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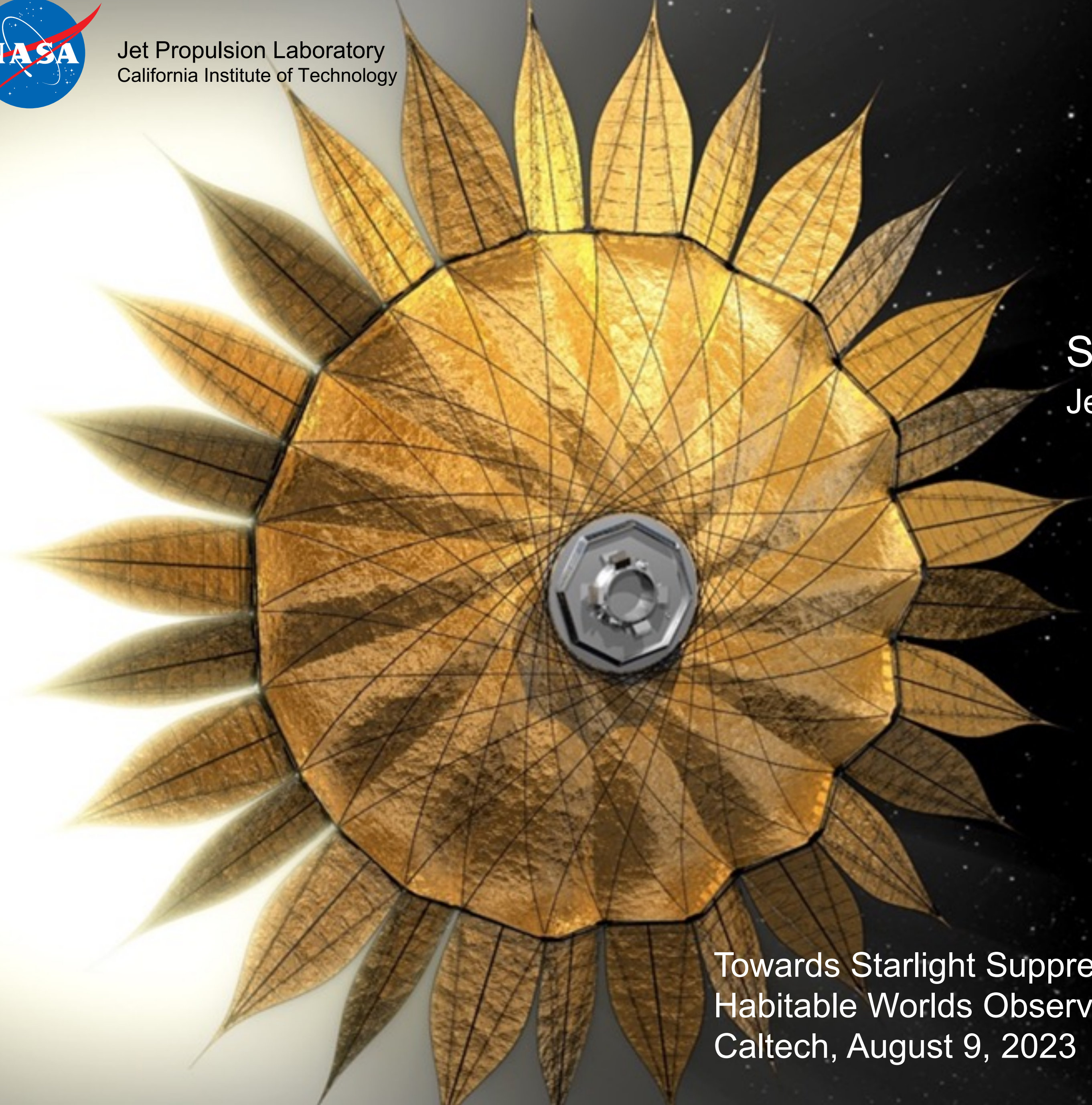

STARSHADE ATTRIBUTES

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Towards Starlight Suppression for the
Habitable Worlds Observatory Workshop
Caltech, August 9, 2023

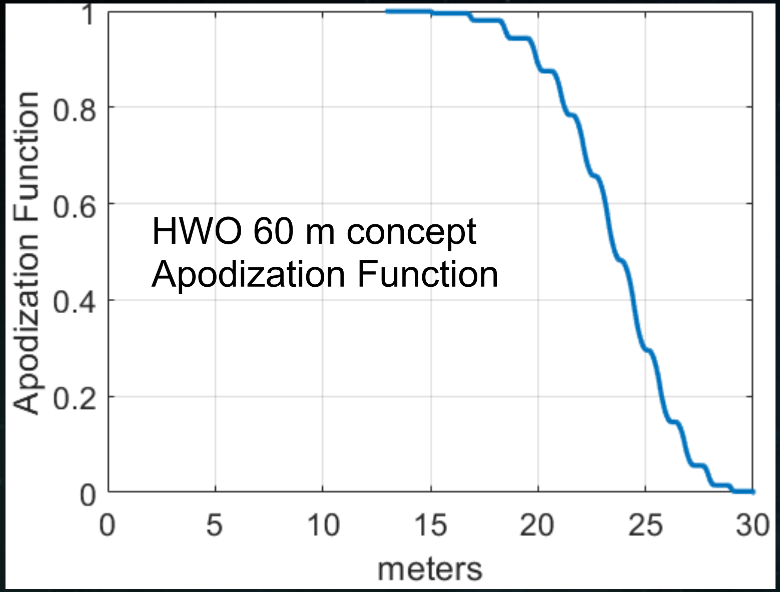
Why Starshades?

Starshades remove the starlight before it can scatter into the telescope.

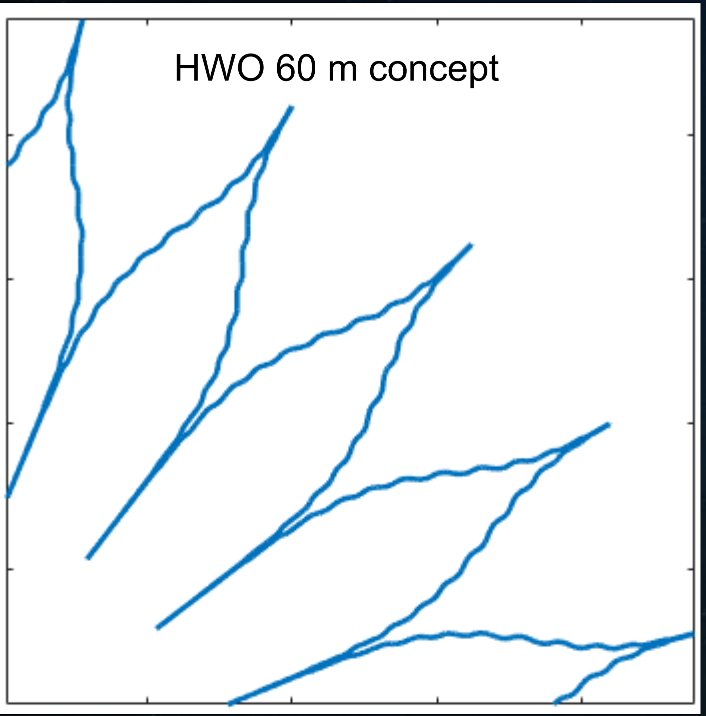
Parameter	HWO 60-m Starshade concept	Demonstrated
IWA	>1.89 λ/D	1.8 λ/D
OWA	Unlimited	3.6 λ/D
Bandwidth	67%	12.5%
Instrument Contrast	< 4e-11	<1e-10 (75% search area)
Throughput	100%	90%
Telescope stability, shape, segmentation	Works equally well with any aperture: on- or off-axis, segmented or monolith, does not drive stability, does not drive coating uniformity.	Circular aperture

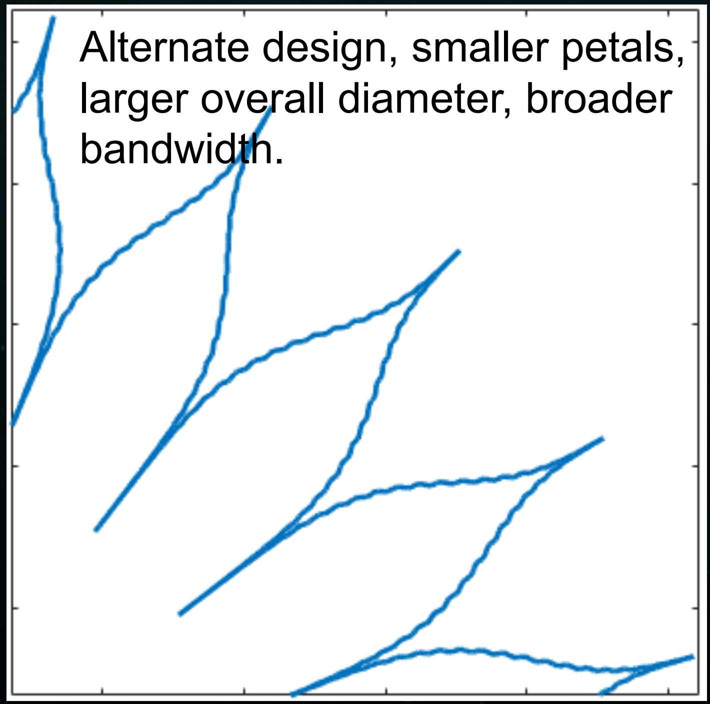
SHAPE

- Flower-like shape is binary approximation to a smooth apodization function.
  - ➢ Required for deep contrast and a wide shadow.
  - ➢ Balance IWA, shadow size, starshade diameter
- Optimization tools (e.g. Cady et al, Opt. Express 2010) let us design for:
  - ➢ Minimum diameter for a given IWA, bandpass, and shadow size
  - ➢ Accommodate for engineering constraints:
    - ▪ Petal length, petal tip width, petal gap width
- HWO concept parameters:
  - ➢ Tip width: 16 mm
  - ➢ Gap width: 2.1 mm
  - ➢ Petal length: 16 m
  - ➢ Disk Diameter: 28 m



Design tool has been validated at 1e-10 contrast in the Princeton Starshade Testbed.





