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

CL#16-5333

Logistical Information

- NASA HQ Room 1Q39 (Glennan Conference Room)
- 12-2pm(PT)=3-5pm(ET)
- Webex screen share: https://jplwebex.jpl.nasa.gov
  - Meeting ID: 993979091
- Dial in: 844-575-9329 Meeting ID: 993979091

Outline and Agenda

• Introduction	Sara Seager and
– Purpose, Executive Summary, Trade Criteria	Gary Blackwood
• Option Descriptions	Charley Noecker
– Assumptions	
• Evaluation by Chief Technologist Team	Nick Siegler
• Evaluation by Technology Management Team	Tupper Hyde
• Trade Process	Gary Blackwood
– Musts, Wants, Risks, Opportunities	
• Summary of Recommended Option	Charley Noecker
– Why ground validation is sufficient	
• Dissent Discussion	Gary Blackwood
• ExoTAC Assessment	Alan Boss
• Closing Remarks/Next Steps	Sara Seager
• Discussion	All

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

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[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

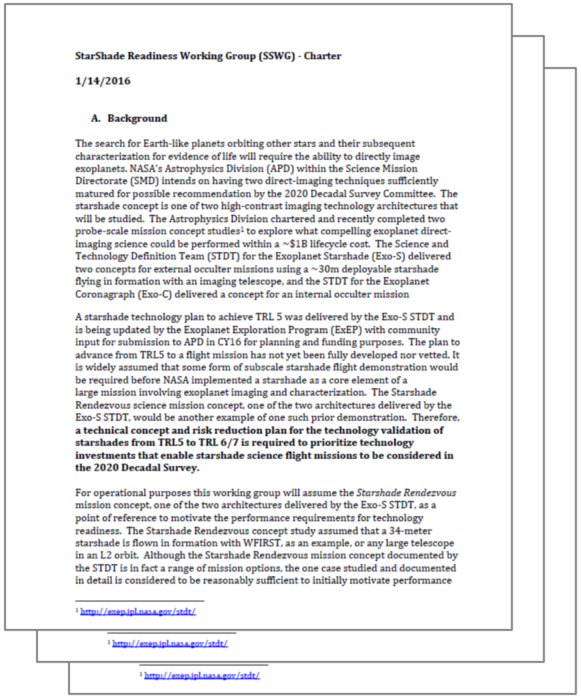
  - Sara Seager, Chair (MIT)
  - W. Cash (U. Colorado)
  - S. Domagal-Goldman (NASA-GSFC)
  - N. J. Kasdin (Princeton U.)
  - M. Kuchner (NASA-GSFC)
  - A. Roberge (NASA-GSFC)
  - S. Shaklan (NASA-JPL)
  - W. Sparks (STSci)
  - M. Thomson (NASA-JPL)
  - M. Turnbull (GSI)

  JPL Design Team

  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 to be delivered November 30 2016, final decision prior to KDP-B

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

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

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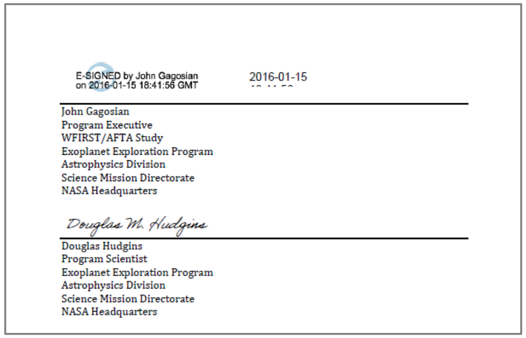
SSWG chartered by NASA APD
January 15, 2016



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on 2016-01-15 18:41:56 GMT 2016-01-15

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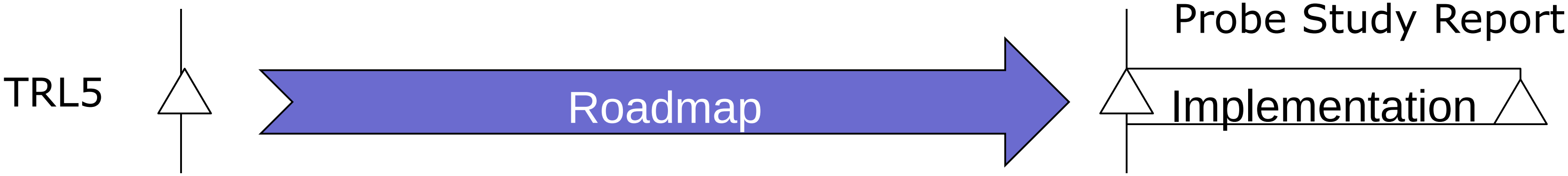
Program Executive
WFIRST/AFTA Study
Exoplanet Exploration Program
Astrophysics Division
Science Mission Directorate
NASA Headquarters

Douglas M. Hudgins

Douglas Hudgins
Program Scientist
Exoplanet Exploration Program
Astrophysics Division
Science Mission Directorate
NASA Headquarters

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



Adopted from Exo-S Probe Study Report

TRL5

Roadmap

Implementation

(Declared by Nick, fy19)

SSWG Creates this Roadmap for =>

KDP-C for a Starshade Science Mission

LRD

SSWG Chartered Membership

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
Remi Soummer	STScI
Tom Greene	NASA / ARC
Charley Noecker	NASA / JPL
Mark Melton	NASA / GSFC WFIRST
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
Kerri Cahoy	MIT	
Matt Greenhouse	NASA / GSFC	
Brent Knight	NASA / MSFC	
Denise Podolski	NASA HQ / STMD	
Steve Battel	Battel Engineering	
Keith Warfield	NASA ExEP/ JPL	
Lee Feinberg	NASA / GSFC JWST	
Geoff Andersen	US Air Force Academy	
Joe Pelliciotti	NASA/ GSFC JWST	

- **Subject Matter Experts and Guests:**

Analysts for Science and Technical figures of merit:

Dan Scharf	NASA / JPL
Robert Laskin	NASA / JPL
Peg Frerking	NASA / JPL
Simone D'Amico	Stanford
Neerav Shah	NASA / GSFC
Mark Clampin	NASA / GSFC
Bruce Macintosh	Stanford
Ann Shipley	U. of Colorado

SMD representative

Douglas Hudgins	NASA APD

STMD representative

Jeff Sheehy	NASA HQ / STMD
Keith Belvin	LaRC / STMD

Industry

Chip Barnes	Ball Aerospace
Alison Nordt	Lockheed Martin
Jeff Hunt	Boeing
Kurt Klaus	Boeing
Steve Warwick	Northrop Grumman
Jon Arenberg	Northrop Grumman

WFIRST:

David Content	NASA / GSFC – WFIRST

ExoTAC

Alan Boss	Carnegie Institution DTM
Joe Pitman	Exploration Sciences
Lisa Poyneer	LLNL
Steve Ridgway	NOAO
Rebecca Oppenheimer	AMNH

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

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Aki Roberge	NASA / GSFC	Exo-S STDT
Matt Greenhouse	NASA / GSFC	
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<u>STMD representative</u>

Keith Belvin	LaRC / STMD

<u>Industry</u>

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

<u>ExoTAC</u>

Alan Boss	Carnegie Institution DTM
Joe Pitman	Exploration Sciences

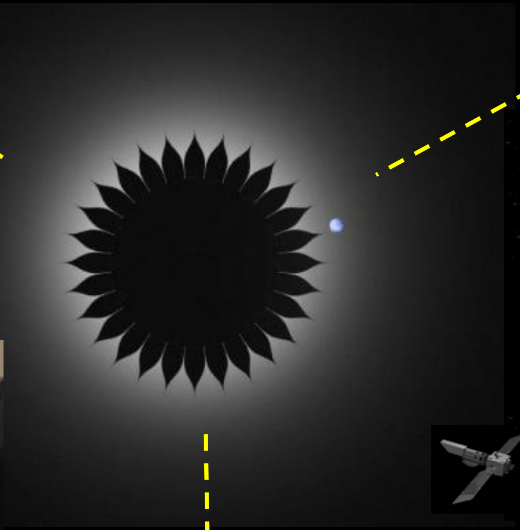
The Three Key Technology Areas for a Starshade

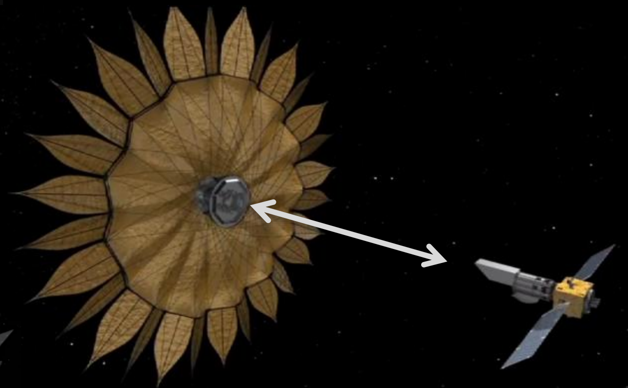
(mapped to 5 gaps S1-S5)

