Jet Propulsion Laboratory
California Institute of Technology

Engineering Strategy to Demonstrate Starshade Technical Readiness

Recommendation of the Starshade Readiness Working Group (SSWG)

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January 06, 2017

Starshade Development for Direct Imaging of Exoplanets

Grapevine, TX

Artist concept of Kepler-16b

Purpose of the Starshade Readiness Working Group (SSWG)

- The SSWG product (per charter) is to recommend a plan to validate starshade technology to the Astrophysics Division Director
- The SSWG answers these questions:
  1. How do we go from TRL5 to TRL 6?
  2. Imagine ourselves at KDP-C for a possible starshade science mission. Looking back, how did we convince all stakeholders to approve the mission?
  3. Put another way: Is a flight tech demo required to prove TRL6, and if so, what is it?
- SSWG workshop guideline we adopt the following (to make our work well-posed, without prescribing the future):
  - Rendezvous-CS (Concept Study[1]) as setting the "threshold science" of the "enabled starshade science mission"
  - The purpose of the recommended technology validation strategy is to enable a starshade science mission

[1] Exo-S final report: http://exoplanets.nasa.gov/stdt/

Executive Summary

- The SSWG conducted an open, technical evaluation using public evaluation criteria in a series of workshops and telecons
- The SSWG reached a broad consensus on the basis for the recommendation, on all points and for all findings, with all but one member
- The independent Technical Analysis Committee (TAC) fully concurs with the conclusions of this study, including the assumptions made, the process of evaluating the options, and the findings presented

SSWG Findings:

1. A ground-only development strategy exists to enable a starshade science flight mission such as WFIRST Starshade Rendezvous
2. A prior flight technology demonstration is not required prior to KDP-C of WFIRST Rendezvous
3. Development solutions exist that support a WFIRST Starshade Rendezvous by LRD FY26-28
4. Technology development for a Starshade Rendezvous mission is likely to provide significant technology benefits to both the HabEx and LUVOIR large mission studies
5. Two optional enhancements to the SSWG-recommended development approach recognized:
   a. A flight technology demonstration (mDOT) would enhance the ground development strategy for formation flying sensing and control and optical performance with additional cost and technical risk
   b. Long baseline ground demonstrations in air may provide some additional benefit for optical verification but at medium-to-high risk for interpretation of results

Current Starshade Context: Developments since 2015

- **3/2015:** Final report from Exo-S Probe-Scale Study. Developed concept for (34m) starshade standalone mission and introduced concept for WFIRST Starshade Rendezvous (34m)

Membership

- Sara Seager, Chair (MIT)
- W. Cash (U. Colorado)
- S. Domagal-Goldman (NASA-GSFC)
- N. J. Kasdin (Princeton U.)
- M. Kuchner (NASA-GSFC)
- A. Roberge (NASA-GSFC)
- S. Shaklan (NASA-JPL)
- W. Sparks (STSci)
- M. Thomson (NASA-JPL)
- M. Turnbull (GSI)

JPL Design Team

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R. Baran
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R. Trabert
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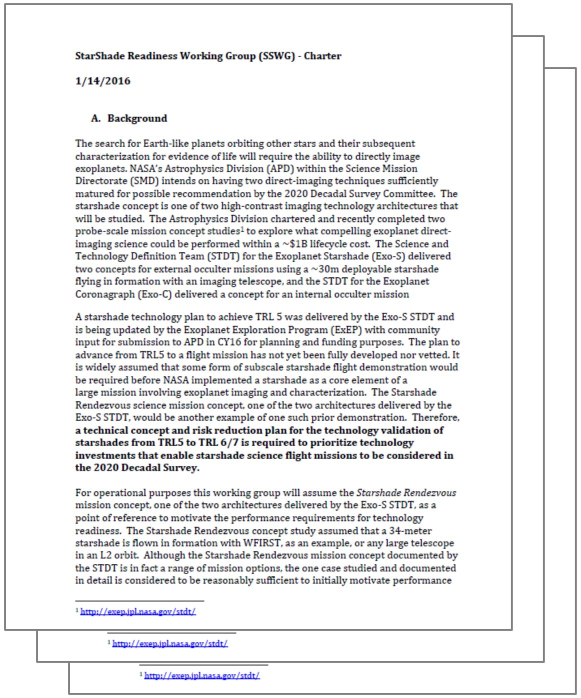
- **1/2016:** Signed charter of the Starshade Readiness Working Group (SSWG)
- **2/2016:** Final Report of the Exo-S Extended Study. Explored Rendezvous variants: larger (40m) and smaller (26m) starshade sizes
- **3/2016:** Starshade Technology Project created to achieve TRL5. Community workshop planned for Dec 1 2016
- **4/2016:** Decadal large studies chartered, both HabEx and LUVOIR considering starshades for exoplanet direct imaging
- **6/2016:** APD directs WFIRST to study starshade accommodation

SSWG Charter:
Working Group creates the Roadmap following TRL5



StarShade Readiness Working Group (SSWG) - Charter

1/14/2016

A. Background

The search for Earth-like planets orbiting other stars and their subsequent characterization for evidence of life will require the ability to directly image exoplanets. NASA's Astrophysics Division (APD) within the Science Mission Directorate (SMD) intends on having two direct-imaging techniques sufficiently matured for possible recommendation by the 2020 Decadal Survey Committee. The starshade concept is one of two high-contrast imaging technology architectures that will be studied. The Astrophysics Division chartered and recently completed two probe-scale mission concept studies[1] to explore what compelling exoplanet direct-imaging science could be performed within a ~$1B lifecycle cost. The Science and Technology Definition Team (STDT) for the Exoplanet Starshade (Exo-S) delivered two concepts for external occulter missions using a ~30m deployable starshade flying in formation with an imaging telescope, and the STDT for the Exoplanet Coronagraph (Exo-C) delivered a concept for an internal occulter mission

A starshade technology plan to achieve TRL 5 was delivered by the Exo-S STDT and is being updated by the Exoplanet Exploration Program (ExEP) with community input for submission to APD in CY16 for planning and funding purposes. The plan to advance from TRL5 to a flight mission has not yet been fully developed nor vetted. It is widely assumed that some form of subscale starshade flight demonstration would be required before NASA implemented a starshade as a core element of a large mission involving exoplanet imaging and characterization. The Starshade Rendezvous science mission concept, one of the two architectures delivered by the Exo-S STDT, would be another example of one such prior demonstration. Therefore, **a technical concept and risk reduction plan for the technology validation of starshades from TRL5 to TRL 6/7 is required to prioritize technology investments that enable starshade science flight missions to be considered in the 2020 Decadal Survey.**

For operational purposes this working group will assume the *Starshade Rendezvous* mission concept, one of the two architectures delivered by the Exo-S STDT, as a point of reference to motivate the performance requirements for technology readiness. The Starshade Rendezvous concept study assumed that a 34-meter starshade is flown in formation with WFIRST, as an example, or any large telescope in an L2 orbit. Although the Starshade Rendezvous mission concept documented by the STDT is in fact a range of mission options, the one case studied and documented in detail is considered to be reasonably sufficient to initially motivate performance