Size: Examples

Telescope	Tel. Diam. (m)	Bandpass (nm)	IWA (mas) Tip / 50%	Starshade Diam. (tip to tip, m)
HWO	6	500-1000	65 / 51	60
HWO (UV)	6	225-500	65 / 51	35
HabEx	4	300-1000	70 / 58	52
Roman Rendezvous	2.4	615-800	104 / 85	26
Occulting Ozone Obs.	0.6-1.5	200-500	103/85	16

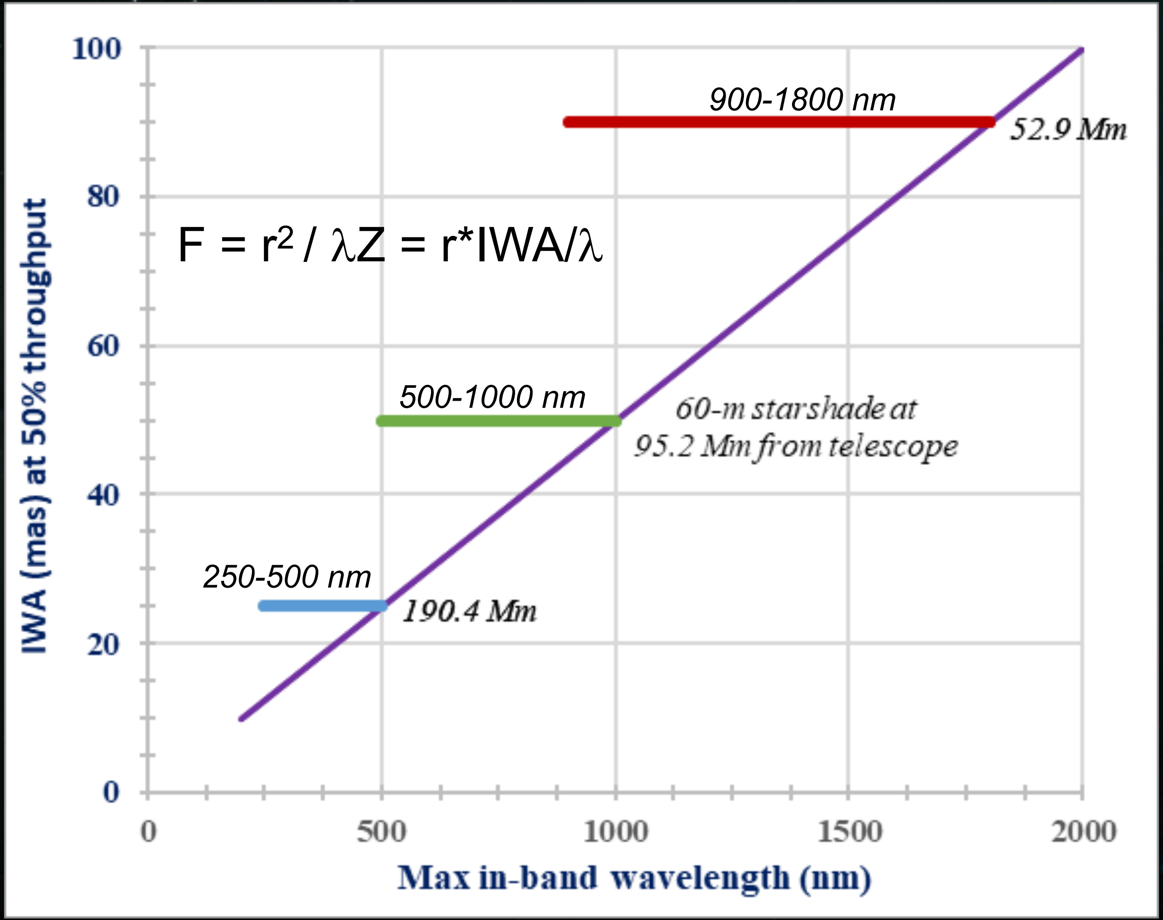
Starshade diameter scales more slowly than telescope diameter.

The HWO concept starshade has a diameter of 60 m and an IWA_{tip} of 65 mas.

Bandpass and IWA

The same starshade can be used at ANY maximum wavelength. The IWA scales with wavelength.

HWO 60 m starshade IWA (tip) and Separation



HWO 60 m starshade IWA and Separation

Bandpass (nm)	IWA (mas) Tip / 50%	Distance (Mm)
250-500	32.5 / 43	190.4
500-1000	65 / 51	95.2
900-1800	117 / 92	47.6

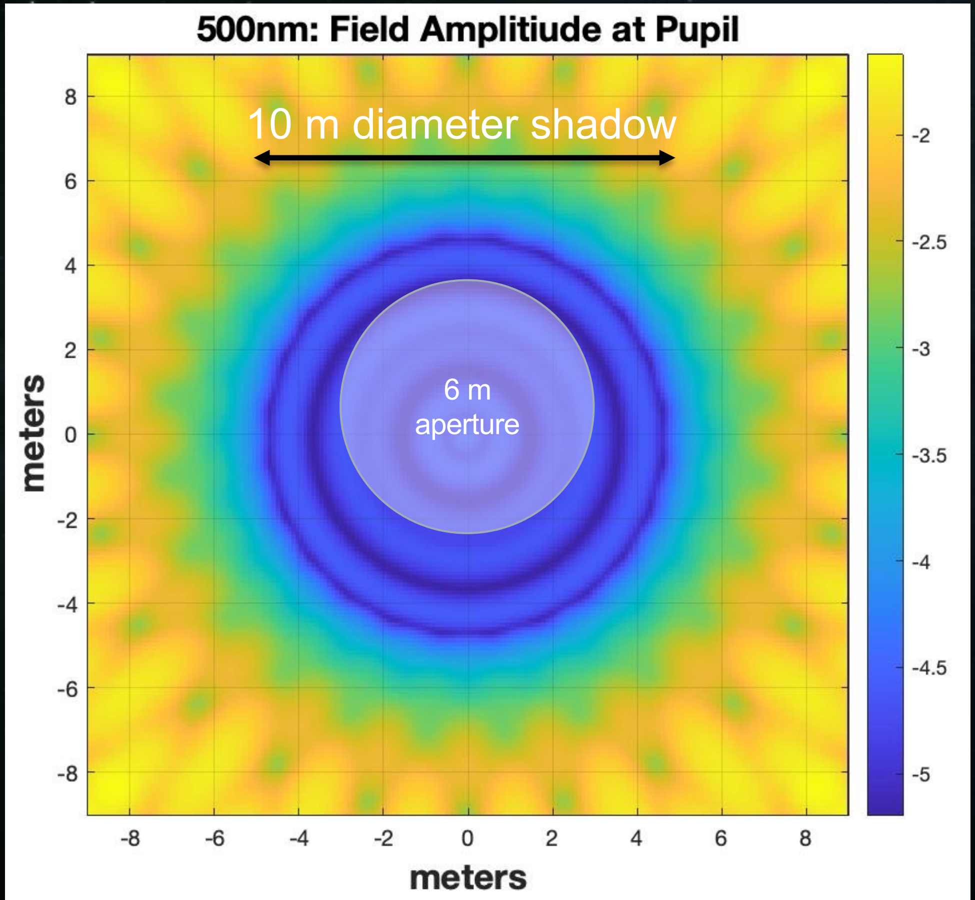
HWO 35 m starshade IWA and Separation

Bandpass (nm)	IWA (mas) Tip / 50%	Distance (Mm)
225-500	65 / 51	55.5
338-750	97.5 / 76	37.0
450-1000	130 / 102	27.8

For the 60 m, IWA_{tip} is at 1.89 λ/D.
For the 35 m, $IWA_{0.5}$ is 3.0 λ/D.

Flying in the Shadow

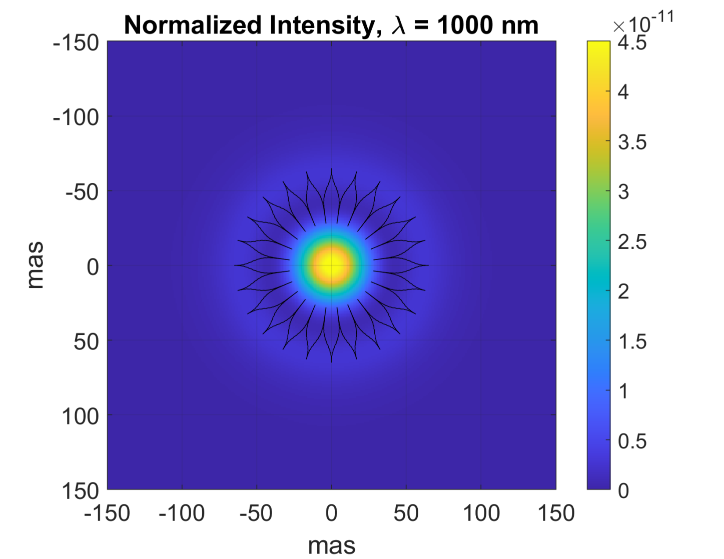
The shadow is designed to be larger than the telescope pupil to allow for lateral motion. For the HWO concept, we designed the shadow to be 10 m in diameter, for a +/- 2 m radial tolerance.

