Jet Propulsion Laboratory
California Institute of Technology

State of the Art of Starshades (and how it applies to Remote Occulter)

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May 14, 2019

Starshade Technology Development Activity (S5)

- S5 advances starshade technology to TRL5 for future space telescope missions
- Key Performance Parameters, test articles, and relevant environments in S5 defined w.r.t. Starshade Rendezvous and HabEx
- S5 is designed to close starshade technology gaps maintained in ExEP Technology Plan Appendix
- Both the Technology Plan Appendix and S5 Plan are ‘living documents’
  - Gaps and milestones specific to Remote Occulter can be added through existing change cycle


Starshade to TRL5 (S5) Technology Development Plan

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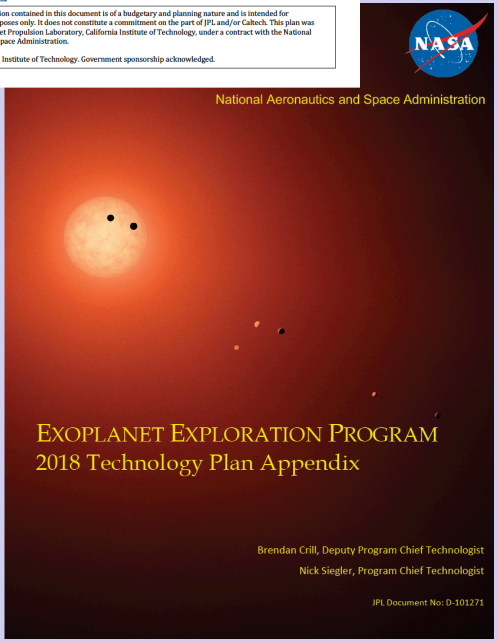
National Aeronautics and Space Administration

EXOPLANET EXPLORATION PROGRAM
2018 Technology Plan Appendix

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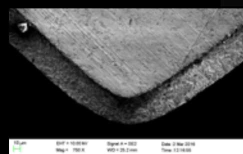
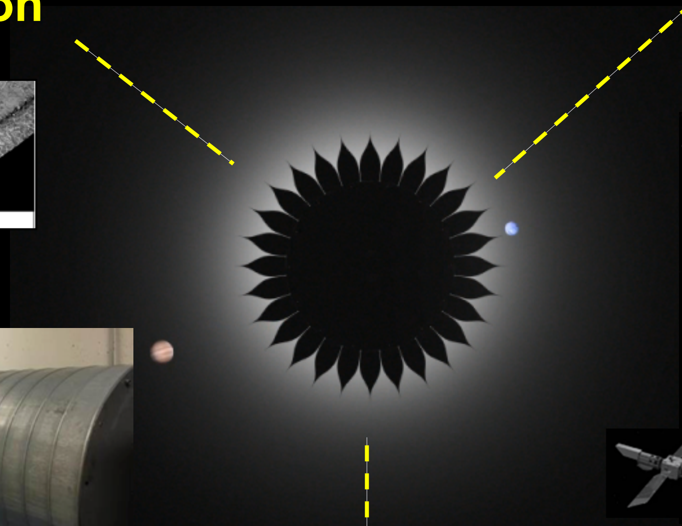
JPL Document No: D-101271

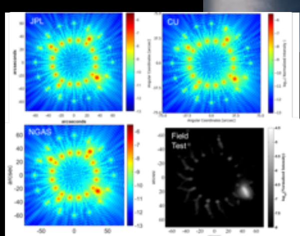
The Three Starshade Technology Gaps

(1) Starlight Suppression

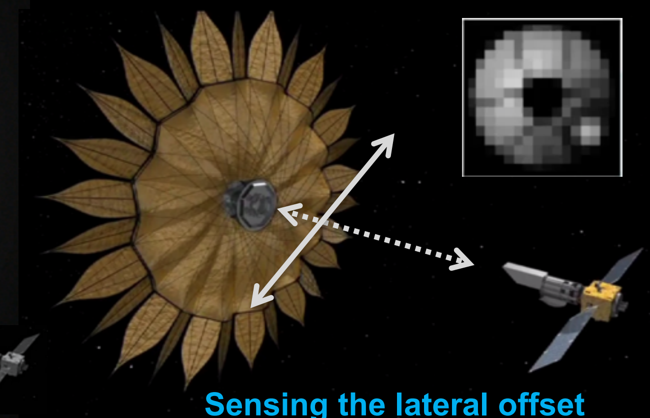
Suppressing scatted light off petal edges from off-axis Sunlight (S-1)





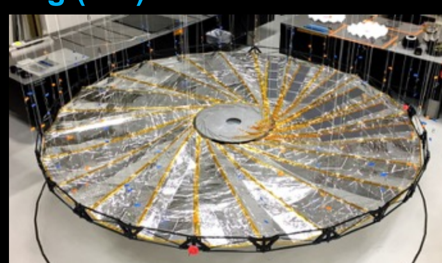
Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