(1) Starlight Suppression

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

(3) Formation Sensing and Control

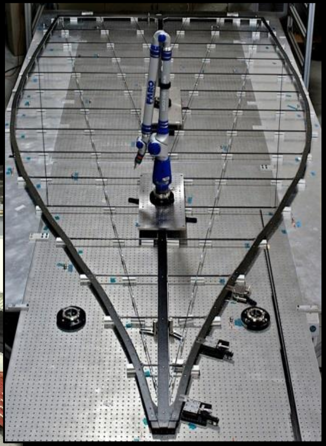




Maintaining lateral offset requirement between the spacecrafts **(S-3)**

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

(2) Deployment Accuracy and Shape Stability



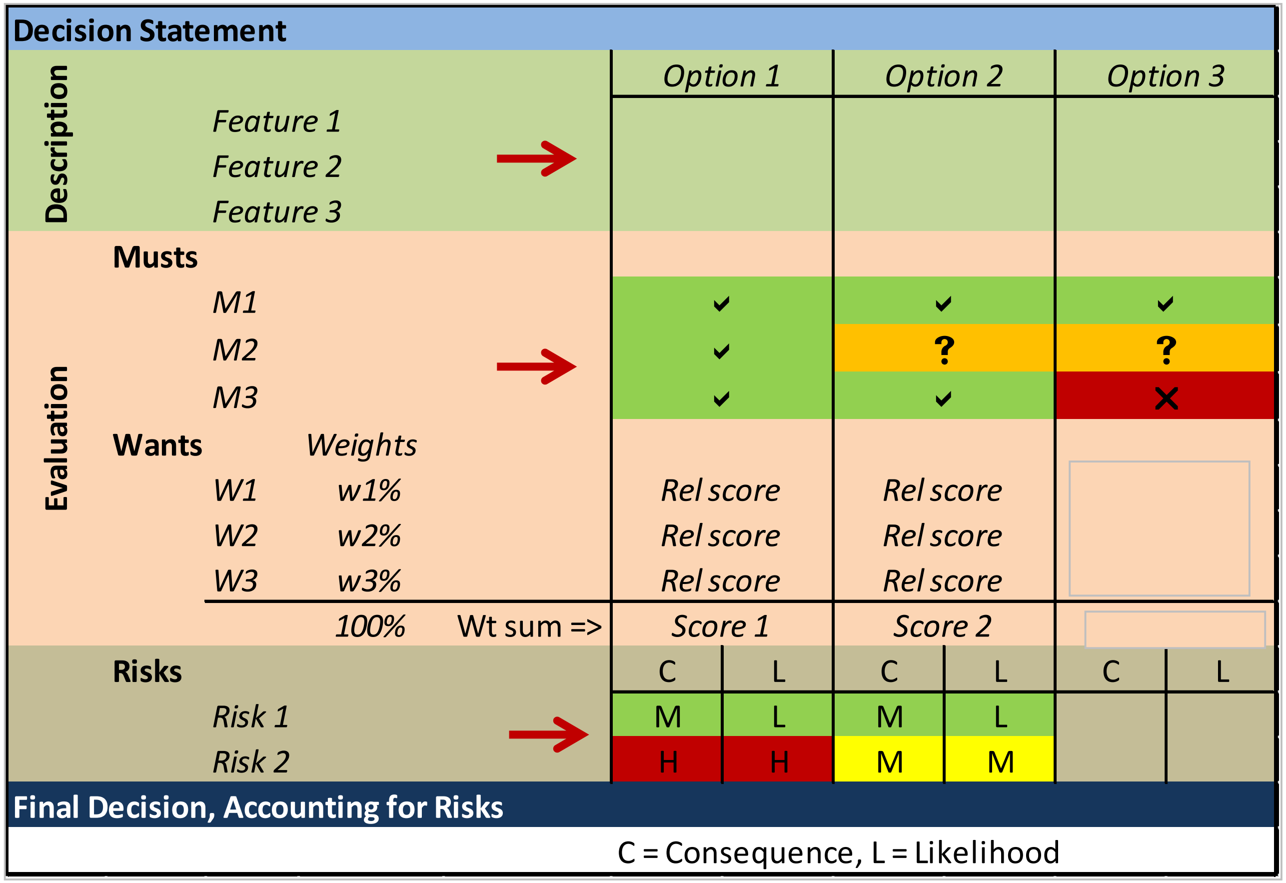
Fabricating the petals to high accuracy **(S-4)**

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 Approach for SSWG

- Adapted from Kepner-Tregoe methods. The Rational Manager, Kepner and Tregoe, 1965
- A systematic approach for creating options and decision making



Decision Statement										
Description					*Option 1*		*Option 2*		*Option 3*	
		Feature 1								
		Feature 2								
		Feature 3								
Evaluation	**Musts**									
		M1			✓		✓		✓	
		M2			✓		?		?	
		M3			✓		✓		✗	
	Wants		*Weights*							
		W1	*w1%*		*Rel score*		*Rel score*			
		W2	*w2%*		*Rel score*		*Rel score*			
		W3	*w3%*		*Rel score*		*Rel score*			
			100%	Wt sum =>	*Score 1*		*Score 2*			
	Risks				C	L	C	L	C	L
		Risk 1			M	L	M	L		
		Risk 2			H	H	M	M		
Final Decision, Accounting for Risks										
C = Consequence, L = Likelihood										

