Jet Propulsion Laboratory
California Institute of Technology

Next Steps in Starshade Technology Development

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AAS Meeting Splinter Session
Starshade Development for Direct Imaging of Exoplanets
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Starshade to TRL 5

Introduction to S5

Direction from NASA Astrophysics Division:

- Develop starshade technology to discover Earth-like planets in habitable zones around Sun-like stars for future space telescope missions
- Reach a technology readiness level of 5 (component and/or breadboard validation in relevant environment)
- Deliver a TRL-5 Development Plan by end of 2017; key decision point based on this plan will determine if this activity continues

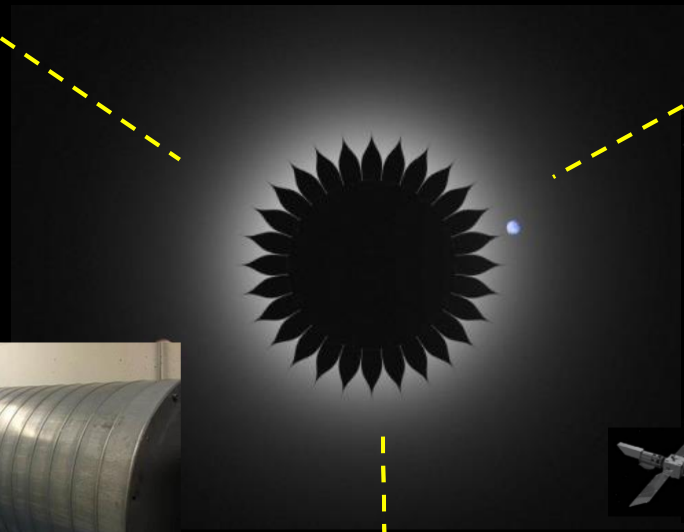
Starting Points

- Regardless of budget, first year focuses on planning and conducting trades, highest priority first
- Exo-S rendezvous study is our point of departure, but baseline will be updated as WFIRST Rendezvous and HabEx and LUVOIR concepts mature
- NASA will make no decision on conducting a starshade mission until after the 2020 Decadal Survey

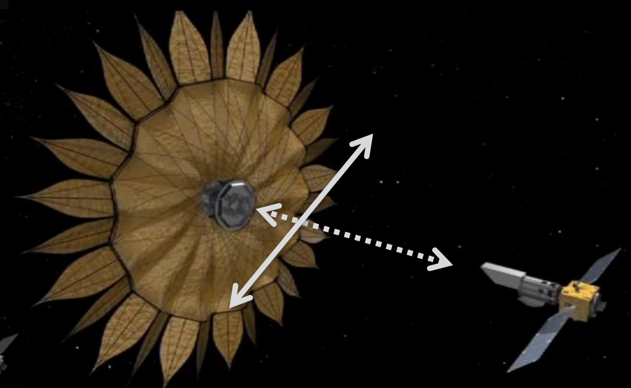
The Three Key Technology Areas for a Starshade

(1) Starlight Suppression

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



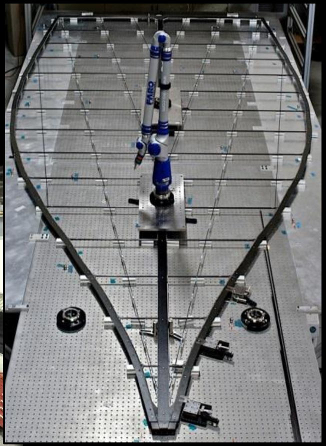
(2) Formation Sensing and Control



Maintaining lateral offset requirement between the spacecraft (S-3)

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

(3) Deployment Accuracy and Shape Stability



Fabricating the petals to high accuracy (S-4)