(2) Formation Sensing

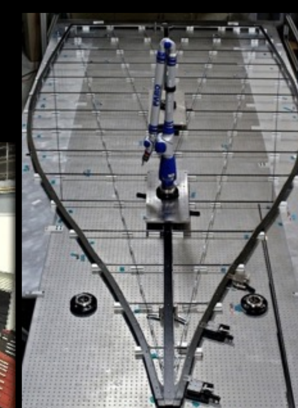


Sensing the lateral offset between the spacecraft (S-3)

(3) Deployment Accuracy and Shape Stability

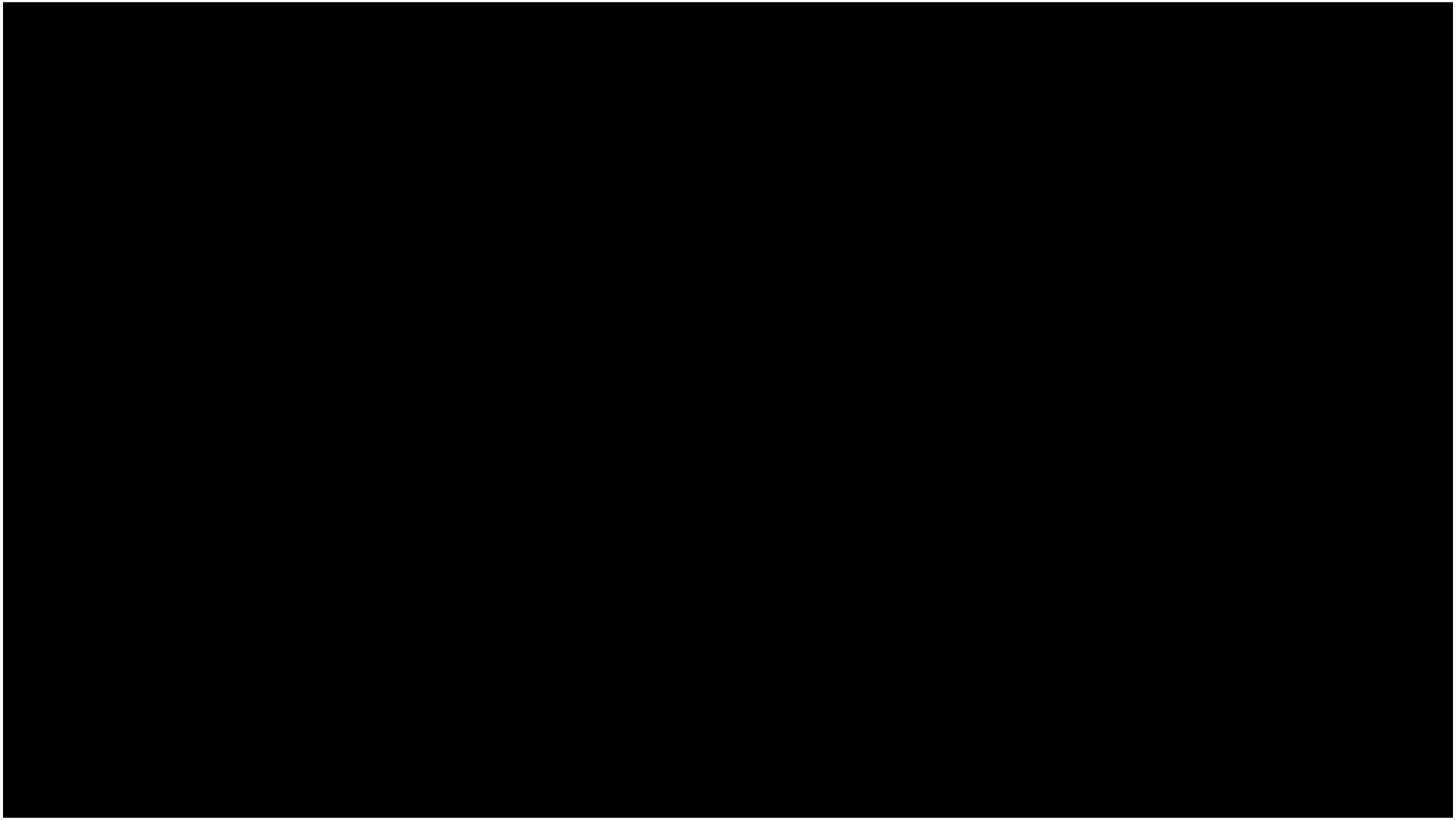



Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)



Fabricating the petals to high accuracy (S-4)

S-# corresponds to ExEP Starshade Technology Gap (http://exoplanets.nasa.gov/exep/technology/gap-lists)