[1] http://exep.jpl.nasa.gov/stdt/

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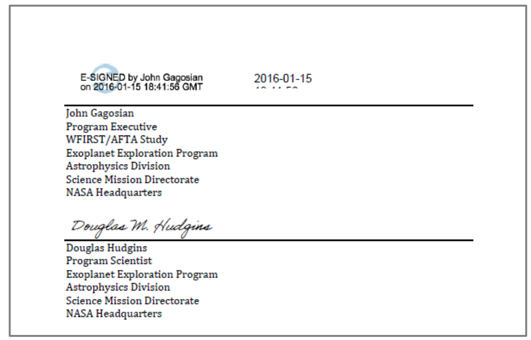
SSWG chartered by NASA APD
January 15, 2016



E-SIGNED by John Gagosian
on 2016-01-15 18:41:56 GMT   2016-01-15

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Program Scientist
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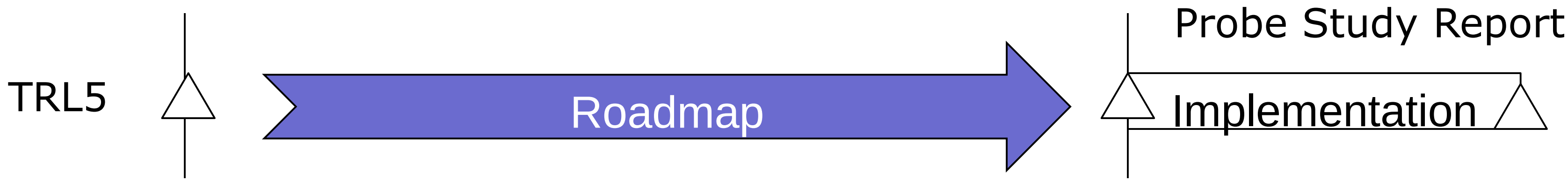
Science Mission Directorate
NASA Headquarters

https://exoplanets.nasa.gov/exep/studies/sswg/

Adopted from Exo-S
Probe Study Report



(Declared by
Siegler, fy19)

SSWG Creates this
Roadmap for =>

KDP-C for a
Starshade Science
Mission

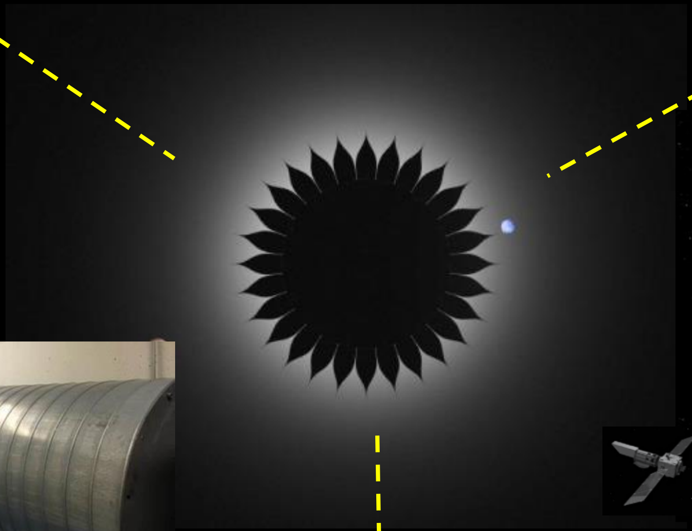
LRD

The Three Key Technology Areas for a Starshade

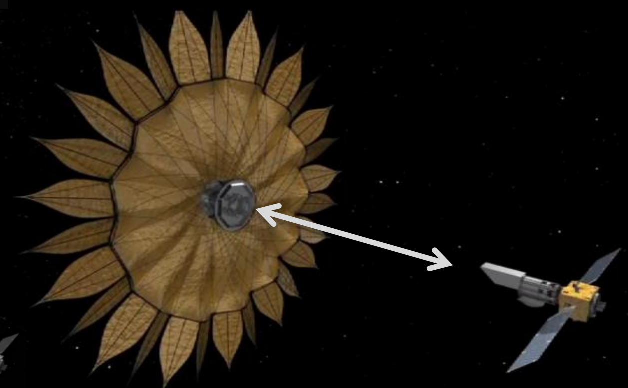
(mapped to 5 gaps S1-S5)

(1) Starlight Suppression

Suppressing scatted light off petal edges from off-axis Sunlight (S-2)



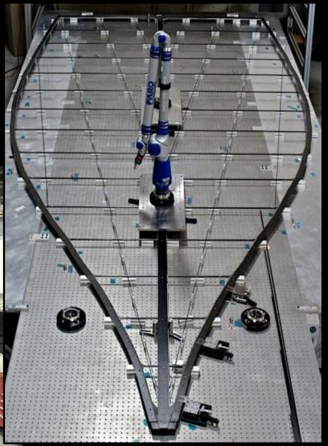
(3) Formation Sensing and Control



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

Suppressing diffracted light from on-axis starlight (S-1)

(2) 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)

Trade Criteria (1 of 2): Defining a Successful Outcome (created and adopted at the first face-to-face meeting)

TRADE STATEMENT: Recommend a development strategy to enable a starshade science flight mission

MUSTS (Requirements): ***Go/No_Go***

WANTS (Goals): ***Relative to each other, for those that pass the Musts:***

1. Technical: Relative technical criteria
2. Programmatic: Relative cost, schedule, other

   See details to follow

RISKS and OPPORTUNITIES – scored as H,M,L

MUSTS	
	Technical
M1	Achieves TRL-6 by starshade KDP-C for the N=3 critical technologies
M2	Compatible with Rendezvous-CS technical needs
M3	Forward traceable to expected HabEx and LUVOIR technical needs
M4	Likely to convince responsible critics at KDP-C to proceed with a starshade flight mission
	Schedule
M7	Schedule-compatible with Rendezvous-CS launch within WFIRST prime mission (assume: LRD of Starshade Rendezvous by late fy28)
M8	SSWG completes recommendation by November
	Cost
M9	Total cost of technology development strategy < *10% of LCC (~$100M)*

Trade Criteria (2 of 2): Defining a Successful Outcome (created and adopted at the first face-to-face meeting)

WANTS (DISCRIMINATORS)		**Weights**
	Technical	High
W1	Relative degree to which the strategy exceeds TRL6 at KDP-C for N=3 critical technologies	
W2	Admits enhancing Starshade technologies	
W3	Minimize the number N of critical enabling technologies	
	Schedule	Med+
W4	Enables Earliest launch within WFIRST prime misssion	
W5	Exceed TRL gates at key intermediate milestones (2020 DS, KDP-A, KDP-B, KDP-C)	
	Cost	Med
W6	Lowest cost of tech development strategy	
W7	Relative leverage of other programs outside of SMD/STMD	
	Other / Programmatic	Med
W8	Closest alignment to something in which STMD would invest	
W9	Maximizes even playing field for industry in potential prime contract for science mission	

OPTION DESCRIPTIONS

Overview of the Options Table (Descriptive)