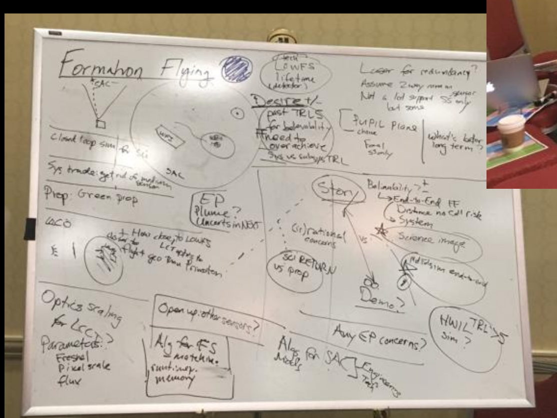
Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)

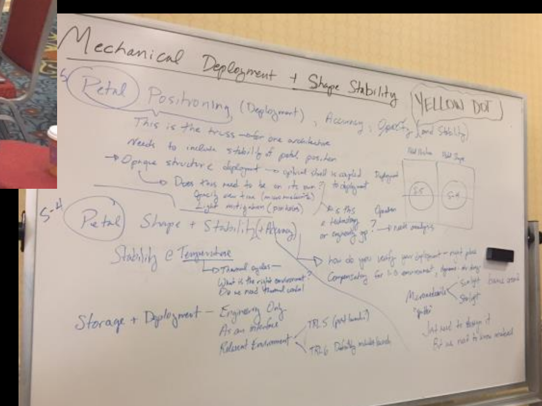
S-# corresponds to ExEP Starshade Technology Gap number (http://exoplanets.nasa.gov/exep/technology/gap-lists)

Keys to Our Success

- We must be ready for 2020 Astrophysics Decadal (submission sometime in early 2019)
  - Technologies need to be mature enough to enable starshades to be in the trade space for possible WFIRST Rendezvous and future large telescope missions
  - Complete near-term milestone of an approved TRL 5 Plan
  - Technical progress in prioritized areas, meeting milestones on time with some early successes
- Our models
  - We will reach higher TRLs based on meeting error budget requirements developed through validated performance models (optical diffraction, scattering, mechanical, thermal, etc.)
  - Ground based tests must focus on validating performance models and error budget as well as demonstrations of meeting requirements that are derived from the error budget
- Independent reviews of our plan and technical progress