S5 Starshade Error Budget

ExoPlanet Exploration Program

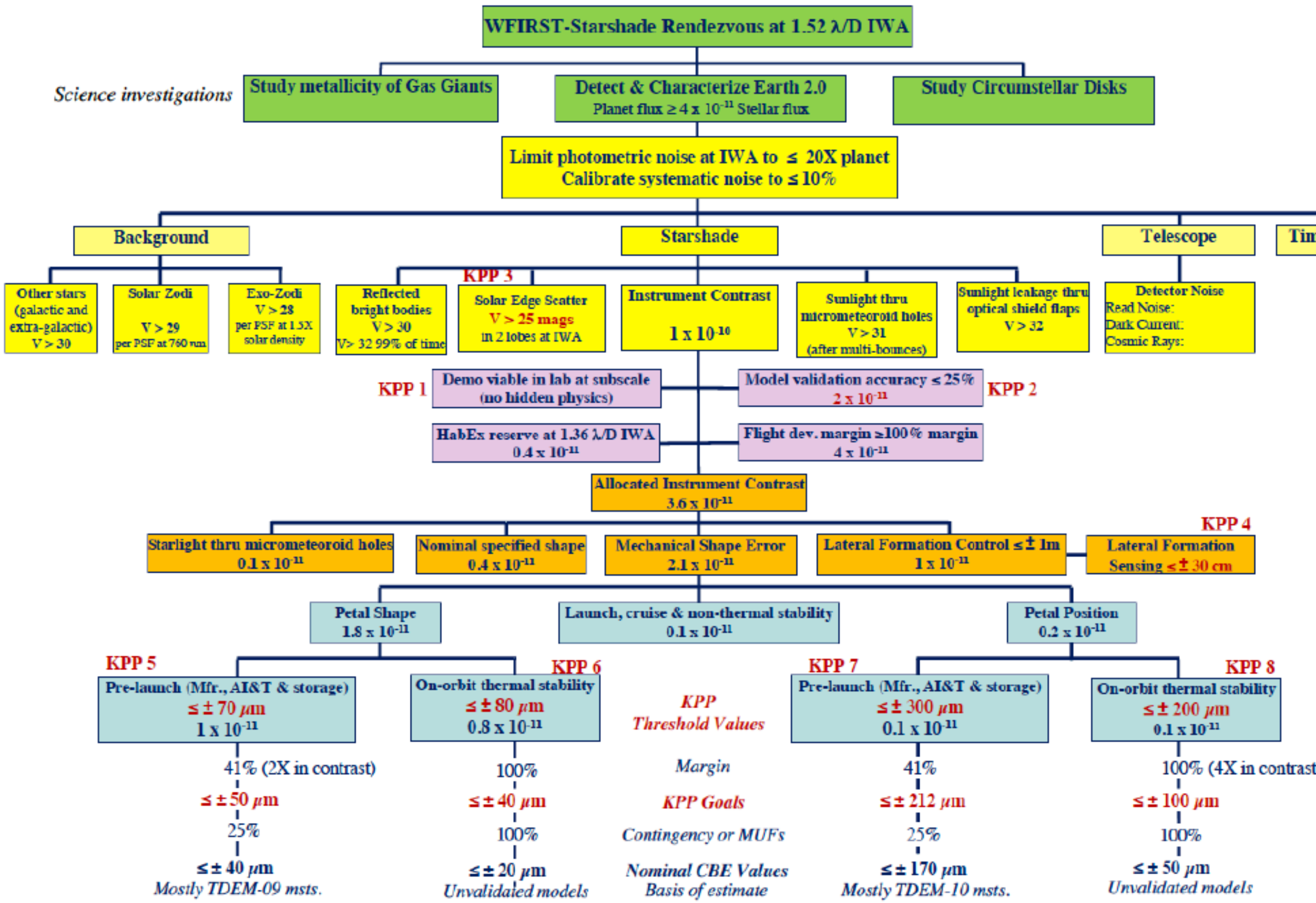
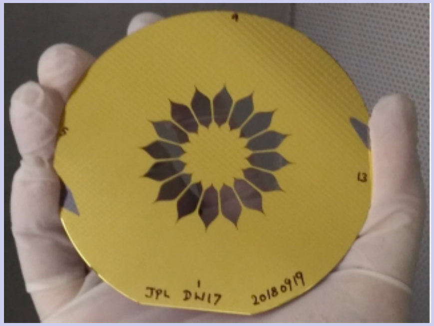
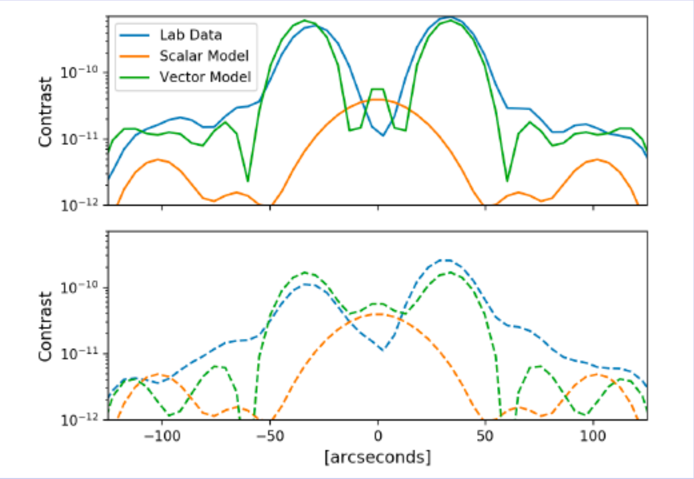


Figure 2: Flow down of Key Science Parameters of Starshade Rendezvous mission to Key Performance Parameters of starshade itself.