Basic Ground | **Extended Ground** | **Space Demo**

	Basic Ground				Extended Ground		Space			
	Option 1a Focused ground TRL6 to flight	Option 1b	Option 4a	Option 4b Rendezvous Extended Study	Option 2c	Option 2d	Option 2a mDOT	Option 2b	Option 6a	Option 6b Optical Diffraction Demo at ISS
Presented on	6/16/2016 8/31/2016	2/25/2016 8/31/2016	6/9/2016 7/13/2016 7/21/2016	6/9/2016 7/13/2016 7/21/2016	7/26/2016	3/24/2016 6/20/2016	7/20/2016	6/9/2016	3/24/2016 6/13/2016	5/19/2016 5/26/2016
Steward	Jon Arenberg (NGAS)	Jon Arenberg (NGAS)	Doug Lisman (JPL)	Doug Lisman (JPL)	Web Cash (Colorado)	Steve Warwick (NGAS)	Simone D'Amico (Stanford)	Neerav Shah (GSFC)	Steve Warwick (NGAS)	Charley Noecker (JPL)
Brief Description	Focused ground demonstrations in all 3 technology areas. Prototype sub-assemblies at TRL-6 are the same size as the starshade for rendezvous with WFIRST for a science mission	Identical to Option 1a but recast as preparation for a tech demo starshade mission, rendezvousing with WFIRST, serving HabEx & LUVOIR.	Focused ground demonstrations in all 3 technology areas. A starshade prototype for TRL-6 is the same size (26 m) as the starshade for rendezvous with WFIRST for a science mission.	Same as Option 4a except: - Starshade diameter is 22 m - 2 yr Class D science mission	Long baseline (up to 30 km) tests at outdoor ground facilities, using stars or artificial light sources, to verify optical performance models and tracking/ formation flying technologies	Long baseline (10-20 km) tests in the Atacama Desert using a siderostat with stars, to verify optical scaling relations	Optical performance and formation flying demonstrations in an elliptical high Earth orbit with a 3-4m starshade	Formation flying demonstrations in a geosynchronous transfer orbit, with a 40 cm non-science starshade	Conducts a mechanical deployment demonstration with an 8 m starshade prototype fixed to the ISS.	Optical performance and formation flying demonstration with a 1-3 m starshade in halo orbit around the ISS.
Deployment Accuracy	- Full-scale high-fidelity deployment prototype components & systems - Off-loaded unassisted operation - Extensive analysis relates performance to flight requirements		- Full-scale high-fidelity deployable prototype starshade - Off-loaded unassisted operation - Extensive analysis relates performance to flight requirements		Includes all of "Deployment Accuracy" from Option 1a or 4a Non-deployed starshades, unlike WFIRST rendezvous	Includes all of "Deployment Accuracy" from Option 1a or 4a Non-deployed starshades, unlike WFIRST rendezvous	Includes all of "Deployment Accuracy" from Option 1a or 4a Starshade deployment is unlike WFIRST rendezvous	Includes all of "Deployment Accuracy" from Option 1a or 4a Starshade deployment is unlike WFIRST rendezvous	Includes all of "Deployment Accuracy" from Option 1a or 4a Adds 8 m prototype starshade on ISS; deployment approach similar to the WFIRST rendezvous mission Verification via photogrammetry.	Includes all of "Deployment Accuracy" from Option 1a or 4a Starshade deployment is unlike WFIRST rendezvous
Structural Stability	- Improved Thermal and Dynamics model fidelity - Edge distortions from thermal and dynamics used as input to the optical models to understand stray light effects		- Thermal and dynamic testing - Revise and validate STOP analyses - 8m petal test article, 10m central disk	Identical to Option 4a except petals are 6 m	Includes all of "Structural Stability" from Option 1a or 4a Starshade metering structure is unlike WFIRST rendezvous	Includes all of "Structural Stability" from Option 1a or 4a Starshade metering structure is unlike WFIRST rendezvous	Includes all of "Structural Stability" from Option 1a or 4a Starshade metering structure is unlike WFIRST rendezvous	Includes all of "Structural Stability" from Option 1a or 4a No tests to verify structural stability	Includes all of "Structural Stability" from Option 1a or 4a Can test thermal stability and dynamics of the starshade in a space environment	Includes all of "Structural Stability" from Option 1a or 4a Starshade metering structure is unlike WFIRST rendezvous
Formation Sensing & Control	- Validate diffraction models for out-of-band (low suppression) alignment sensing using WFIRST LOWFS engineering model sensor in diffraction testbed - Refine control system algorithm/models and incorporate sensor test data from the WFIRST LOWFSC EM - Simulate sensing and control scenarios		- Validate diffraction models for out-of-band (low suppression) alignment sensing using WFIRST LOWFS engineering model sensor in diffraction testbed - Refine control system algorithm/models and incorporate sensor test data from the WFIRST LOWFSC EM - Simulate sensing and control scenarios		Includes all of "Formation Sensing & Control" from Option 4a Adds demonstration of alignment sensing and control via the siderostat following the WFIRST rendezvous approach	Includes all of "Formation Sensing & Control" from Option 4a Could borrow from 2c	Develop Formation Control technology from TRL-5 to TRL-7 with a small-satellite mission demonstrating formation acquisition and mode transitions, formation alignment control in HEO	Includes all of "Formation Sensing & Control" from Option 4a. Adds a small-satellite mission demonstrating formation acquisition and mode transitions, formation alignment control in HEO	Includes all of "Formation Sensing & Control" from Option 4a	Includes all of "Formation Sensing & Control" from Option 4a, with minor exceptions Adds a small-satellite mission demonstrating formation acquisition and mode transitions, formation alignment control, in challenging LEO timeline
Optical Diffraction Modeling	- 25mm starshades tested at Princeton with form of flight designs - 100mm starshades tested indoors (XRCF?) at contrast of 1E-9, with measurement uncertainty <10% and agreement with models within uncertainties - Tests explore dependence on wavelength, starshade diameter, and separation distance in the neighborhood of flight-like Fresnel number		- 25mm starshades tested at Princeton with form of flight designs - 100mm starshades tested indoors (XRCF?) at contrast of 1E-9, with measurement uncertainty <10% and agreement with models within uncertainties - Tests explore dependence on wavelength, starshade diameter, and separation distance in the neighborhood of flight-like Fresnel number		Includes all of "Optical Diffraction" from Option 1a or 4a. Adds a quantitative model validation for a 0.5-0.9 m diam starshade operated at flight-like Fresnel number for 10-30 km distance in outdoor atmosphere with starlight or artificial light.	Includes all of "Optical Diffraction" from Option 1a or 4a, perhaps omitting XRCF tests. Adds a quantitative model validation for a 0.3-0.7 m diam starshade operated at flight-like Fresnel number for 10-20 km distance in outdoor atmosphere with starlight. Could include formation flying activilities from Option 2c .	Includes all of "Optical Diffraction" from Option 1a or 4a, but omitting XRCF tests Adds a high-fidelity flight demo of optical diffraction at intermediate size & separation (extended range of model validation)	Includes all of "Optical Diffraction" from Option 1a or 4a	Includes all of "Optical Diffraction" from Option 1a or 4a	Includes all of "Optical Diffraction" from Option 1a or 4a, perhaps omitting XRCF tests. Adds a high-fidelity flight demo of optical diffraction at intermediate size & separation (extended range of model validation).
Solar Edge Scatter	- Verify manufacturability of edges and coatings for lengths of many meters - Verify methods of scatter measurement for ~1m sections over long distances (indoors, in air) - Develop statistical understanding of scatter and variations to scatter at that scale - Verify edge performance after environment tests of samples		- Verify manufacturability of edges and coatings for lengths of many meters - Verify methods of scatter measurement for ~1m sections over long distances (indoors, in air) - Develop statistical understanding of scatter and variations to scatter at that scale - Verify edge performance after environment tests of samples		Includes all of "Solar Edge Scatter" from Option 1a or 4a Adds testing of solar diffraction at petal "valleys"	Includes all of "Solar Edge Scatter" from Option 1a or 4a Adds testing of solar diffraction at petal "valleys"	Includes all of "Solar edge scatter" from Option 1a or 4a Adds to that a possible on-orbit demo of solar edge scatter performance.	Includes all of "Solar Edge Scatter" from Option 1a or 4a	Includes all of "Solar Edge Scatter" from Option 1a or 4a	Includes all of "Solar Edge Scatter" from Option 1a or 4a