SSWG trade used qualitative not quantitative weights

Consider opportunities in addition to risks

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

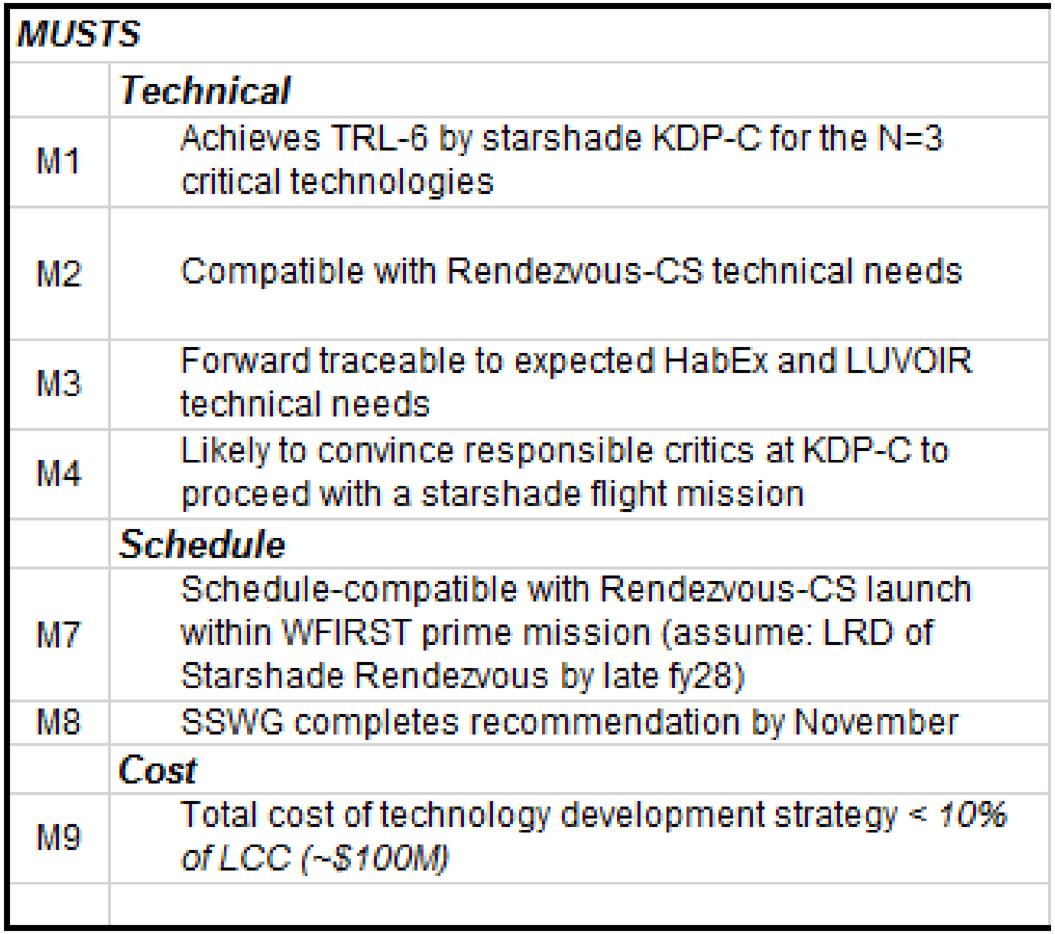
MUSTS (Requirements): ***Go/No_Go***

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

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

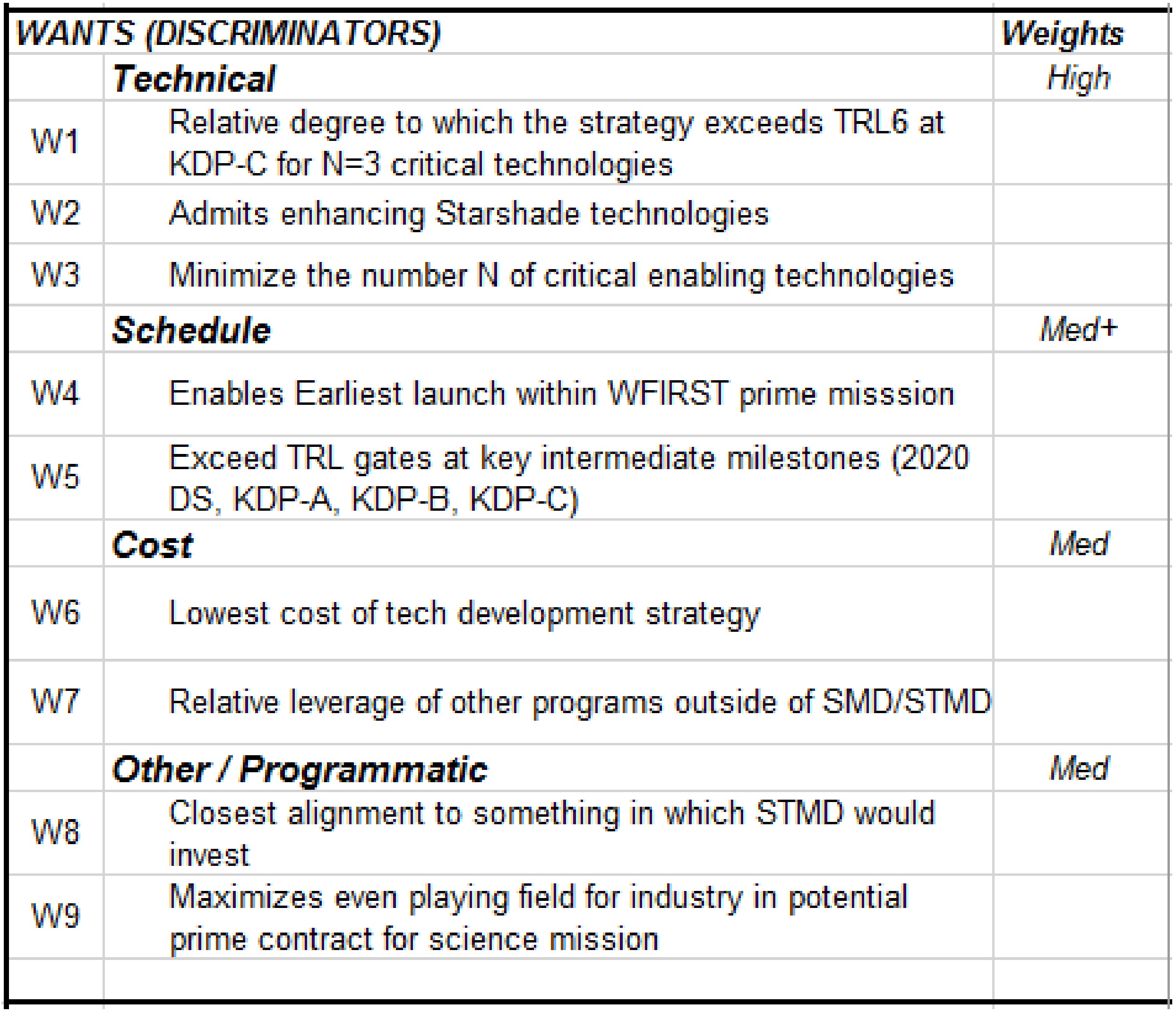
   See details to follow

RISKS and OPPORTUNITIES – scored as H,M,L



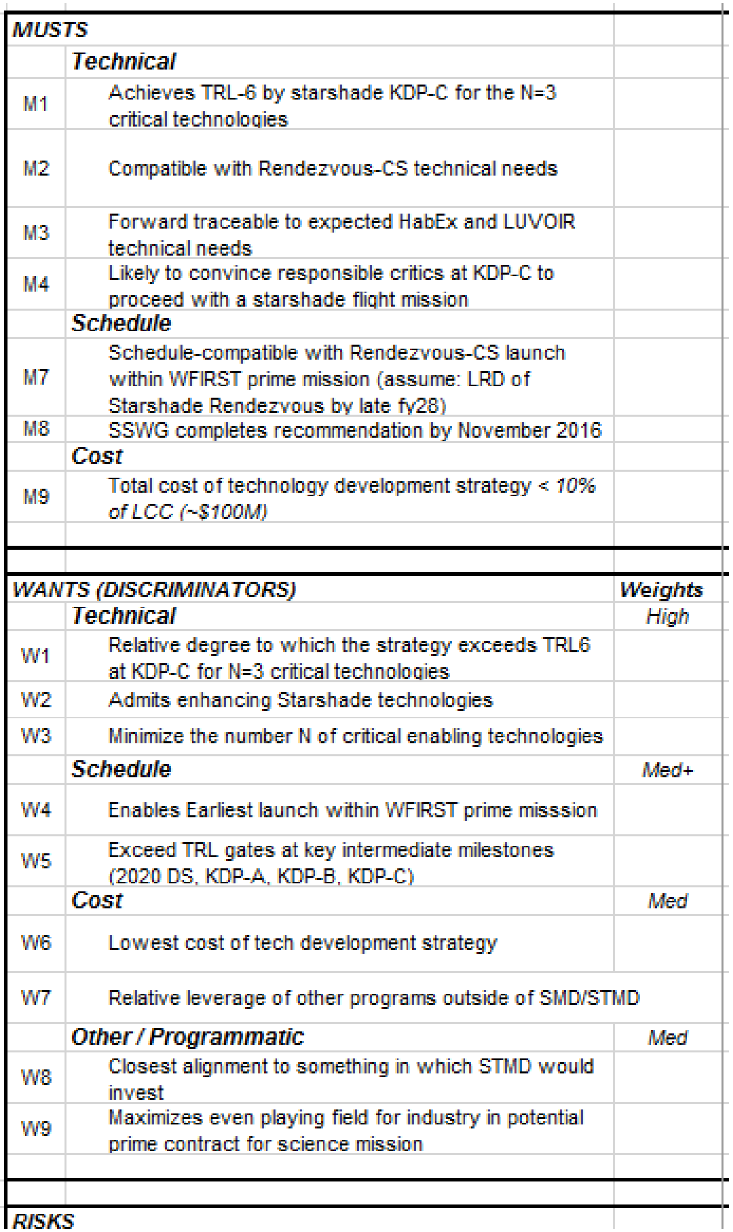
MUSTS	
	Technical
M1	Achieves TRL-6 by starshade KDP-C for the N=3 critical technologies
M2	Compatible with Rendezvous-CS technical needs
M3	Forward traceable to expected HabEx and LUVOIR technical needs
M4	Likely to convince responsible critics at KDP-C to proceed with a starshade flight mission
	Schedule
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	

Trade Evaluation: Scoring Method



MUSTS		
	Technical	
M1	Achieves TRL-6 by starshade KDP-C for the N=3 critical technologies	
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	Schedule	
M7	Schedule-compatible with Rendezvous-CS launch within WFIRST prime mission (assume: LRD of Starshade Rendezvous by late fy28)	
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	Technical	*High*
W1	Relative degree to which the strategy exceeds TRL6 at KDP-C for N=3 critical technologies	
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	Other / Programmatic	*Med*
W8	Closest alignment to something in which STMD would invest	
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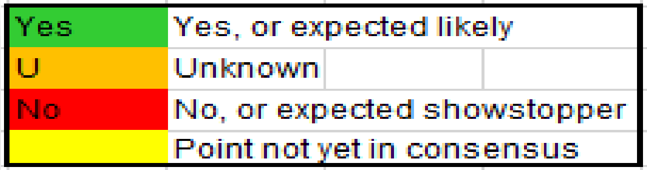
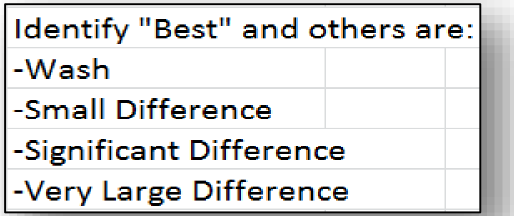
RISKS		



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



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

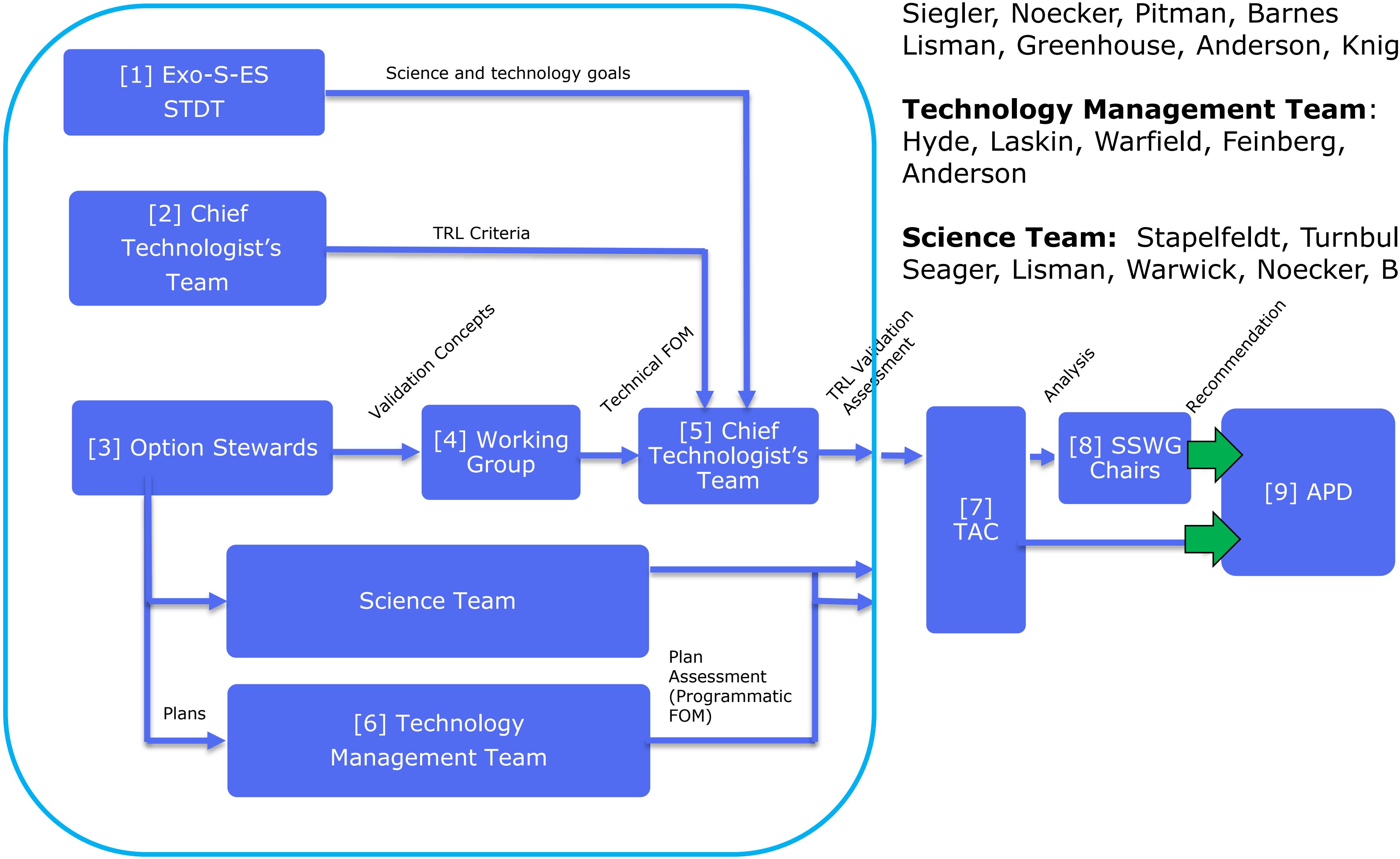
These Criteria and Risks Emerged as Significant Discriminators

