Results of the Starshade Readiness Working Group (SSWG)

Dr. Gary Blackwood, Exoplanet Exploration Program Manager
NASA Jet Propulsion Laboratory

Dr. Sara Seager, Professor of Planetary Science and Physics
Massachusetts Institute of Technology

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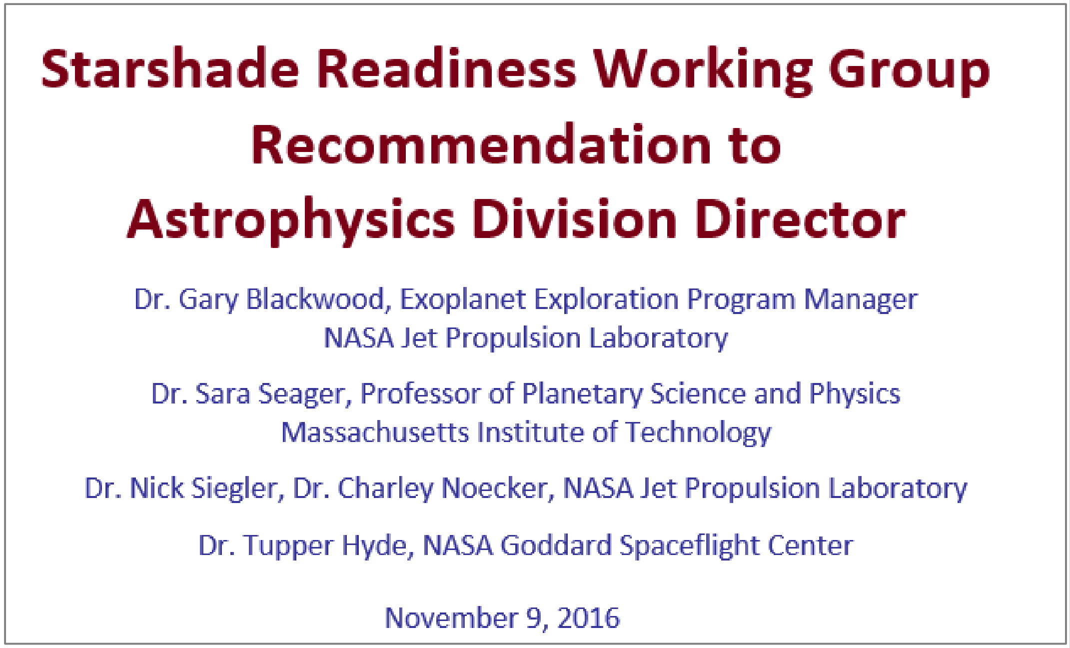
Introduction

- Summary of final briefing to APD Director on 11/9/2016
- Full presentation: https://exoplanets.nasa.gov/exep/studies/sswg/



Starshade Readiness Working Group Recommendation to Astrophysics Division Director

Dr. Gary Blackwood, Exoplanet Exploration Program Manager
NASA Jet Propulsion Laboratory

Dr. Sara Seager, Professor of Planetary Science and Physics
Massachusetts Institute of Technology

Dr. Nick Siegler, Dr. Charley Noecker, NASA Jet Propulsion Laboratory

Dr. Tupper Hyde, NASA Goddard Spaceflight Center

November 9, 2016

- Introduction
  - Purpose, Executive Summary, Trade Criteria
- Option Descriptions
  - Assumptions
- Evaluation by Chief Technologist Team
- Evaluation by Technology Management Team
- Trade Process
  - Musts, Wants, Risks, Opportunities
- Summary of Recommended Option
  - Why ground validation is sufficient
- Dissent Discussion
- ExoTAC Assessment
- Closing Remarks/Next Steps
- Discussion

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

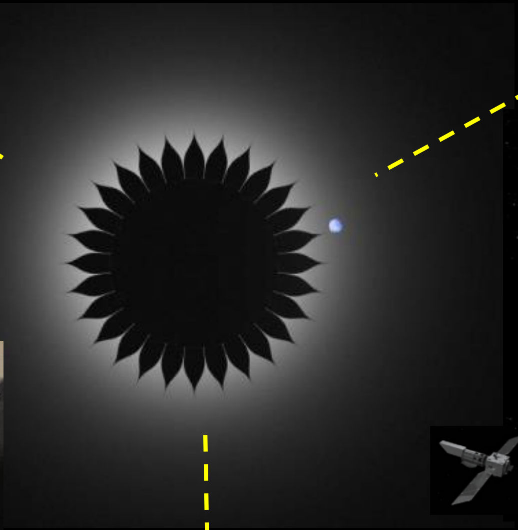
[1] Exo-S final report: http://exoplanets.nasa.gov/stdt/

The Three Key Technology Areas for a Starshade

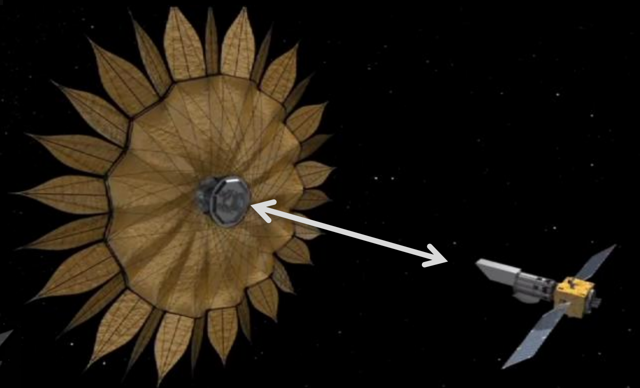
(mapped to 5 gaps S1-S5)

(1) Starlight Suppression

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



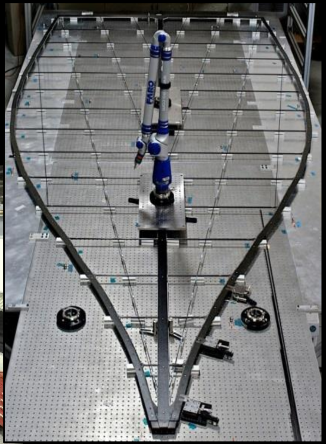
(3) Formation Sensing and Control



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)

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

  K. Warfield, Lead
  D. Lisman
  R. Baran
  R. Bauman
  E. Cady
  C. Heneghan
  S. Martin
  D. Scharf
  R. Trabert
  D. Webb
  P. Zarifian

- **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 be designed to accommodate a starshade, under study by project, ExEP and SITs. Interim assessment by Project in Dec 2016, final decision by NASA prior to KDP-B

Record of SSWG Active Participation
Since Charter Signature - *Thank you* for your participation!