- Four "Basic Ground" options and six piggy-backers (Extended Ground & Space)
  - Basic Ground options are supposedly sufficient for TRL-6
  - Piggyback options add value to a Basic Ground to fill a perceived gap
- Brief descriptions
- Summaries for the 3 technology areas comprising 5 technology gaps

Option Comparison (1/2)

- Basic Ground Options
  Full suite of laboratory tests to cover all three critical technologies
  - Option 1a: for Rendezvous-CS (science focused 3 year)
  - Option 1b: for Rendezvous-CS recast as HabEx-LUVOIR technology mission, 3 year – same design and performance as 1a
  - Option 4a: for Rendezvous-ES (science focused 3yr)
  - Option 4b: for Rendezvous-ES (science focused 1yr)

  - Main differences between 1* and 4*:
    - Size of Rendezvous starshade
    - Size & fidelity of TRL 6 test article
      → Implications for cost, schedule, and risk getting to Rendezvous mission

SSWG created and analyzed a rich option space

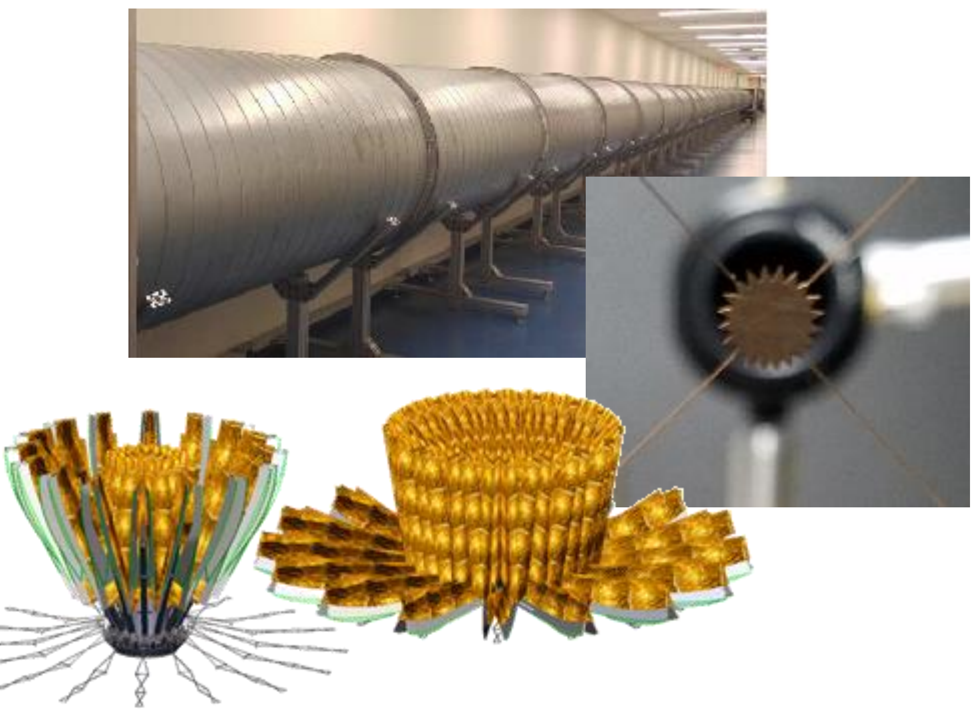
Option Comparison (2/2)

- Extended Ground Options (piggybacking on a Basic Ground option)
  - Option 2c: Adds testing in an outdoor range with artificial source or with siderostat and starlight
  - Option 2d: Adds testing in an outdoor range with artificial source and siderostat
  - Minor differences between 2c and 2d, amenable to merging
    - Option 2c emphasizes a science goal: survey of exoplanet stars to detect exozodi
- Space Options (piggybacking on a Basic Ground option)
  - Option 2a: Adds a small-sat starshade optical and formation flying demonstration in high Earth orbit, with science observation of one or two stars (such as Canopus or Beta Pictoris) and WFIRST-like sensors and algorithms
  - Option 2b: Adds a small-sat starshade formation flying demonstration in high Earth orbit, with a non-science starshade and WFIRST-like sensors and algorithms
  - Option 6a: Adds a zero-g ISS-based demonstration of deployment accuracy and structural stability with an 8m scale model starshade
  - Option 6b: Adds an ISS-based optical and formation flying demonstration

Sharing the best features among the options improved them all

Options 1a, 1b

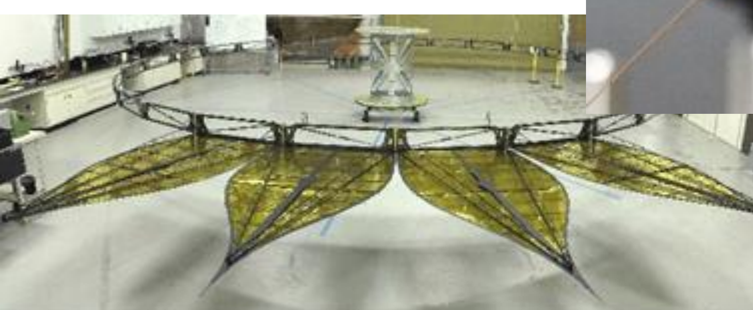
- Based on Rendezvous-CS concept, JWST, Non-NASA experience
- Structural demos are kept size-agnostic as long as possible
- Formation sensing & control in lab and in simulation
- High accuracy diffraction tests, in vacuum if needed
- Solar edge scatter manufacturing and testing extended to large samples



	Option 1a Focused ground TRL6 to flight	Option 1b Starshade rendezvous as tech demo
Deployment Accuracy (S-4)	• Full-scale high-fidelity deployment prototype <u>components & systems</u> • Off-loaded unassisted operation • Extensive analysis relates performance to flight requirements	
Structural Stability (S-5)	• Improved Thermal and Dynamics model fidelity • Edge distortions from thermal and dynamics used as input to the optical models to understand stray light effects	
Formation Sensing & Control (S-3)	• Validate diffraction models for out-of-band (low suppression) alignment sensing using WFIRST LOWFS engineering model sensor in diffraction testbed • Refine control system algorithm/models and incorporate sensor test data from the WFIRST LOWFSC EM • Simulate sensing and control scenarios	
Optical Diffraction Modeling (S-1)	• 25mm starshades tested at Princeton with form of flight designs • 100mm starshades tested indoors (XRCF?) at contrast of 1E-9, with measurement uncertainty <10% and agreement with models within uncertainties • Tests explore dependence on wavelength, starshade diam, and separation distance in the neighborhood of flight-like Fresnel number	
Solar Edge Scatter (S-2)	• Verify manufacturability of edges and coatings for lengths of many meters • Verify methods of scatter measurement for ~1m sections over long distances (indoors, in air) • Develop statistical understanding of scatter and variations to scatter at that scale • Verify edge performance after environment tests of samples	