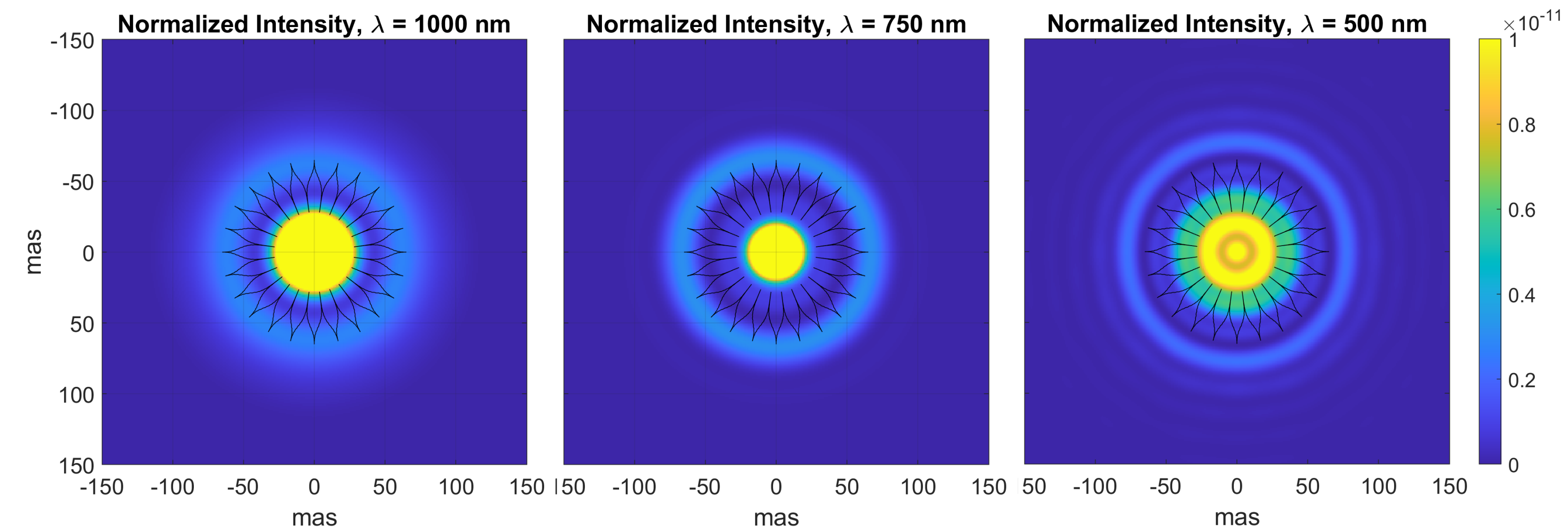


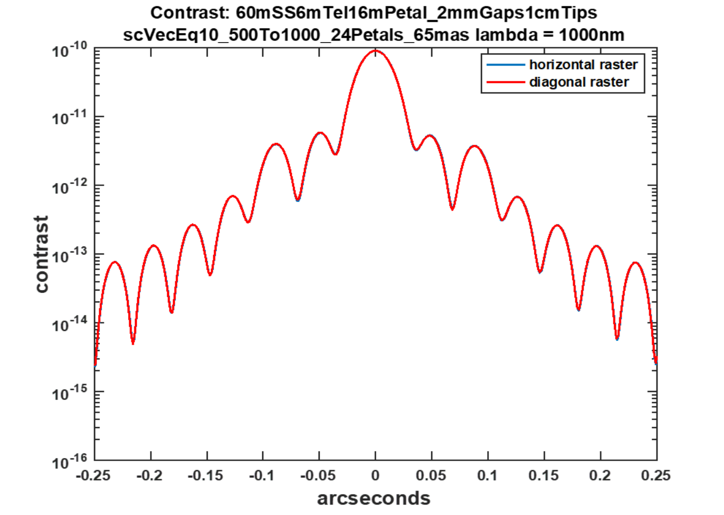
With a +/- 2 m radial tolerance, the sensing requirement is significantly relaxed compared to laboratory results, and the formation control bandwidth is ~ 600 s.

Contrast (Starlight Leakage)

Starshade designs with reasonable engineering constraints will perform better than 1e-10. Here are the diffraction patterns for the HWO 60 m starshade (the as designed shape, no perturbations).







The design contrast at IWA_{tip} is ~ 5e-12. In practice, with lab-proven tolerancing, the instrument contrast at the IWA will be ~4e-11.

Contrast improves with working angle, ringing down to nearly zero at 150 mas. There is no outer working angle limitation.

BANDWIDTH

A finite bandpass is desirable because the bright light leaking on either side of the suppression band can be used for formation flying.

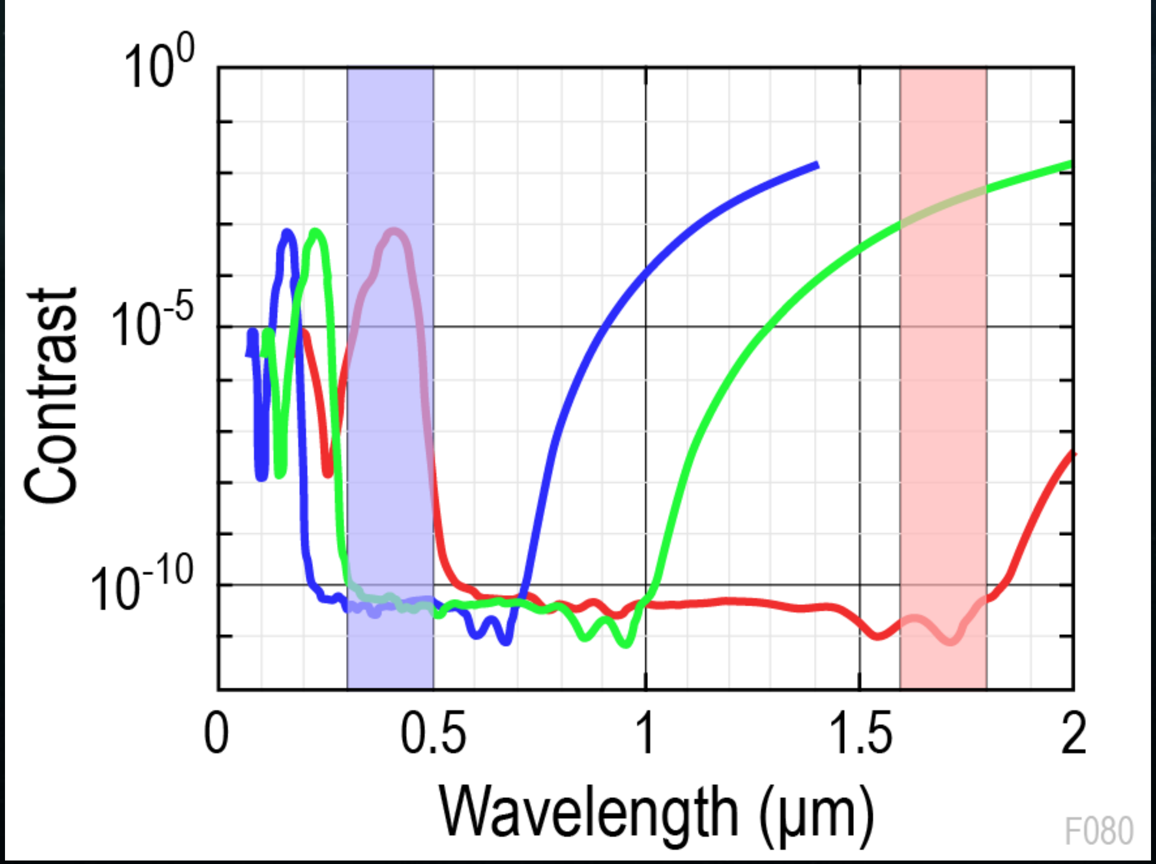
We use HabEx as an example. HWO will be similar.

When positioned for the visible band (green line), the red box 1.6-1.8 um provides the formation flying signal.

When positioned for the IR band, the blue box 0.3-0.5 um provides the formation flying signal.

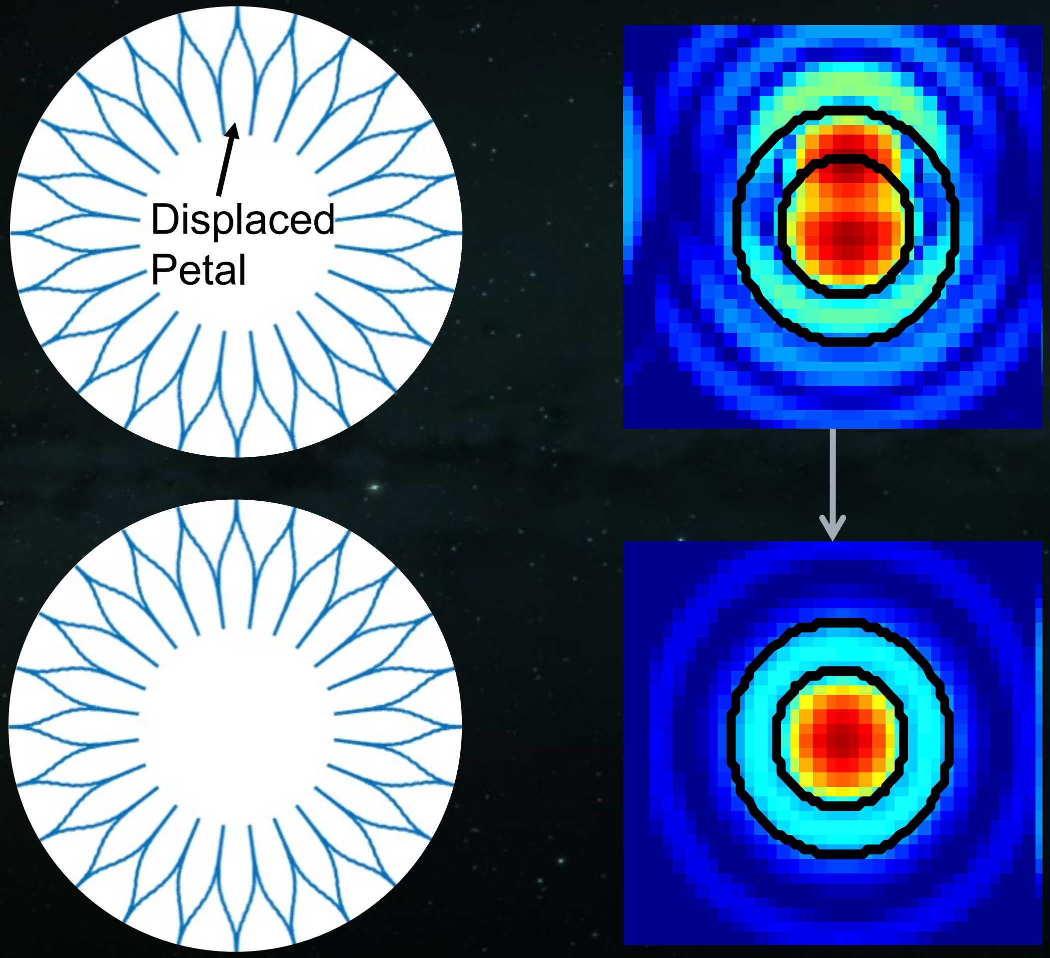
The formation flying alignment signal is the leaked Poisson spot from the star.