Working Group Membership

- **Co-Chairs:**

Sara Seager	MIT
Gary Blackwood	NASA ExEP / JPL

- **Steering Committee**

Nick Siegler	NASA ExEP / JPL
Karl Stapelfeldt	NASA ExEP / JPL
Tupper Hyde	NASA / GSFC
Tom Greene	NASA / ARC
Charley Noecker	NASA / JPL
Neil Gehrels	NASA/GSFC WFIRST

- **Members**

(aim to reach to consensus, including Steering Committee)

Web Cash	U. of Colorado	Exo-S STDT
Jeremy Kasdin	Princeton U.	Exo-S STDT
Maggie Turnbull	SETI	Exo-S STDT
Stuart Shaklan	NASA / JPL	Exo-S STDT
Mark Thomson	NASA / JPL	Exo-S STDT
Doug Lisman	NASA / JPL	Exo-S STDT
Aki Roberge	NASA / GSFC	Exo-S STDT
Matt Greenhouse	NASA / GSFC	
Brent Knight	NASA / MSFC	
Denise Podolski	NASA HQ / STMD	
Keith Warfield	NASA ExEP / JPL	
Lee Feinberg	NASA / GSFC JWST	
Geoff Andersen	US Air Force Academy	

- **Subject Matter Experts and Guests:**

Analysts for Science and Technical figures of merit:

Dan Scharf	NASA / JPL
Robert Laskin	NASA / JPL
Jeff Booth	NASA/JPL
Simone D'Amico	Stanford
Neerav Shah	NASA / GSFC
Ann Shipley	U. of Colorado

STMD representative

Keith Belvin	LaRC / STMD

Industry

Chip Barnes	Ball Aerospace
Alison Nordt	Lockheed Martin
Stuart Wiens	Lockheed Martin
Jeff Hunt	Boeing
Steve Warwick	Northrop Grumman
Jon Arenberg	Northrop Grumman
Tiffany Glassman	Northrop Grumman

ExoTAC

Alan Boss	Carnegie Institution DTM
Joe Pitman	Exploration Sciences

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

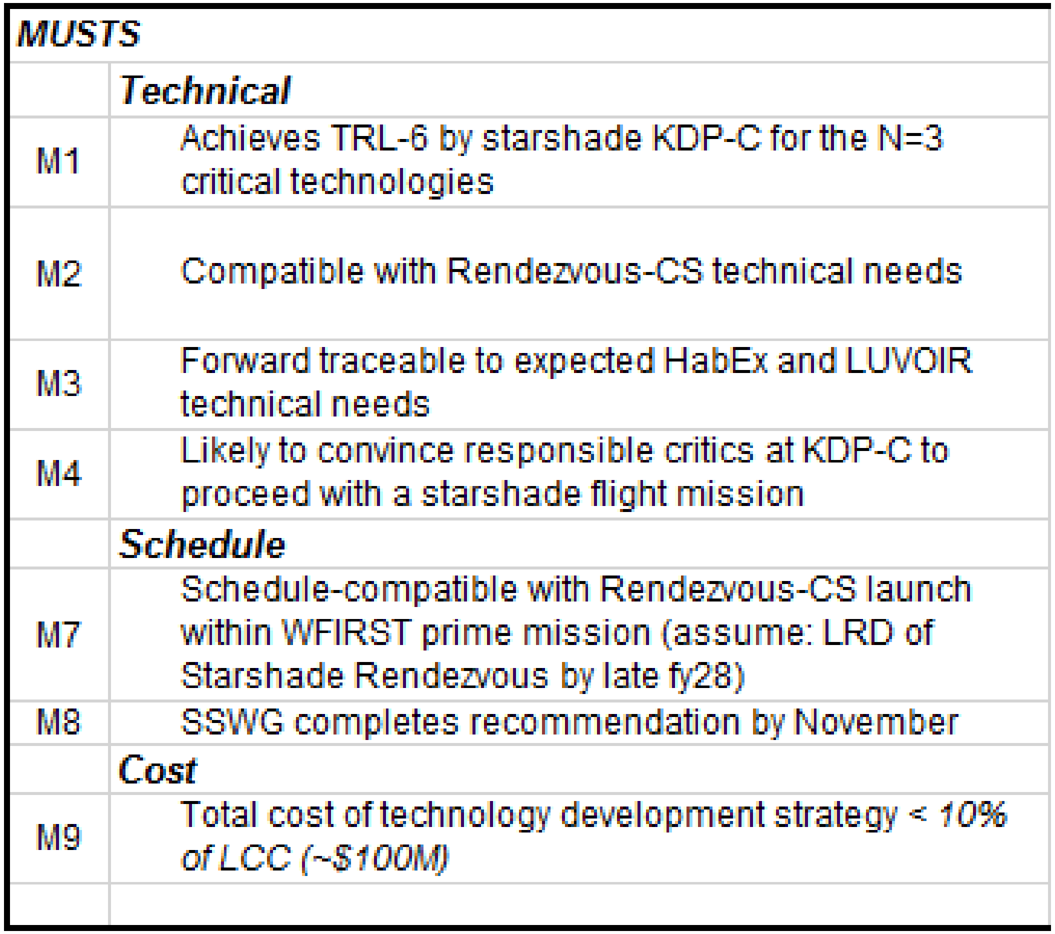
SSWG Findings:

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

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***



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)*

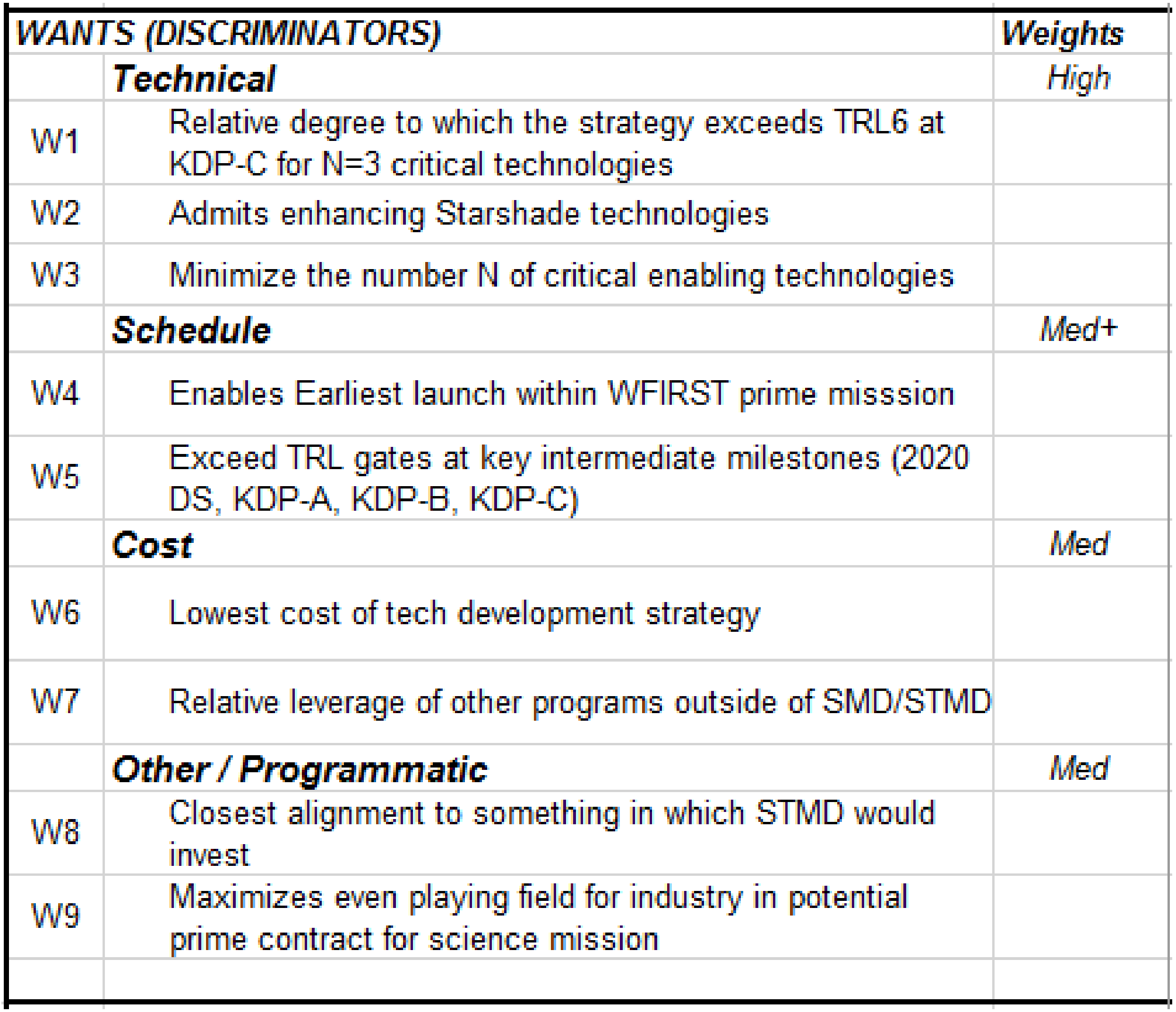
WANTS (Goals): ***Relative to each other, for those that pass the Musts:***

