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Coronagraph Design Survey for Future Exoplanet Direct Imaging Space Missions: Interim Update

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ABSTRACT

NASA is about to embark on an ambitious program to develop a Habitable Worlds Observatory (HWO) flagship mission to directly image ~25 potentially Earth-like planets and spectroscopically characterize them for signs of life, as recommended by the Astro2020 decadal survey. In addition, Astro2020 recommended a new approach for flagship formulation, which involves increasing the scope and depth of early, pre-phase A trades and technology maturation, as part of the new Great Observatories Maturation Program (GOMAP). The critical capability of the HWO mission is starlight suppression. To inform future architecture trades, it is necessary to survey a wide range of technologies, from the relatively mature ones such as the ones described in the LUVOIR and HabEx reports, to the relatively new and emerging ones, which may lead to breakthrough performance. In this paper, we present an interim update on a new effort, initiated by NASA's Exoplanet Exploration Program (ExEP), to survey coronagraph design options for HWO. We present a preliminary summary of the survey, including: (1) a current list of coronagraph design options; (2) proposed evaluation criteria, such as expected mission yields and feasibility of maturing to TRL5 by 2029; and (3) tools and methods which we are using to quantify evaluations of different designs. While not charged to down-select or prioritize the different coronagraph designs, this survey is expected to be valuable in informing future mission teams of coronagraph design options. All interested coronagraph researchers are welcome to participate in this survey by contacting the first two authors of this paper.

Keywords: coronagraph, high contrast, habitable, planet, habitable worlds observatory, HWO

1. INTRODUCTION AND MOTIVATION

NASA is about to embark on an ambitious program to develop the flagship mission recommended by the Astro2020 decadal survey [1], now known as the Habitable Worlds Observatory (HWO). The driving science goal of HWO, also recommended by Astro2020, is to directly image ~25 potentially Earth-like planets and spectroscopically characterize them for signs of life (see Figure 1). In addition, HWO will detect and spectroscopically characterize a plethora of other planet types and disks around stars, and perform transformative science in many other subfields of astrophysics. HWO is expected to consist of a ~6m inscribed diameter ultra-stable space telescope with a coronagraph capable of reaching $\sim 10^{10}$ contrast. It builds on numerous previous mission concept studies, most notably HabEx [2] and LUVOIR [3], and will build on the upcoming Coronagraph Instrument on the Roman Space Telescope, a flagship mission scheduled to launch by 2027 that will demonstrate many coronagraph technologies potentially valuable for HWO.

In addition, Astro2020 recommended a new approach for flagship formulation, which involves increasing the scope and depth of early, pre-phase A trades and technology maturation, as part of the new Great Observatories Maturation

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Program (GOMAP). A critical capability of the HWO mission is starlight suppression. To inform future architecture trades, it is necessary to survey a wide range of coronagraph technologies, from the relatively mature ones such as the ones in the Roman Coronagraph Instrument, to the relatively new and emerging ones, which may lead to breakthrough performance.

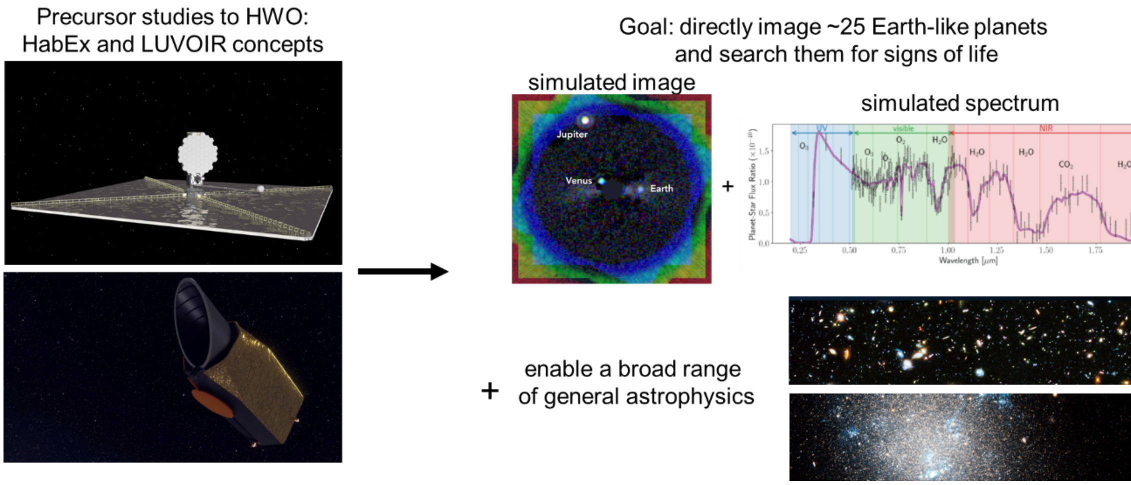

Figure 1. Left: the Habitable Worlds Observatory will build on the LUVOIR and HabEx mission concepts as well as the upcoming Coronagraphic Instrument on the Roman Space Telescope. Right: the driving science goal of HWO is to directly image ~25 Earth-like planets and search them for spectroscopic biomarkers.

It is natural to ask why such a survey is needed, given the scope of the LUVOIR and HabEx reports, which described already feasible designs on which the Astro2020 recommendation was based. There are several reasons for conducting a new survey. First, in the ~4 years since the HabEx and LUVOIR reports, coronagraph technology has improved, both in terms of designs and lab demonstrations. For example, there are coronagraph designs today which increase the expected exo-Earth yield by ~60% relative to the designs in the LUVOIR and HabEx concepts. In terms of lab demonstrations, although the in-lab contrast record of $4\text{x}10^{-10}$ in a 10% band has stood since 2019 [4], we now have a demonstration of this contrast in a 20% band along with a greater understanding of the limiting factors [5], as well as demonstrations of more efficient coronagraphs at $\sim 10^{-9}$ and $\sim 10^{-8}$ contrast, and these are expected to improve. A key goal of our survey is to provide an update that captures this new landscape.