Example out-of-band guiding signal from HabEx report.



SPINNING

The starshade is spun about its axis at 12 revolutions per hour

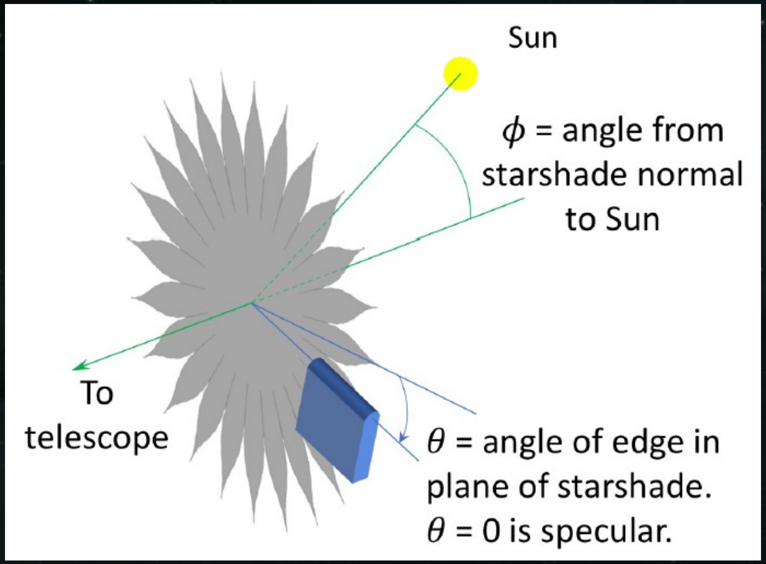


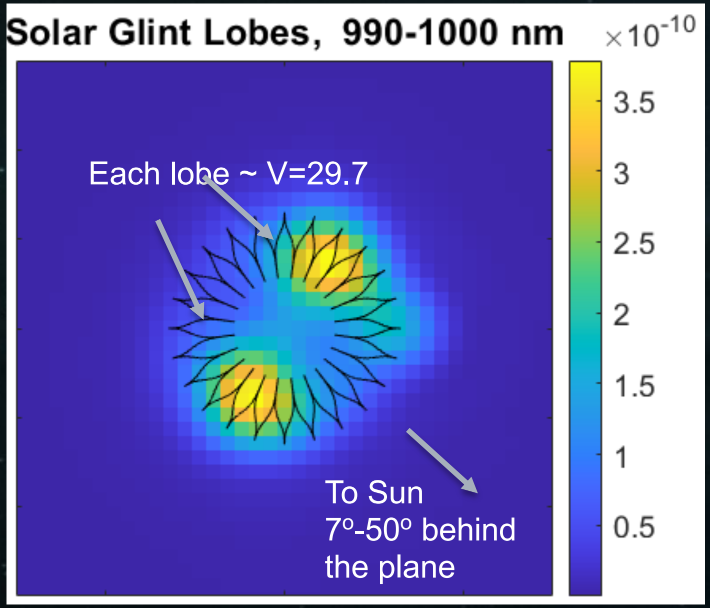
- Benefits of spinning
  - Reduce local thermal shape variations
  - Circularize leakage from shape defects
    - **Speckles smear into annuli, not to be confused with an exoplanet.**
    - Relaxes deformation requirements: driven by photometric leakage rather than systematic leakage.
    - But does not eliminate localized solar glint and formation flying scatter
  - No big reaction wheels
  - Robust fault tolerance
- Downside
  - Requires some additional fuel to rotate the angular momentum vector

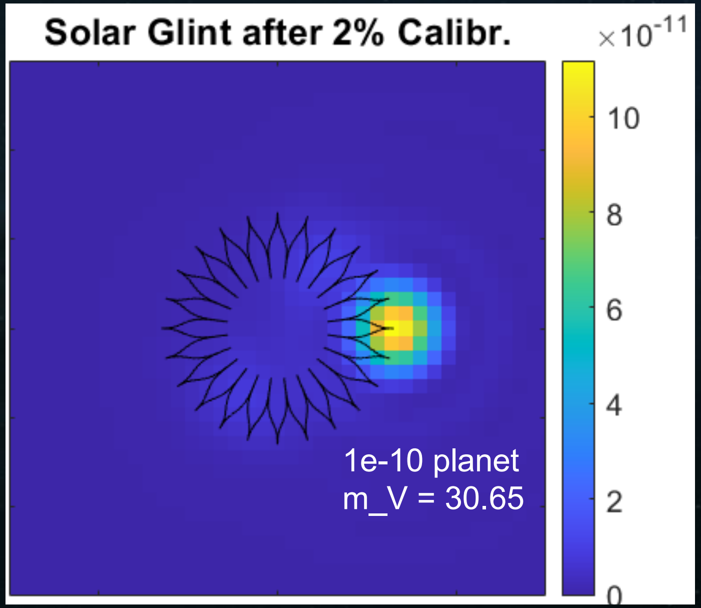
Spinning relaxes instrument calibration requirements.

SOLAR GLINT LOBES: THE MAIN INSTRUMENT NOISE

The brightest contributors to instrument background near the IWA are the two solar glint lobes resulting from the Sun illuminating the edges of the starshade. Here we simulate imaging of a G4V V=5.65 star.







The brightness of solar glint lobes is mitigated by employing sharp, anti-reflection coated edges. Highly accurate calibration is performed during initial on-orbit checkout by moving the starshade closer to the telescope.

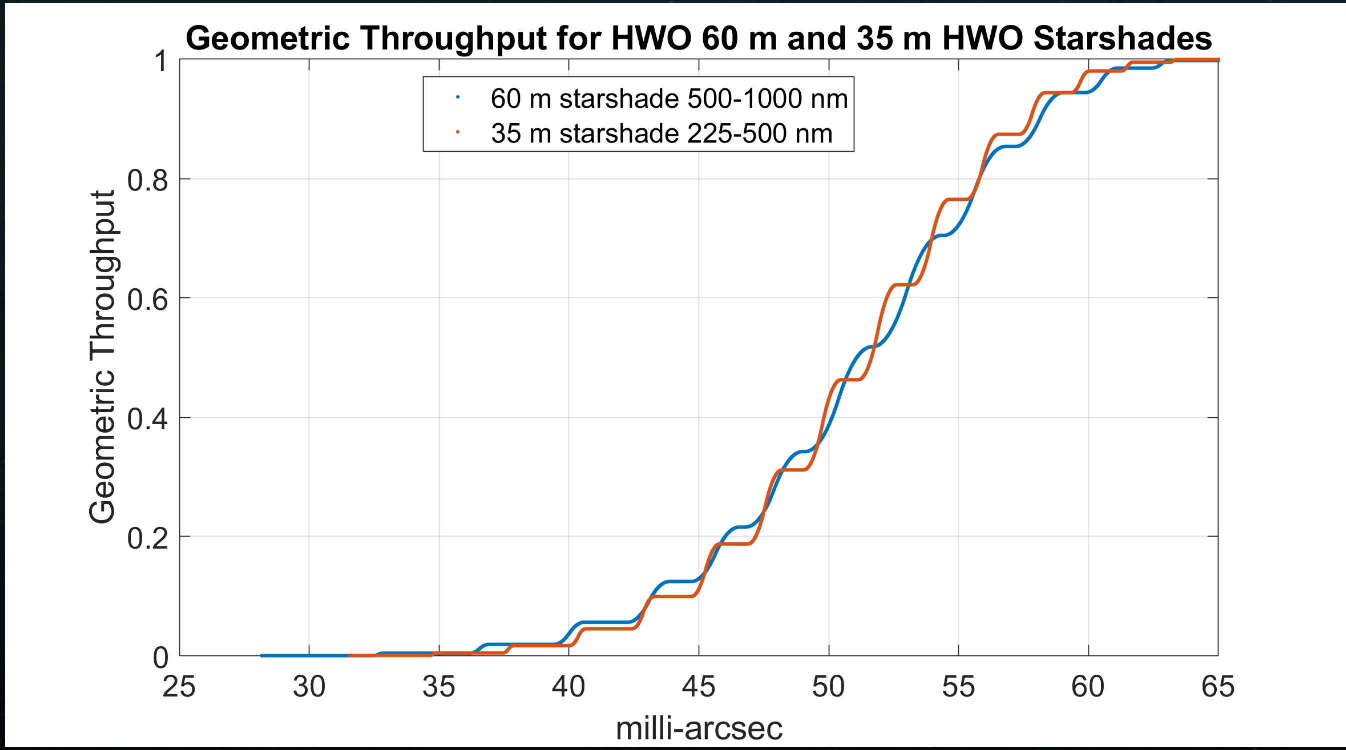
Solar glint lobes will have a visual magnitude of ~ 30 averaged over the IWA.

THROUGHPUT

Starshade throughput approximately follows the geometric opening of the petals (shown here). Instrument throughput is high because the cameras and spectrometers are relatively simple.