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

   See details to follow

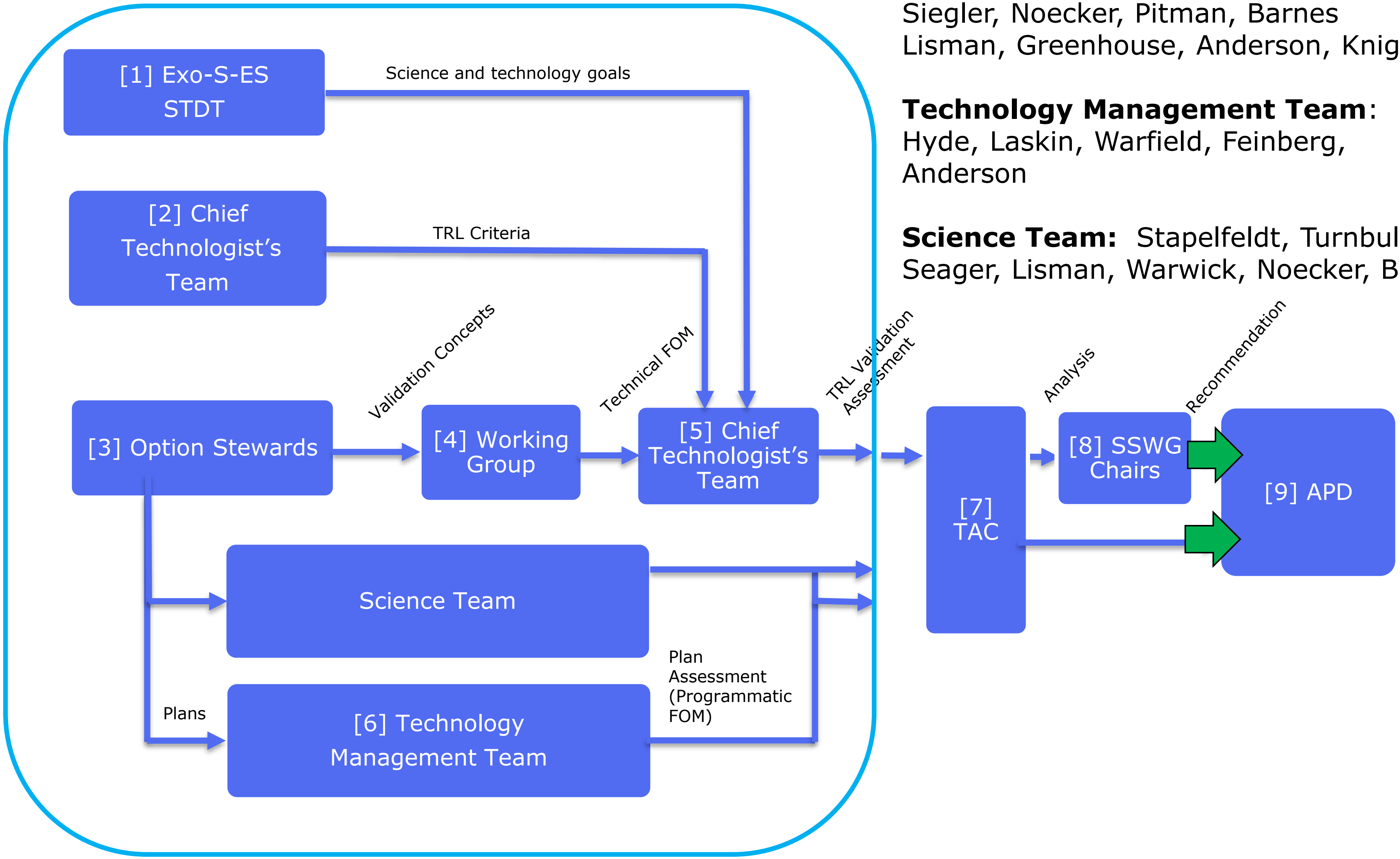
RISKS and OPPORTUNITIES – scored as H,M,L

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	

SSWG Work Flow
Each team performed a detailed evaluation



Chief Technologist Team: Siegler, Noecker, Pitman, Barnes Lisman, Greenhouse, Anderson, Knight

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

Science Team: Stapelfeldt, Turnbull, Seager, Lisman, Warwick, Noecker, Boss

The TRL6 Criteria that SSWG Options Need to Meet

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

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

OPTION DESCRIPTIONS

BASIC GROUND: 1A, 1B, 4A, 4B
EXTENDED GROUND: 2C, 2D
SPACE: 2A, 2B, 6A, 6B

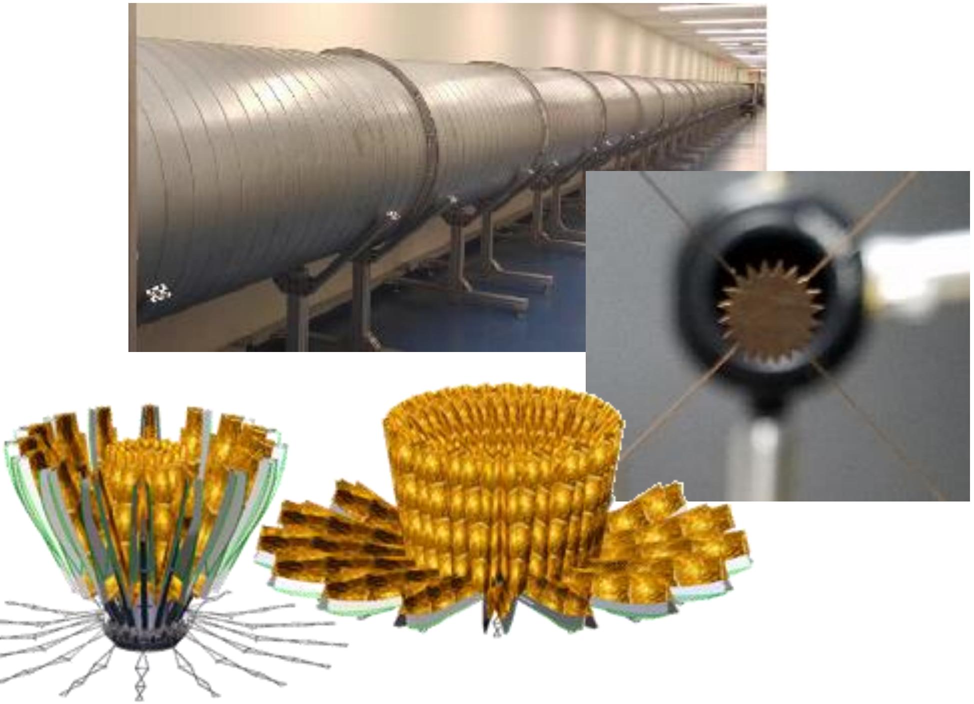
Basic Ground Options 1a, 1b, 4a, 4b

- These 4 are stand-alone ground-based options, aiming to satisfy TRL 6 for all technology areas AND
- These are the basis for completeness of all the *other* options (piggybacking)
- We must scrutinize these closely because of their greater importance
- Stewards focused on two familiar structural concepts to frame the tech development plans; but the plans are architecture-independent