SSWG Work Flow
Each team performed a detailed evaluation

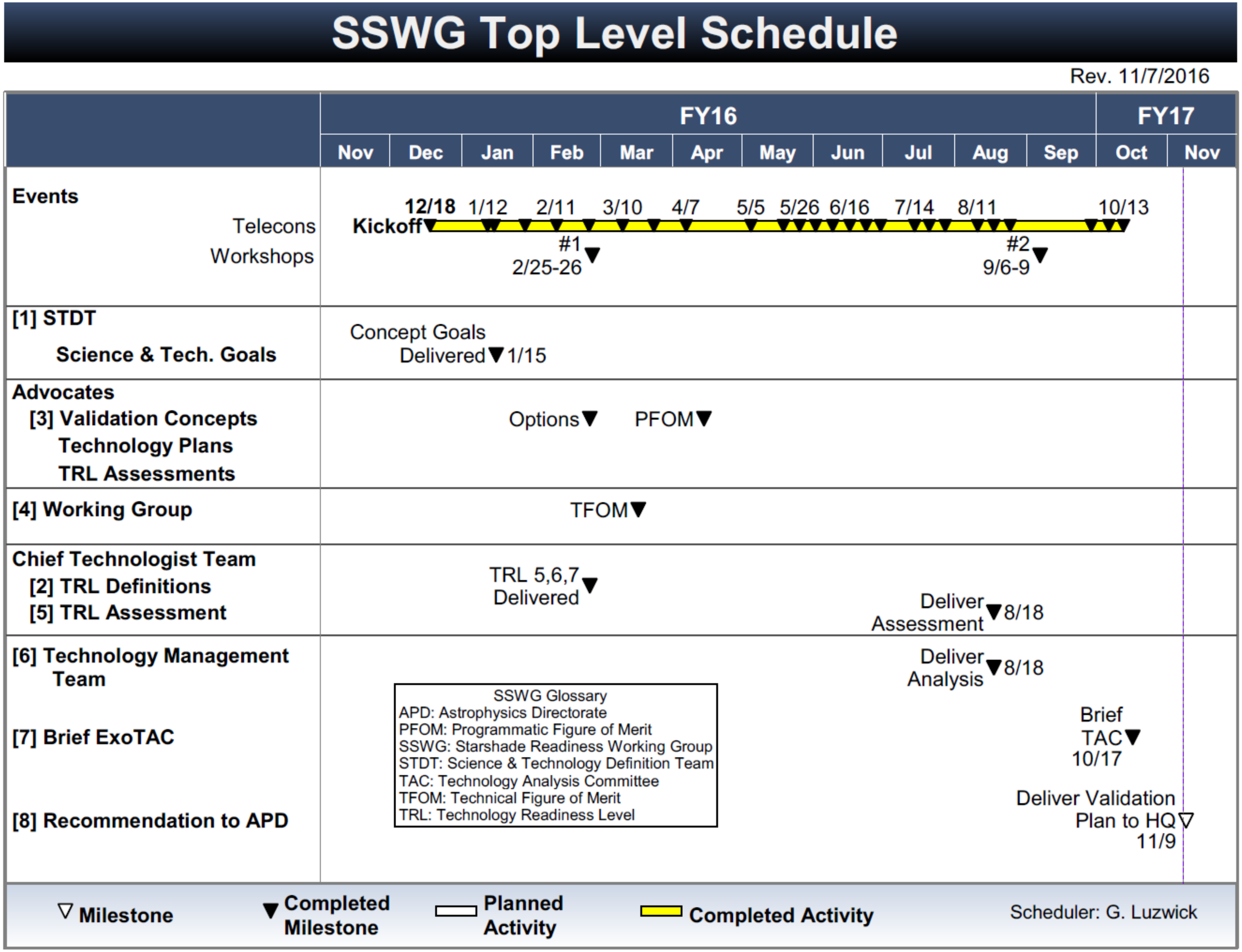
Chief Technologist Team:
Siegler, Noecker, Pitman, Barnes
Lisman, Greenhouse, Anderson, Knight

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

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



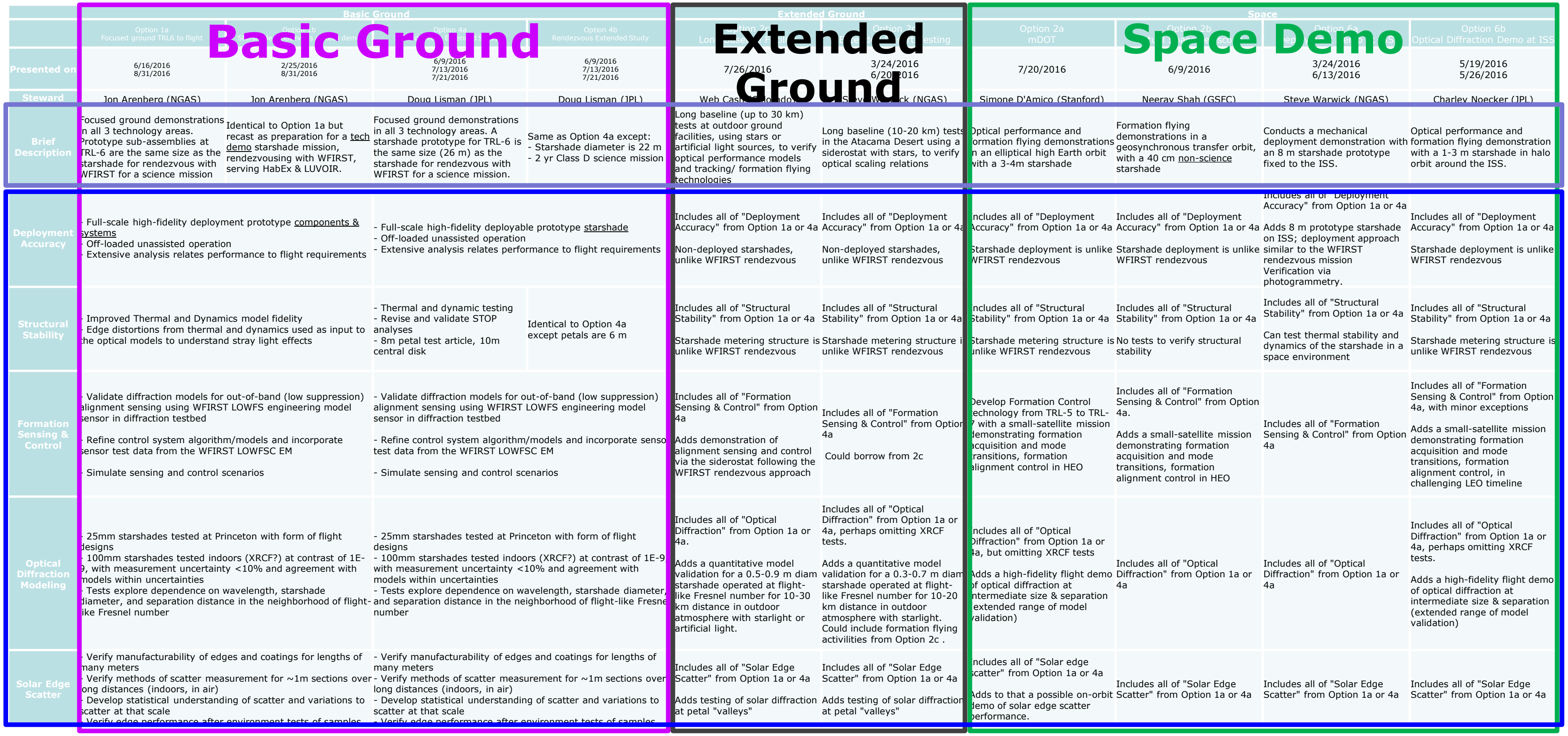
Schedule



SSWG Glossary
APD: Astrophysics Directorate
PFOM: Programmatic Figure of Merit
SSWG: Starshade Readiness Working Group
STDT: Science & Technology Definition Team
TAC: Technology Analysis Committee
TFOM: Technical Figure of Merit
TRL: Technology Readiness Level

OPTION DESCRIPTIONS

Overview of the Options Table (Descriptive)