State of the Art: Starlight Suppression

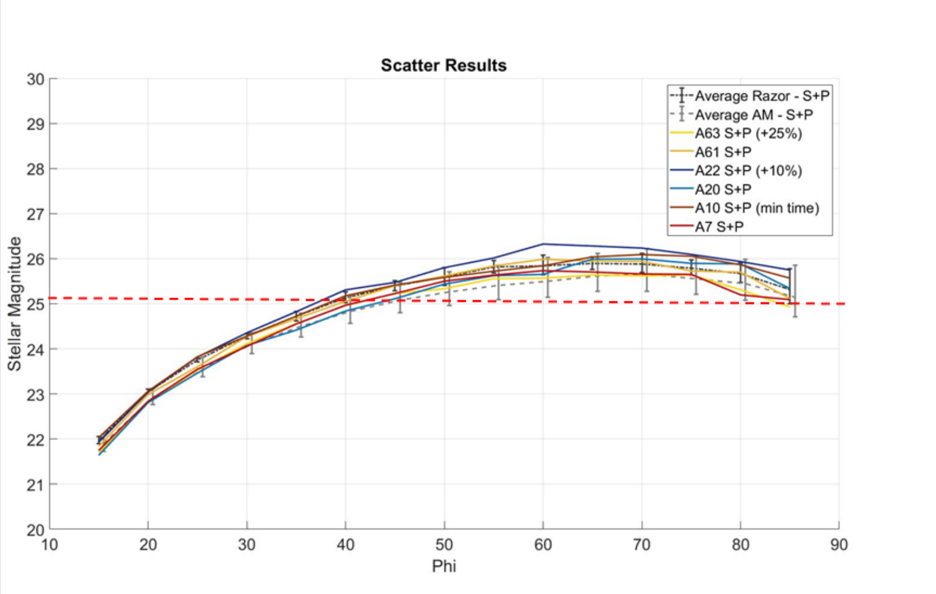


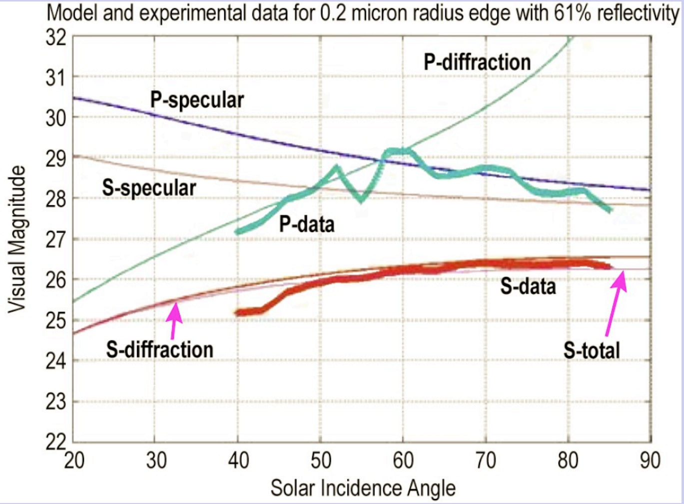


- S5 KPP is 10^{-10} contrast at starshade inner working angle
  - Exozodi background yields diminishing returns to better contrast
  - Goal is to do better anyway, of course
- State of the art for demonstrated suppression is recent results from Princeton Testbed, showing better than 10^{-10} contrast over significant fraction of IWA at both narrowband and 10% broadband operation
- Remote occulter contrast KPP is likely relaxed as small telescope PSF reduces background limits

Solar Scatter

- KPP is solar glint lobes less than 25th magnitude
  - Would like to do better- Goal is 26th magnitude, at this level limit is purely diffraction
  - Can perhaps do better with ‘stealth edges’ at price of no starshade rotation
- State of the art is measurements of amorphous metal edges consistent with V = 25.5