	Basic Ground			
	Option 1a Focused ground TRL6 to flight	Option 1b Starshade rendezvous as tech demo	Option 4a Rendezvous Extended Study	Option 4b Rendezvous Extended Study
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
Steward	Jon Arenberg (NGAS)	Jon Arenberg (NGAS)	Doug Lisman (JPL)	Doug Lisman (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

Options 1a, 1b

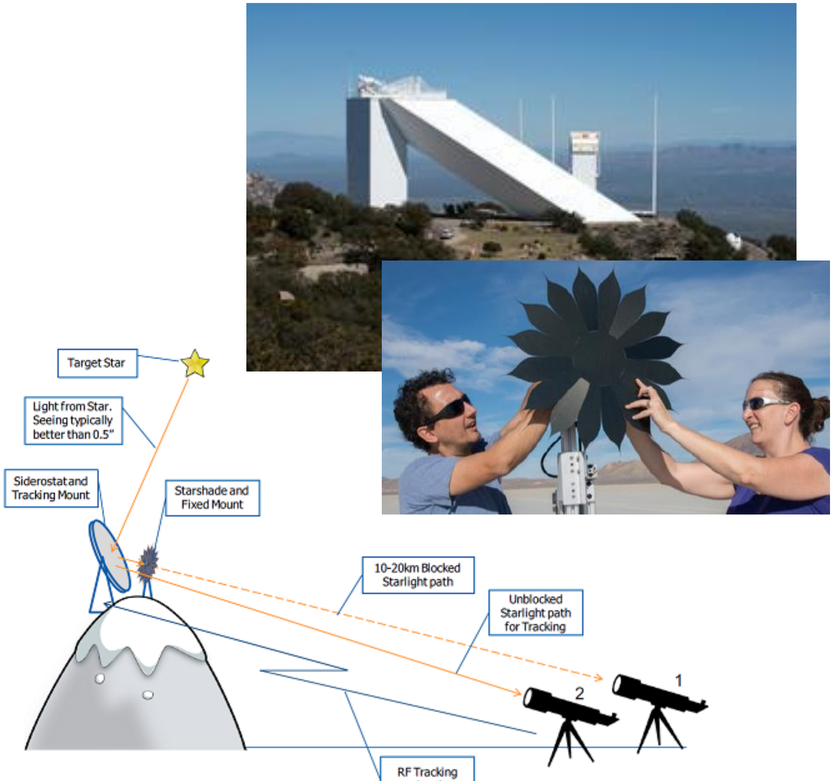
- Based on Rendezvous-CS concept, JWST, Non-NASA experience
- Structural demos are kept size-agnostic as long as possible
- Formation sensing & control in lab and in simulation
- High accuracy diffraction tests, in vacuum if needed
- Solar edge scatter manufacturing and testing extended to large samples



	Option 1a Focused ground TRL6 to flight	Option 1b Starshade rendezvous as tech demo
Deployment Accuracy (S-4)	• Full-scale high-fidelity deployment prototype components & systems • 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	

Extended Ground Options 2c, 2d

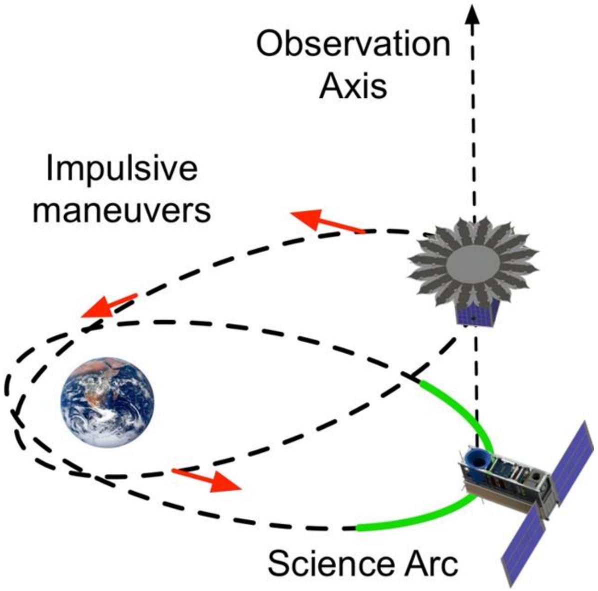
- Two augmentations of Basic Ground
- Adding long-baseline starshade tests in atmosphere, outdoors
  - Test optical diffraction models at intermediate size and distance
  - Conduct starshade science observations
- Options evolved to be very similar, leaning toward merger



	Extended Ground	
	Option 2c Long Baseline Facility	Option 2d Extended Desert Testing
Presented on	7/26/2016	3/24/2016 6/20/2016
Steward	Web Cash (Colorado)	Steve Warwick (NGAS)
Brief Description	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

Option 2a: mDOT

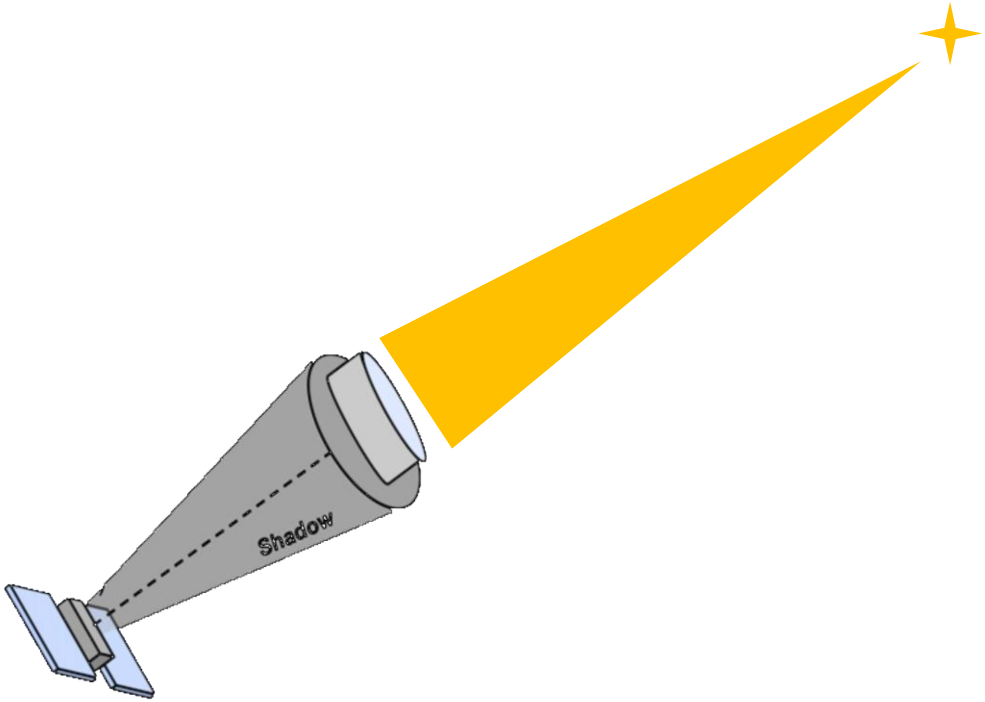
- Miniaturized Distributed Occulter & Telescope
- Flight mission concept with the possibility of a scientific result
- Formation flying & control with representative disturbances
- Optical diffraction demo at 3m size
- Align to and image one/two exoplanet systems