Options 4a, 4b

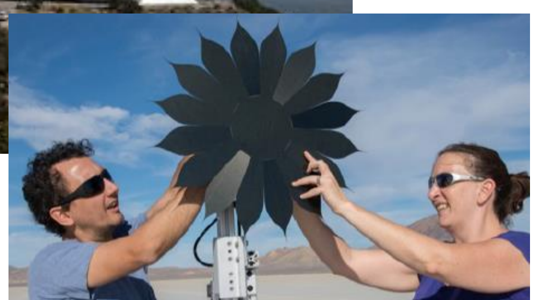
- Tech development based on Rendezvous-ES
- Structure demos use TRL5 hardware in TRL6 development, same size as Rendezvous-ES
- Formation sensing & control in lab and in simulation
- High accuracy diffraction tests, in vacuum if needed
- Solar edge scatter manufacturing and testing extended to large samples

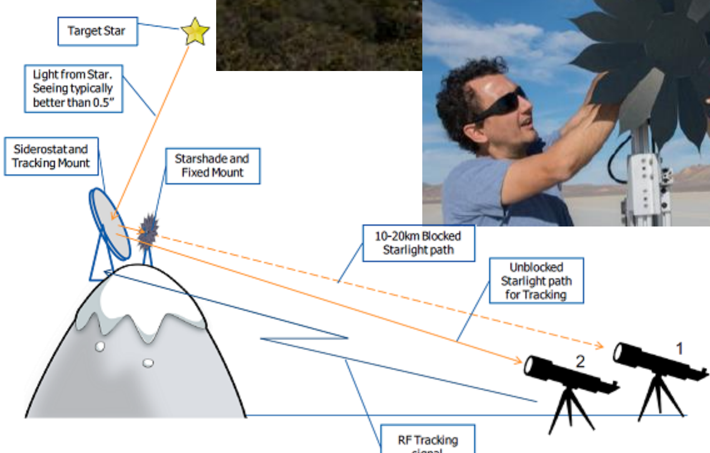


	Option 4a Rendezvous Extended Study	Option 4b Rendezvous Extended Study
Deployment Accuracy (S-4)	• Full-scale high-fidelity deployable prototype starshade • Off-loaded unassisted operation • Extensive analysis relates performance to flight requirements	
Structural Stability (S-5)	• Thermal and dynamic testing • Revise and validate STOP analyses • 8m petal test article, 10m central disk	Identical to Option 4a except petals are 6 m
Formation Sensing & Control (S-3)	• Validate diffraction models for out-of-band (low suppression) alignment sensing using WFIRST LOWFS engineering model sensor in diffraction testbed • Refine control system algorithm/models and incorporate sensor test data from the WFIRST LOWFSC EM • Simulate sensing and control scenarios	
Optical Diffraction Modeling (S-1)	• 25mm starshades tested at Princeton with form of flight designs • 100mm starshades tested indoors (XRCF?) at contrast of 1E-9, with measurement uncertainty <10% and agreement with models within uncertainties • Tests explore dependence on wavelength, starshade diam, and separation distance in the neighborhood of flight-like Fresnel number	
Solar Edge Scatter (S-2)	• Verify manufacturability of edges and coatings at lengths ~1-2m • Verify methods of scatter measurement for ~1m sections over long distances (indoors, in air) • Statistical understanding of scatter and its variations at that scale • Verify edge performance after environment tests of samples	

Extended Ground: 2c, 2d

- Piggybacking to Basic Ground; augments Option 1a,b or 4a,b
- Long baseline tests outdoors to look for any deviations from diffraction "standard model"
- Alignment control also needed, opportunity for demos
- Minor differences, possible merger

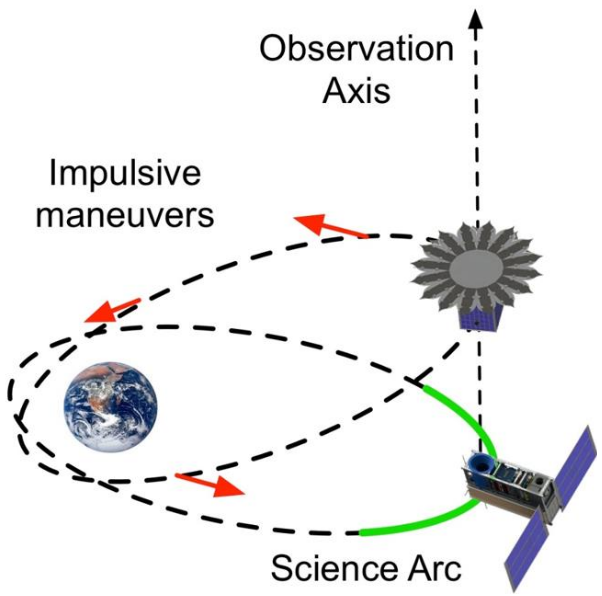




	Option 2c Long Baseline Facility	Option 2d Extended Desert Testing
Deployment Accuracy (S-4)	**Includes all of "Deployment Accuracy" from Option 1a or 4a** • Non-deployed starshades, unlike WFIRST rendezvous	**Includes all of "Deployment Accuracy" from Option 1a or 4a** Non-deployed starshades, unlike WFIRST rendezvous
Structural Stability (S-5)	**Includes all of "Structural Stability" from Option 1a or 4a** • Starshade metering structure is unlike WFIRST rendezvous	**Includes all of "Structural Stability" from Option 1a or 4a** Starshade metering structure is unlike WFIRST rendezvous
Formation Sensing & Control (S-3)	**Includes all of "Formation Sensing & Control" from Option 1a or 4a** • Adds demonstration of alignment sensing and control via the siderostat following the WFIRST rendezvous approach	**Includes all of "Formation Sensing & Control" from Option 4a** Could include formation flying activities from Option 2c.
Optical Diffraction Modeling (S-1)	**Includes all of "Optical Diffraction" from Option 1a or 4a.** • Adds a quantitative model validation for a 0.5-0.9 m diam starshade operated at flight-like Fresnel number for 10-30 km distance in outdoor atmosphere with starlight or artificial light.	**Includes all of "Optical Diffraction" from Option 1a or 4a, perhaps omitting XRCF tests.** Adds a quantitative model validation for a 0.3-0.7 m diam starshade operated at flight-like Fresnel number for 10-20 km distance in outdoor atmosphere with starlight.
Solar Edge Scatter (S-2)	**Includes all of "Solar Edge Scatter" from Option 1a or 4a** • Adds testing of solar diffraction at petal "valleys"	**Includes all of "Solar Edge Scatter" from Option 1a or 4a** Adds testing of solar diffraction at petal "valleys"