Second, Astro2020 recommends thorough, early, well-funded trade studies and technology development in order to lower the risks and costs of HWO (a similar theme also runs through the Large Mission Study Report [6]). Coronagraph designs span a very rich trade space (Figure 2) and represent several potentially powerful levers to lower the risks and costs of HWO. For example, the greatest risk and cost drivers on HWO may be in demonstrating $\sim 10^{10}$ contrast and ~10pm telescope stability, so any opportunity to reduce these requirements should be investigated. Improvements in coronagraph designs provide just this kind of opportunity. For example, HWO contrast requirements may potentially be relaxed by improving other coronagraph parameters, such as throughput and inner working angle (IWA), while still retaining the same yield of exo-Earths [7]. Similarly, telescope stability requirements can be relaxed by making the coronagraphic instrument more robust to wavefront aberrations [8]. In the past 4 years, new coronagraph designs have appeared that achieve better throughput, IWA, and robustness to low-order aberrations. In addition, new wavefront and post-processing techniques promise to achieve better robustness to all aberrations. If these technologies can be developed at lower cost and risk than developing an ultra-stable space telescope and/or demonstrating $1.0\text{x}10^{-10}$ raw contrast (as opposed to, say $3\text{x}10^{-10}$), then overall HWO mission cost and risk could be reduced. In addition, the performance of coronagraphs for on-axis apertures has been advancing, both in terms of expected science yield and in terms of laboratory performance, and it is possible that in the future, the performance of coronagraphs on obstructed apertures will be comparable to unobstructed apertures [8].

A third reason is that improving the performance of an instrument is a very powerful and flexible lever to reduce risk and cost. For example, if one wishes to increase the photon flux at the science detector by 10%, one can either improve the instrument efficiency by 10%, or the telescope collecting area by 10%. On a flagship, it is (probably) easier and less costly to do the former. In general, the larger the mission, the more leverage one gets from investments in instrument improvements. We hope that CDS will expose opportunities for such improvements, in ways that reduce mission risk, cost, and/or improve science.

A fourth motivating reason for our survey is to help future mission designers understand the impact and sensitivities of engineering trades to science yield and margin. There are several considerations that make this especially important for HWO. For example, the expected science yields of early mission concepts are often optimistic, and erode as mission concepts mature. HWO in particular may be vulnerable to this “yield erosion” because of the uncertainty on eta_Earth. Another consideration is that the science of HWO needs to remain competitive relative to the expected science landscape of the 2040s, with Extremely Large Telescopes (ELTs) likely delivering some forms of exo-Earth imaging from the ground. An expected benefit of our study is that it will identify opportunities that would enhance yields, provide science margin, guard against yield erosion, and ensure relevance in the science landscape of the 2040s. Of course, opportunities that increase science and lower science risk often (but not always!) come at the expense of increased mission cost and technology risk. The existence of such opportunities and options would allow future trade studies to better optimize HWO and balance different risks against each other, likely resulting in a better mission overall.

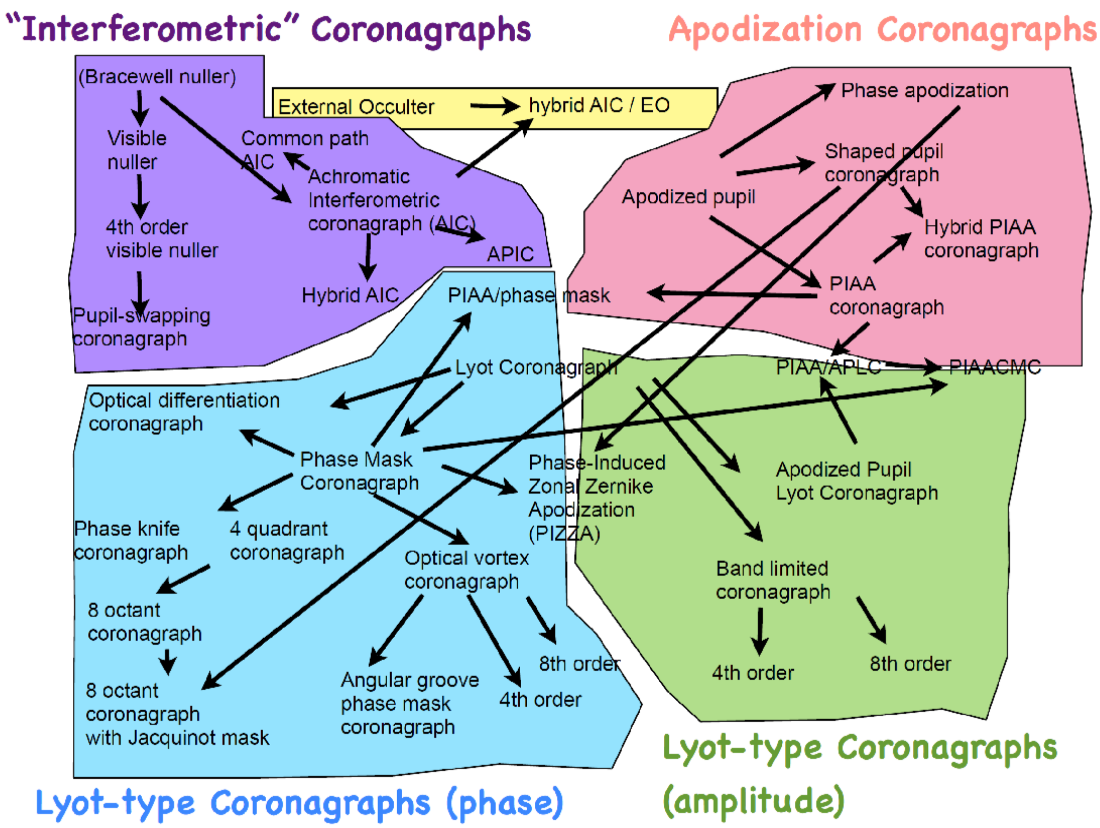

Figure 2. Coronagraph designs have a rich and varied trade space. (Image courtesy of Olivier Guyon.)

2. GOALS, INTENDED PRODUCTS, AND WORKFLOW

The Coronagraph Design Survey is a 1-year effort (roughly calendar year 2023), initiated by NASA’s Exoplanet Exploration Program (ExEP) in part for the reasons and motivations described in the previous section. It consists of 20 members from a diversity of institutions, backgrounds, and career levels. Members are led by 2 co-chairs (Belikov and Stark). ExEP chief technologist (Siegler) serves an advisor. Although the formal CDS team has limited membership, any interested coronagraph researchers worldwide are welcome and encouraged to participate in our survey by contributing their designs, as well as any feedback about our activity (see section 2.3 and conclusions for details). In addition, CDS is coordinating its activities with other parallel studies related to HWO, such as the Coronagraph Roadmap Team (CTR), Coronagraph Deformable Mirror Roadmap (DMTR), and the Ultra-Stable Observatory Roadmap Team (USORT).