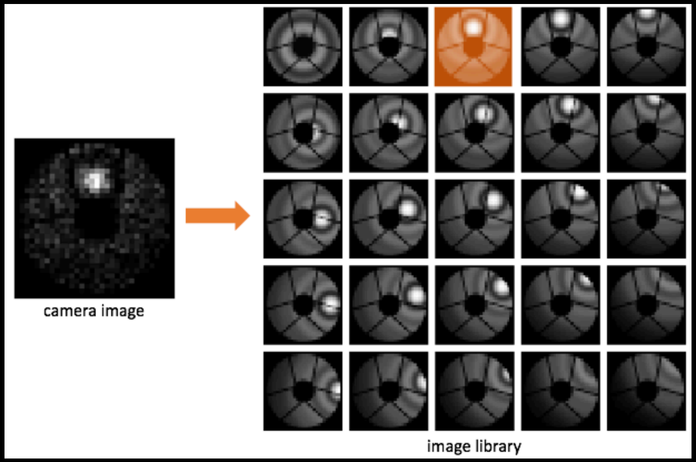


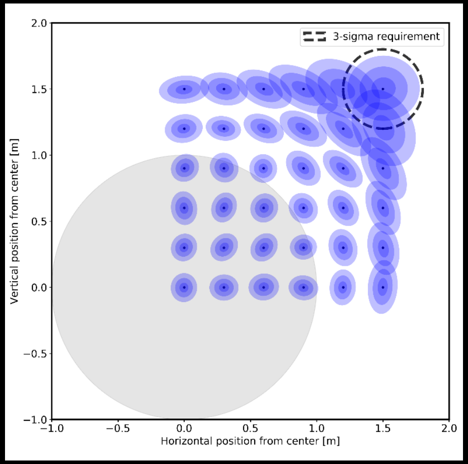


Formation Flying

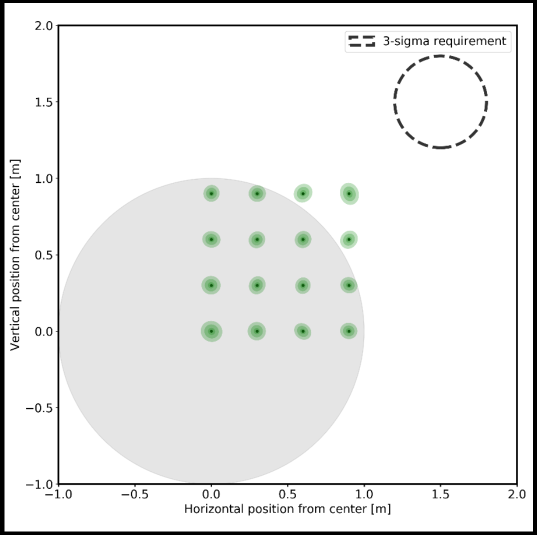
Lateral Offset Sensing

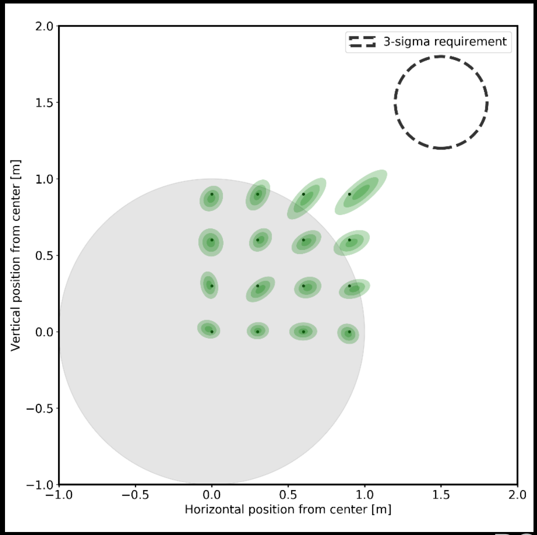
- Pupil image is collected and compared to library of stored offset pupil images to determine direction and distance of lateral offset





Optical model



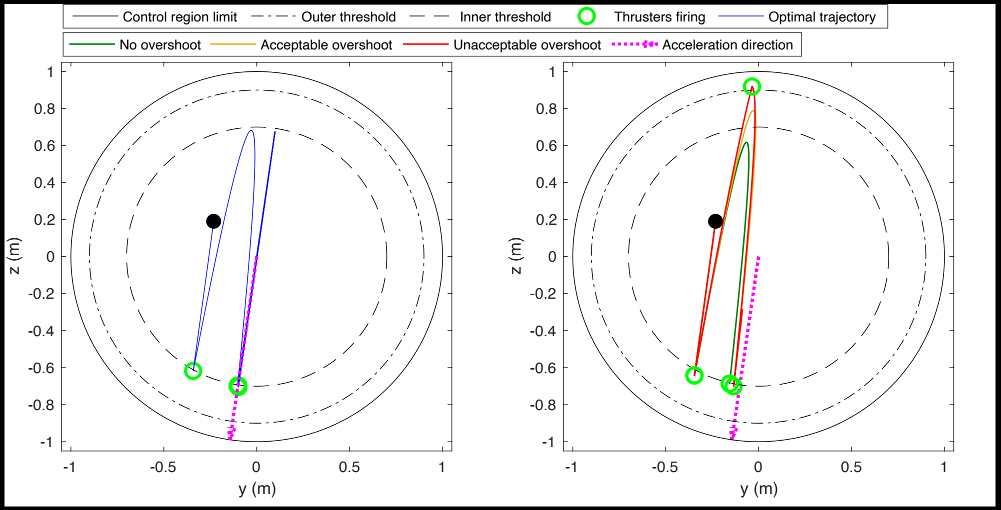


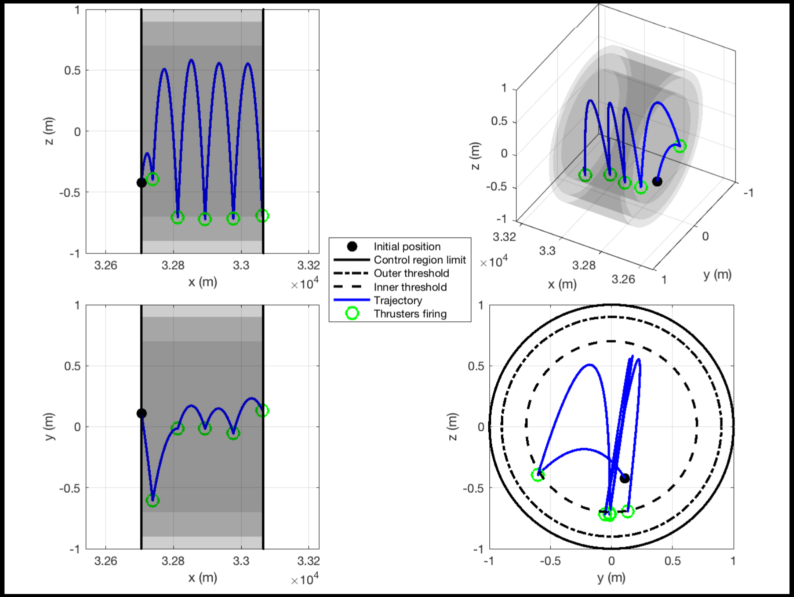
SLATE results

POC: Michael Bottom (JPL)