	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

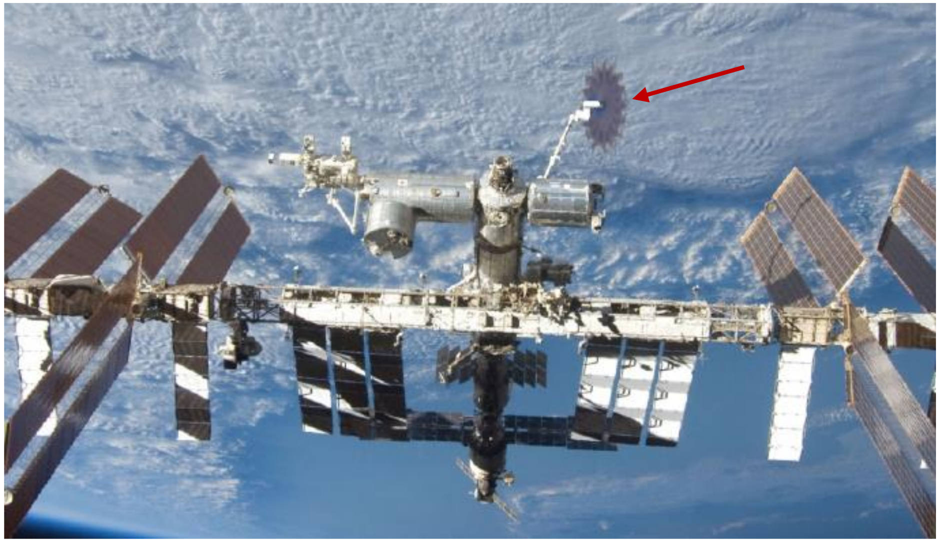
- Pure formation flying demo
- Starshade to diffract light for an alignment signal, not to suppress starlight
- Use WFIRST-relevant sensors and avionics subsystems



	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

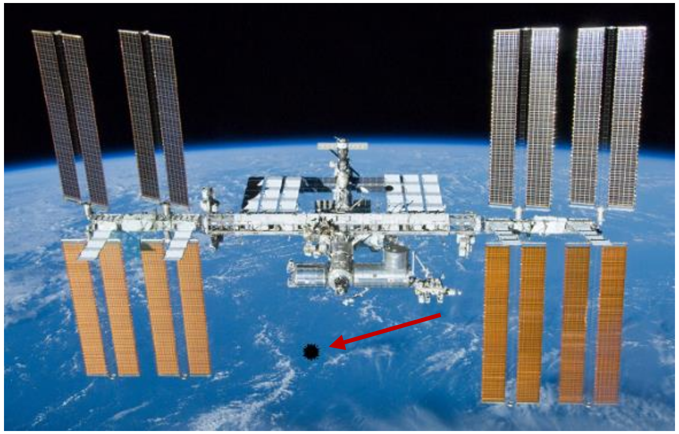
- Deployment test article at 8m size, operated at ISS
- Photogrammetry to verify accurate deployment
- Accelerometers to study dynamics

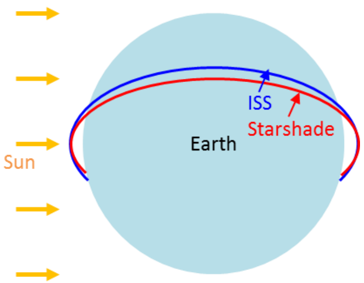


	Option 6a Deployment Demo at ISS
Deployment Accuracy	**Includes all of "Deployment Accuracy" from Option 1a or 4a** Adds 8 m prototype starshade on ISS; deployment approach similar to the WFIRST rendezvous mission Verification via photogrammetry.
Structural Stability	**Includes all of "Structural Stability" 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

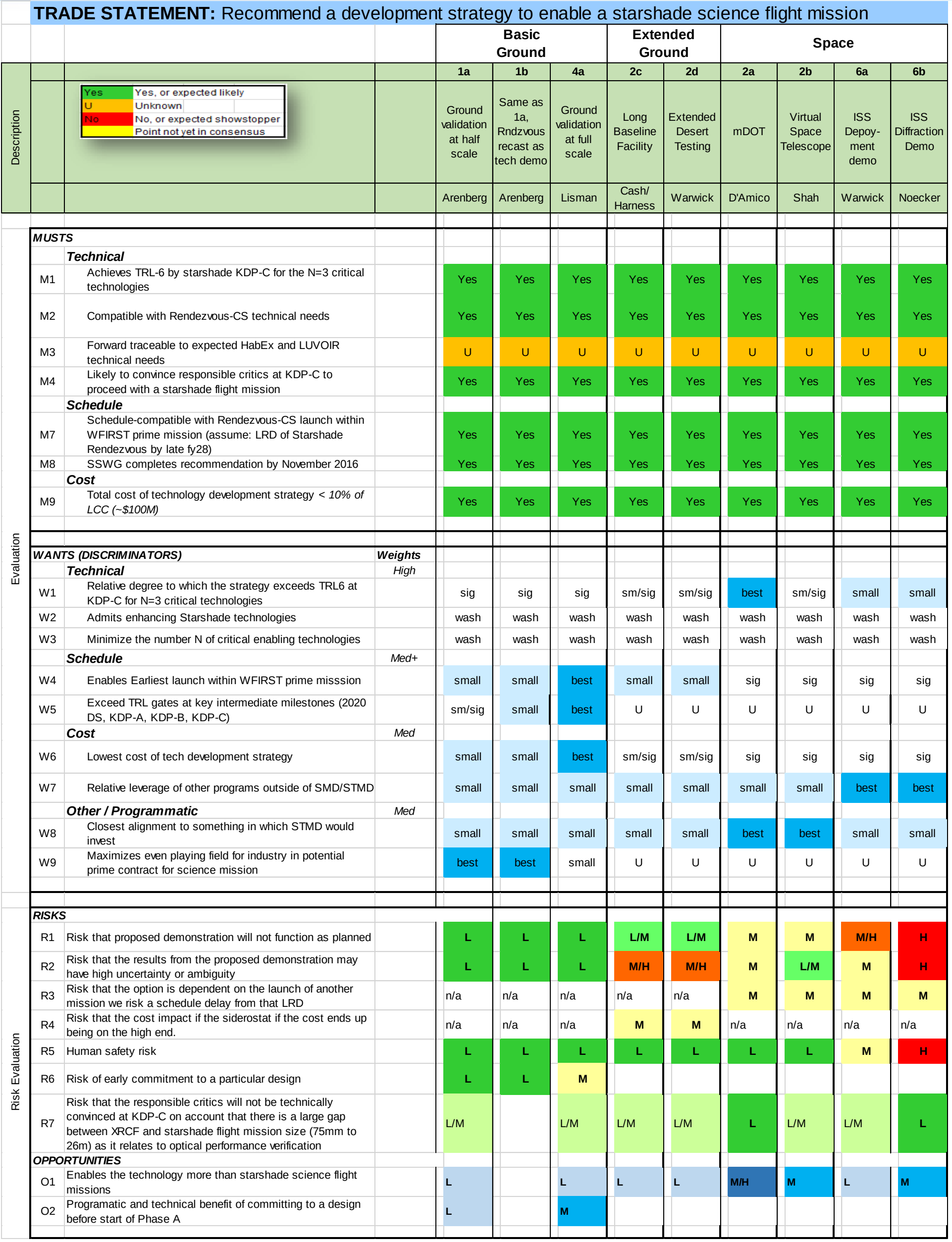




	Option 6b Optical Diffraction Demo at ISS
Deployment Accuracy	Includes all of "Deployment Accuracy" from Option 1a or 4a Starshade deployment is unlike WFIRST rendezvous
Structural Stability	Includes all of "Structural Stability" from Option 1a or 4a Starshade metering structure is unlike WFIRST rendezvous
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

