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Background Context

In 2016, the Exoplanet Exploration Program (ExEP) funded three teams to study coronagraph designs for large segmented-aperture space telescopes capable of directly imaging exo-Earths around Sun-like stars. This memo summarizes the plan for the second year of the Study. The plan for the first year can be found at:

https://exoplanets.nasa.gov/system/internal_resources/details/original/210_SCDA_Summary.pdf The segmented apertures are described and compared here:

https://exoplanets.nasa.gov/files/exep/SCDAApertureDocument050416.pdf

A summary of progress during the first year of the study is attached to this memo. Highlights of the FY2016 work are:

- Generated white paper on segmented coronagraph aperture
- Powerful new optimization approaches employed for Vortex and PIAA coronagraphs.
- Significant advances have been made in coronagraph throughput for on-axis segmented mirrors.
  - Throughput of APLC has doubled, and bandwidth increased by 50% compared to 2015.
- Significant advances in coronagraph robustness.
  - APLC designs allow ~0.6% scale errors, and wavefront control allows an additional 0.2% margin.
- Significant progress in coronagraph contrast
  - Broadband (10%) contrast of 1e-10 for both APLC and VC.
  - Viable VC designs did not exist for segmented apertures in 2015.
- Inner working angles of >3 lambda/D for APLC and VC.
- Supercomputers employed to explore thousands of designs (APLC).
- Powerful new optimization approach opens design space for VC.
  - Viable solutions with amplitude-only masks (DMs not needed).
- Pie-wedge and Keystone emerging as significantly higher throughput than Hex segment apertures.
  - On-axis APLC designs approach off-axis (unobscured) in coronagraph performance.
  - With VC, off-axis design has double the throughput of on-axis.

Task Objectives for Year 2

The objectives for the second year of the program are to further improve the designs and to begin testbed demonstrations of the Apodized Pupil Lyot Coronagraphs (APLC), Vortex Coronagraphs (VC), and Hybrid Lyot Coronagraphs (HLC). Teams at STScI and Caltech will receive renewed funding to continue their work from Year 1. The Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC) will also be further developed using the remaining funds from 2016. Additionally, there is funding at JPL to continue development of the Auxiliary Field Optimization (AFO) algorithm (Ruane et al, Proc. SPIE 9912, 2016), to perform design evaluation using PROPER tools (open-source light propagation model with diffraction analysis), to develop a segmented telescope stability error budget, to provide pupil and image plane masks specifically for the APLC and VC designs, and to oversee the SCDA task.

The design goals for HLC and VC are to improve upon design robustness (so as to relax alignment requirements), to apply AFO to focal plane masks, and to optimize science return. The design goals for APLC are to consider degrees of freedom in the image plane to improve bandwidth and throughput, to improve robustness, combine wave front control with apodization masks, and to optimize science return.

The APLC and VC/HLC teams will provide JPL with mask designs for use in their respective testbeds. The masks will be fabricated at the JPL Micro Devices Laboratory. The goal for the testbeds is to demonstrate high contrast at the limit of ambient demonstrations (expected to be better than 10^{-7} contrast) and to identify any design, modeling, or manufacturing issues that limit performance.

JPL will develop a stability error budget that includes tolerances on segment position and shape stability. An error budget will be generated for an APLC and a VC design. These have shown the most design maturity.

Study Details

1. Stuart Shaklan (NASA-JPL) will coordinate this task on behalf of the ExEP:

2. Coronagraph designs to be evaluated in this task will include the:
   - PIAA CMC (University of Arizona)
   - APLC/SPC (Space Telescope Science Institute/Princeton)
   - Vortex (Caltech/JPL)
   - Hybrid Lyot (Caltech/JPL)

3. The reference apertures defined in 2016 will continue to be used for the study. Off-axis version (no secondary obscuration, no secondary support struts) and on-axis monolith versions (no segment gaps) have been added to help identify design sensitivities. In addition, the hexagonal-segment apertures with ‘cutout’ pieces at the outermost hexagonal edges have been supplemented by filling in the cutouts to form circular apertures. This is in response to results from design teams showing that the ‘cutout’ portions along the perimeter of the aperture caused important throughput loss.

   As with year 1 of the study, the selected apertures are <u>not</u> intended to be the final set of mission design apertures for any of the ongoing APD mission concept studies but rather just a set of representative apertures intended to be studied.

4. The study will consider the sensitivity of the coronagraph designs to wavefront error sources such as segment motion, segment phasing, and thermal drifts. An error budget will be developed to show how these errors effect coronagraph performance.

5. The same open-source light propagation model with diffraction analysis that was used by the 2013 AFTA Coronagraph Working Group to downselect the coronagraph for WFIRST-AFTA (PROPER; John Krist) will be utilized as the standard coronagraph design evaluation modeling tool.

6. Coronagraph designers will submit their designs to Stuart Shaklan who will work with John Krist to evaluate the designs. Designers will be able to iterate with John to understand where their designs may need improvement.

7. The yield-based modeling tool developed in year one will be used to evaluate science return.

8. John Krist and Stuart Shaklan edit the final report of design results with inputs from all the coronagraph designers.

9. The JPL Micro Devices Laboratory (MDL) will fabricate masks for the APLC and VC pupils and provide them to the design teams. The design teams are responsible for providing the detailed designs to MDL and for working with them through K. Balasubramanian (JPL) to ensure that the teams are provided with mask for their segmented aperture testbeds.

   The teams will demonstrate high-contrast imaging with segmented apertures using their testbeds. It is expected that the laboratory environment will limit contrast performance to ~10^{-7} contrast at the inner working angle. The goal is to show results in broadband light if possible. However, it is recognized that monochromatic light may be a more realistic goal for this year.

The attached presentation summarizes progress in year 1. It was presented at the High Contrast Imaging Workshop at STScI in November 2016.

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