrates a statistical confidence of 90% that the mean contrast goal has been reached.

3.4. Elements 3.1 – 3.3 must be satisfied on three separate occasions with a reset of the wavefront control system software (DM set to scratch) between each demonstration.

Rationale: This provides evidence of the repeatability of the contrast demonstration. The wavefront control system software reset between data sets ensures that the three data sets can be considered as independent and do not represent an unusually good configuration that cannot be reproduced. For each demonstration the DM will begin from a "scratch" setting and the algorithm used to converge will have no memory of settings used for prior demonstrations. There is no time requirement for the demonstrations, other than the time required to meet the statistics stipulated in the success criteria. There is no required interval between demonstrations; subsequent demonstrations can begin as soon as prior demonstrations have ended. There is also no requirement to turn off power, open the vacuum tank, or delete data relevant for the calibration of the DM influence function.

4. Differences between Laboratory Demonstration and Flight

Environment

The milestone will be achieved in a laboratory environment with a super-continuum light source rather than the focal plane of a telescope at the input of the instrument. The super-continuum source has temporal drift and variation and is significantly brighter than any star system. Additionally the lab environment is less stable than the spacecraft in orbit, thus in the lab we sample faster (higher control bandwidth) and with a source significantly brighter than the target stars. These two effects are used to mitigate the laboratory environment.

Overview of Coronagraphic architecture

The coronagraph system architecture is a VNC developed at GSFC and used for the previous milestone. It is adopted for the current milestone and this milestone is simpler than what is required for flight. We will demonstrate with a single 40 nm bandwidth channel, whereas the flight instrument requires at least several broadband channels to cover the full 400 nm to 900 nm spectral range.

The VNC consists of a source module with filters fed by a super-continuum source and injected into the telescope with a fiber feed. It splits the light (~50:50) into two paths and recombines them. It uses a single DM consisting of 169 segments (163 actuated), each controlled for piston, tip, and tilt, and the DM is used in the non-common path. The lab DM has fewer actuators than expected for flight and results in a smaller dark hole region in the lab than flight. Additionally the use of a single DM, results in correction, or a dark hole, on one side of the focal plane only.

5. Milestone Validation Procedure

The DM is set to scratch, i.e., shutdown and power recycled, and the wavefront control system software is also restarted.

Wavefront control iterations are performed to iteratively converge to settings of the DM actuator driver voltages that give an acceptable high-contrast wavefront solution for the target dark zone. This typically takes approximately 3 hours, starting from scratch.

When contrast in the dark zone stops improving, the high-contrast measurement begins while the wavefront control iterations are being performed, as described below:

Wavefront control iterations are continuously performed at 40 Hz sampling with an integrator to 4 Hz. This attempts to optimize the dark hole contrast in the specified region (red region of Figure-2).

For each wavefront control iteration, one measurement is acquired with the best DM shape for high-contrast (no additional deformation on the DM to probe speckles). This measurement is used toward contrast measurement and toward the next control step.

6. Milestone Certification Data Package

Model predictions of performance will precede the demonstrations, and revised modeling will be conducted after the demonstrations with the aim of identifying potential sources of error.

The calculation of the contrast metric and confidence limits will be according to established Program guidelines.

The following data or data images to be presented in a final report:

1. Model predictions of contrast performance and revised post-demonstration analysis
2. Calibrated images of the reference star collected by opening and closing the VNC shutters.
3. The coronagraph focal plane scale and calibrated spectral filter function
4. A set of 19 realization images per DCE; three DCEs in all
5. A contrast metric value for the target area for each of the DCEs
6. A statistical analysis of contrast values, with 90% confidence contrast value for the data set
7. A histogram and cumulative histogram of the brightness distribution of pixels in the dark field for each of the high contrast realizations for each DCE

The source data of images will be made available to the Exoplanet Exploration Program.

7. Milestone Report

The Principal Investigator will assemble a milestone report for review by the Exoplanet Exploration Program and its Technology Assessment Committee (TAC). In the event of a consensus determination that the success criteria have been met, the Program will submit the findings of the ExEP TAC to NASA HQ for official certification of milestone compliance. In the event of a disagreement between the Program and the TAC, NASA HQ will determine whether to accept the data package and certify compliance or request additional work.

8. Approvals

Approved/ Richard G. Lyon ____April 3, 2014____

Richard Lyon
Principal Investigator, NASA/Goddard Space Flight Center

Date

Approved/ Pete Lawson April 3, 2014

Peter Lawson
Exoplanet Exploration Program Chief Technologist, JPL

Date

Approved/ Gary Blackwood April 8, 2014

Gary Blackwood
Exoplanet Exploration Program Manager, JPL

Date

Approved/ Douglas Hudgins April 9, 2014

Douglas Hudgins
Exoplanet Exploration Program Scientist, NASA HQ

Date