For exoplanet characterization, overall throughput is high due to a combination of:

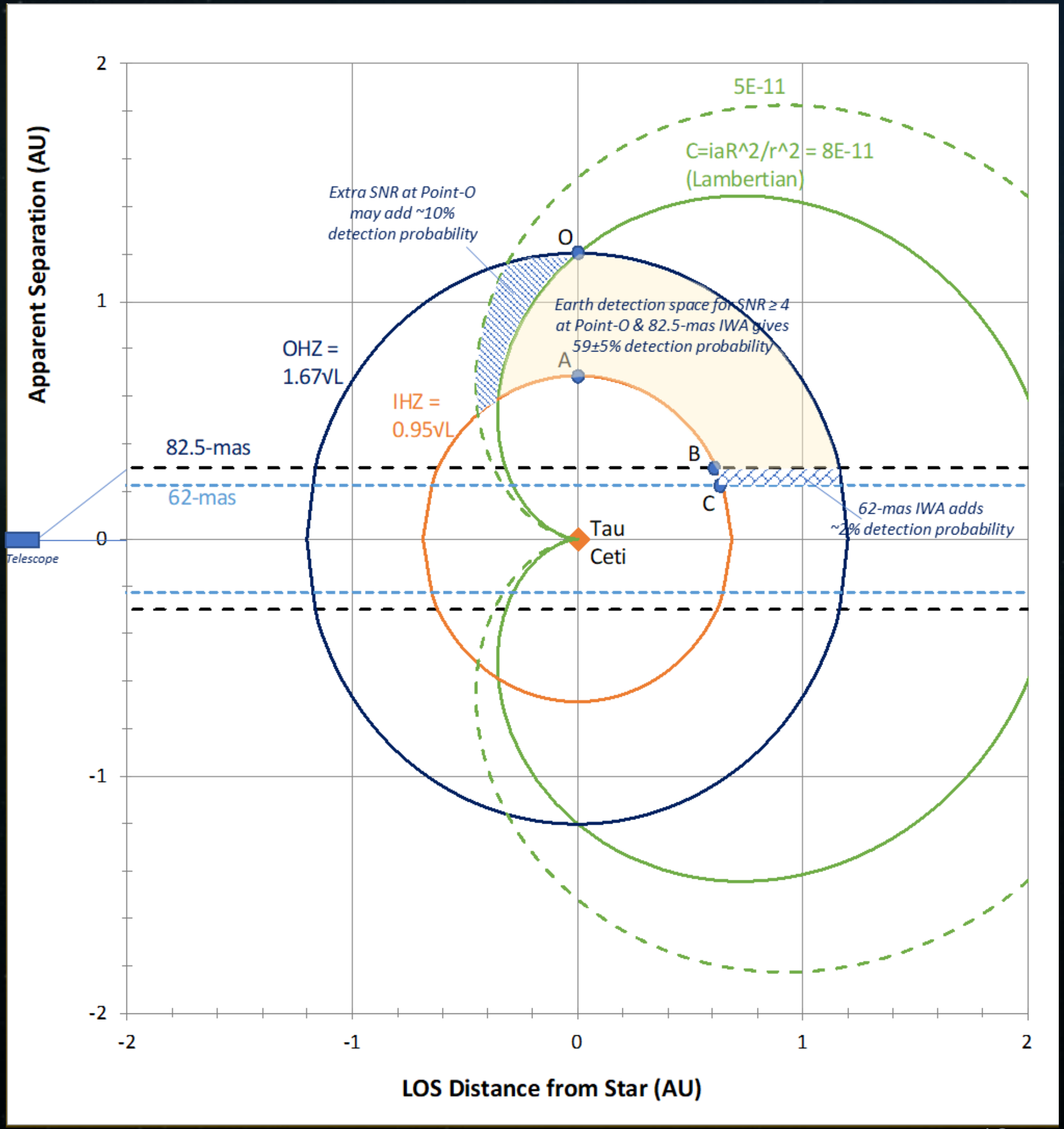
- High starshade throughput
- High camera throughput
- Large instantaneous bandwidth
- Small calibration overhead



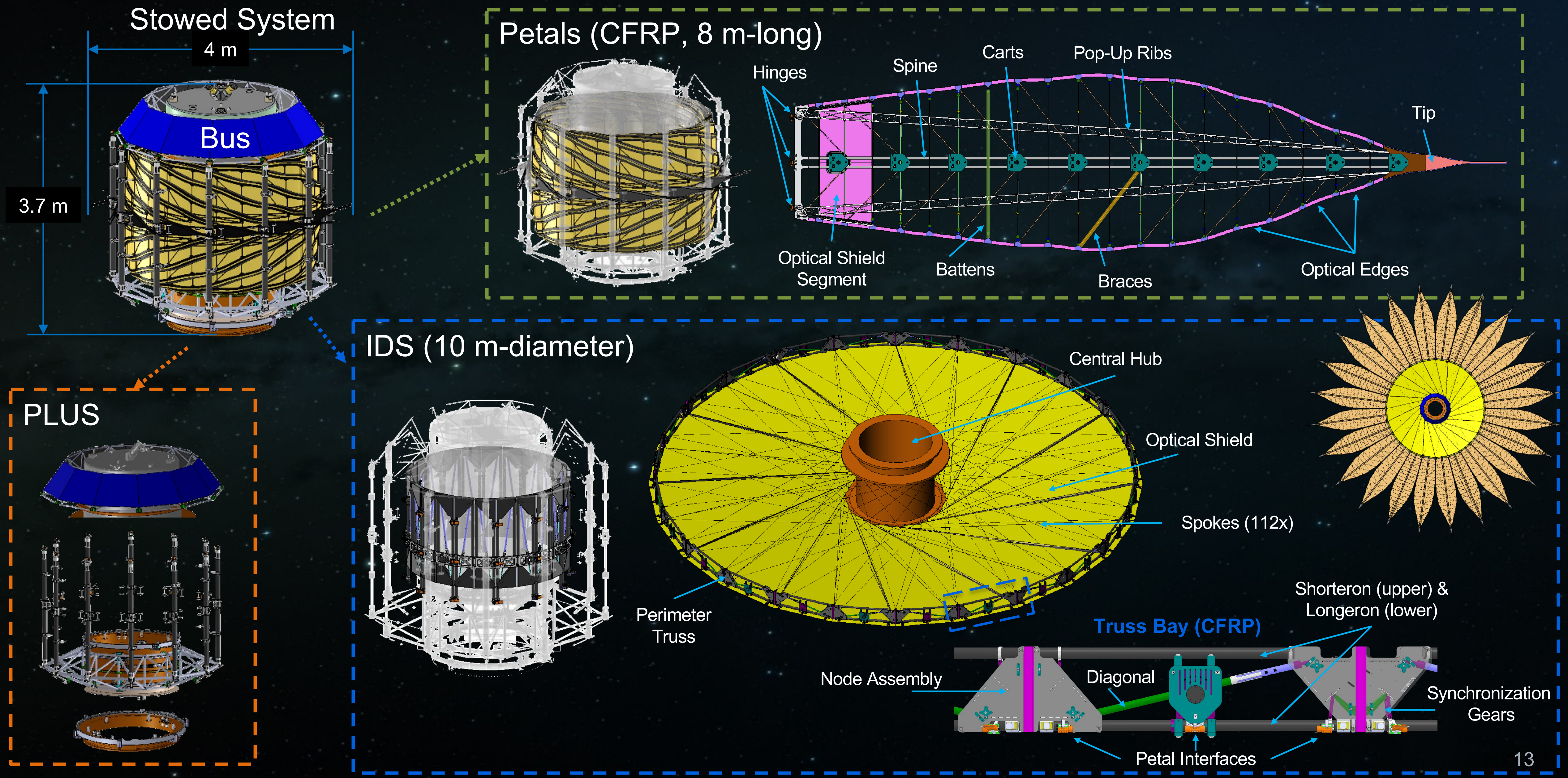
Observational Completeness

A starshade Design Reference Mission (DRM) favors a list of targets with high average observational completeness.

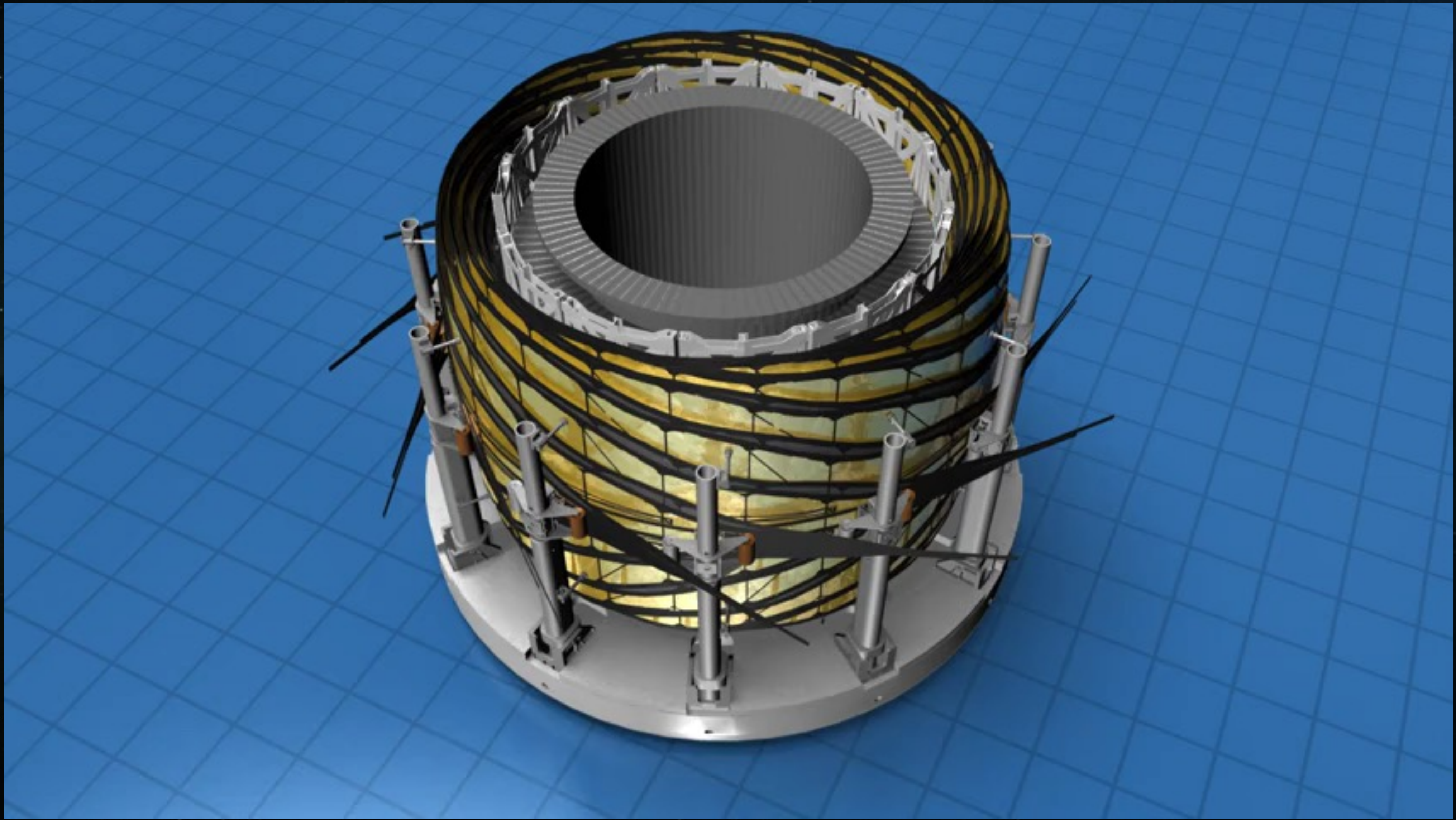
Attributes for high-completeness per target	What you gain
Small IWA	Access to IHZ
Unlimited OWA, improving contrast with WA	Access to OHZ
High throughput, wide bandwidth, low calibration overhead	Detected planets can be characterized before they disappear
Weekly or slower cadence per target	Limited number of observations
NET RESULT	**Focus on fewer high-completeness stars.** **More access to early type stars.** **Higher success rate for revisits, e.g. orbit determination.**



