Segmented Coronagraph Design and Analysis

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Task Objectives

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?

How does performance depend on the telescope aperture?
How much more science do we get with one aperture vs. another?
What are the limitations of the proposed apertures, and what changes enable better science?

- Initial design investigation
  - Get us past the breakthrough stage, and to the point where future advances are incremental.
- Collaboration/ Cross-fertilization encouraged
  - Not funded as a competitive proposal process. One win all win.
- Will inform technology gap and future technology investments.
  - Large segments? Narrow gaps? Off-axis? Exotic coronagraph components?

What We're Funding

- APLC/SP: Remi et al
- Vortex and HLC: Mawet and Ruane
- PIAA: Olivier and Codona, including Rus for CMC optimization and cross-fertilization
- Note: Visible Nuller team has TDEM money.
- Science yield tool (Princeton, working with ExEP tool and Stark tool)

Telescope Parameters

- 12 m diameter
- f/1.25 primary
- 13.1 m to secondary
- 1.68 m secondary obscuration
- f/9.8 diffraction-limited Cassegrain focus on axis, few arcsec FOV
- TMA wide field design

Polarization

- Ignore polarization for now.
- At f/1.25, we will need separate channels to correct each polarization.
- At f/1.25, cross-polarization in each channel will be acceptable (maybe 1e-10? 1e-9, TBD).

Pointing and Dynamics

- Pointing
  - Assume pointing error is smaller than star diameter, e.g. ~1 mas.
  - Look at the fundamental performance limitation due to finite star diameter.
  - Later look at degradation at different pointing performance to set requirements.
- Segment motion
  - Ignore segment motion for now. All designs will have more or less the same sensitivity at a few lambda/D.

Optimize Science Return

- The goal is to optimize the science return of the designs, with focus on detecting HZ Earths.
  - Assume center of the band is 600 nm.
- You'll trade bandpass, IWA, OWA, throughput, contrast.
  - We should probably agree on a minimum OWA.
  - Assume all reflective surfaces have 97% reflectivity across the band.
  - Asssume all transmissive elements have 96% throughput across the band (this is 98% per surface, with no material absorption).

Schedule

- Goal of a first ‘complete’ design by June 30.
  - No missing pieces, i.e., buildable stuff, no miracles
  - Science yield
- Final report January 2017
  - Science yield evaluated by ExEP
  - Performance verified by John Krist
- Possible follow-on funding.