Option 2a: mDOT

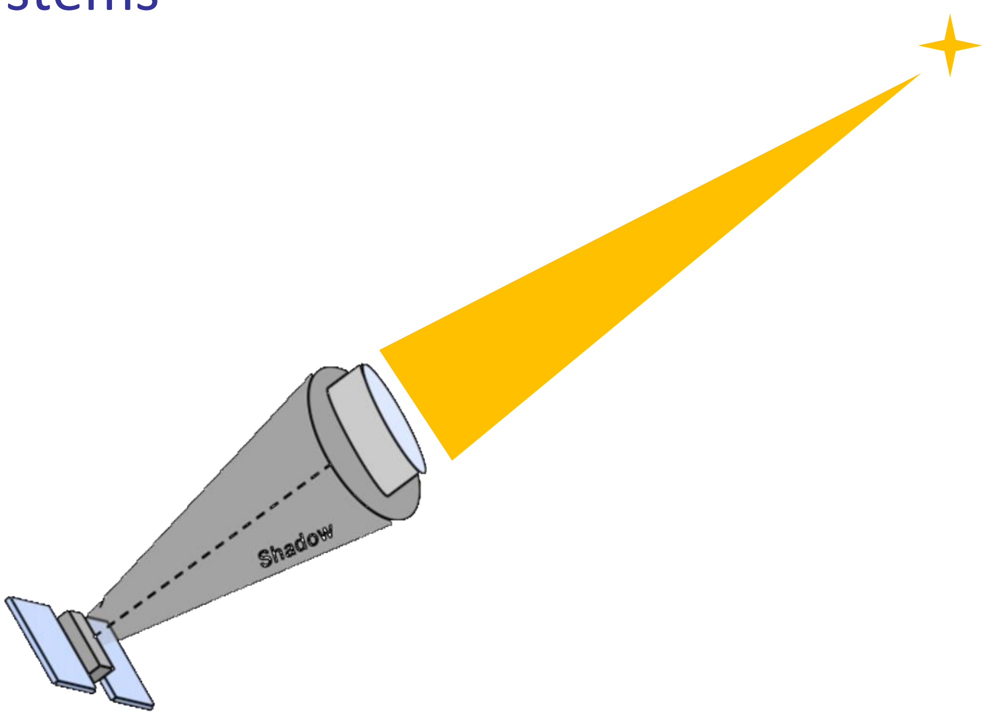
- Miniaturized Distributed Occulter & Telescope
- Flight mission concept with the possibility of a scientific result
- Formation flying & control with representative disturbances
- Optical diffraction demo at 3m size
- Align to and image one/two exoplanet systems



	Option 2a mDOT
Deployment Accuracy	**Includes all of "Deployment Accuracy" from Option 1a or 4a**
Structural Stability	**Includes all of "Structural Stability" from Option 1a or 4a**
Formation Sensing & Control	**Develop Formation Control technology from TRL-5 to TRL-7** Small-satellite mission demonstrating formation acquisition and mode transitions, formation alignment control in HEO
Optical Diffraction Modeling	**Includes all of "Optical Diffraction" from Option 1a or 4a** Adds a high-fidelity flight demo of optical diffraction at intermediate size & separation (extended range of model validation)
Solar Edge Scatter	**Includes all of "Solar edge scatter" from Option 1a or 4a** Adds to that a possible on-orbit demo of solar edge scatter performance.

Option 2b: Virtual Space Telescope

- Pure formation flying demo
- Starshade to diffract light for an alignment signal, not to suppress starlight
- Use WFIRST-relevant sensors and avionics subsystems



	Option 2b Virtual Space Telescope
Deployment Accuracy	**Includes all of "Deployment Accuracy" from Option 1a or 4a**
Structural Stability	**Includes all of "Structural Stability" from Option 1a or 4a**
Formation Sensing & Control	**Includes all of "Formation Sensing & Control" from Option 1a or 4a** Adds a small-satellite mission demonstrating formation acquisition and mode transitions, formation alignment control in HEO
Optical Diffraction Modeling	**Includes all of "Optical Diffraction" from Option 1a or 4a**
Solar Edge Scatter	**Includes all of "Solar Edge Scatter" from Option 1a or 4a**

Option 6a: ISS deployment demo

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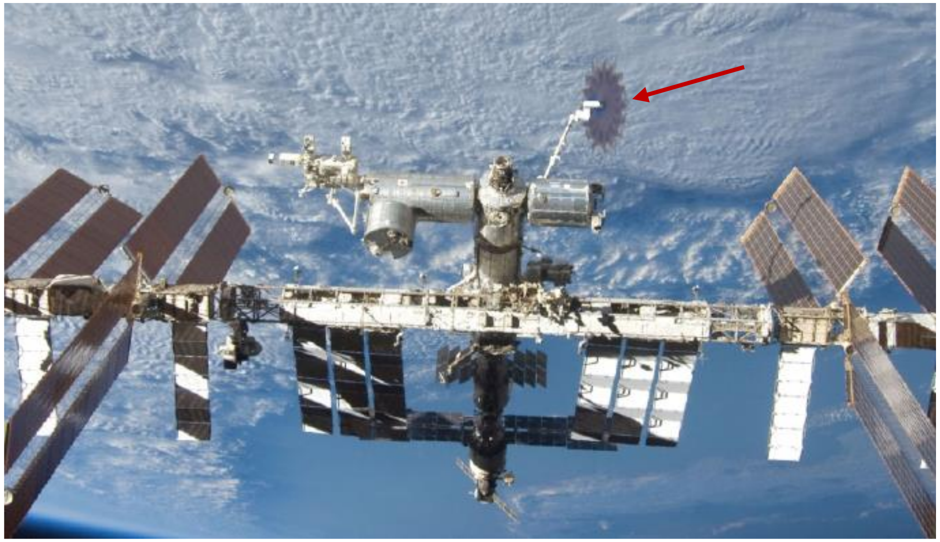
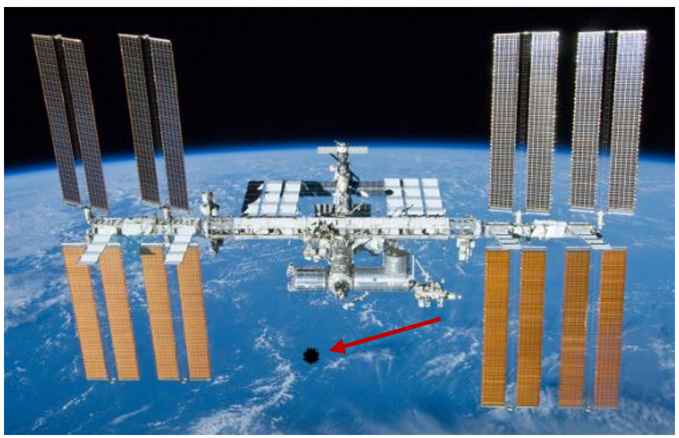
- Deployment test article at 8m size, operated at ISS
- Photogrammetry to verify accurate deployment
- Accelerometers to study dynamics

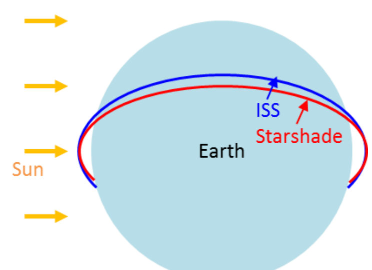


	Option 6a Deployment Demo at ISS
Deployment Accuracy	**Includes all of "Deployment Accuracy" from Option 1a or 4a** Adds 8 m prototype starshade on ISS; deployment approach similar to the WFIRST rendezvous mission Verification via photogrammetry.
Structural Stability	**Includes all of "Structural Stability" from Option 1a or 4a** Can test thermal stability and dynamics of the starshade in a space environment
Formation Sensing & Control	**Includes all of "Formation Sensing & Control" from Option 4a**
Optical Diffraction Modeling	**Includes all of "Optical Diffraction" from Option 1a or 4a**
Solar Edge Scatter	**Includes all of "Solar Edge Scatter" from Option 1a or 4a**