STARSHADE CONFIGURATION

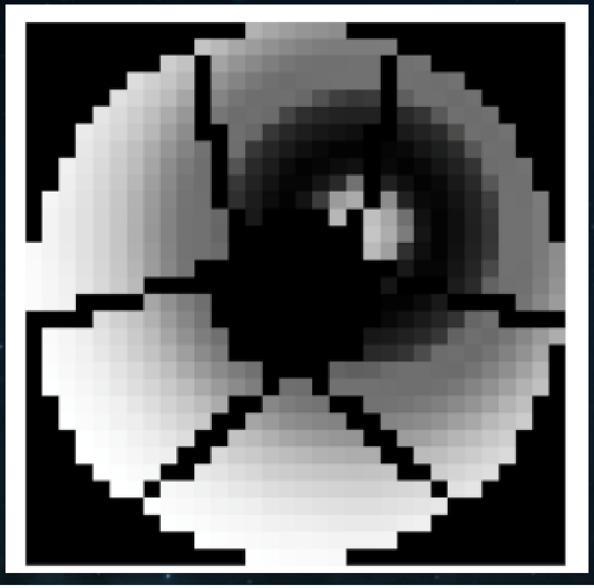


Starshade Deployment



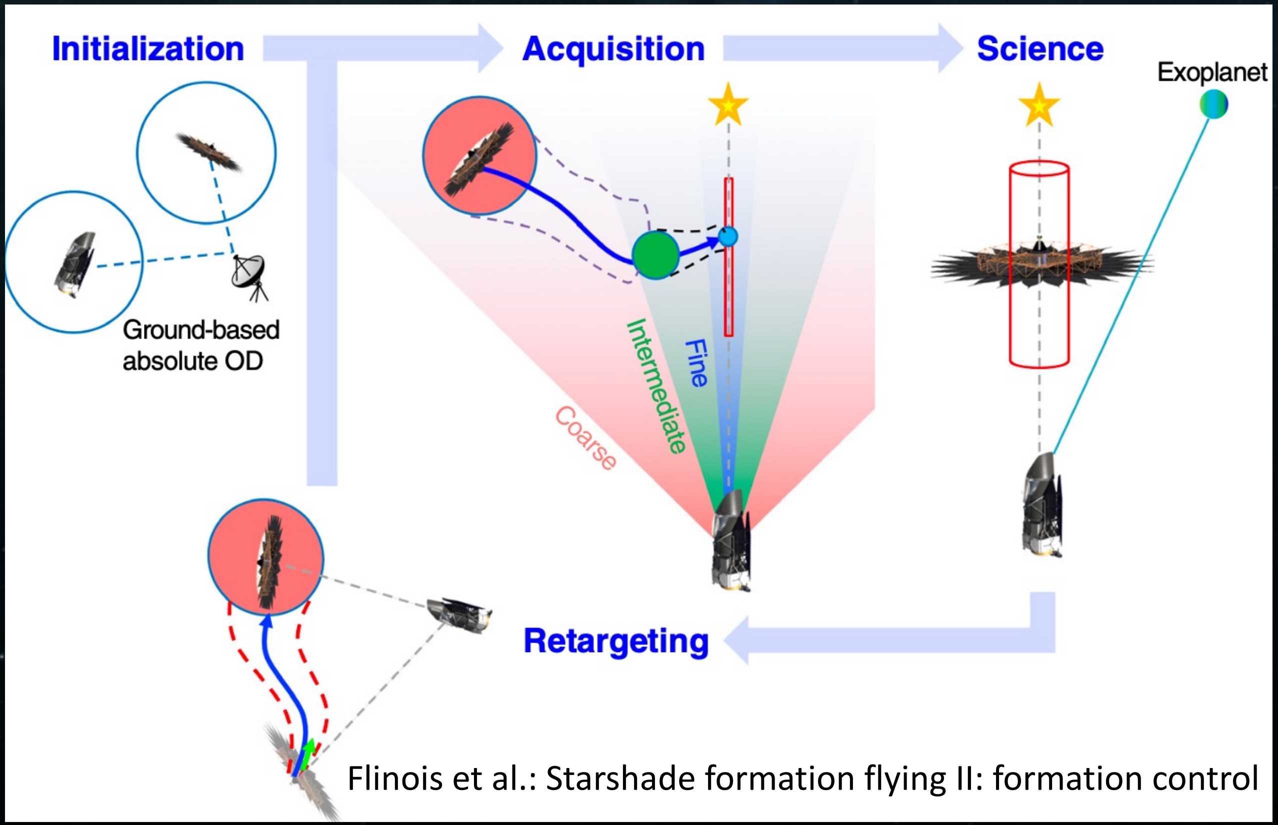
FORMATION SENSING & CONTROL

- A starshade's lateral formation error is readily sensed in a telescope pupil-plane via its prominent Poisson Spot in out of band starlight
- A laser beacon on the starshade supports acquisition only
- A RF transponder relays the error to the starshade for control via biprop thrusters



- Low gravity gradients at E-S L2 & even less solar pressure give ~10-min. thruster firing periods, for a lateral control band of ± 2m (i.e., 10-m dia. shadow)
- Potential detector saturation due to solar scatter from residual exhaust for ~10s can be avoided by reading out at a high rate
- Starshade sends thruster fire alerts via RF transponder

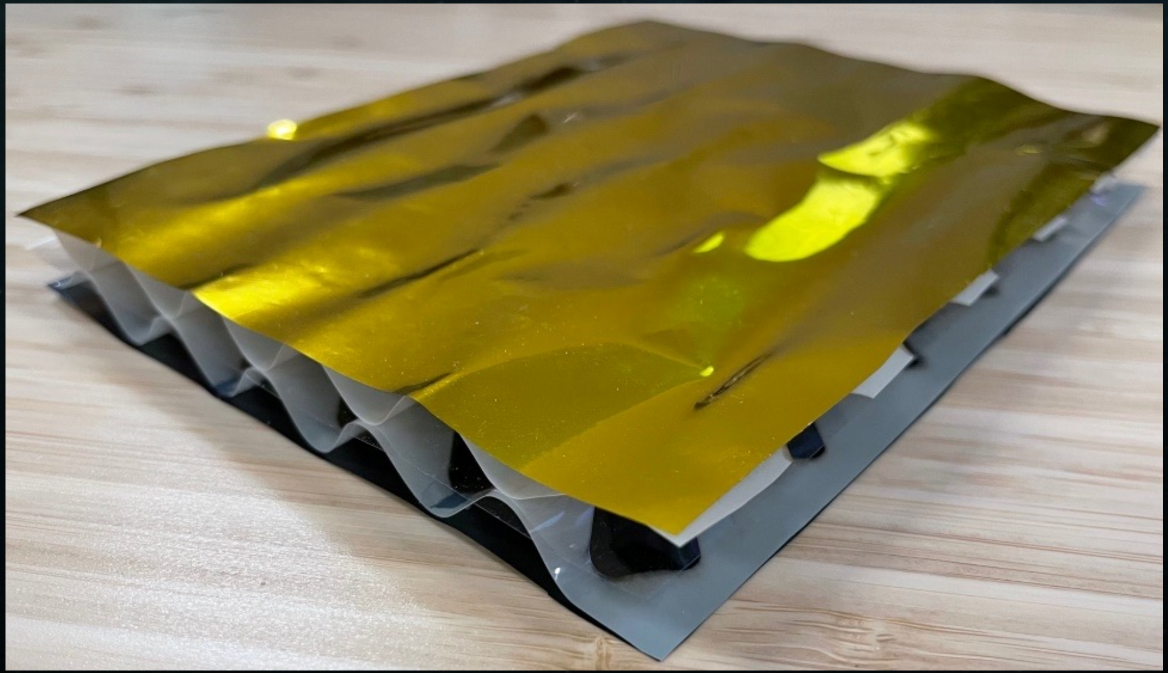
- Formation error contributes ≤ 1E-11 to instrument contrast