Formation Flying
Closed Loop Formation Flying Model

- Control scheme attempts to keep starshade ballistically ‘bouncing’ within inner threshold. Outer threshold deal gracefully with ‘overshoots’ to maintain ±1m positioning.





- Models demonstrate successful position control with lab-validated optical performance.

Formation Flying

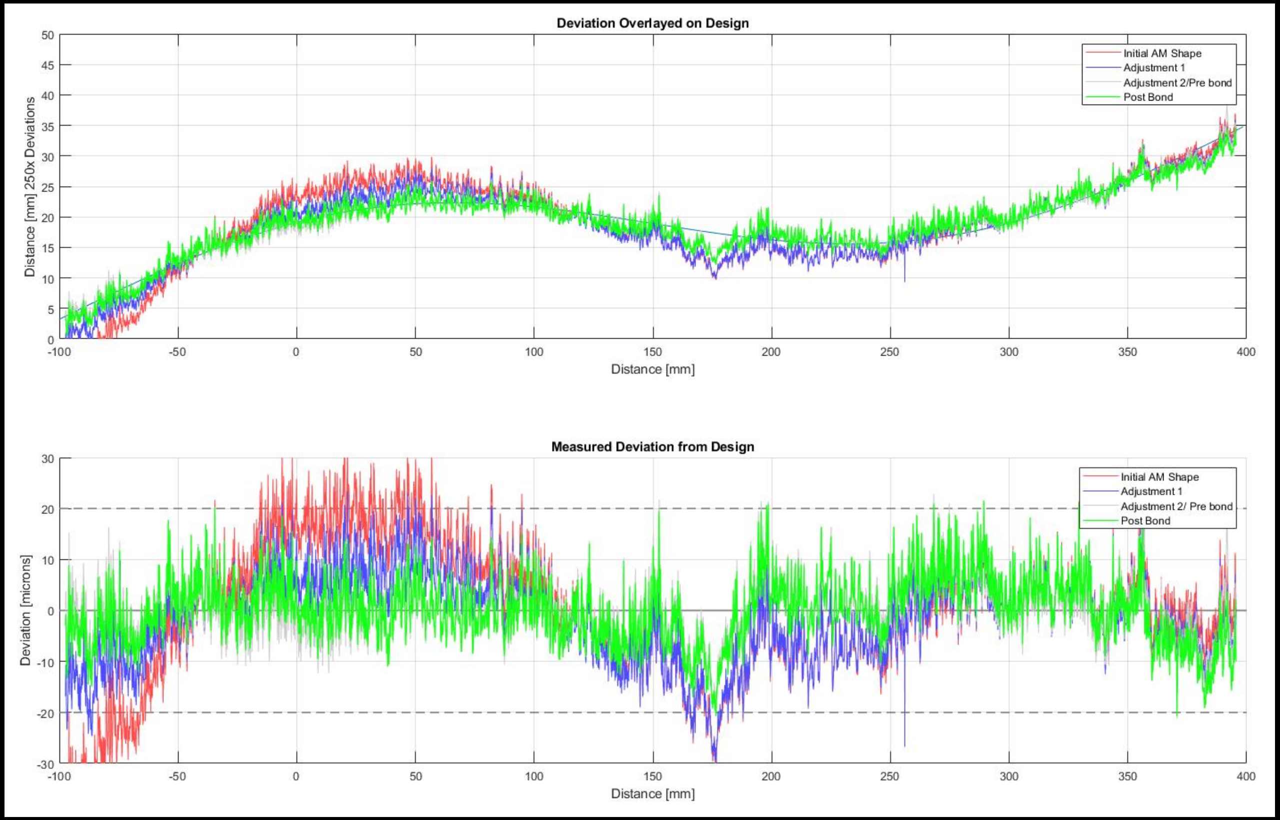
- Formation flying is standard NASA technology- we do it every time a capsule docks at ISS. Technology gap is (was) sensing lateral displacement at large distances
- S5 KPP is lateral position sensing within 0.3 m to control lateral position offset to within 1 m; related to oversizing of starshade shadow w.r.t. telescope aperture
- State of the art: this technology is now at TRL5 for the L2-orbit starshade missions.
- Formation flying technology is likely much less mature for remote occulter concept: accelerations and conops are very different