2.1 Goals and intended products

The top-level goals of the CDS are as follows:

1. Survey and document viable coronagraph designs across the world that can inform the Habitable Worlds Observatory about their capabilities and technology readiness.
2. Facilitate future evaluation and comparison of the coronagraph designs to advance, based on a set of technical and programmatic assessment criteria.
3. Identify novel coronagraph technologies that could mature rapidly for which NASA's technology development investments could be efficiently leveraged.

The intended application is to provide to GOMAP, future HWO teams, and other stakeholders, an assessment of coronagraph technologies that can be used to evaluate risk and performance for the HWO. Note that the CDS is a fact-finding effort and *will not be performing any down-selects*; the focus of CDS is gathering information, design options, and providing a unified set of criteria and pipeline to assess them.

The CDS effort started in the beginning of 2023, and is planned to complete in early 2024. The intended products of the survey are the following:

- a table that summarizes our gathered information and metrics (see Figure 3 for a current draft version)
- a semi-automated pipeline used to compute any machine-computable metrics on the table, in order to enable future teams and the community to compute these metrics for any future designs after the CDS effort is completed
- a report containing descriptions of all the coronagraph technologies surveyed by the CDS, with full details of computed metrics, evaluated maturity, and documentation of process

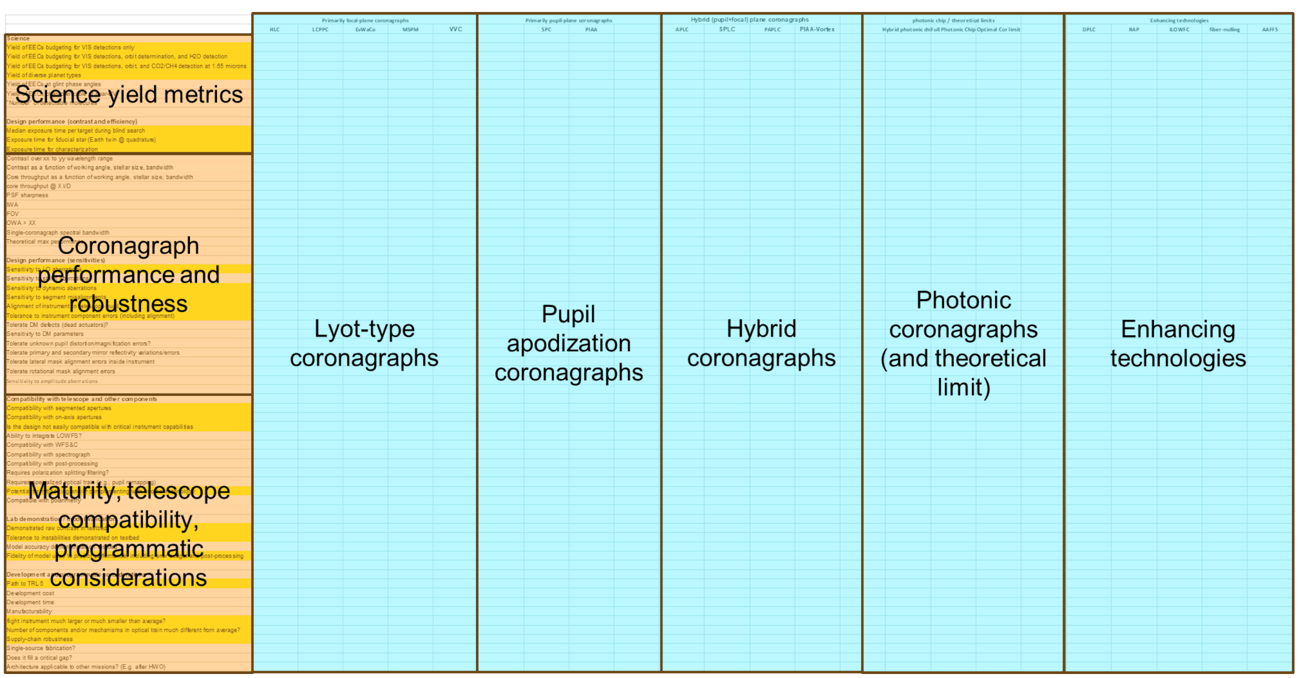

Figure 3. The results of the coronagraph survey will be summarized in a matrix similar to the above. The columns correspond to coronagraph designs, and the rows correspond to the metrics. See later sections for a more detailed description of these rows and columns.

2.2 Draft table of coronagraph designs and metrics

A draft table showing the currently identified coronagraph designs and metrics is shown in Figure 3. This figure is meant to show a high-level organization, with details of rows and columns being covered in later sections. The columns in the matrix correspond to the 19 coronagraph designs collected from the community so far, which are organized into categories depending on the basic type of architecture. The rows correspond to metrics and are grouped into three categories: science yield; coronagraph performance and robustness; maturity, compatibility, and programmatic considerations. The CDS team consists of three working groups, each tasked with computing or evaluating each of these three groups of metrics for all coronagraph designs to provide a consistent set of evaluations. The majority of the science yield metrics, as well as coronagraph performance and robustness metrics, will be computed by a mostly automated pipeline which will provide a high degree of consistency across all coronagraph designs. The category of maturity, compatibility, and programmatic considerations does not lend itself to machine computations and is therefore somewhat subjective, but the CDS will still apply a uniform process to evaluate those metrics for all coronagraphs (see section 3).

2.3 First step for entry into the design survey: high-level description in a quad chart

The first step for an interested coronagraph designer to participate in the CDS is to fill out a quad chart with some basic high-level information about their design. This quad chart is shown in Figure 4. For purposes of the survey, a "coronagraph design" is defined as anything that can be reasonably described by this quad chart (including cases where a couple of the bullet points may not be applicable). At a high level, this means a design of the part of the high-contrast imaging system that lies between the entrance and exit pupils of the instrument. The intent is to mainly focus on the design of the coronagraphic masks, optics, and their geometric layout. However, designers can optionally include coronagraphic subsystems such as wavefront control and low-order wavefront sensor as part of their design (but not detector or post-processing, which would be handled by separate working groups). The design fidelity can range from a very simple and abstract unfolded layout with idealized components, to designs with more realistic layouts that also include realistic manufacturing errors. This allows capturing a diversified portfolio of designs, ranging from already mature ones that have the lowest technical risk, to less mature ones that provide opportunities to reduce the risk and cost of the telescope and/or enhance the science.