Flinois et al.: Starshade formation flying II: formation control

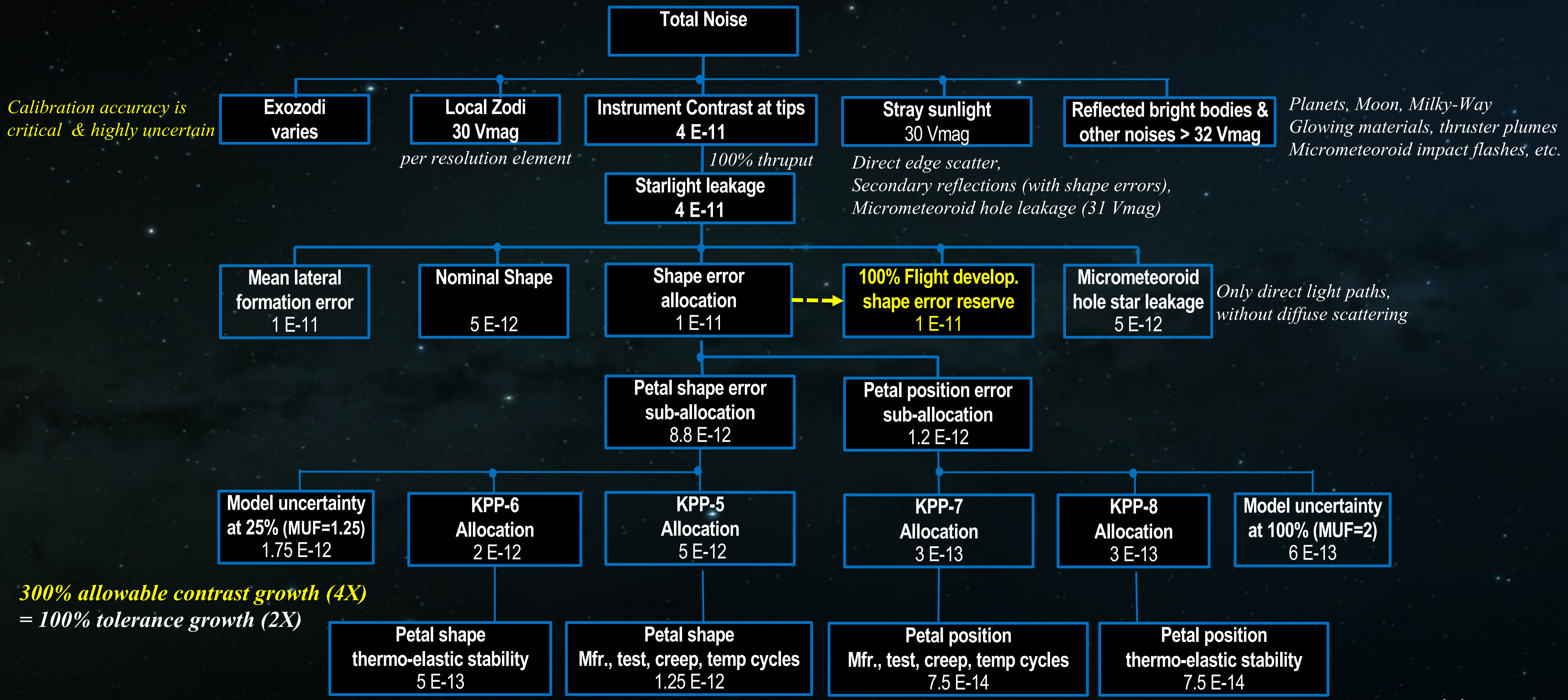
MICROMETEOROIDS AND MISSION LIFETIME

- **An opaque optical shield mitigates micrometeoroids with multiple spaced layers**
  - **Stops smaller highest flux particles**
  - **Requires many scattering reflections for off-axis sunlight to pass on-axis to the telescope**
  - **Limits solid angle for on-axis starlight to pass straight through without any scattering**
- **HabEx study estimates provide useful HWO placeholders**
  - **Off-axis sunlight ≥ 31 Vmag**
  - **On-axis starlight ≤ 5E-12 contrast**



- **HWO's larger launch fairings/stowed volume allow more layers & greater layer separation to improve micrometeoroid stopping power**
- **A 10-yr. life may be viable, but requires a detailed design study**

STARSHADE INSTRUMENT CONTRAST BUDGET

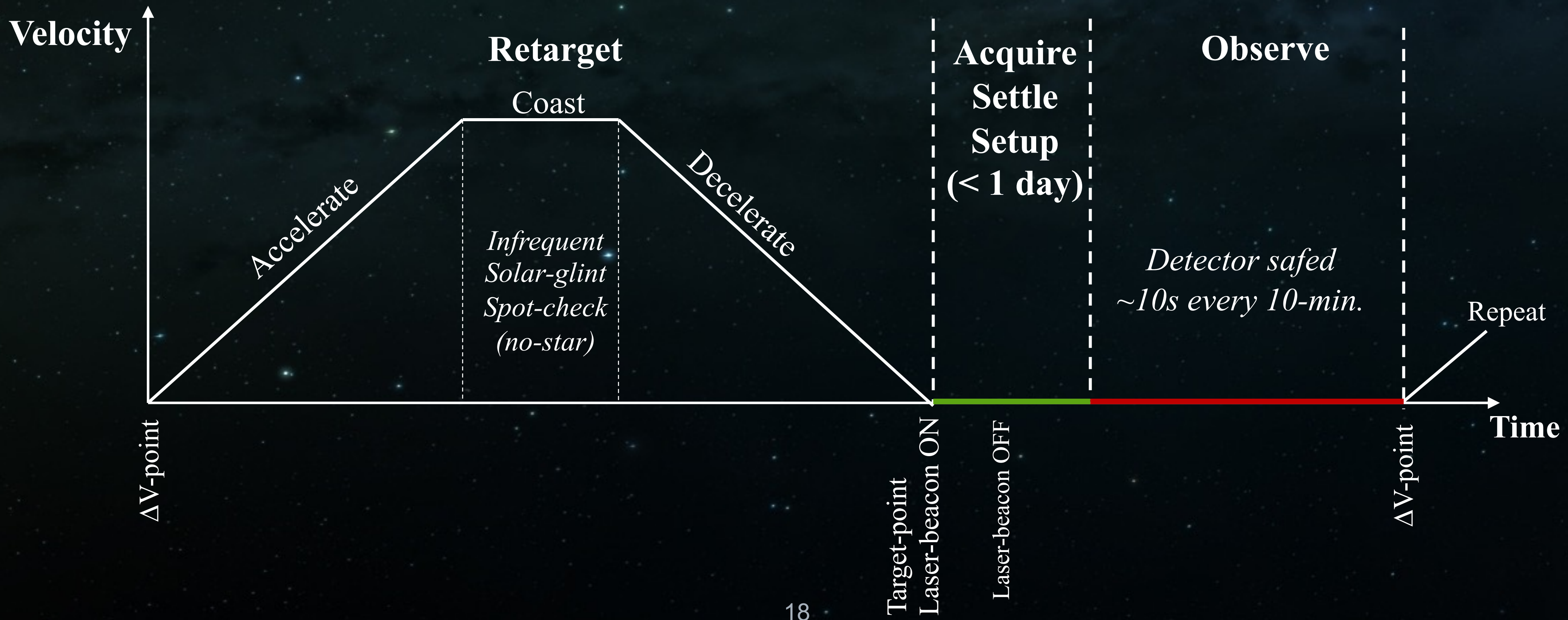


Max expected contrast at 3σ, or not to exceed levels that derive from S5 experiments & HWO simulations at 1.9 λ/D

The starshade limits instrument contrast to ≤ 4E-11 including large margins on top of max expected shape errors, demonstrated via ExoTAC approved technology milestones

Observation cadence

- **Starshade observations always follow a retarget maneuver, to line up on the target, & an acquisition, which typically limits the encumbered telescope time to ~25%**
- **Observations are uninterrupted, except for ~10-s every ~10-min. for formation control thruster firings**

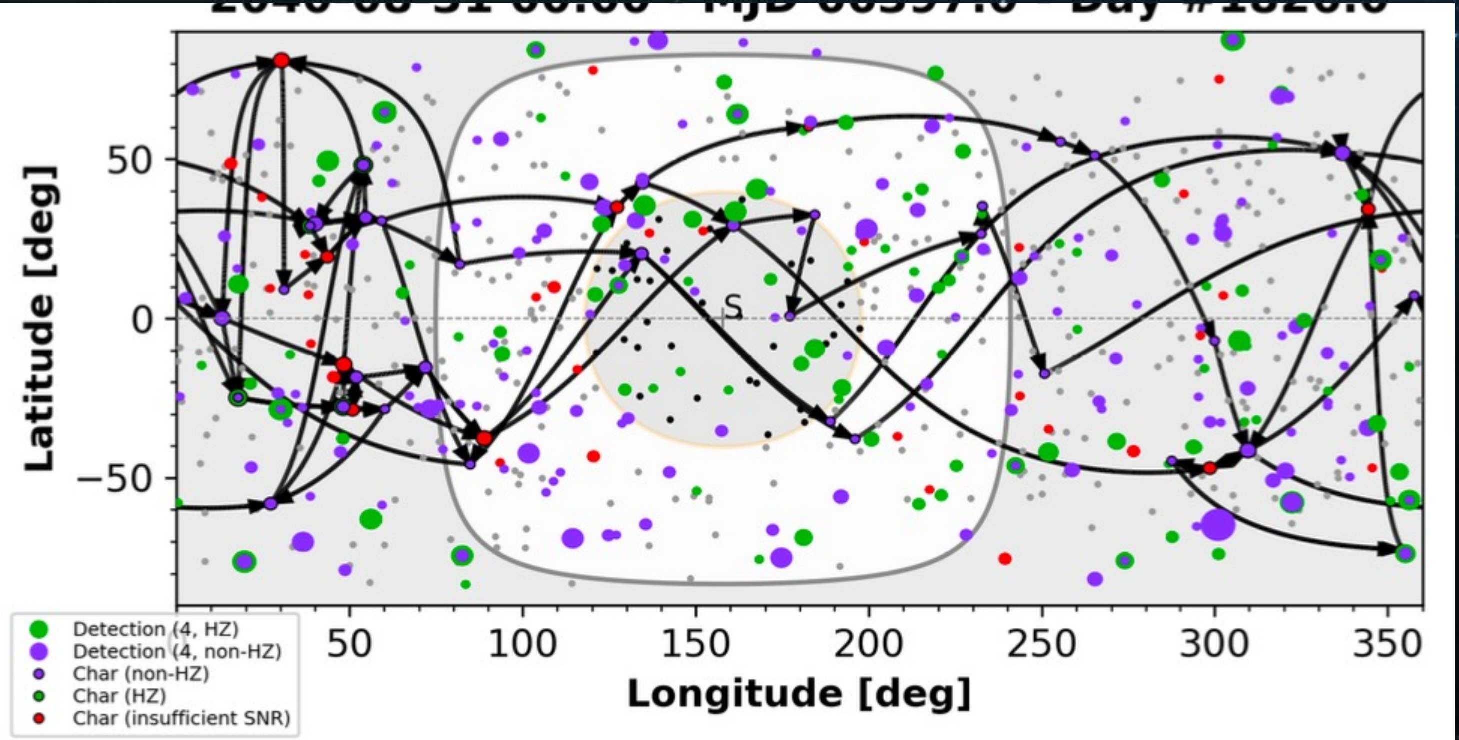


Starshade Field of Regard (FOR)