Reference Apertures and Secondary Supports

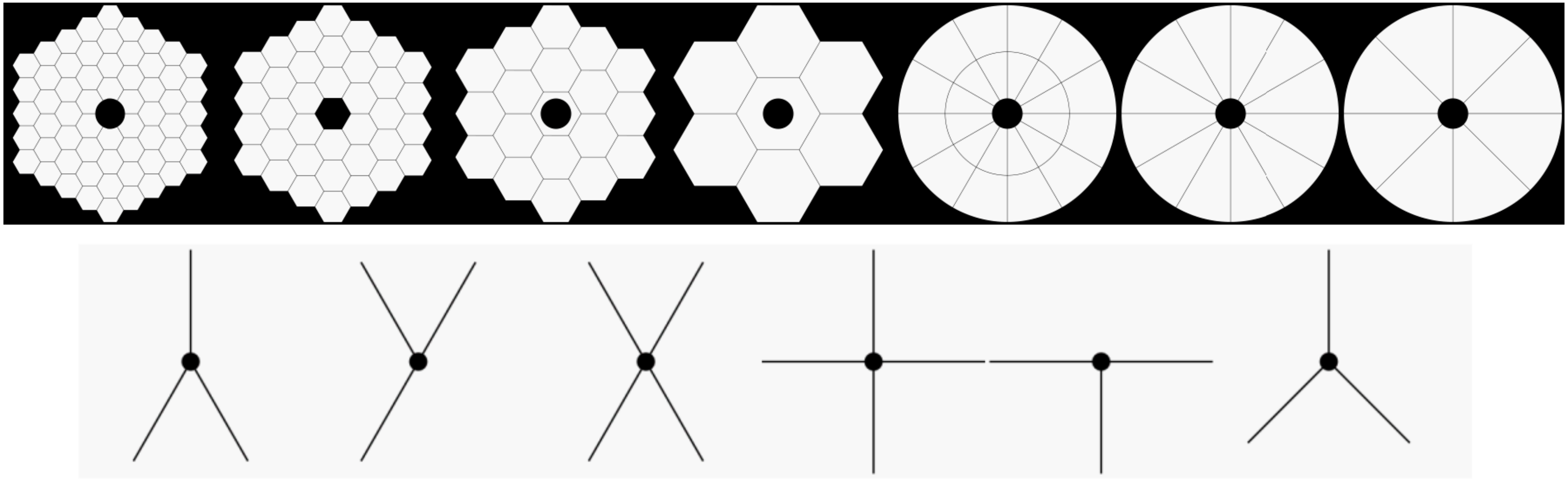

Figure 1 Apertures and secondary support structures selected for the study include four composed of hexagonal segments, one with keystone segments, and 2 with pie wedges. All are 12 m flat-to-flat or 12 m in diameter with 1.68 m diameter secondary obscurations (except the missing hex segment in the 3-ring hex). All segment edge gaps including edge roll-off are 20 mm wide. Secondary support strut widths are 25 mm and 100 mm. Aperture names, from left to right, are: 4-ring Hex, 3-ring Hex, 2-ring Hex, 1-ring Hex, Keystone-24, Pie wedge-12, and Pie wedge-8. Secondary supports are referred to as "Y", "y," "X", and "T," with two versions of "X" and "Y" for the respective hex and circular apertures.

Relative Design Challenges

Table 1 Relative challenges of designs under consideration. Green to red designates least to most challenging. No absolute scale of difficulty is implied, and the relative challenge scale of each row may be different.

	APERTURES						
	4 ring	3 ring	2 ring	1 ring	Keystone 24	Pie wedge 12	Pie wedge 8
Segment Shape	Hex	Hex	Hex	Hex	Keystone	Pie wedge	Pie wedge
Max Segm. Dimension	1.54 m	1.98 m	2.77 m	4.62 m	2.5 m x 3.14 m	5 m x 3.14 m	5 m x 4.71 m
Segments	green	yellow	orange	red	orange	red	red
Backplane	green	green	orange	red	orange	orange	red
Stability	green	yellow	yellow	red	yellow	red	red
Launch Configuration	yellow	green	orange	red	orange	red	red
SM Support	green	green	green	yellow	orange	red	red
Overall Ranking	green	yellow	orange	red	orange	red	red

See memo: Apertures for Segmented Coronagraph Design and Analysis, by Feinberg, Hull, Knight, Krist, Lightsey, Matthews, Shaklan, and Stahl (May 2016).

Disclaimer: The group had general but not unanimous agreement on this chart.

Keep in mind: no telescope has ever been built to meet coronagraph requirements. The requirements and performance are tied to TBD coronagraph WFS/C capabilities.

Segmentation

- We assumed ULE or Zerodur or Clearceram-Z
  - High quality surfaces, very low CTE, high stability
- Smaller is generally easier
  - Infrastructure in place
  - Easier to handle and test
  - Wavefront sensitivity is smaller
- As segments approach 4 m…
  - Engineering needed for launch load survival.
  - More difficult to back out gravity sag.
  - Mirror depth and packaging are more challenging, adding manufacturing risk.
  - Limit of current infrastructure for closed-back and open-back mirrors.
- Keystone or Pie Wedge vs. Hex
  - Asymmetry of segment shapes complicates the load distribution and mounting, e.g. 5 point vs. 3 point for hex.
  - More cross-talk in actuation modes.
  - Pie wedge might require warping harnesses.

Backplane Configuration

- Assume a composite or high-stability construction, deployment needed, and not cryogenic.
- Requirements are to survive launch loads, react against segment positioning forces.
- Driving issue is mirror distortion due to loads from the backplane.
- Very difficult trade:
  - Large mirrors are more difficult to support (and asymmetric ones add to the complexity).
  - Smaller mirrors are more sensitive to backplane motion and produce high spatial frequency errors when they move.

Stability

- Require few picometers wavefront stability for minutes to hours.
  - Thermal stability of segments dominated by front-to-back gradients, WFE ~ r^2
  - Increasing thermal mass and time constant improves stability. But can be more difficult to maintain a set point.
  - Assume 1 mK temperature control
  - Mitigation through LOWFS? Edge Sensors? Laser metrology?
- For constant areal density, small mirrors will be more stable.
- Dynamics
  - Want segments to be stiff at frequencies a few x above wheel speeds, e.g. first mode 500 Hz (goal).
  - Big driver. Trade against other dynamics in the system, e.g. secondary tower (10 Hz?).
  - Reduce disturbances vs. developing stiff, lightweight mirrors.
- Another reason to have stiff mirrors is dealing with gravity sag.
  - JWST has 100-200 nm, with 5-10% model uncertainty. Even 4-ring Hex is challenged to achieve sufficient stiffness for 10 nm segment WFE.