	Basic Ground				Extended Ground		Space			
	Option 1a Focused ground TRL6 to flight	Option 1b [illegible]	Option 4a [illegible]	Option 4b Rendezvous Extended Study	[illegible]	Option 2d [illegible]esting	Option 2a mDOT	Option 2b [illegible]	Option 6a [illegible]	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[illegible]016	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 Cas[illegible]olorado)	[illegible]ck (NGAS)	Simone D'Amico (Stanford)	Neerav Shah (GSFC)	Steve Warwick (NGAS)	Charley Noecker (JPL)
Brief Description	Focused ground demonstrations n 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 n 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 i 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 senso 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 Fresne 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

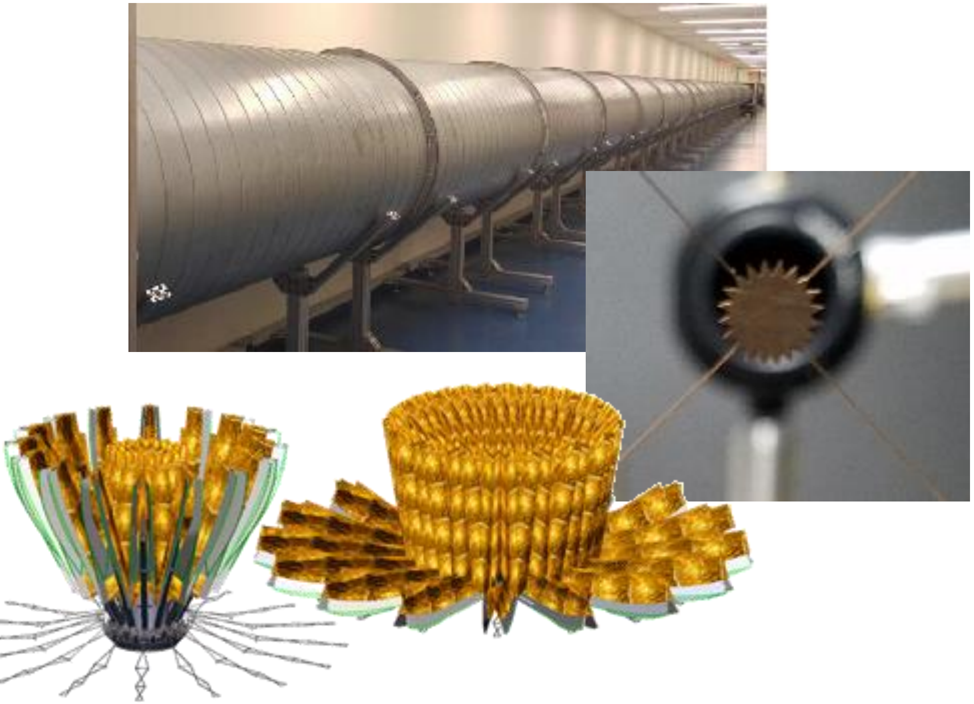
Basic Ground Options 1a, 1b, 4a, 4b

- 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 <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	

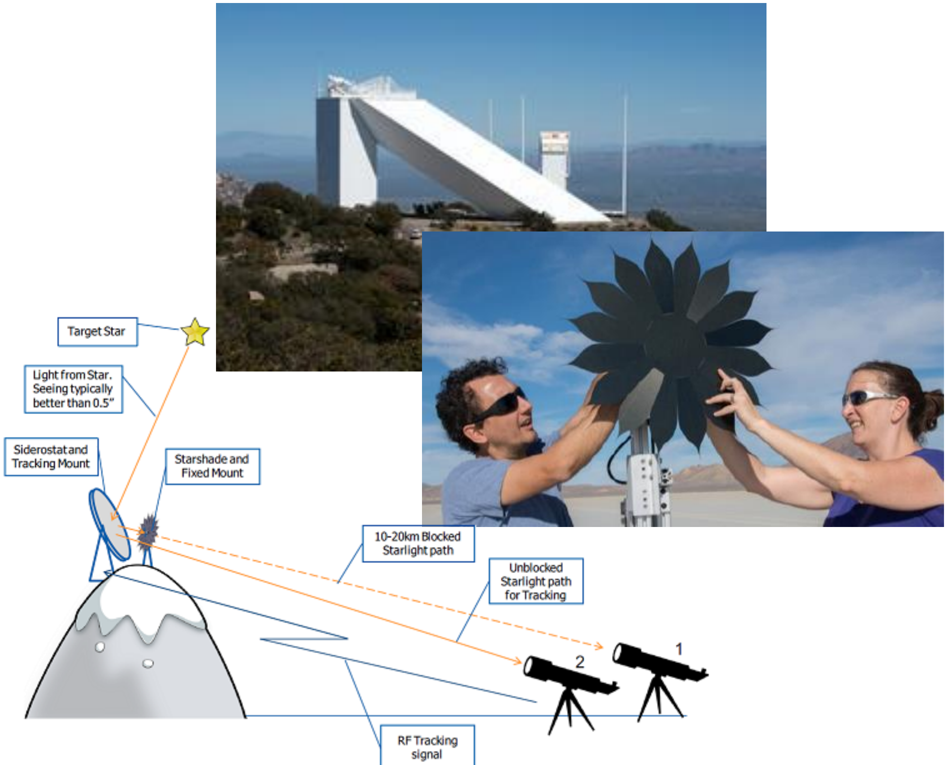
Extended Ground Options 2c, 2d

- 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

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

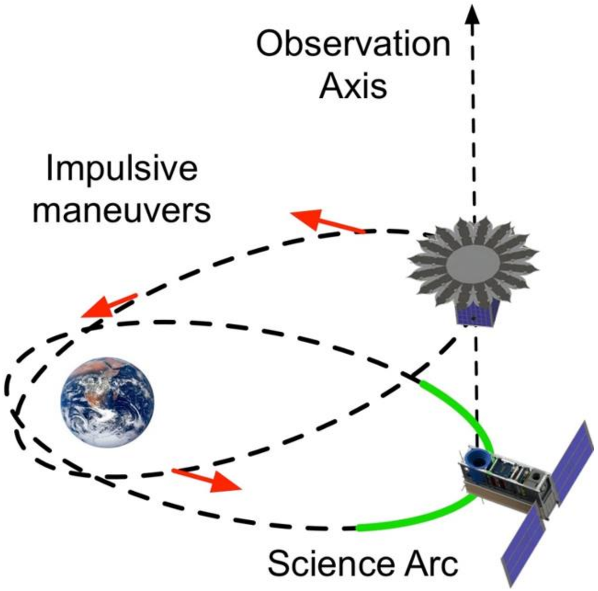


	Option 2c Long Baseline Facility	Option 2d Extended Desert Testing
Deployment Accuracy (S-4)	**Includes all of "Deployment Accuracy" from Option 1a or 4a** • Non-deployed starshades, unlike WFIRST rendezvous	**Includes all of "Deployment Accuracy" from Option 1a or 4a** Non-deployed starshades, unlike 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

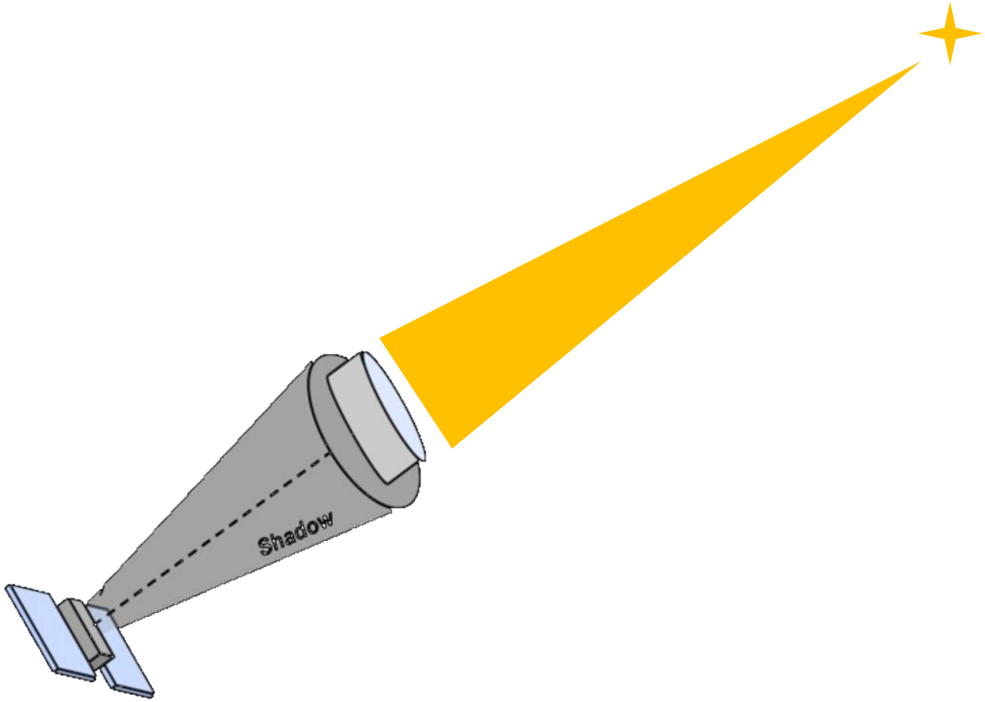
- Miniaturized Distributed Occulter & Telescope
- Flight mission concept with the possibility of a scientific result
- Formation flying & control with representative disturbances
- Optical diffraction demo at 3m size
- Align to and image one/two exoplanet systems