Option 6b: ISS-based Diffraction demo

- Starshade flying on halo orbits near ISS
- Telescope on ISS
- Demonstrate alignment acquisition and control on a star
- Demonstrate deep suppression





	Option 6b Optical Diffraction Demo at ISS
Deployment Accuracy	Includes all of "Deployment Accuracy" from Option 1a or 4a Starshade deployment is unlike WFIRST rendezvous
Structural Stability	Includes all of "Structural Stability" from Option 1a or 4a Starshade metering structure is unlike WFIRST rendezvous
Formation Sensing & Control	Includes all of "Formation Sensing & Control" from Option 4a, with minor exceptions Adds a small-satellite mission demonstrating formation acquisition and mode transitions, formation alignment control, in challenging LEO timeline
Optical Diffraction Modeling	Includes all of "Optical Diffraction" from Option 1a or 4a, perhaps omitting XRCF tests. Adds a high-fidelity flight demo of optical diffraction at intermediate size & separation (extended range of model validation)
Solar Edge Scatter	Includes all of "Solar Edge Scatter" from Option 1a or 4a

Technology Readiness Level Definitions
NASA NPR 7123.1B

TRL-5	TRL-6	TRL-7
Component and/or breadboard validation in relevant environment.	System/subsystem model or prototype demonstration in a relevant environment.	System prototype demonstration in an operational environment.
A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	A high fidelity engineering unit/prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).

- **TRL-5 is the assumed initial condition of the SSWG by FY19**
- **TRL-6 is the <u>necessary</u> state at a potential starshade mission KDP-C.**
- **The question for the SSWG is to determine if TRL-6 is <u>sufficient</u>? Or is a furthering of technology needed in some areas approaching TRL-7 (e.g. a flight demo) to sufficiently mitigate risk?**

The TRL6 Criteria that SSWG Options Need to Meet

Column 1 (Performance) identical to TRL5 chart. TRL6 addressing critical scaling, interfaces

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Technology Area	Key Performance Tolerances (3σ)	TRL-6 End-State Fidelity (Prototype)			Tested in Relevant Environment; Life Testing	Performance Verification	Model Validation
		Fit	Form	Function			
Deployment Accuracy and Shape Stability	**Petal Shape and Stability**						
	In-plane envelope: ± 100 μm	High fidelity with scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	Deploy and thermal cycles	Measure shape after deployment and thermal cycles; long-term stowed bending strain	CTE, CME, creep
					Temperature and humidity	Measure shape with optical shield at temp; moisture absorption and loss (de-gassing)	Shape vs. applied loads
					Stowed strain	Test on-orbit petal shape with all errors	Shape vs. temperature
	Deployed Petal Position						
	In-plane envelope: ± 1 mm	High fidelity with 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	Test 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	High fidelity with scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	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	**Sunlight Suppression**						
	Edge radius x reflectivity: ≤ 10 μm-%	High fidelity with scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	Same as for petal shape and stability	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	Test 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)	High fidelity with scaling issues understood (including Fresnel #)	High-fidelity prototype	Required performance demonstrated with critical interfaces	Space	Measure image plane suppression between 500-850 nm	Optical performance, sensitivity to perturbations

All critical scaling and interface issues addressed

Programmatic Figures of Merit
Evaluated by Technology Management Team

Technology Management Team: Hyde, Laskin, Warfield, Feinberg, Anderson

- Evaluated Differences in Cost and Schedule
- Base of the 1ab/4ab costs, plus, additional impacts or benefits in red

Summary of SSWG TMT cost assesments after initial review (as of 7 Sep, during the SSWG face-to-face)								
	Basic Ground		Extended Ground		Space Demo			
	1ab	4ab	2c	2d	2a	2b	6a	6b
	TRL6 on ground, 3 tracks	Ground test only, 3 tracks	Long Baseline Facility	Extended Desert Testing	mDOT	Virtual Telescope	ISS-deployment demo	ISS-optical & FF demo
	Arenberg	Lisman	Cash	Warwick	Damico	Shah	Warwick	Noecker
Optical test (<1km)-XRCF	$10M	$10M	$10M	$10M	$10M	$10M	$10M	$10M
plus Optical test (<30km)-Atacama,US,HI	.	.	$10-20M	$10-20M	.	.	.	.
plusOptical test (>100km in space)	.	.	.	.	$75M	.	.	$25M
Edge scattering	$10M	$10M	$10M	$10M	$10M	$10M	$10M	$10M
plus in space edge scatter demo subscal	.	.	.	.	yes	.	yes	yes
Deployed shape and stability, full scale	$15M	$15M	$15M	$15M	$15M	$15M	$15M	$15M
plus in-space deployment demo subscal	.	.	.	.	.	.	$25M	.
FF sensing and FF ops simulations	$2M	$2M	$2M	$2M	$2M	$2M	$2M	$2M
plus in-space FF demo subscale	.	.	.	.	yes	$50M	.	partial
TOTAL COST:	$37M	$37M	$47-57M	$47-57M	$112M	$87M	$62M	$62M
SCHEDULE:								
Years to complete all tracks TRL-6 (yrs)	2.5	2.5	3.5	3.5	4+	4+	4+	4+

Cost and schedule data from Tech Management Team used by entire group to score the trade matrix

Final Trade Evaluation and Findings

Options 1a,b,4a are the best options overall, accounting for risks and opportunities

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TRADE STATEMENT: Recommend a development strategy to enable a starshade science flight mission

Yes	Yes, or expected likely
U	Unknown
No	No, or expected showstopper
	Point not yet in consensus