TRADE EVALUATION

Results: Full Trade Matrix



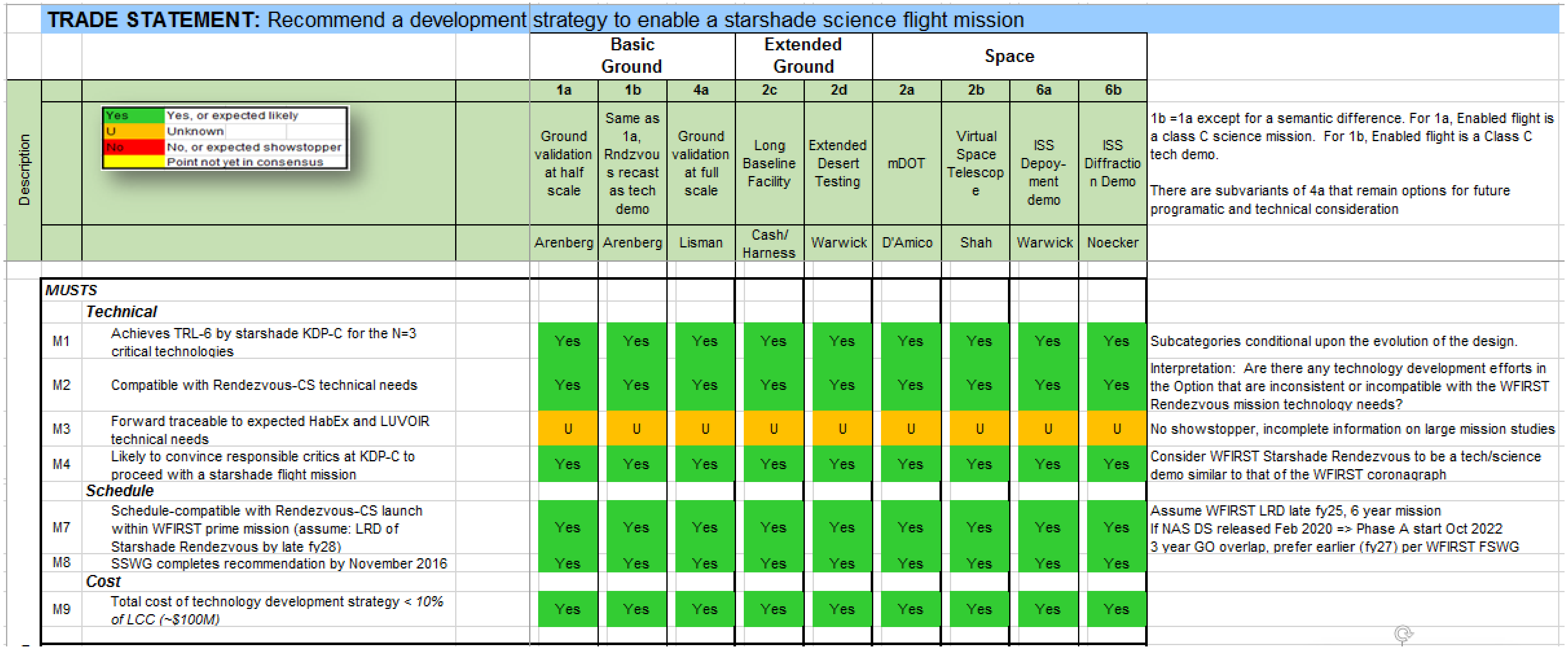
TRADE STATEMENT: Recommend a development strategy to enable a starshade science flight mission

				Basic Ground			Extended Ground		Space			
Description				1a	1b	4a	2c	2d	2a	2b	6a	6b
		🟩 Yes: Yes, or expected likely 🟧 U: Unknown 🟥 No: No, or expected showstopper 🟨 Point not yet in consensus		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	Cash/ Harness	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	sm/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	sm/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	n/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	L/M	L/M	**L**	L/M	L/M	**L**
	OPPORTUNITIES											
	O1	Enables the technology more than starshade science flight missions		**L**		**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**						

- Scores entered as group
- Consensus sought but not required
- Consensus of those in room and telecon reached after ~16 hours of group discussion on all points
- Dissent from one member not participating in group discussion

These Criteria and Risks Emerged as Significant Discriminators

Results: Musts



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

		Basic Ground			Extended Ground		Space				
Description		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	1b =1a except for a semantic difference. For 1a, Enabled flight is a class C science mission. For 1b, Enabled flight is a Class C tech demo. There are subvariants of 4a that remain options for future programatic and technical consideration
		Arenberg	Arenberg	Lisman	Cash/ Harness	Warwick	D'Amico	Shah	Warwick	Noecker	
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	Subcategories conditional upon the evolution of the design.
M2	Compatible with Rendezvous-CS technical needs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Interpretation: Are there any technology development efforts in the Option that are inconsistent or incompatible with the WFIRST Rendezvous mission technology needs?
M3	Forward traceable to expected HabEx and LUVOIR technical needs	U	U	U	U	U	U	U	U	U	No showstopper, incomplete information on large mission studies
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	Consider WFIRST Starshade Rendezvous to be a tech/science demo similar to that of the WFIRST coronagraph
	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	Assume WFIRST LRD late fy25, 6 year mission If NAS DS released Feb 2020 => Phase A start Oct 2022 3 year GO overlap, prefer earlier (fy27) per WFIRST FSWG
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	

The MUSTS did not reveal a showstopper that eliminated an option – rather, the MUSTS strengthened all options

M7 Evaluation: Compatible with WFIRST prime mission operations

The MUST M7: Schedule-compatible with Rendezvous-CS launch within WFIRST prime mission
Implies: Launch Readiness Date (LRD) of Starshade Rendezvous no later than late FY28.

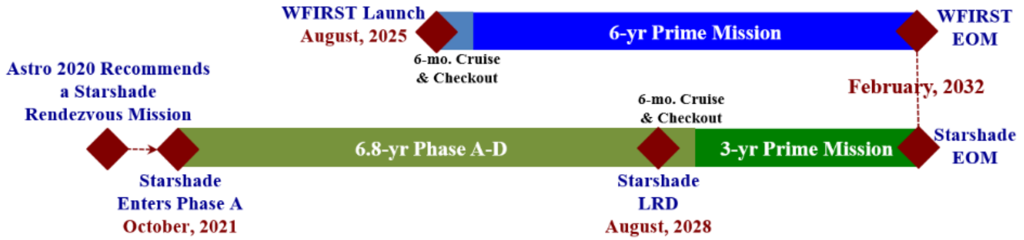
- All options passed M7

Basis for this MUST: to take advantage of the WFIRST opportunity for a starshade rendezvous

- A Rendezvous-CS launch no-later-than late FY28 permits a 3 year overlap with the Guest Observer Program. The WFIRST Formulation Science Working Group prefers an earlier (FY27) LRD,

Analysis:

- Given PPBE planning baseline of WFIRST LRD late FY25 (6 year mission); and
- Given Probe CATE of 7.8 yr from Phase A to LRD; and
- Assuming NAS Decadal Survey release Feb 2020; and
- Assuming a Starshade Rendezvous Phase A start in Oct 2022;
- **Then** LRD will be met by late FY28: Aug 2028 = FY22 (start)+ 6.8 yr
- Working Group Observation: probe study lifecycle estimate preceded the Starshade Technology Project formation. Effective STP will have the effect of shortening the lifecycle by 1 year to 6.8 yr.