The CDS makes the following additional assumptions:

- Designs should have a plausible TRL path on time scales relevant to the Habitable Worlds Observatory (TRL5 by early 2030s, given adequate funding). However, since robotic servicing is expected to be possible, we will not turn away less mature designs.
- Baseline telescope apertures are shown in Figure 5 (created by the USORT and meant to be similar to the JWST pupils). CDS will prioritize the off- and on-axis apertures shown in Figure 5, but will consider other custom apertures submitted by coronagraph designers. These apertures are provided to all interested designers.
- Telescope diameter is ~6m (inscribed).
- The telescope, but not necessarily the coronagraph, will have IR, V, and UV capabilities. The initial focus of our survey is on visible coronagraph designs, but IR and UV-specific designs are also welcome.
- The CDS will accept designs for technologies and coronagraph subsystems that are not complete systems, as long as this subsystem functions somewhere between the entrance pupil and the exit pupil of the coronagraph instrument. For example, a new design for a low order wavefront sensor is within scope, but new detector technologies are outside – those will be handled by a separate detector working group. Designs for subsystems will be paired with one of our existing coronagraphs for purposes of evaluating metrics. This paired coronagraph can either be chosen by our team, or by the designer, if they wish. The CDS will then evaluate the performance of that coronagraph with and without the new subsystem to quantify the impact of the new subsystem.

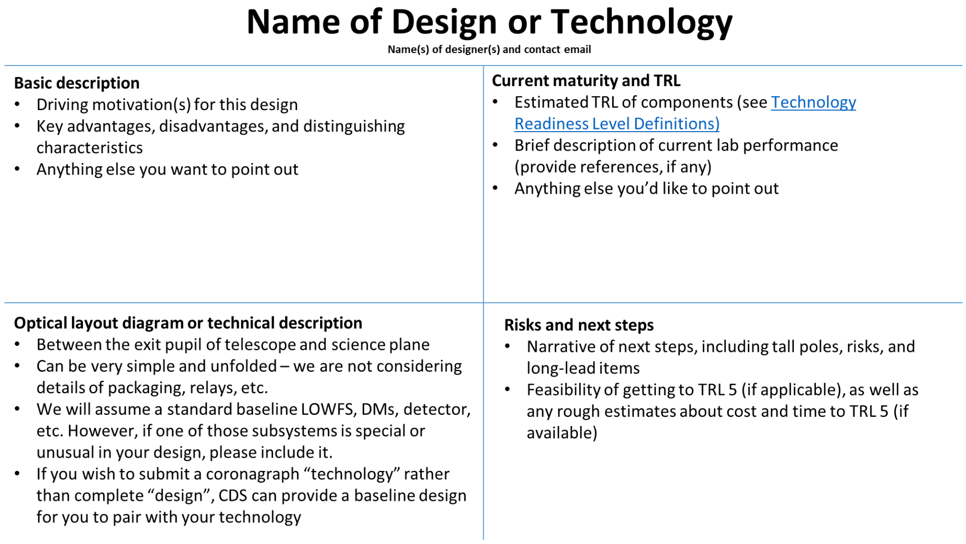

Figure 4. Coronagraph quad chart questionnaire: the first step for prospective coronagraph designers to enter the design survey.

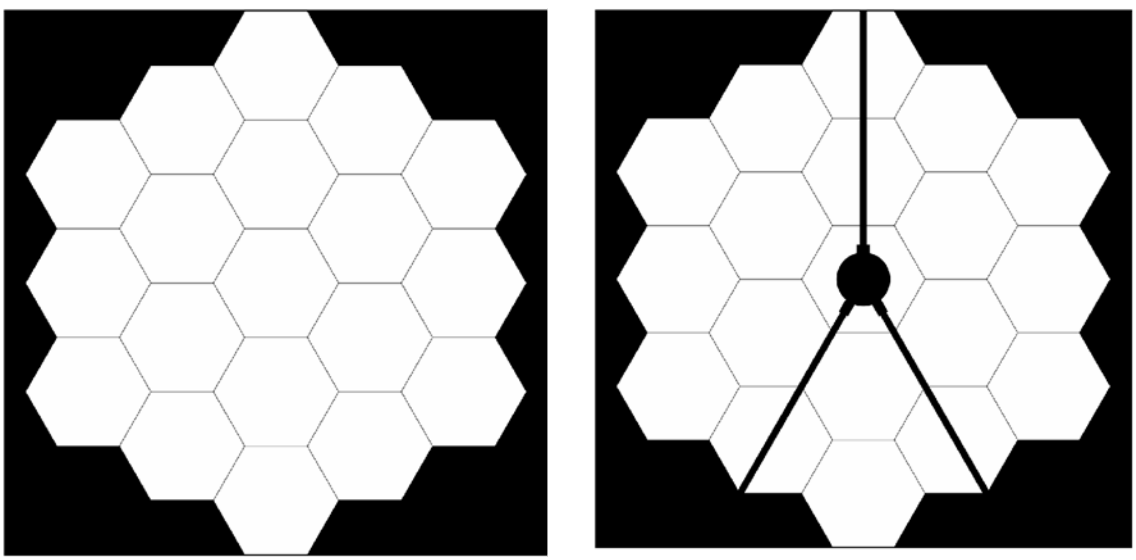

Figure 5. Baseline apertures for CDS, created by the USORT team and meant to be similar to JWST in order to leverage its heritage. Coronagraph designers are encouraged to design for the left and/or right aperture (in that priority order), but we will not turn away designs for other apertures.

The submission of a coronagraph quad chart initiates the workflow diagrammed in Figure 6. The CDS team (blue boxes, each corresponding to one of the three working groups within the CDS) works with the coronagraph design teams (green box, who can be anyone in the world) to obtain two items: the "coronagraph" operator (section 3.2.1) and information on coronagraph maturity and compatibility with HWO (section 3.2.3). The coronagraph operator is processed by a mostly automated pipeline, which produces two sets of outputs: the "yield input package" (a set of standard files needed for the computation of yields, see section 3.2.1), and a standard set of coronagraph performance metrics (contrast, throughput curves, robustness, etc. – see section 3.2.3). A mostly automated yield code (Altruistic Yield Optimizer, or AYO [7]) computes the expected mission yield (see Section 3.2.2.).