- **Starshade observes ≥ 40 deg. (TBR) from Sun, to keep sunlight out of the telescope barrel**
- **Starshade observes ≤ 83 deg. from Sun, to avoid solar illumination of telescope-facing surfaces**

- **Target stars move through this FOR**

- **A typical avg. retarget slew rate of ~ 2 deg/day gives an efficient observation sequence, keeping the starshade in the FOR**



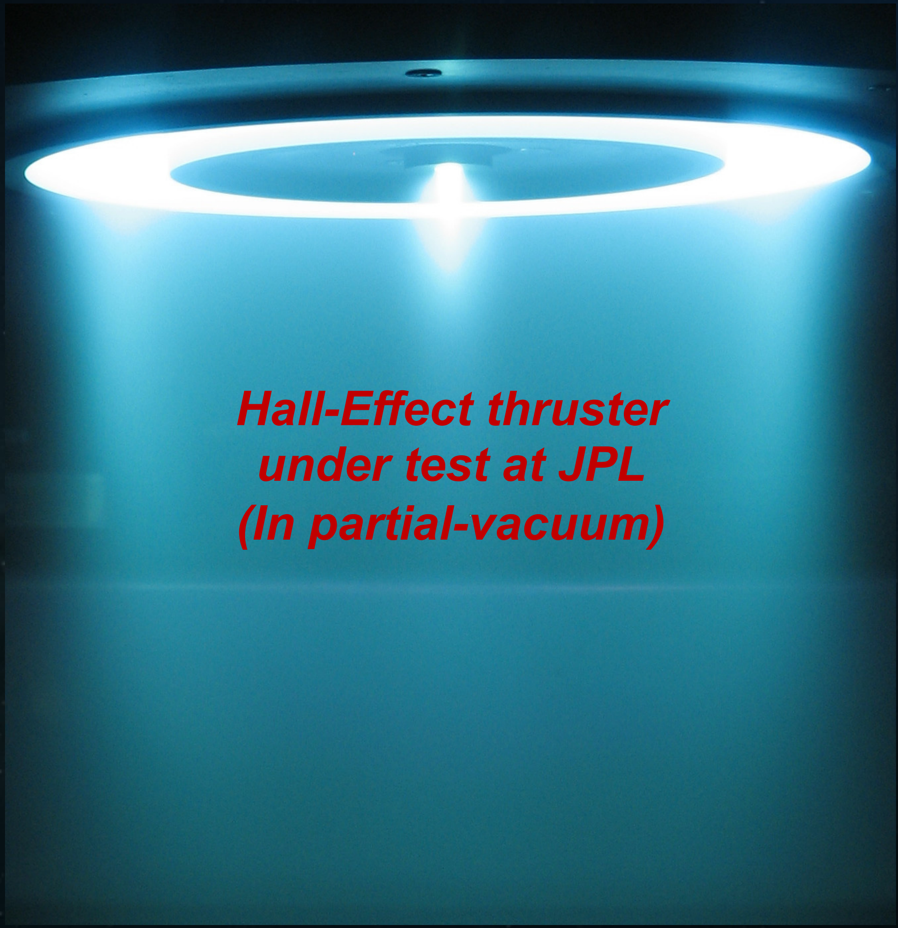
.3-3. EXOSIMS design reference mission simulation scheduling observations planned for the broad and deep survey c
Starshade retargeting transits over a nominal 5-year mission (2035–2040) are indicated by black arrows. Using realist
ich as solar field-of-regard, transit times and fuel usage, 100 starshade transits can be accommodated with fuel ma

HabEx Final Report

C-13

STARSHADE RETARGET PERFORMANCE

- Retargets use Gateway's Hall Effect thruster with Xenon gas
  - Hall Effect Rocket with Magnetic Shielding (HERMeS)
  - 2,900-s specific impulse & 0.6-mN thrust, per engine
- PV cells on the starshade disk provide SEP power, with available disk area limiting total thrust
  - 35-m starshade powers 1 engine for 0.6-mN thrust
  - 60-m starshade powers 3 engines for 1.8-mN total thrust



- Starshades carry large propellant loads for significant science yield and refueling either augments the yield or adds a new mission phase
- A 35-m starshade is relatively agile & can blind-search ~150 stars in 4-years, then after refueling can revisit ~36 Earth candidates 4X each over 4 additional years
- Rhonda Morgan will next speak to 60-m starshade yield, sans refueling

STARSHADE CONCERNS

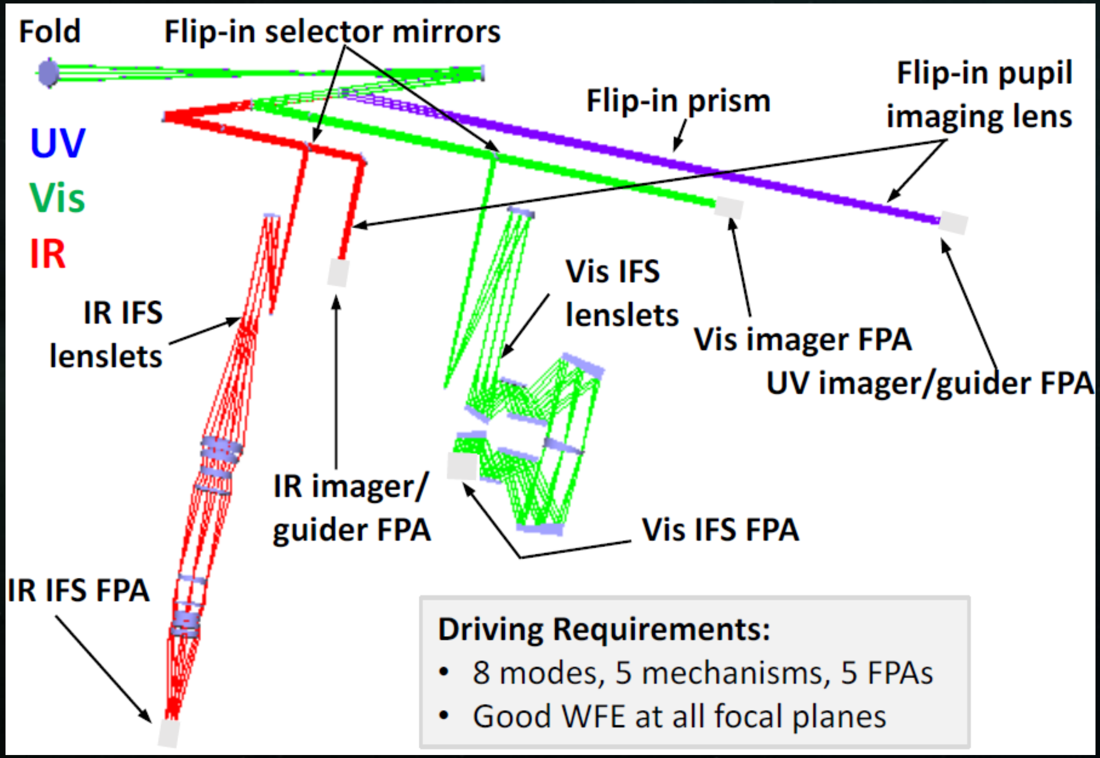
Concerns, Risks, or Challenges	Mitigations
Maintaining sufficient starshade cleanliness to limit solar scatter	Clean-room assembly with shielding from gravity offload equipment Deployed tests mostly with telescope facing surface pointed down Stow within dry-N2 purged container/thermal shroud Remove before flight peel-off coating on optical edges
Optical performance demo. & models validated only at subscale	Ground tests match HWO mission petal Fresnel zones & n λ/D IWA. Future testbed of 3X length reduces polarization by 3X.
Optical perf. demo. & models validated only over part of band	Ground tests match HWO mission petal Fresnel zones & n λ/D IWA
Refueling & long mission makes micrometeoroids life-limiting	Larger launch vehicle fairings allow more optical shield layers with greater layer spacing to greatly improve micrometeoroid stopping power
Programmatic risk of a 60-m 1st starshade flight development (large standing army cost)	Develop a high fidelity full-scale TRL-6 starshade system & treat like flight, with noted exceptions

BACKUP

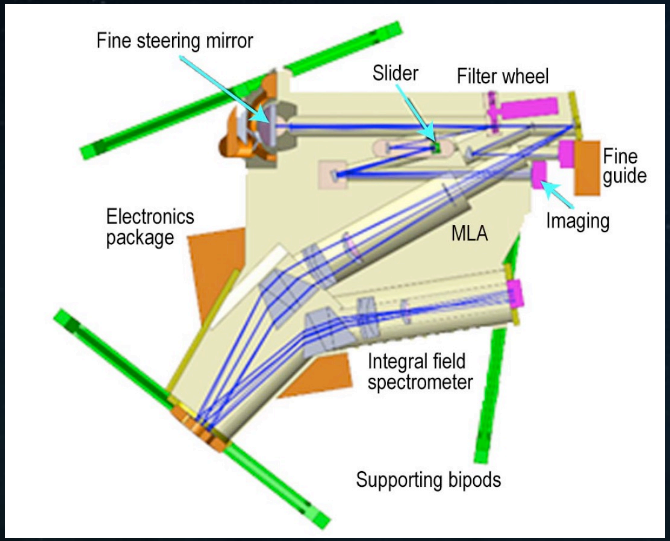
CAMERAS

Starshade cameras and IFSs: Compact, High Throughput, Simple.
Here are some examples:

A multi-band camera with IR and Vis IFS
(Habex Lite 2018) IFS.



Exo-S Optical Instrument



A UV dedicated high-throughput camera with (O3 report).