Launch Configuration

- Small segments: very stiff backplane would be very deep.
- Large segments: backplane needs to be able to react to launch loads and is more massive.
- Deployment schemes:
  - Table fold (JWST-like), Fold-forward/fold-aft (Lockheed JWST concept), Segment stacking, Sunflower, Clam shell
  - We considered only table and multi-fold based on JWST heritage. Did not consider on-orbit assembly.
- Folding requires space in front of aperture or behind it.
  - Folding forward complicates secondary mirror support.
  - Folding backward runs into s/c
- Desire not to have fold lines between secondary base supports
- Hex well suited to table fold along parallel lines.
- Radial segments requires fold forward or aft or other.
  - Beware of large cantilevers.

Possible Fold Lines

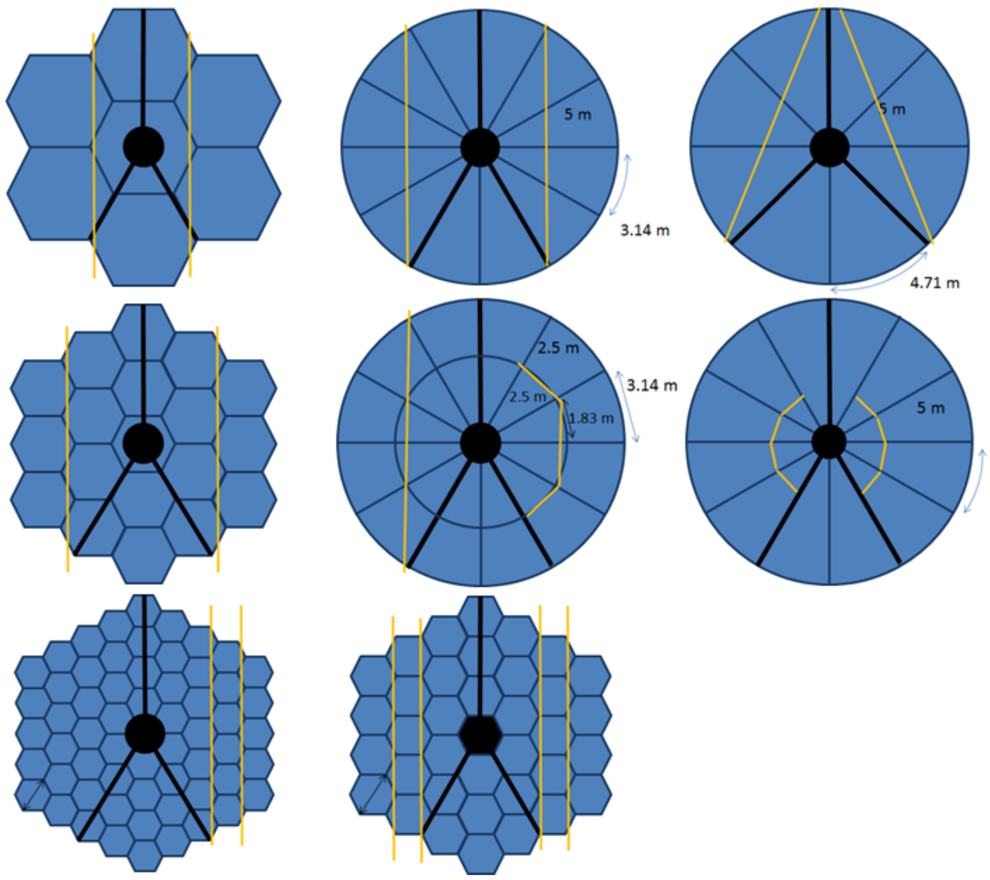

Figure 2 Some possible fold lines.

Secondary Support

- Secondary > 10 m from primary; deployment required.
- Considered X, Y, y, T. Did not consider single tower or 6-strut system (complexity, obscuration).
- Considered latches and hinges, but not free-floating legs that latch post-deploymnet.
- Arranged to run parallel to segment gaps – no additional diffraction spike.
- X and Y have symmetry advantage, ading on-orbit and 1-g testing.
- Y and T allow single DOF hnges and latches. 'y' requires multi-axis hinge.
- Table fold designs allow wide, stiff base. Tougher to do with multi-fold.

Summary

- Some apertures appear to be preferable from an engineering/heritage perspective.
- We want to learn whether there are strong science drivers pointing to one aperture or another, and even beyond the provided apertures.
- The first step is to break through with a viable solution for one or more of the apertures being considered.