Starshade Technology Workshop, December 1, 2016





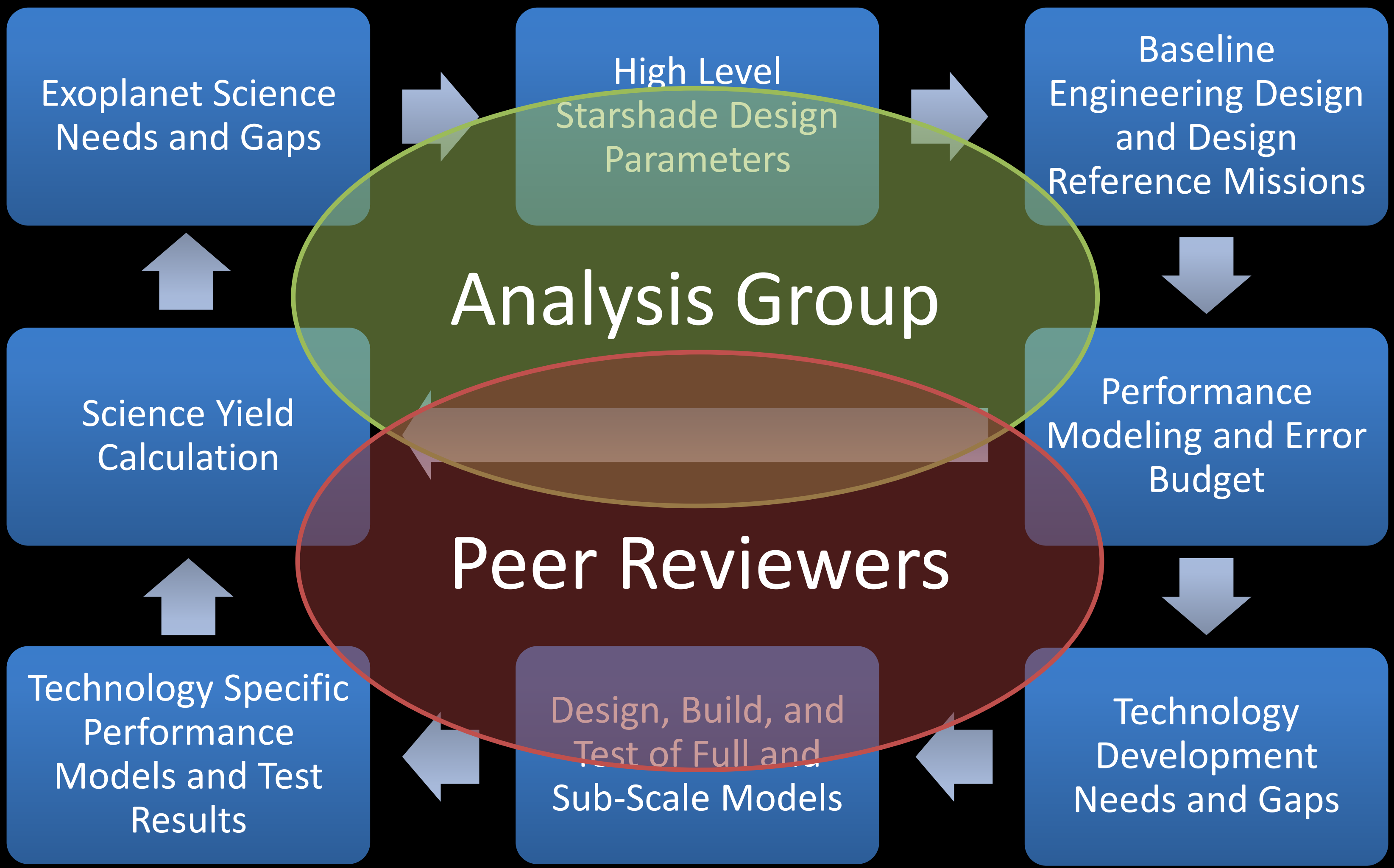
Near-Term Activities and Plans

- Held an all-day public Starshade Technology Workshop in Pasadena, CA on December 1, 2016
  - Broad institutional participation – over 80 local and remote participants from NASA, industry, and academia
  - Discussed the technology development needs and opportunities for future planning and prioritization
- Use follow-on workshops (technology topic specific) in late February, March, and April to plan out how TRL 5 will be reached and kick-off high priority trade analysis that needs to be complete by end of FY17
- Update engineering baseline design in August 2017
- Preliminary Technology Plan by Sept 2017
- Final reviewed plan delivered to APD Director by end of CY17 (TBC based on final budget)

Analysis Group, Peer Reviewers, and ExoTAC

- S5 will be putting out a public call to form an analysis group consisting of 5-6 exoplanet scientists and engineers in early 2017
  - Will help keep the science case current, guide the trade studies, and ensure consistency
  - Will provide the best analysis possible heading into peer and independent reviews
  - Will be a direct link to the exoplanet community
- Positions on the analysis group will be funded to conduct analysis and recommend future directions for S5
- S5 will convene separate, independent peer reviews of technical material prior to formal program reviews
- ExoTAC is a review board convened by ExEP Manager and APD to formally evaluate the technology plan and future milestone achievements prior to delivery to APD

S5 Activity Process Loops



Example of Key TRL-5 Requirements

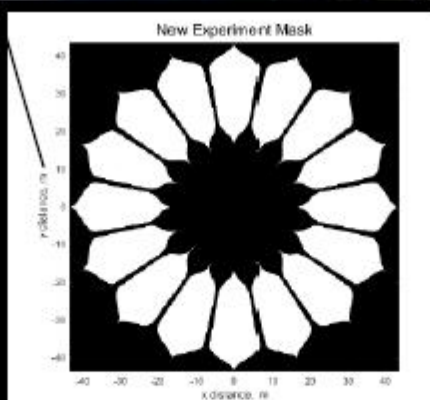
Quantified performance needs tied to Error Budgets, Vetted Gap Lists, Exo-S