	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

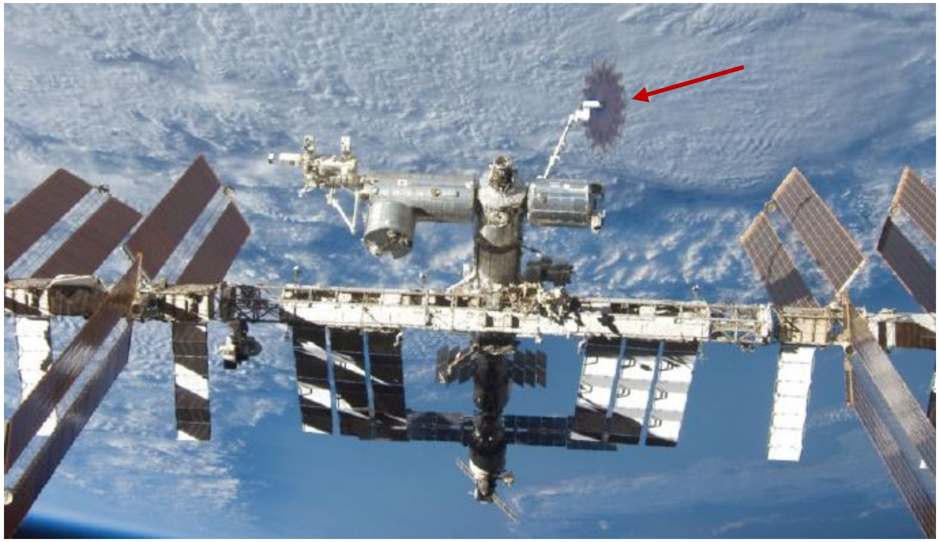
- Pure formation flying demo
- Starshade to diffract light for an alignment signal, not to suppress starlight
- Use WFIRST-relevant sensors and avionics subsystems



	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

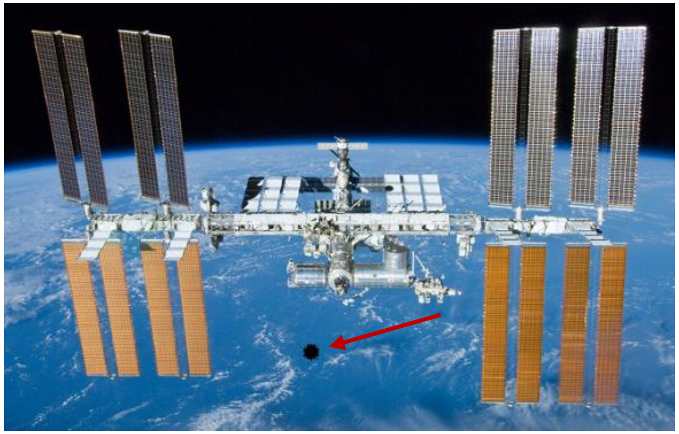
- Deployment test article at 8m size, operated at ISS
- Photogrammetry to verify accurate deployment
- Accelerometers to study dynamics

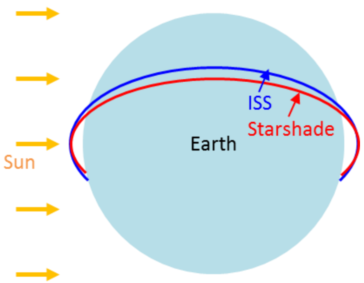


	Option 6a Deployment Demo at ISS
Deployment Accuracy	**Includes all of "Deployment Accuracy" from Option 1a or 4a** Adds 8 m prototype starshade on ISS; deployment approach similar to the WFIRST rendezvous mission Verification via photogrammetry.
Structural Stability	**Includes all of "Structural Stability"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

Additional Key Assumptions for Purpose of this Trade and Resulting Risk Evaluations

- Assume that the Starshade Technology Project delivers TRL5 by 2019 for purposes of programmatic evaluation (cost and schedule)
- A new mission start in FY22 for WFIRST Starshade Rendezvous
- A mission new start in FY22 requires:
  - Additional parallel and adequate mission concept development (pre-project)
  - WFIRST retains starshade accommodation features
  - WFIRST mission concept maturation is sufficient and parallel
- Testbed availability:
  - XRCF is available for technology testing

Modest variations in dates for TRL5 or new start do not affect the conclusion of this trade study

CHIEF TECHNOLOGIST TEAM EVALUATION

Technology Readiness Level Definitions
NASA NPR 7123.1B

TRL-5

Component and/or breadboard validation in relevant 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.

TRL-6

System/subsystem model or prototype demonstration in a relevant environment.

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.

TRL-7

System prototype demonstration in an operational environment.

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

Assumed TRL-5 Starting Point for SSWG Options:

Technically-quantified performance needs tied to Error Budgets, Vetted Gap Lists

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

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

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

CTT Assessment Process

- **Each Steward presented their Option to the CTT**
  - 6 virtual "face-to-face" telecons (12 work hours)

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

- **CTT convened 12 times to assess all the Options (26 work hours)**
  - Assessed 2 Musts and 3 Wants relative to technology
  - Two new Risks and two new Opportunities were captured and proposed
  - Consensus achieved on all

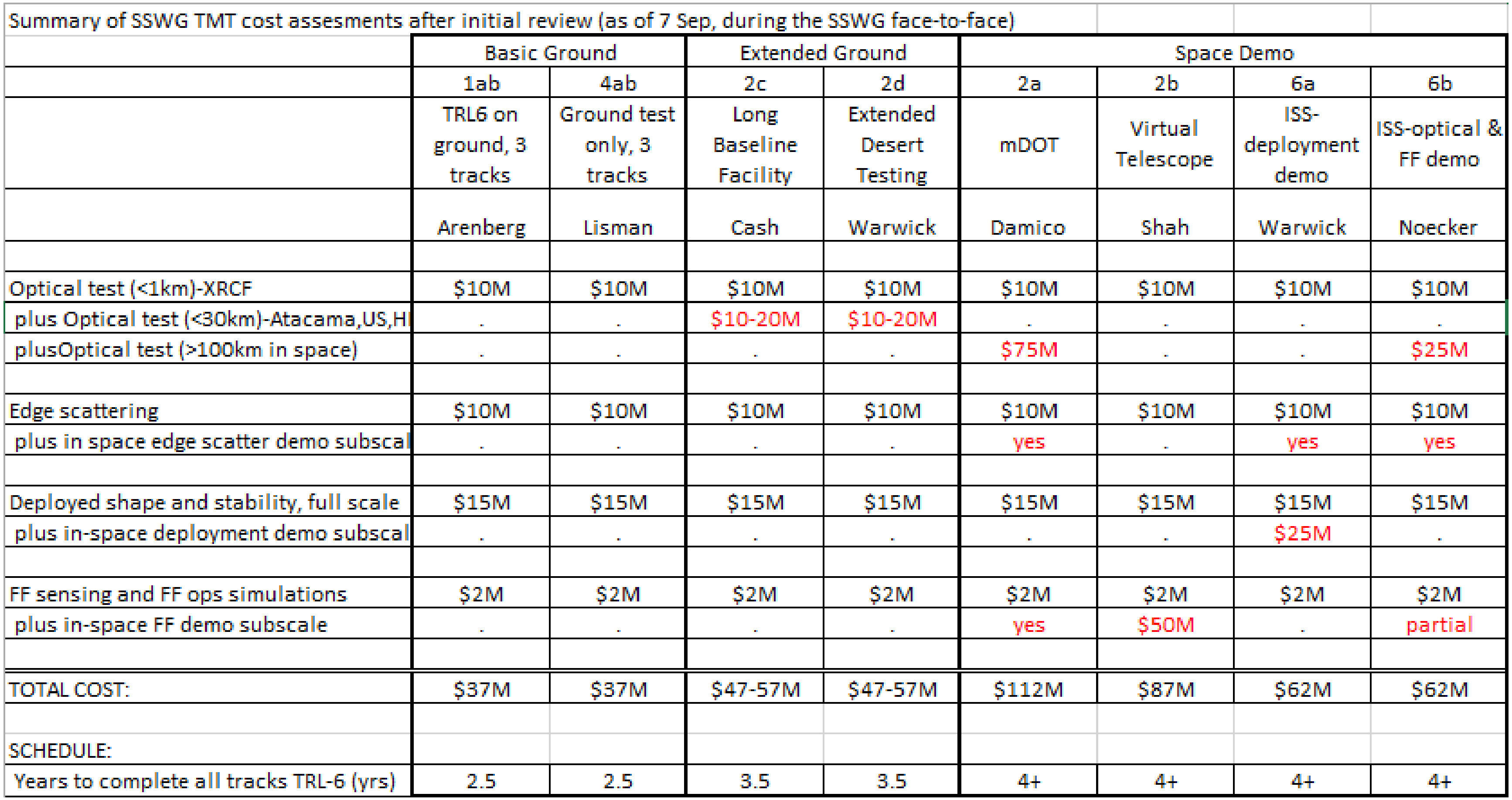
- **Piggybacking (SSWG): to leverage off someone else's technology development approach**
  - **Benefit**:
    - enabled some Stewards to focus only on specific space or ground techniques while gaining all the achievements of the pig-ee in reaching TRL-6
    - Pig-ee: Pure ground demonstration approaches: Options 1a/b and 4a/b
  - **Consequences**:
    - All Options that piggyback might succeed or fail with the assessment of the pig-ee
    - Potentially reduced the distinguishing value of the technology Musts
    - Placed more emphasis on the other criteria – Wants and Risks