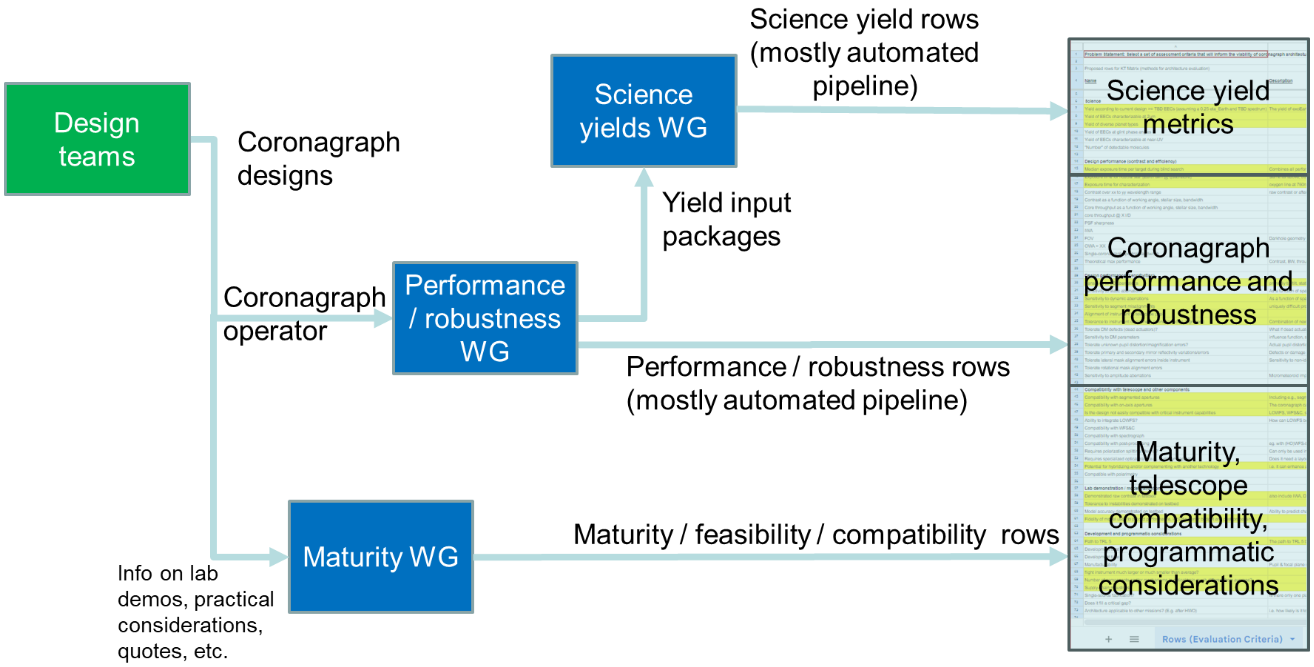

Figure 6. Workflow and pipeline of the Coronagraph Design Survey. Design teams (green box, which can consist of anyone in the world) work with the CDS working groups (blue boxes) to provide the coronagraph operator and information on the maturity of their coronagraph technology. The CDS working groups compute and evaluate different metrics of that design, including yields, coronagraph performance and robustness, maturity, telescope compatibility, and programmatic considerations (see section 3 for details).

3. INTERIM PROGRESS AND PRELIMINARY RESULTS

3.1 Contributed coronagraph designs

The CDS issued a public invitation to contribute coronagraph designs to our study in May of 2023 and as of this writing collected 19 designs (quad charts), shown in Table 1. These designs are currently being processed using the workflow in Figure 6. New designs from any coronagraph researchers are welcome and encouraged throughout the duration of our study, although with earlier contributions, designers will have more of an opportunity to iterate their design through our pipeline to optimize it.

The 19 designs that were collected so far range from traditional coronagraphs that are already planned for flight on the Roman Coronagraph Instrument (Shaped Pupil Coronagraph, or SPC, and Hybrid Lyot Coronagraph, or HLC), and the coronagraphs baselined for the LUVOIR and HabEx mission concepts (Vector Vortex Coronagraph, or VVC, and Apodized Pupil Lyot Coronagraph, or APLC) to more modern designs, including the emerging class of photonic chip coronagraphs. Also included are several enhancing technologies, such as better low-order wavefront sensors.

For better visualization, the designs were grouped into ones where the key component is: a focal plane element (e.g. HLC, VVC); pupil plane element (e.g. SPC, PIAA, or Phase Induced Amplitude Apodization); hybrid designs where pupil-plane and focal-plane elements are equally important (e.g. APLC, PIAA-vortex); an emerging class of coronagraphs based on photonic chips; and enhancing technologies (e.g. LOWFS, fiber nulling). Photonic designs also include an optimal n-th order coronagraph, which is not a specific design, but a theoretical limit for the performance of all coronagraphs [8], but in theory is implementable by a photonic chip. This theoretical limit serves to show how much improvement remains possible with further advances in coronagraph design and technology. In particular, by improving coronagraph throughput, inner working angle, and robustness, HWO exo-Earth yields can be improved by a factor of 2-4 relative to the LUVOIR and HabEx final reports. (A similar level of improvement can additionally be gained by improvements in certain other coronagraph parameters, such as bandwidth and end-to-end quantum efficiency.) Although normally technologies with TRL as low as photonic chips would be too risky to consider for a flagship; the difference in this case is that the development of photonic chips is driven by a ~$1 trillion dollar telecommunications industry. With such a strong technology driver, photonic chips may revolutionize optics in a similar way that electronic chips revolutionized the electronics industry in the 1960s. Of course, it remains to be seen whether such a revolution will come on time scales relevant to HWO (or at all), and whether development of photonic chips by the telecom industry would proceed in a direction relevant to HWO, but it does provide a potential game-changing opportunity.

Our list also represents a diversified portfolio of coronagraphs in terms of risk/reward ratio: ranging from ones that are already implemented for flight on Roman (HLC, SPC), to other relatively mature ones with TRLs of 3-4 (VVC, APLC, PAPLC, PIAA), to less mature but higher performing designs (e.g., PIAA-Vortex, and many of the options on the enhancing technologies group), to the least mature but maximally performing designs (photonic chips and optimal n-th order coronagraph). This diversity facilitates future trades, such as trading coronagraph risk against science risk, as well as coronagraph risk against telescope risk. These kinds of trades are necessary in order for HWO teams to find the optimal point that minimizes the overall global risk and cost of the mission.