WFIRST Launch
August, 2025

6-mo. Cruise
& Checkout

6-yr Prime Mission

WFIRST
EOM

February, 2032

Astro 2020 Recommends
a Starshade
Rendezvous Mission

6-mo. Cruise
& Checkout

6.8-yr Phase A-D

3-yr Prime Mission

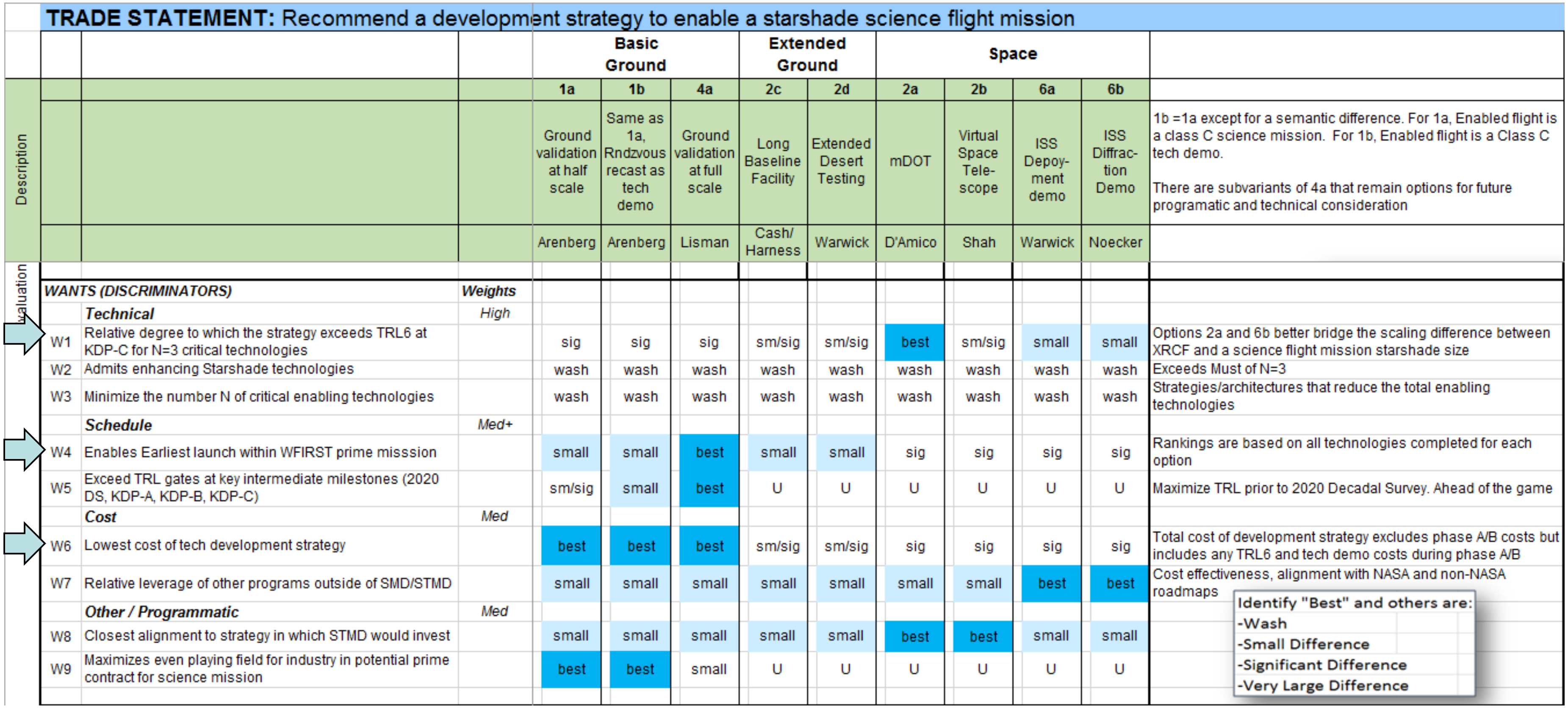
Starshade
EOM

Starshade
Enters Phase A
October, 2021

Starshade
LRD
August, 2028

A Starshade LRD in late FY28 is compatible with WFIRST prime mission and can be met by a 6.8-year development preceded by STP and FY22 new start

Results: WANTS



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

				Basic Ground			Extended Ground		Space				
Description				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 Tele-scope	ISS Depoy-ment demo	ISS Diffrac-tion Demo	1b =1a except for a semantic difference. For 1a, Enabled flight is a class C science mission. For 1b, Enabled flight is a Class C tech demo. There are subvariants of 4a that remain options for future programatic and technical consideration
				Arenberg	Arenberg	Lisman	Cash/ Harness	Warwick	D'Amico	Shah	Warwick	Noecker	
Evaluation		***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	sm/sig	sm/sig	best	sm/sig	small	small	Options 2a and 6b better bridge the scaling difference between XRCF and a science flight mission starshade size
	W2	Admits enhancing Starshade technologies		wash	wash	wash	wash	wash	wash	wash	wash	wash	Exceeds Must of N=3
	W3	Minimize the number N of critical enabling technologies		wash	wash	wash	wash	wash	wash	wash	wash	wash	Strategies/architectures that reduce the total enabling technologies
		Schedule	*Med+*										
	W4	Enables Earliest launch within WFIRST prime misssion		small	small	best	small	small	sig	sig	sig	sig	Rankings are based on all technologies completed for each option
	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	Maximize TRL prior to 2020 Decadal Survey. Ahead of the game
		Cost	*Med*										
	W6	Lowest cost of tech development strategy		best	best	best	sm/sig	sm/sig	sig	sig	sig	sig	Total cost of development strategy excludes phase A/B costs but includes any TRL6 and tech demo costs during phase A/B
	W7	Relative leverage of other programs outside of SMD/STMD		small	small	small	small	small	small	small	best	best	Cost effectiveness, alignment with NASA and non-NASA roadmaps
		Other / Programmatic	*Med*										
	W8	Closest alignment to strategy 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	

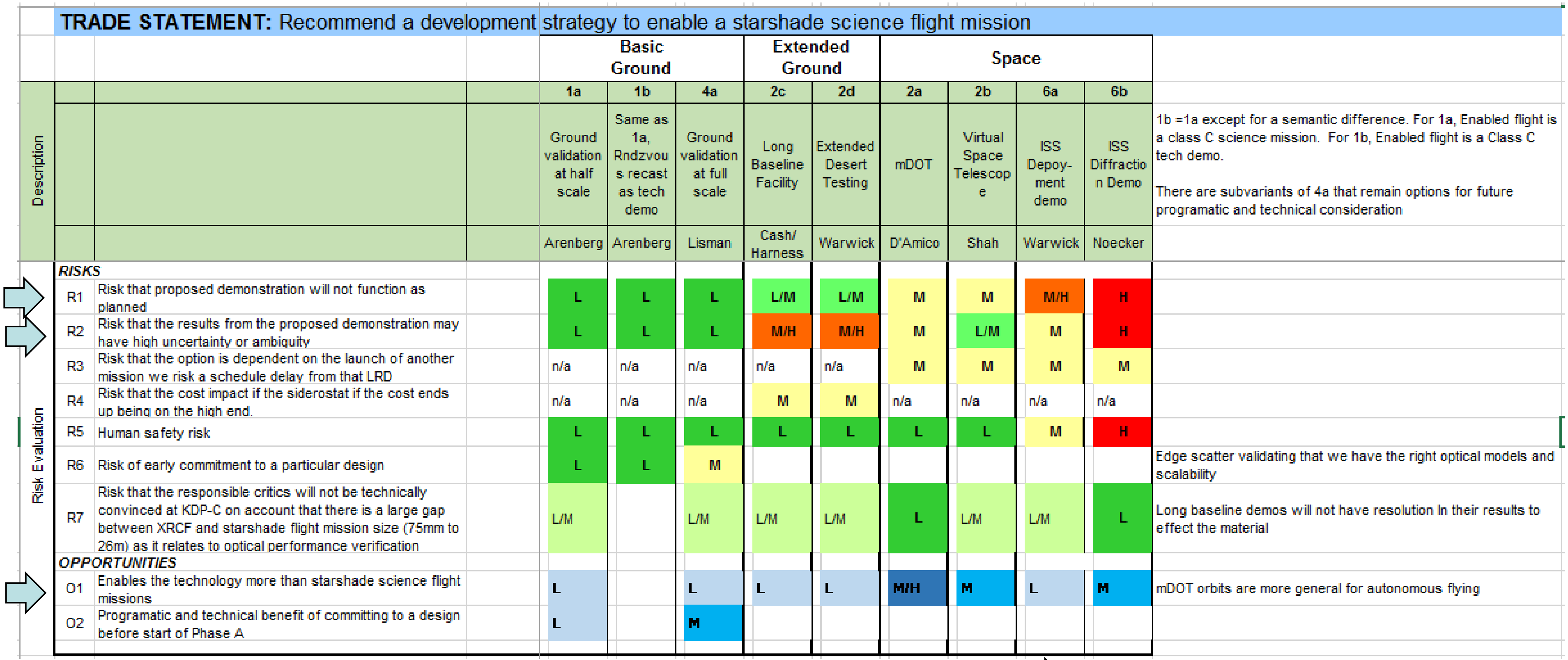
Identify "Best" and others are:
-Wash
-Small Difference
-Significant Difference
-Very Large Difference