TECHNOLOGY MANAGEMENT TEAM EVALUATION

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

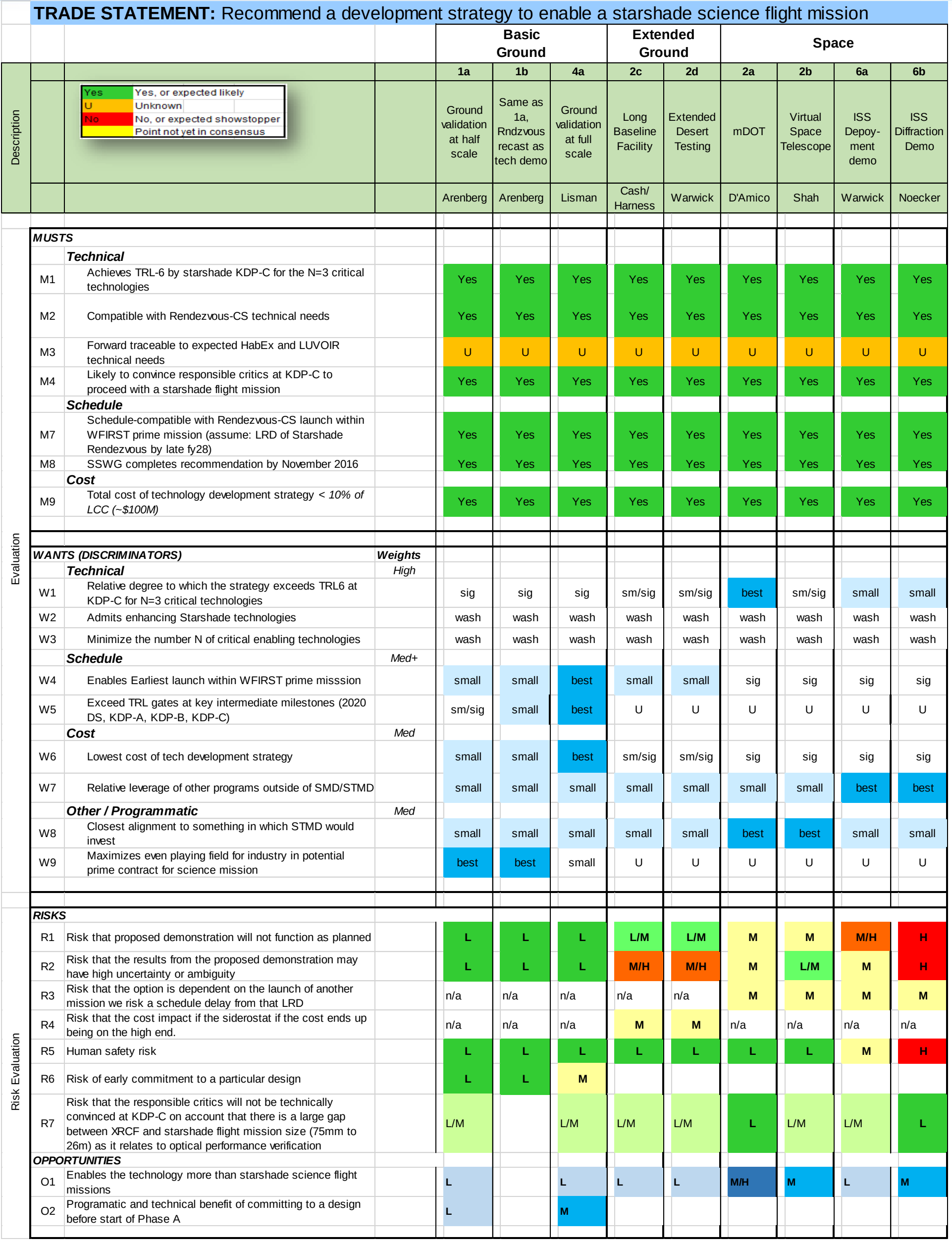


Summary of SSWG TMT cost assesments after initial review (as of 7 Sep, during the SSWG face-to-face)								
	Basic Ground		Extended Ground		Space Demo			
	1ab	4ab	2c	2d	2a	2b	6a	6b
	TRL6 on ground, 3 tracks	Ground test only, 3 tracks	Long Baseline Facility	Extended Desert Testing	mDOT	Virtual Telescope	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

TRADE EVALUATION

Results: Full Trade Matrix



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

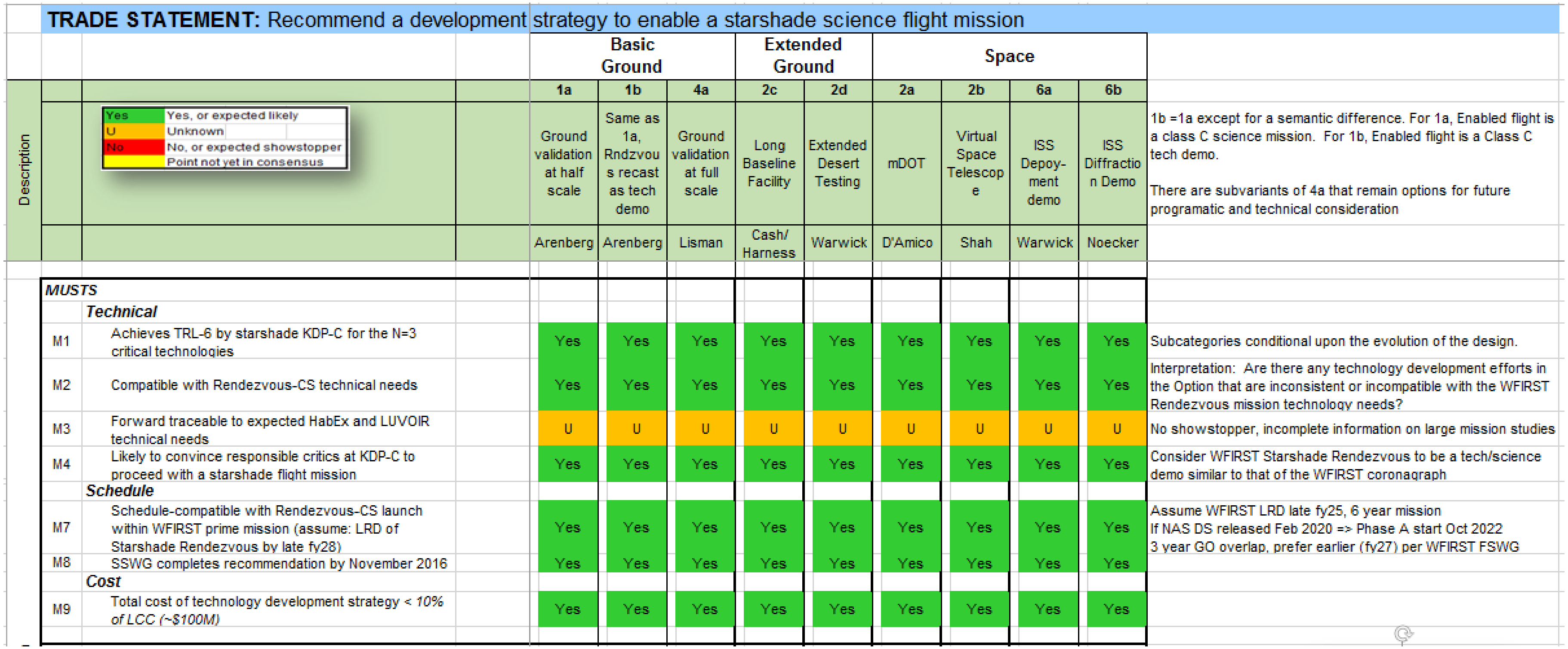
🟩 Yes — Yes, or expected likely
🟧 U — Unknown
🟥 No — No, or expected showstopper
🟨 Point not yet in consensus

	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	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

	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 Deployment 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

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

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.