	Description		Basic Ground			Extended Ground		Space			
			1a	1b	4a	2c	2d	2a	2b	6a	6b
			Ground validation at half scale	Same as 1a, Rndzvous recast as tech demo	Ground validation at full scale	Long baseline facility	Extended Desert Testing	mDOT	Virtual Space Telescope	ISS Depoy-ment demo	ISS Diffraction Demo
			Arenberg	Arenberg	Lisman	...ash/ ...rness	Warwick	D'Amico	Shah	Warwick	Noecker
Evaluation											
	MUSTS										
	Technical										
M1	Achieves TRL-6 by starshade KDP-C for the N=3 critical technologies		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
M2	Compatible with Rendezvous-CS technical needs		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
M3	Forward traceable to expected HabEx and LUVOIR technical needs		U	U	U	U	U	U	U	U	U
M4	Likely to convince responsible critics at KDP-C to proceed with a starshade flight mission		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Schedule										
M7	Schedule-compatible with Rendezvous-CS launch within WFIRST prime mission (assume: LRD of Starshade Rendezvous by late fy28)		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
M8	SSWG completes recommendation by November 2016		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Cost										
M9	Total cost of technology development strategy *< 10% of LCC (~$100M)*		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	WANTS (DISCRIMINATORS)	***Weights***									
	Technical	*High*									
W1	Relative degree to which the strategy exceeds TRL6 at KDP-C for N=3 critical technologies		sig	sig	sig	m/sig	sm/sig	best	sm/sig	small	small
W2	Admits enhancing Starshade technologies		wash	wash	wash	wash	wash	wash	wash	wash	wash
W3	Minimize the number N of critical enabling technologies		wash	wash	wash	wash	wash	wash	wash	wash	wash
	Schedule	*Med+*									
W4	Enables Earliest launch within WFIRST prime misssion		small	small	best	small	small	sig	sig	sig	sig
W5	Exceed TRL gates at key intermediate milestones (2020 DS, KDP-A, KDP-B, KDP-C)		sm/sig	small	best	U	U	U	U	U	U
	Cost	*Med*									
W6	Lowest cost of tech development strategy		small	small	best	m/sig	sm/sig	sig	sig	sig	sig
W7	Relative leverage of other programs outside of SMD/STMD		small	small	small	small	small	small	small	best	best
	Other / Programmatic	*Med*									
W8	Closest alignment to something in which STMD would invest		small	small	small	small	small	best	best	small	small
W9	Maximizes even playing field for industry in potential prime contract for science mission		best	best	small	U	U	U	U	U	U
Risk Evaluation											
	RISKS										
R1	Risk that proposed demonstration will not function as planned		L	L	L	L/M	L/M	M	M	M/H	H
R2	Risk that the results from the proposed demonstration may have high uncertainty or ambiguity		L	L	L	M/H	M/H	M	L/M	M	H
R3	Risk that the option is dependent on the launch of another mission we risk a schedule delay from that LRD		n/a	n/a	n/a	a	n/a	M	M	M	M
R4	Risk that the cost impact if the siderostat if the cost ends up being on the high end.		n/a	n/a	n/a	M	M	n/a	n/a	n/a	n/a
R5	Human safety risk		L	L	L	L	L	L	L	M	H
R6	Risk of early commitment to a particular design		L	L	M						
R7	Risk that the responsible critics will not be technically convinced at KDP-C on account that there is a large gap between XRCF and starshade flight mission size (75mm to 26m) as it relates to optical performance verification		L/M		L/M	M	L/M	L	L/M	L/M	L
	OPPORTUNITIES										
O1	Enables the technology more than starshade science flight missions		L		L		L	M/H	M	L	M
O2	Programatic and technical benefit of committing to a design before start of Phase A		L		M						

Findings:

1. **A ground-only development strategy** exists to enable a starshade science flight mission such as WFIRST Starshade Rendezvous
2. **A prior flight technology demonstration is not required** prior to KDP-C of WFIRST Rendezvous
3. Development solutions exist that support a WFIRST **Starshade Rendezvous by LRD FY26-28**
4. Technology development for a Starshade Rendezvous mission likely to provide significant **technology benefits to both HabEx and LUVOIR** large mission studies
5. **Two optional enhancements** to the SSWG-recommended development approach were recognized:
   a. A flight technology demonstration **(mDOT) would enhance the ground development strategy** for formation flying sensing and control and optical performance with additional cost and technical risk
   b. **Long baseline ground demonstrations in air** may provide some additional benefit for optical verification but at medium-to-high risk for interpretation of results

Differences among 1a,1b,4a,4b were design-dependent; will become future design trades in STP. Distinctions not pursued further in SSWG

Why is Ground Based Verification Good Enough for Structural Stability and Deployed Shape ?

- **Ground tests of high-fidelity full-scale prototypes can fully verify deployment**
  - Ambient deployment tests with negligible air drag and imperfect gravity compensation conservatively envelope the space vacuum and 0-g environments
  - High deployed stiffness enables gravity compensation of manageable complexity
  - Thermo-vac tests of high-fidelity full-scale assemblies (e.g. petals & inner disk truss) fully validate thermal models
  - Vibration tests of a full-scale stowed system fully validate structural models
- **Laser metrology and precision photogrammetry can fully verify deployed shape**
  - Tolerances are 100 µm on petal shape and 1 mm on petal position.
- **Structural Thermal Optical Performance analysis with validated models can verify on-orbit stability**
- **Ground based verification is standard practice for large deployable structures within the aerospace industry (e.g. communication antennas, JWST)**

Ground verification of full-scale prototypes will reduce residual risks in stability and deployment sufficiently before launch

Why is Ground Based Verification Good Enough for Formation Sensing and Control ?

- **Sensor suite for formation acquisition is well defined and leverages existing WFIRST sensors used in similar fashion by its coronagraph**
  - Coarse acquisition with a modified star tracker
  - Intermediate acquisition with the WFIRST coronagraph imager
  - Fine sensing with the WFIRST coronagraph low-order wavefront sensor
- **Flight-like sensor performance at modest contrast (10^{-3}) is reliably simulated with small-scale laboratory validation tests**
  - Sensor uses out of band starlight at high flux, and diffraction is well understood
- **Control system algorithms can be tested in all-software simulations using high-fidelity sensor models validated in the laboratory**
- **Lateral control requirement to ±1 m in ≤ 20 μg disturbance environment is well within the current state-of-art**
  - more precise control done regularly for docking in LEO

Ground verification plans for sensing and control will reduce residual risks sufficiently before launch

Why is Ground Based Verification Good Enough for Starlight Suppression Demonstration?

- **Flight-like optical diffraction can be reliably tested in a small scale laboratory**
  - Matching the flight Fresnel number yields identical diffraction performance at all scales
  - Optical model can be validated over a range of starshade size, telescope separation distance, and wavelength
  - Tests at Princeton are now underway; may extend to a larger facility if needed
    - If precision manufacturing doesn't meet tolerances on the small masks, or
    - If air turbulence in the lab prevents validation at sufficient fidelity and precision.
  - Optical model validations and associated error budget will be traceable to flight requirements and will include ample allocations for model uncertainty

- **The mitigation of scattered Sun light off the petal edges can be demonstrated through extensive lab scatter testing of small and full-scale samples**

Ground optical verification of a sub-scale starshade with model validation will reduce residual risks sufficiently before launch

Summary of Why Ground Validation is Sufficient

- **Ground verification plans will adequately verify all critical requirements for the key technology areas:**
  - Starlight suppression
  - Deployment accuracy and shape stability
  - Formation sensing and control

- **Ground verification plans will significantly and adequately reduce residual risk prior to flight**

- **All NPR 7120.5 flight readiness requirements can be fully verified with a ground-based test program**

A flight technology demonstration is not required prior to KDP-C of WFIRST Rendezvous

TAC Assessment - Summary

- Alan Boss (Chair, ExoTAC) and Joe Pitman participated in every meeting of the SSWG evaluation process.
- The TAC fully concurs with the conclusions of this study, including the assumptions made, the process of evaluating the options, and the findings presented.
- The SSWG process was thorough, fair, and open-minded, allowing all participants to share equally.
- The process was rigorous and based in part on the results of ongoing TDEM technology development efforts for star shades.
- The fact that a consensus recommendation was reached even for a group of this size strengthens the conclusions considerably.
- The one concern of the dissenter regarding exozodi levels was addressed by the ExoPAG EC and found to be manageable.

Acknowledgements

Additional contributions as subject matter experts:
Stanford University, Langley Research Center, Ball Aerospace, Lockheed Martin, Boeing, Northrop Grumman, Carnegie Institution for Science, Exploration Sciences, Lawrence Livermore National Laboratory, National Optical Astronomy Observatory, and American Museum of Natural History

Full presentation:
https://exoplanets.nasa.gov/exep/studies/sswg/