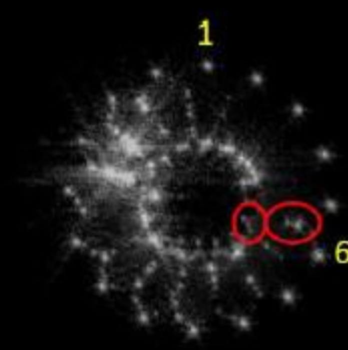
Technology Area	Key Performance Tolerances (3σ)	Proposed End-State Fidelity (TRL-5+): Fit	Proposed End-State Fidelity (TRL-5+): Form	Proposed End-State Fidelity (TRL-5+): Function	Tested in Relevant Environment; Designed to Meet Life Rqmt	Performance Verification	Model Validation
Deployment Accuracy and Shape Stability	**Petal Shape and Stability**						
	In-plane envelope: ± 100 μm	High fidelity, full-scale	High-fidelity prototype	Required performance demonstrated	Deploy and thermal cycles	Measure shape after deployment and thermal cycles	CTE, CME, creep
					Temperature and humidity	Measure shape with optical shield at temp.	Shape vs. applied loads
					Stowed strain	Predict on-orbit petal shape with all errors	Shape vs. temperature
	Petal Deployment Accuracy						
	In-plane envelope: ± 1 mm	High fidelity, half-scale inner disk; scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	0-gravity and vacuum	Measure position after deployment cycles in air with negligible air drag and imperfect gravity comp.	CTE, CME, creep
					Temperature and humidity	Measure position with optical shield at temp.	Shape vs. applied loads
					Stowed strain	Analyze on-orbit petal shape with all errors	Shape vs. temperature
Formation Sensing and Control	**Bearing Angle Sensing and Control**						
	Sensing: ± 1 mas Control (modeling): ± 1 m	Medium fidelity, using small-scale starshade; scaling issues	Medium-fidelity prototype	Basic functionality demonstrated	Large separation distance	Measure angular offsets with brassboard guide camera (coronagraph instrument) that simulates PSFs and fluxes from beacon and star	PSFs bearing angle vs. signal
Contrast	**Scattered Sunlight**						
	Edge radius x reflectivity: ≤ 10 μm-%	High fidelity, full-scale petal with full-scale optical edges	High-fidelity prototype	Required performance demonstrated with critical interfaces	Same as for petal shape	Measure petal level scatter after environment tests at discrete angles	Scatter vs. sun angle Scatter vs. dust
					Sun angle	Measure coupon level scatter after environment tests at all sun angles	
					Dust in launch fairing	Analyze effect for on-orbit solar glint	
	Starlight Suppression						
	Test at a flight-like Fresnel: Contrast (test) < 10^{-9} (traceable to 10^{-10} system performance with validated model)	Medium fidelity, small-scale starshade; scaling issues understood	Medium-fidelity prototype	Basic functionality demonstrated	Space	Measure image plane contrast between 500-850 nm	Optical performance, sensitivity to perturbations

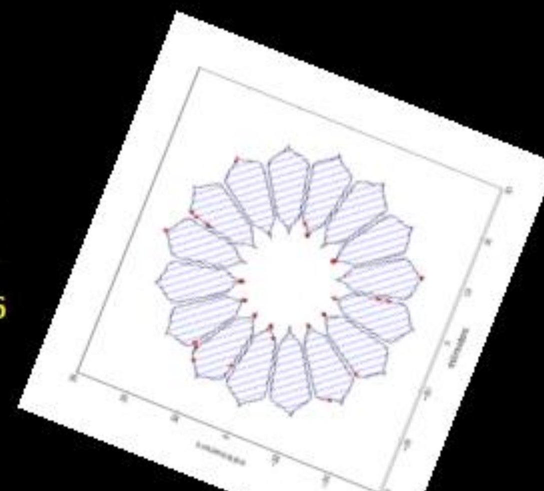
(to be concurred by a TAC at the end of Starshade Technology Formulation)

Optical Demonstrations at Princeton

- Goal is to observe 1e-9 suppression – consistent with flight requirements and about 3 orders of magnitude deeper than previous tests.