Petal Shape Accuracy and Stability

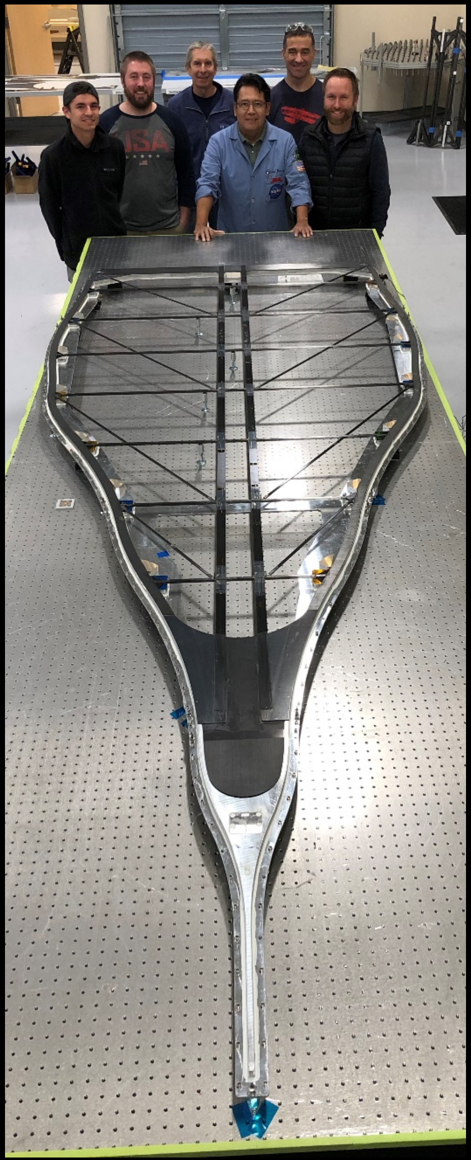
- Petal shape determines the apodization function of starshade- petals must be built right, survive deployment, and stay stable through thermal environment
- S5 Shape KPP flows down from contrast requirement of 10^{-10}, leads to 10's of microns tolerances in petal shape
- State of the art: petals are manufacturable with needed tolerances and stay in spec through early tests, but much testing still left to do.
- Remote occulter shape KPP likely less stringent to match likely lower contrast requirement

Recent Petal Progress

First flight-like edge segment meets shape spec, and small deviations can be corrected before bonding



First petal article built



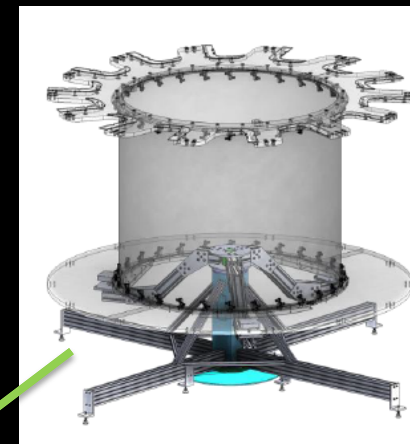
Petal Position Accuracy and Stability

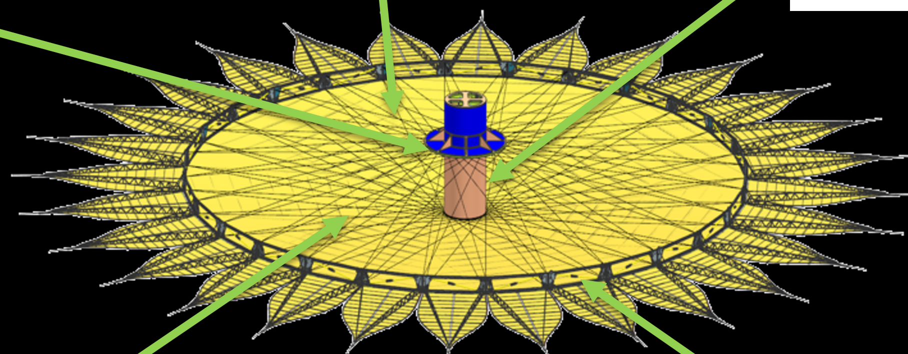
- Petals must be deployed to (and stay at) correct positions for apodization to do any good.
- S5 Position KPP also flows down from 10^{-10} contrast KPP, in this case to 100's of micron tolerances
- State of the art: inner disk is based upon Astromesh antenna with high flight heritage; deployment accuracy and stability testing are planned over next few years.
- Remote occulter Petal Position KPP likely less stringent for same reasons as for Petal Shape

Inner Disk and Optical Shield

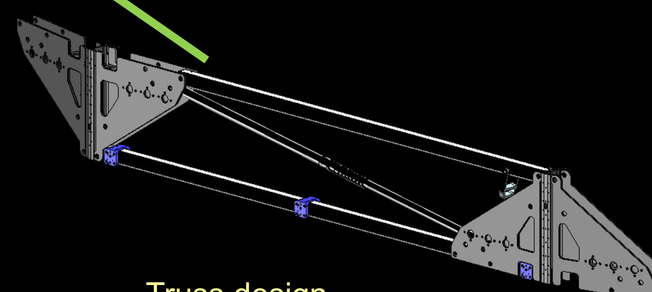
Spoke and 'nipple'

Hub design





Prototype shield segment



Truss design

How Does Remote Occulter Differ from Rendezvous and HabEx?