Table 1. Contributed coronagraph designs to date, organized by type

Primarily focal-plane coronagraphs	Hybrid Lyot Coronagraph (Trauger et al.)
	Liquid-crystal Phase-plate Coronagraph (Doleman et al.)
	Evanescent Wave Coronagraph (Alagao et al.)
	Metasurface Scalar Phase Mask (Lorenzo et al.)
	Vector Vortex Voronagraph (Ruane et al.)
Primarily pupil-plane coronagraphs	Shaped Pupil Voronagraph (Kasdin et al.)
	Phase Induced Amplitude Apodization (Sirbu et al.)
	Interferometric Apodization by Homeothety (Chafi et al.)
Hybrid (pupil+focal) coronagraphs	Apodized Pupil Lyot Coronagraph (Pueyo et al.)
	Shaped Pupil Lyot Coronagraph (Riggs et al.)
	Phase Apodized Pupil Lyot Coronagraph (Por et al.)
	PIAA-Vortex Coronagraph (Fogarty et al.)
Photonic Coronagraphs / theoretical limits	Hybrid Photonic Coronagraph (Por et al.)
	Photonic Coronagraph (Jewell et al.)
	Optimal n-th Order Coronagraph (Belikov et al.)
Enhancing Technologies	Dual-purpose Lyot Coronagraphs (Wallace et al.)
	Redundant Apodized Pupil (Leboulleux et al.)
	Integrated Dynamic Low-Order Wavefront Control (Trauger et al.)
	Single-Mode Fiber Nulling Coronagraph (Serabyn et al.)
	Adaptive Apodization for Fiber-Fed Spectroscopy (Carlotti et al.)

3.2 Examples of analysis products

Our survey will evaluate coronagraphs according to three types of metrics: (1) coronagraph performance and robustness; (2) expected science yields; and (3) maturity, feasibility, and compatibility of coronagraphs with HWO. See Figure 6 for a list of metrics/criteria (rows of the table), as well as coronagraphs (columns of the table, which are the same as the coronagraph list in Table 1). These are described in more detail below.

3.2.1 Performance / robustness pipeline and products

The CDS is developing an automated pipeline which inputs a "coronagraph operator" (provided by a coronagraph designer) corresponding to a given coronagraph design and outputs performance and robustness metrics for that design. The definition of a coronagraph operator bears some discussion, because it reflects many of the simplifying assumptions our study has made. In particular, our aim was to maximally simplify and streamline the evaluation process, so that a large number of coronagraph designs can be processed, while still retaining at least a minimally meaningful degree of fidelity. This required boiling down the functionality of the instrument to its most important and fundamental essentials.

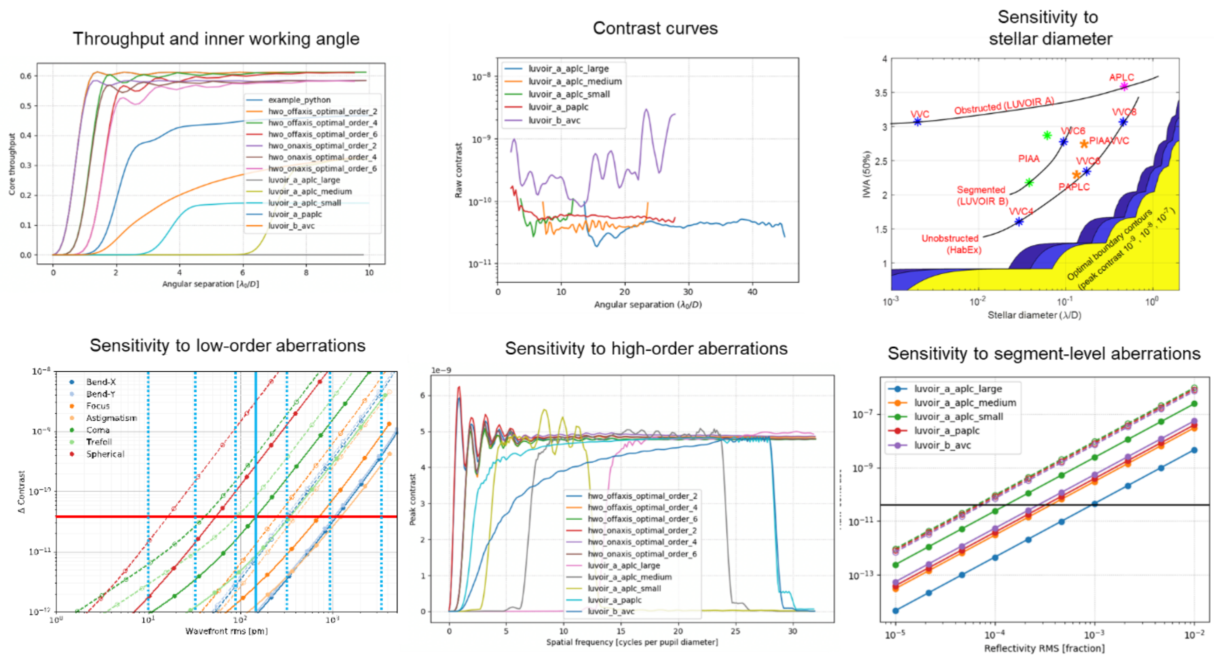

Figure 7. Examples of products to be produced by the CDS performance and robustness pipeline. The pipeline is semi-automated, and provides a consistent and streamlined way of computing several performance metrics for different coronagraphs from different designers. Top-right subfigure adapted from [8]; bottom-right subfigure adapted from [9]; the rest are already produced by the CDS pipeline.