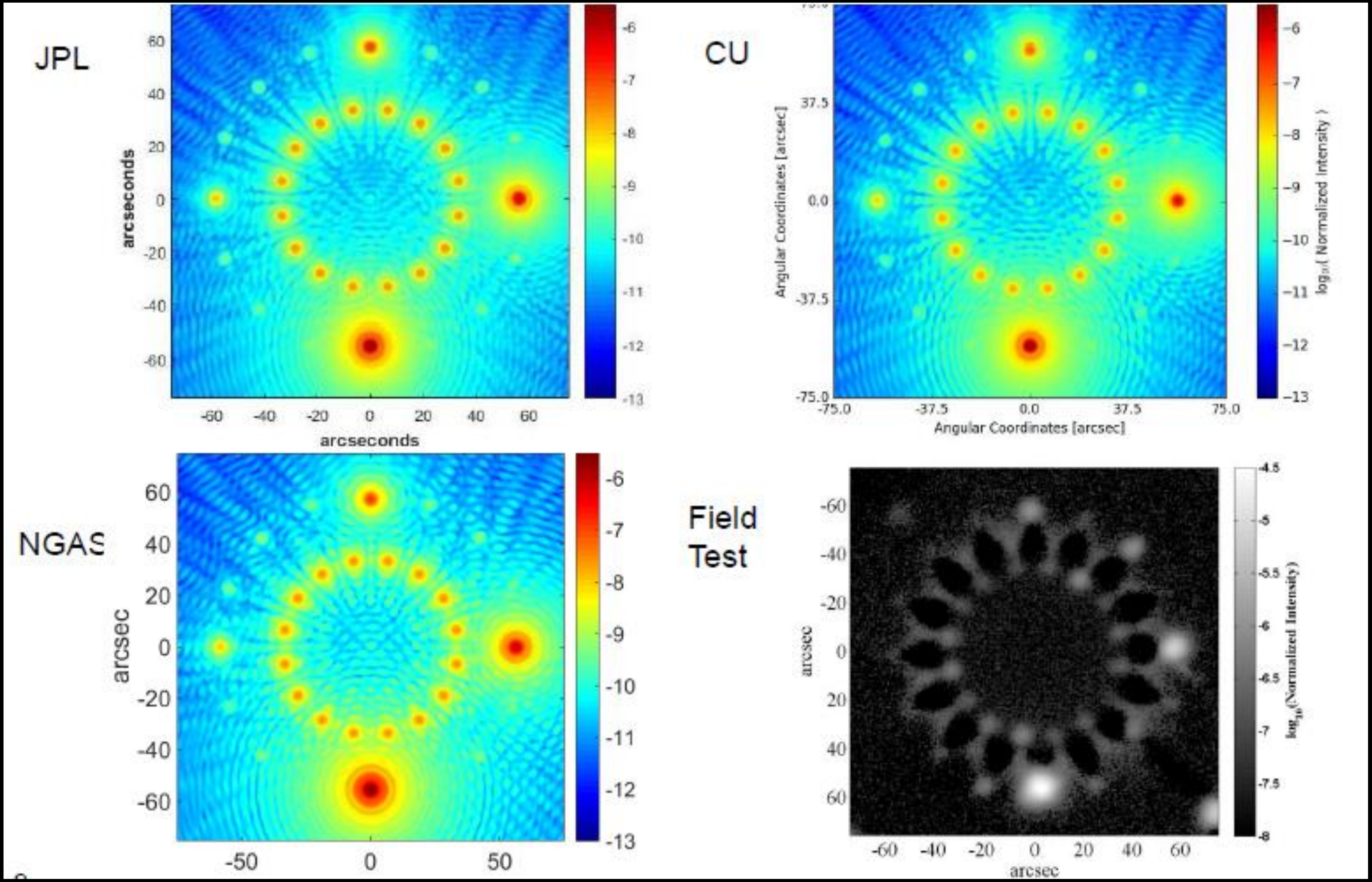




POC: Jeremy Kasdin (Princeton)

Optical Modeling Convergence

Intentionally flawed starshade

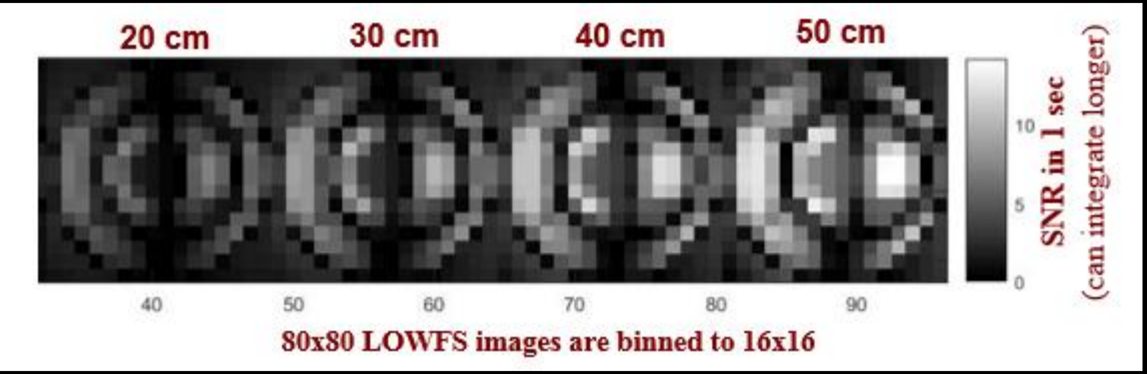


POC: Jeremy Kasdin (Princeton), Web Cash/Anthony Harness (UC-Boulder), Steve Warwick (NGAS), Stuart Shaklan (JPL)

Formation Sensing

- Novel approach using WFIRST as a reference mission:
  - Initial acquisition: Starshade Acquisition Camera
  - Intermediate acquisition: existing WFIRST Coronagraph Imager
  - Final acquisition: existing WFIRST Coronagraph Low-Order Wavefront Sensor

- Using pupil plane wavefront sensor reduces contrast requirement between starshade laser beacon and leaked out-of-band stellar diffraction with minimal impact to WFIRST Coronagraph
  - Starshade drift to the right clearly shows in the pupil plane



POC: Doug Lisman (JPL)

Areas for Focus on Starshade Technology Trades

- Starlight suppression demonstration
  - Review past and current work from testbeds and larger ground-based experiments as well as potential future demonstration options
  - Develop a plan for future demonstrations, if necessary
- High-level deployment architecture
  - Many elements have been developed and worked on by multiple teams over time, but we need to focus efforts
  - Develop a plan with milestones and evaluation criteria that will be used to recommend a path forward
- Petal edge characteristics
  - Specular vs. diffuse edges (sharpness and coating options)
  - Develop and test coupons as well as models that can be verified to evaluate the technical trade between various options
- Formation flying TRL 5 demonstration
  - Use testbeds and simulations to demonstrate TRL 5 early-on

Summary

- Focused starshade technology activity has begun
- This is mainly a planning year with technical progress continuing in pre-selected TDEM areas
- First workshop held in December, follow-on workshops coming up in the next few months
- A technology plan will be ready by the end of 2017
- We are looking for participants in the follow-on workshops and for the analysis group – please contact me if you are interested

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