- Ground Telescope
  - Bigger aperture
  - Need for laser guide star
  - Field of regard
  - Weather
  - Dispersion
- Size
  - Tolerances
  - Mass
  - Launch vehicle
- Earth orbit (vs. L2)
  - Accelerations
  - Retargeting
  - Thermal and radiation environment
  - Earthshine

Matters of Size

- S5 mechanical architecture is expected to be scalable to 100m
- Rendezvous (26m) and HabEx (52m) starshades fit into Falcon Heavy fairing. Remote Occulter (~100m) is marginal for FH, may require SLS.
- Tolerances are likely to be much looser (see Shaklan talk) because smaller telescope PSF mixes much less unsuppressed light with exoplanet signal
- For 100m starshade, dry mass is ~15 metric tons (inc. contingency)

Matters in Earth Orbit (1)

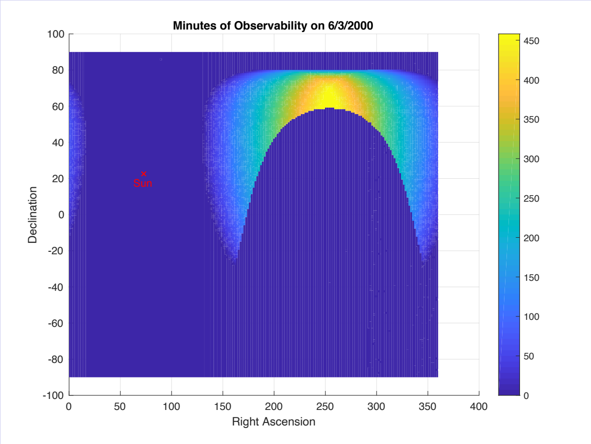
- Relative transverse acceleration between starshade and telescope will be $\lesssim .033\ m/s^2$. For Rendezvous and HabEx at L2, acceleration is ~1000x smaller.
- Given large mass and acceleration, remote occulter will need to thrust during much or all of spectroscopy integration time
  - Analysis indicates thrust plumes may scatter a lot of sunlight into telescope.
  - Not an issue for L2 missions since thrusts are <1 s and occur minutes apart, so little science time is lost by not collecting data during thrusts.
  - Structure needs to be dimensionally stable against thrust.

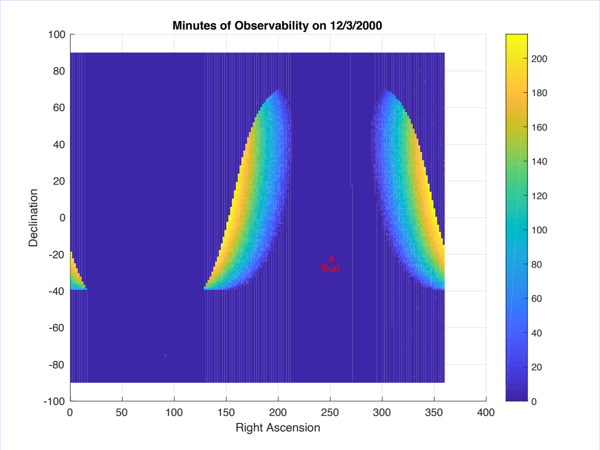
Matters in Earth Orbit (2)

- Retargeting will likely require a lot of fuel to move orbit apogee around the earth, compared to retargeting at L2
- Earth orbits are more stressing:
  - starshade crosses Earth's shadow once per orbit- big thermal swings.
  - Also crossing Van Allen belts
  - Need to be mindful of atmospheric drag- do not want untimely safe mode to burn starshade up (pushes to longer orbits)
- Starshade will essentially always reflect quarter phase Earthshine towards telescope (Earth is always nearly new at L2). Needs to be extra dark.

Matters with Ground Telescope: Field of Regard

- Unique conditions of coupled ground/space mission constrain the field of regard:
  - Telescope requires nighttime operation (sun at least 110 degrees below zenith)
  - Star location above 2 airmasses (starshade less than 60 degrees below zenith)
  - Starshade cannot reflect sunlight into telescope (Sun behind starshade)
  - Starshade can only tilt a small number of degrees from line of sight (assuming 10 degrees here)





Matters with Ground Telescope: Laser Guide Star

- The starshade blocks the obvious natural guide star available for AO. Laser guide star(s) will be necessary.
  - Current ground-based laser guide stars can be used here
  - The starshade itself is a reasonable place to put a laser beacon
    - To keep power manageable, must have narrow divergence, be steerable
- Need to anticipate that >50% of observations will be lost to typical telescope down time: ~30% cloudy, ~10% bad seeing/winds/temps, ~10% technical.
- Most observations occur at 45-60 degrees zenith angle. Atmospheric dispersion will be very large compared to telescope PSF for broad spectra.

Matters with Ground Telescope: Atmosphere and Weather

- Seeing and Rayleigh scattering in air are not expected to limit starshade performance
  - Starshade shadow is already well developed before it reaches the top of atmosphere, has large angular size as seen from ground
    - 1" seeing not sufficient to scatter light back into telescope
    - Rayleigh scattering well outside FOV
- Need to anticipate that >50% of observations will be lost to typical telescope down time: ~30% cloudy, ~10% bad seeing/winds/temps, ~10% technical.
- Most observations occur at 45-60 degrees zenith angle. Atmospheric dispersion will be very large compared to telescope PSF for broad spectra and require good compensation.