The CDS defines a coronagraph operator as a linear passive operator C: $E_{in}(x, y; \lambda) \rightarrow E_{out}(x, y; \lambda)$ that transforms the electric field at an input plane into some other electric field at the output plane. This operator may itself be a function of user-specified parameters (such as different masks in a filter wheel, or different settings of the DM), or vary randomly in time (for example, due to thermal or mechanical instabilities). But, fundamentally, everything that there is to know about the performance, robustness, and expected yield of any coronagraph can be derived from its mathematical operator C. The implementation details of the coronagraph, such as masks, layout, etc., are hidden inside the operator and are irrelevant to calculation of coronagraph performance metrics, as long as the mathematical transformation C is known. For example, the broadband response can be calculated by integrating over the λ parameter. A response to extended sources can be computed by integrating point sources over that extended source. Throughput curves can be computed by calculating the response to off-axis point sources at different separations. Sensitivities to aberrations can be computed by passing that aberration as an input to the coronagraph operator. Note that we do not include wavefront control algorithms as part of the definition of C, but C itself can be a function of DM actuators: $C(a)$, where a is a 2D map of DM actuator settings. Thus, any wavefront control algorithm can be wrapped around the coronagraph C, and is in that sense decoupled from the coronagraph definition. A more detailed and formal description is available in the documentation of our pipeline.

Within our pipeline, a coronagraph operator C is represented as a function with a standard definition (written in either Python or MATLAB). This function has the following input parameters: a 2D electric field at the coronagraph input plane; wavelength; and optional parameters representing any variable parts of the coronagraph the designer wishes to include. It outputs a 2D electric field in the coronagraph output plane. For simplicity, we defined the input and output planes as the entrance and exit *pupil* planes. (This means that the coronagraph operator does not actually propagate all the way to the dark zone, but it allows our pipeline to do the final propagation to the science detector in the same way for all coronagraphs.) Full details about coronagraph operator definition are documented separately and are available upon request.

Once coronagraph designers provide a coronagraph operator function to CDS, the pipeline code calls this function and computes all performance and robustness metrics. An example of several products produced by our pipeline is shown in Figure 7. Our separation of coronagraph operators and evaluation pipeline enables a consistent way to compute metrics for a variety of coronagraphs with very different architectures and implementations.

Both our pipeline, and coronagraph operators from designers, are still in the process of development, so the results in Figure 7 are not meant to represent fully vetted metrics for those coronagraphs. Rather, they are meant to clarify the types of metrics that our pipeline will be producing. These include (but are not limited to): throughput curves, inner working angle, contrast curves, sensitivity to stellar diameter, sensitivity to low-order aberrations, high-order aberrations, and segment-level errors. Note that these plots were produced assuming a fully static system with ideal telescope optics and no manufacturing errors. We expect the initial iteration of our designs and pipeline results to be similarly idealized, and when submitting the first versions of coronagraph operators, coronagraph designers do not need to include DMs in their coronagraph operators. That said, the pipeline architecture is compatible with adding wavefront control to correct for wavefront and manufacturing errors. Future versions of coronagraph operators can either include DMs as part of their coronagraph operator (with DM maps as input parameters), or rely on the wavefront control system model provided by CDS.

In addition to the metrics shown in Figure 7, the pipeline itself can be made publicly available as one of the products of CDS. This will enable post-CDS HWO teams to, if they wish, build on our results to add more coronagraphs and/or more metrics, while maintaining consistency and continuity with original CDS results.

3.2.2 Science yield pipeline

The CDS has established several evaluation metrics to track the potential science yield of each coronagraph design option. These yield metrics range from relatively straightforward calculations, such as visible wavelength detections, to more nuanced science metrics including spectral characterization to search for key molecular features and orbit determination. These yield metrics were chosen to collectively cover a broad range of potential science drivers while pushing multiple aspects of coronagraph design (e.g., throughput vs. IWA).

In order to compute the yields of these science metrics, we will leverage the existing Altruistic Yield Optimizer (AYO) [7] and Exoplanet Open-Source Imaging Mission Simulator (ExoSIMS) [10] tools. The input to these tools is a standard set of files that simulate the on- and off-axis coronagraphic PSFs. In studies prior to CDS, coronagraph designers were typically asked to produce those files themselves. With CDS, we aim to simplify this process by incorporating the production of these files into the CDS pipeline. This reduces the burden on the coronagraph designers, who are now only required to produce the coronagraph operator function. In most cases, we expect that this will only require writing a wrapper around their already existing coronagraph propagation code to conform to CDS definition. This also reduces the burden on the yield computation team, who no longer need to establish a sometimes time-consuming "handshake" with multiple coronagraph design teams.

To perform yield calculations, one must make assumptions about the telescope and instrument design that can significantly impact the absolute yields. To avoid casting a pessimistic light on any coronagraph design submitted to the survey, the CDS defined a nominal set of mission and instrument parameters that, while based on plausible telescope and instrument design layouts, are intentionally more optimistic than the LUVOIR and HabEx assumptions.

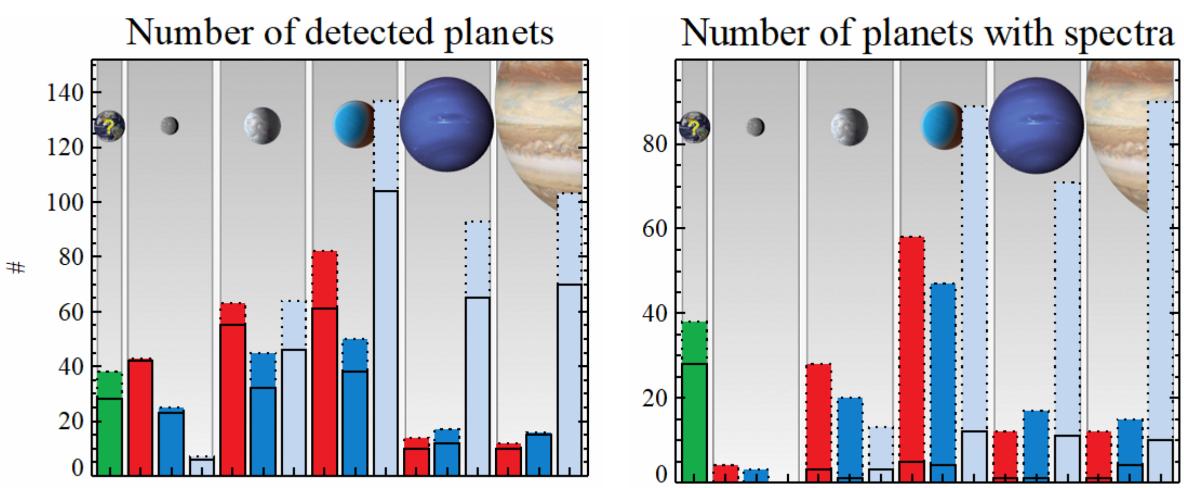

Figure 8. Examples of yield estimates as computed by the Altruistic Yield Optimizer. CDS will produces yield estimates like these (and other yield metrics) for all the submitted coronagraphs. (Images from Howe et al. 2023, submitted to JATIS).

