<u>Exoplanet Exploration Program (ExEP)</u>

Segmented Coronagraph Design & Analysis

Task Description

Author:
Dr. Nick Siegler
Program Chief Technologist
NASA Exoplanet Exploration Program
Jet Propulsion Laboratory/California Institute of Technology

Task Lead:
Dr. Stuart Shaklan
NASA Exoplanet Exploration Program
Jet Propulsion Laboratory/California Institute of Technology

Background Context

In 2013, the NASA Astrophysics Division chartered the AFTA Coronagraph Working Group (ACWG) to select the coronagraph architectures that were closest to demonstrating performance requirements for a potential Wide-Field Infrared Survey Telescope Astrophysics Focused Telescope Assets (WFIRST-AFTA) mission. The process involved many of the advanced coronagraph designs and designers at the time and led to the selection of the baseline and backup coronagraphs for the AFTA study. Coronagraph technologies for space telescopes at the time were focused on unobscured apertures. The ACWG analysis was the first time coronagraph designs were developed specifically for both high contrast ($< 10^{-8}$) and obscured apertures (secondary mirror and its support struts).

In support of possible future mission concepts, the Astrophysics Division and the Exoplanet Exploration Program (ExEP) would like to understand the ability of coronagraphs working with segmented and obscured telescope apertures to probe the habitable zones of a large sample of nearby stars and directly image exo-Earths. Reaching contrast ratio levels of 10^{-10} at close inner working angles (IWA) to detect the reflected visible light of exo-earths is an extremely challenging undertaking that has never been achieved experimentally with segmented apertures in either narrow-band or broadband light. The additional diffraction effects produced by telescopes using segmented apertures and on-axis obscurations add to this challenge.

Task Objectives

The ExEP intends to fund a Segmented Coronagraph Design & Analysis (SCDA) task in FY16 to answer the following questions:

> *Assuming stars with realistic finite angular size, which coronagraph designs enable telescopes with large segmented and obscured apertures to directly image exo-earths in the habitable zones around the nearest stars?*
>
> *What changes to the reference apertures (primary and secondary mirrors) would enable coronagraph designs to meet the exo-earth contrast and IWA needs?*

This analysis is not affiliated with a specific mission concept and is not a down-selection. Instead it is intended to serve as an initial design investigation into the coronagraph capabilities leading to the next step forward in exoplanet imaging. We expect that the results may inform current technology gap analyses as well as technology investments and future mission concept studies that may be chartered by the Astrophysics Division. Since this is not a selection process, we encourage coronagraph designers to collaborate throughout the task.

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:
   - Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAA CMC) - University of Arizona
   - Apodized Pupil Lyot Coronagraph/Shaped Pupil Coronagraph (APLC/SPC) - Space Telescope Science Institute/Princeton
   - Vortex - Caltech/JPL
   - Hybrid Lyot - Caltech/JPL
   - Visible Nulling Coronagraph - NASA–GSFC

3. A reference aperture team will specify the apertures for this task. Leveraging JWST experiences, membership will include experts from NASA-GSFC, NASA-MSFC, NASA-JPL, Ball Aerospace, Harris Corp, and the University of New Mexico. Inputs will be solicited from all the coronagraph design teams. Aperture details will include parameters such as full aperture size, segment shapes and sizes, segment gap size, secondary mirror strut thickness, etc.

   A set of about 7 primary mirror architectures of 12-m diameter will be selected and coronagraph design teams will be asked to use whichever apertures are best suited to their approach. Apertures will be ranked from most to least desirable from a systems point of view based upon a set of criteria developed by the reference aperture team. Possible examples are:

   - a 1, 2, 3, and 4 ring hex (JWST is a 2 ring hex)
   - a central circular monolithic mirror surrounded by pie-wedge shaped and/or keystone-shaped wedges.
   - an unobscured circular aperture 8 m diameter to be evaluated as a benchmark for comparing coronagraph efficiency. The diameter is likely the largest monolithic aperture that could be launched in an SLS fairing.

   Several secondary mirror support systems will be considered. Strut widths will be minimized through modeling and extrapolation. The coronagraph design teams will be asked to compare thicker (e.g. 4 inch wide) and thinner (e.g. 1 inch wide) struts. Strut configurations will include:

   - a JWST-like arrangement with 3 radial struts in a "Y" configuration.
   - four radial struts in an "X" configuration
   - an asymmetric 'y' configuration (a narrow "X" with a missing arm)
   - a "T" configuration which is a square "X" with a missing arm.

Note: the selected apertures are not intended to be the final set of mission design apertures but rather just a set of representative apertures to be studied. The reference aperture team, in collaboration with design teams, will develop strawman architectures to be used by the design teams. The design teams are expected to provide feedback on desired modifications that appear to be beneficial for coronagraphy without impacting telescope performance. New architectures could be added if a second year of this task is added.

This initial study will not include any telescope dynamics but rather study what can be achieved with a static aperture. Finite stellar angular diameters specific to each target star (typically 1 mas for nearby stars) will be assumed to be the limiting factor with respect to off-axis leakage. Residual corrected telescope jitter will be assumed to be smaller than the stellar diameters. This level of performance would have to be achieved through a combination of rigid body pointing and fine-steering mirrors within the coronagraph instrument, informed by a coronagraph's low-order wavefront sensor.

4. If deemed useful, and approved, a follow-on study may include additional expected wavefront error sources such as segment motion, segment phasing, and thermal drifts. Designers would also be enabled to make telescope aperture modification recommendations to obtain high-performance coronagraphs.

5. The same open-source light propagation model with diffraction analysis that was used in the WFIRST-AFTA coronagraph downselect in 2013's ACWG (PROPER; John Krist) will be utilized as the standard coronagraph design evaluation modeling tool.
    - The Visible Nulling Coronagraph will require special treatment, TBD.

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. With the goal of identifying designs that maximize science return, a science yield-based optimization tool will be developed. This optimizer will tie coronagraph characteristics such as IWA, contrast floor, throughput, and bandwidth, to science yield using a yield modeling tool (e.g. ExoSIM or AYO).

8. The ExEP will be responsible for estimating the science return of each design using a yield modeling tool (the ExEP tool is currently in development and intended to be provided open source to the community once completed).

9. John Krist and Stuart Shaklan will summarize the results in a final report with inputs from all the coronagraph designers.

Study Schedule

The task is expected to begin in early CY 16 and last for about one year. No decision has yet been made for further work. Schedules will be defined in the statements of work with each of the coronagraph designers.

Key Milestones:

- Task description circulated and feedback received from the community (Dec 10, 2015)
- Revised Task description (Jan 25, 2016)
- Reference apertures concurred (Jan 28, 2016)
- Contracts in place (Jan 29, 2016)
- First set of designs completed (June 30, 2016)
- Final report (January 15, 2017)