These Criteria Emerged as Significant Discriminators

Note: 4b was not scored by the group since it was a small variant to 4a

The WANTS revealed the key trade between: degree of technical validation, vs the cost and schedule

Results: Risks and Opportunities



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

			Basic Ground			Extended Ground		Space				
Description			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	1b =1a except for a semantic difference. For 1a, Enabled flight is a class C science mission. For 1b, Enabled flight is a Class C tech demo. There are subvariants of 4a that remain options for future programatic and technical consideration
			Arenberg	Arenberg	Lisman	Cash/ Harness	Warwick	D'Amico	Shah	Warwick	Noecker	
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	n/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							Edge scatter validating that we have the right optical models and scalability
	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	L/M	L/M	L	L/M	L/M	L	Long baseline demos will not have resolution In their results to effect the material
	OPPORTUNITIES											
	O1	Enables the technology more than starshade science flight missions	L		L	L	L	M/H	M	L	M	mDOT orbits are more general for autonomous flying
	O2	Programatic and technical benefit of committing to a design before start of Phase A	L		M							

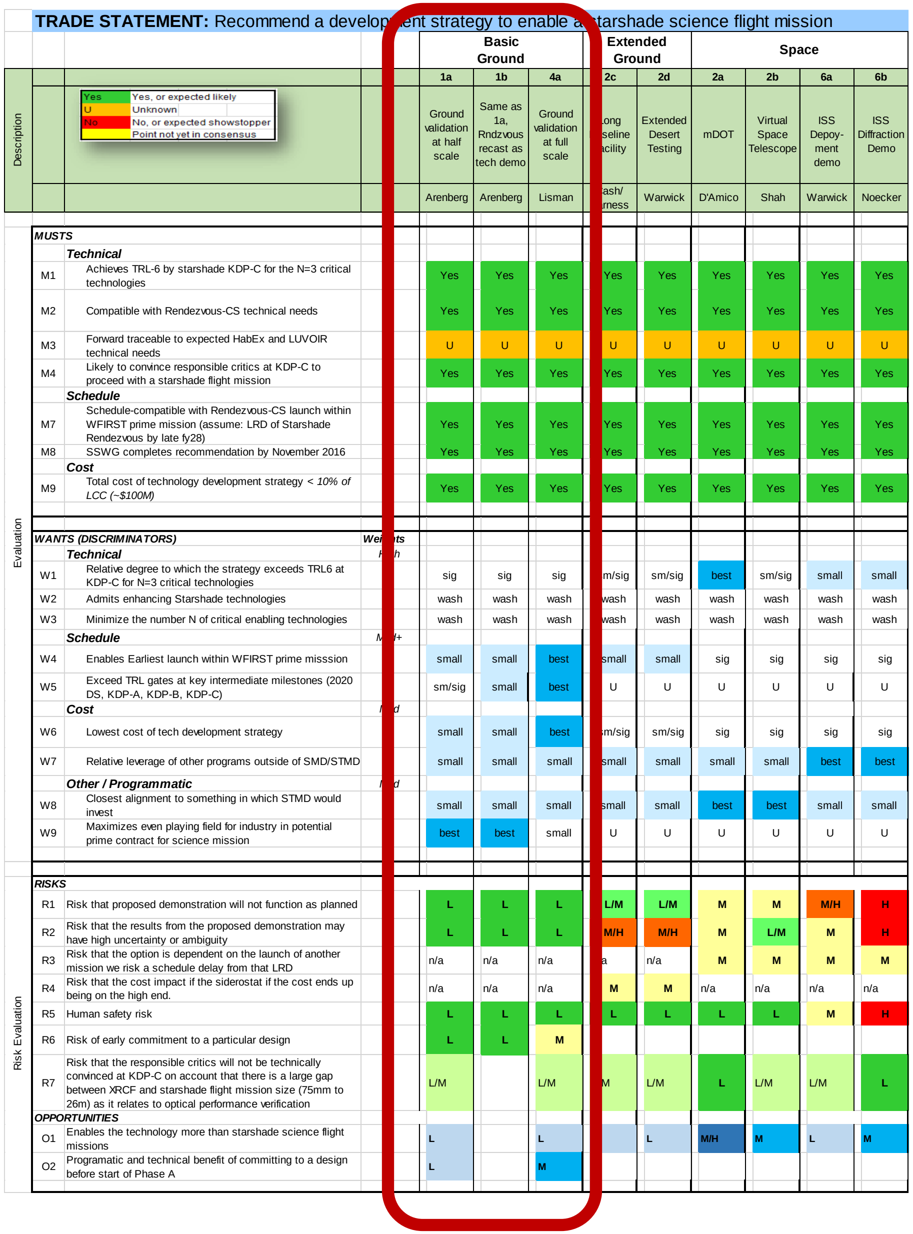
These Risks and Opportunities Emerged as Significant Discriminators

Note: 4b was not scored by the group since it was a small variant to 4a

Risks and Opportunities revealed the largest difference between the Options

Final Trade Evaluation and Findings

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



TRADE STATEMENT: Recommend a develop ent strategy to enable a tarshade science flight mission

				Basic Ground			Extended Ground		Space			
				1a	1b	4a	2c	2d	2a	2b	6a	6b
Description		🟩 Yes – Yes, or expected likely 🟧 U – Unknown 🟥 No – No, or expected showstopper 🟨 Point not yet in consensus		Ground validation at half scale	Same as 1a, Rndzvous recast as tech demo	Ground validation at full scale	ong seline acility	Extended Desert Testing	mDOT	Virtual Space Telescope	ISS Depoyment 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)		***Wei ts***									
		Technical	*H h*									
	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	*M /+*									
	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	*M d*									
	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	*M d*									
	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

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 residue 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

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

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 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

EXOTAC ASSESSMENT

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.

CLOSING

Next Steps

1. Conduct architecture trades (deployment) during FY17 Starshade Technology Project
2. Continue with analysis of WFIRST starshade accommodation
3. Conduct parallel pre-mission studies of WFIRST Starshade rendezvous to solidify context for technology development
4. Convey interest to STMD in an mDOT TDM – enhancement of technical risk reduction involving science measurements and operation, along with benefits for formation flying beyond starshade applications

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Princeton University

SETI Institute

Ames Research Center

NASA Marshall Space Flight Center

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Jet Propulsion Laboratory
California Institute of Technology

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- 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

M3 Evaluation

- **MUST M3: Forward traceable to expected HabEx and LUVOIR technical needs**
- Interpreted as “All options are applicable as technology development for HabEx and LUVOIR decadal large mission studies”
- The "U" reflects uncertainty in the strategic application requirements. Final evaluation pending flagship mission requirements

Conclusion: no showstopper, insufficient data on HabEx/LUVOIR to evaluate at this time