An example of the AYO yield products is shown in Figure 8, which shows yields of different planet types for an example coronagraph. In addition to these exoplanet yield metrics, CDS will also track exposure time metrics for the detection and characterization of exoplanets. .

3.2.3 Maturity / compatibility with telescope / programmatic considerations

A final set of metrics the CDS will be assessing has to do with the coronagraph maturity, compatibility with telescope (and other components), and development/programmatic considerations. A preliminary list of metrics and criteria is shown in Figure 9 (left), with key metrics highlighted in yellow. Because these types of metrics are typically not machine-computable, we developed a standard questionnaire to collect this information from coronagraph designers. Following the questionnaire, CDS will work with designers to make sure the information is complete, accurate, and consistent between different designs before filling out the relevant rows of the table in Figure 3. One key product of this part of the effort that is reasonably objective is a plot of current laboratory demonstrations for different coronagraphs. As an example, Figure 9 shows a plot of some of the best vacuum demonstrations to date for selected coronagraph types.

Compatibility with telescope and other components
Compatibility with segmented apertures
Compatibility with on-axis apertures
Is the design not easily compatible with critical instrument capabilities
Ability to integrate LOWFS?
Compatibility with WFS&C
Compatibility with spectrograph
Compatibility with post-processing
Requires polarization splitting/filtering?
Requires specialized optical train (e.g., pupil remapping)
Potential for hybridizing and/or complementing with another technology
Compatible with polarimetry
Lab demonstration / model validation
Demonstrated raw contrast in testbed
Tolerance to instabilities demonstrated on testbed
Model accuracy demonstrated on testbed
Fidelity of model used to predict performance, including error budget and post-processing
Development and programmatic considerations
Path to TRL 5
Development cost
Development time
Manufacturability
flight instrument much larger or much smaller than average?
Number of components and/or mechanisms in optical train much different from average?
Supply-chain robustness
Single-source fabrication?
Does it fill a critical gap?
Architecture applicable to other missions? (E.g. after HWO)

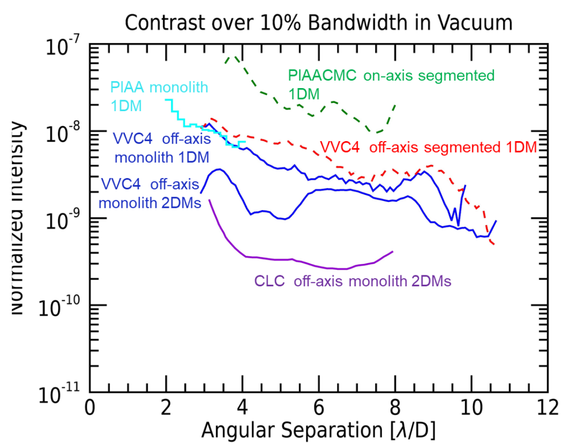

Figure 9. Left: a list of metrics and criteria related to coronagraph maturity, compatibility with telescopes, and programmatic considerations. Right: a list of coronagraphic contrast demonstrations in vacuum. An updated version of this plot will be one of the products of CDS.

4. CONCLUSIONS

The Coronagraph Design Survey is a 1-year effort (roughly calendar year 2023), initiated by NASA's Exoplanet Exploration Program (ExEP). Its goals are threefold: (1) survey and document viable coronagraph designs across the world that can inform the Habitable Worlds Observatory about their capabilities and technology readiness; (2) facilitate future evaluation and comparison of the coronagraph designs to advance based on a set of technical and programmatic assessment criteria; (3) identify novel coronagraph technologies that could mature rapidly for which NASA's technology development investments could be efficiently leveraged.

CDS will *not be performing any downselects*, only gathering and organizing facts, as well as building tools to make the evaluation of current and future coronagraphs as streamlined, simple, and objective as possible. Our products will be detailed in a final report and summarized in a table that assesses different coronagraphs according to different metrics, including science yield, coronagraph performance, robustness, maturity, compatibility with the telescope, and programmatic considerations.

Our results to date include a formulation of ~60 metrics, collecting ~20 coronagraph design quad charts from the world-wide community, and progress on an automated pipeline to evaluate coronagraph performance, robustness and yields, an early version of which is already in operation.

One of our findings to date is that coronagraph designs have improved since the LUVOIR and HabEx reports, both in terms of lab demonstrations and maturity, and in terms of efficiency, and this trend continues. Further, such improvements provide a strong lever to improve HWO performance, and significantly reduce its risk and cost. In addition to advancing lab demonstration to 10^{-10} raw contrast in the lab (which remains an important goal), it also may be possible to relax the 10^{-10} requirement by improving coronagraph efficiency and post-calibration of residual starlight. This is because science yield is a stronger function of throughput and IWA than it is of contrast (once contrast is below about 5×10^{-10}), so efficiency can be traded with contrast without affecting yield. Also, if coronagraphs can be made more robust, they can relax telescope stability requirements and reduce the risk and costs associated with an ultra-stable telescope. If coronagraphs can be made tolerant to obstructions, they can enable a lower cost and lower-risk on-axis aperture, without sacrificing science. Thus, coronagraph tolerance to instabilities and obstructions can be traded against telescope requirements. Finally, photonic chips represent an emerging but potentially game-changing technology that can improve science yields by factors of 2-4 and relax telescope stability requirements. Although they are currently very low TRL, their development is driven by large industrial markets, and it is possible that they will advance very quickly in the next 5 years – a scenario that HWO can benefit from significantly.

In general, there is a very rich trade space of coronagraphs to explore, enabling a large number of paths and opportunities to improve HWO and lower its risk and cost. A concise analysis of this trade space would allow future HWO project teams to trade the risk and cost of the coronagraph against the risk and cost of the ultra-stable telescope, as well as the risk and cost of different science requirements. Such trades are key to finding the optimal balance point that minimizes the global risk and cost of the mission.

All coronagraph designers across the world are welcome and encouraged to participate in our survey (at least for the duration of 2023). To do so, please contact Ruslan Belikov (Ruslan.belikov@nasa.gov) and Chris Stark (Christopher.c.stark@nasa.gov).

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