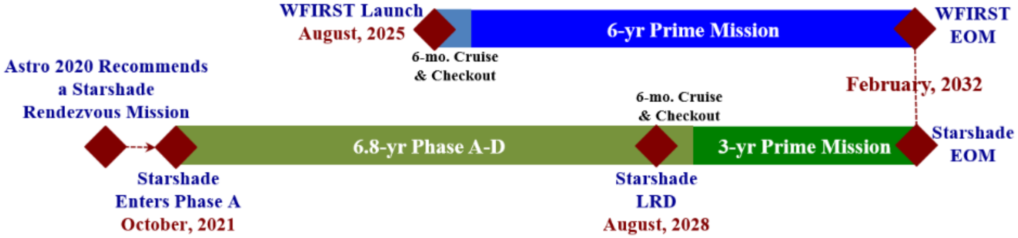
- All options passed M7

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,

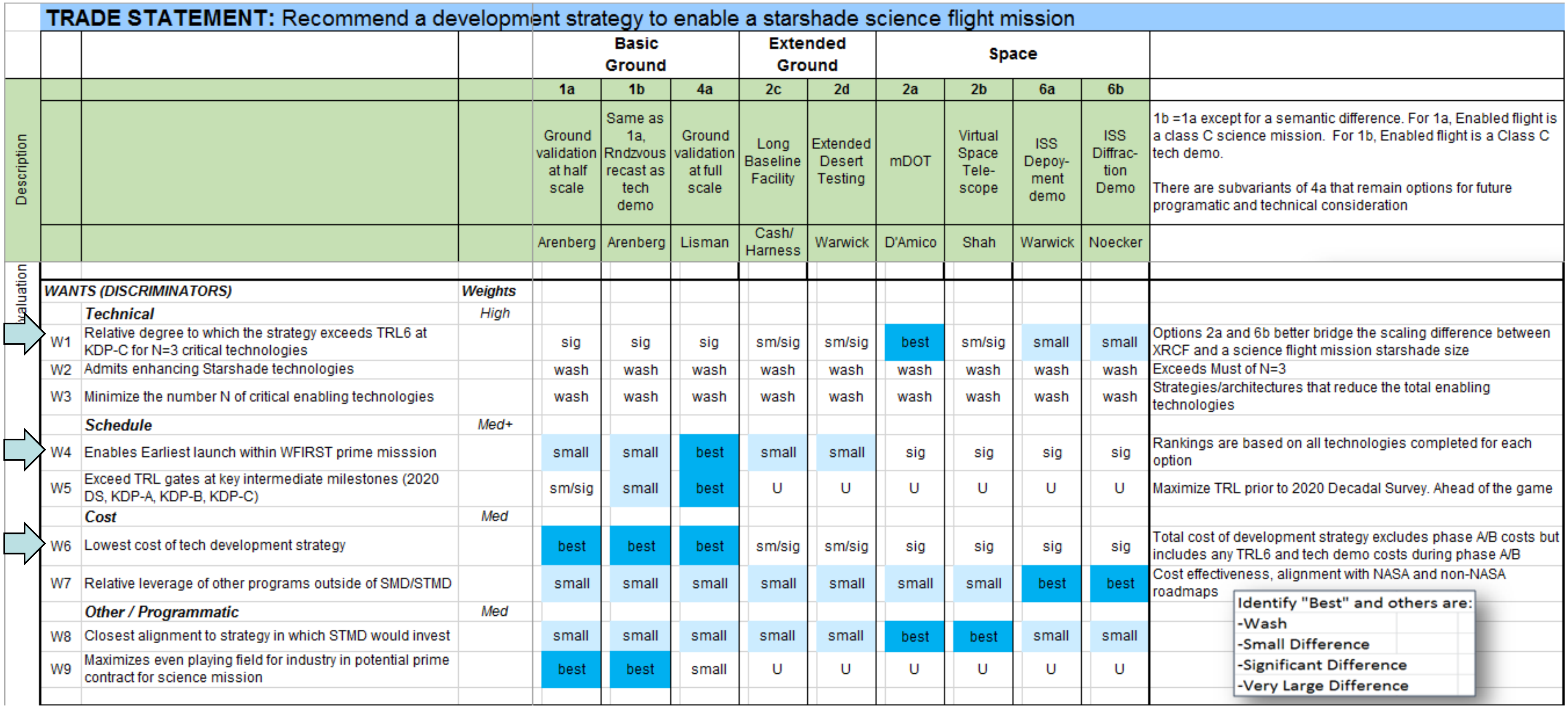
Analysis:

- 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.



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	

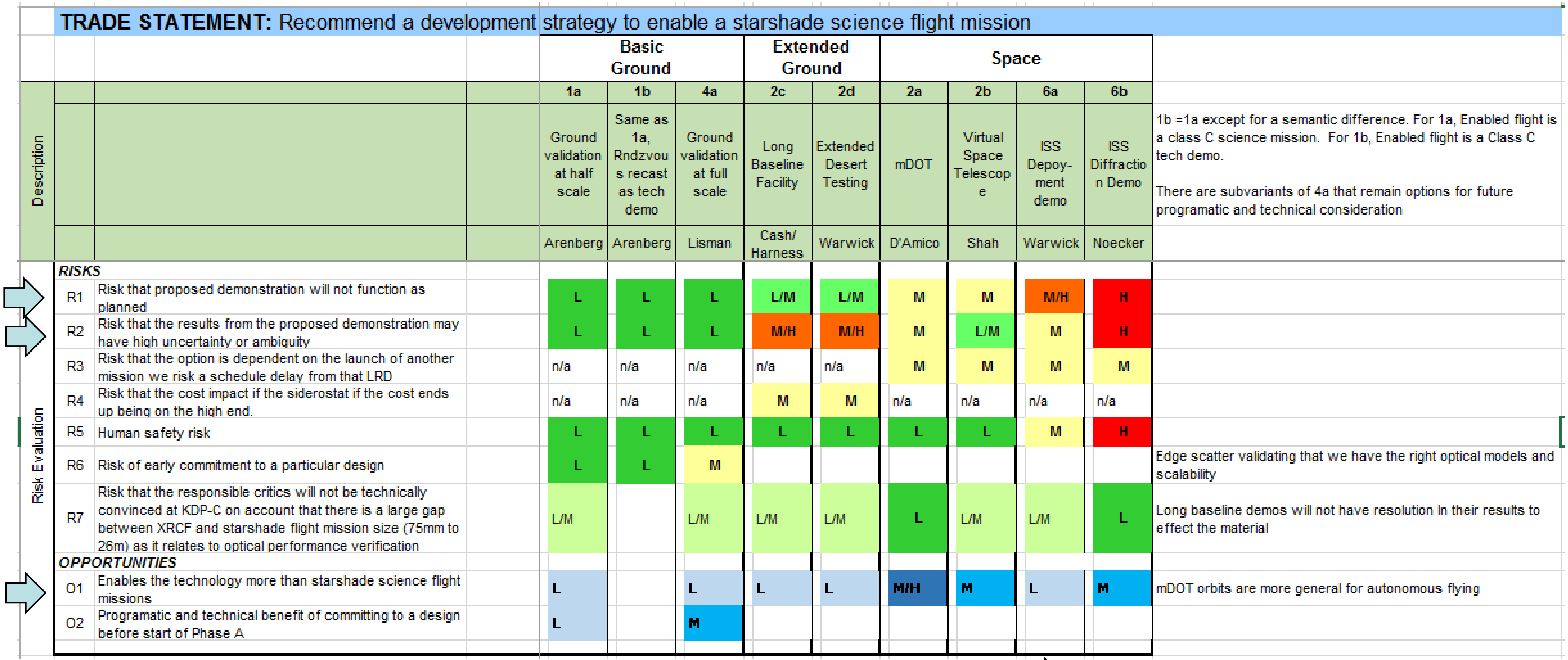
Identify "Best" and others are:
-Wash
-Small Difference
-Significant Difference
-Very Large Difference

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 Depoyment 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							

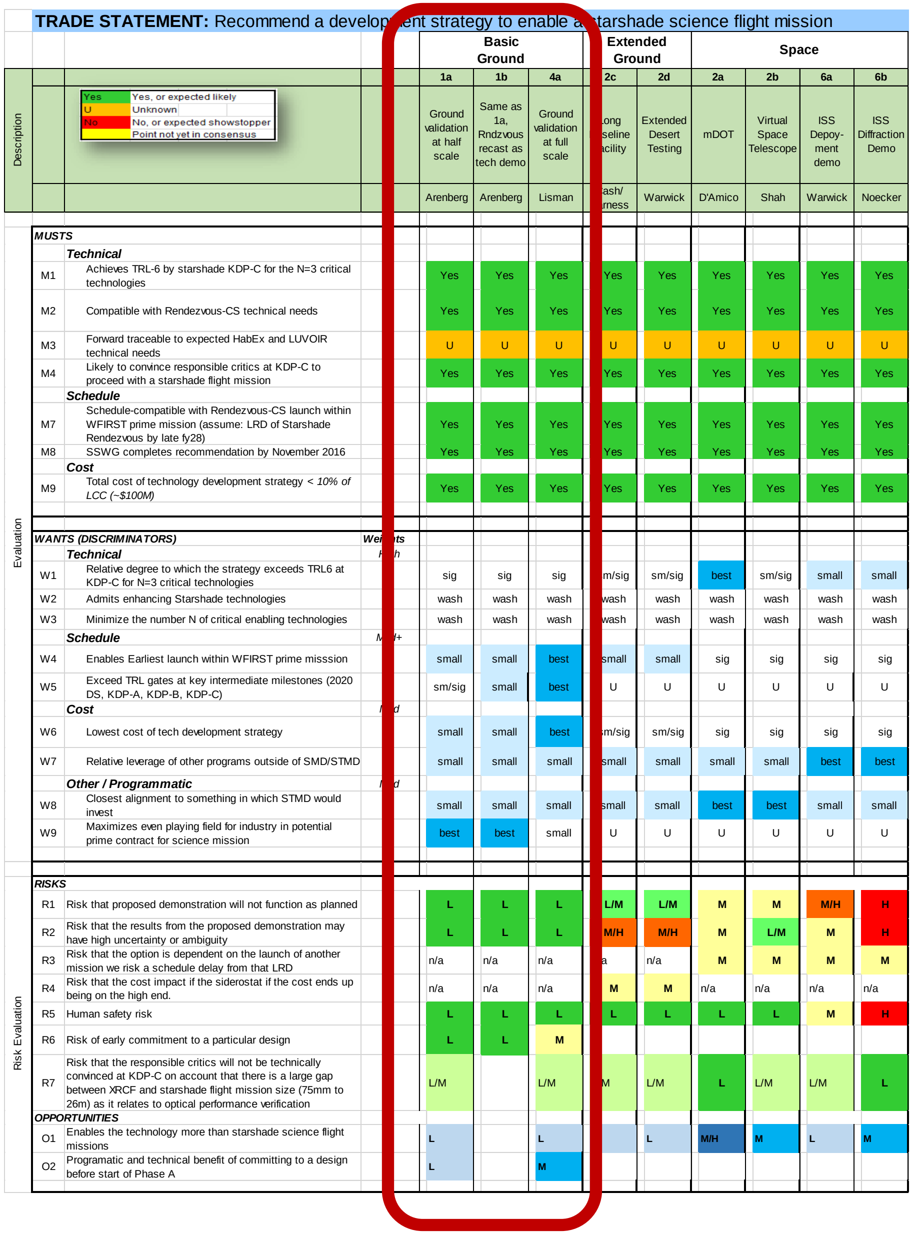
These Risks and Opportunities Emerged as Significant Discriminators

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			
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	.ong seline acility	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)		***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 RECOMMENDED OPTION: WHY GROUND VALIDATION IS SUFFICIENT

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 residue risk prior to flight**

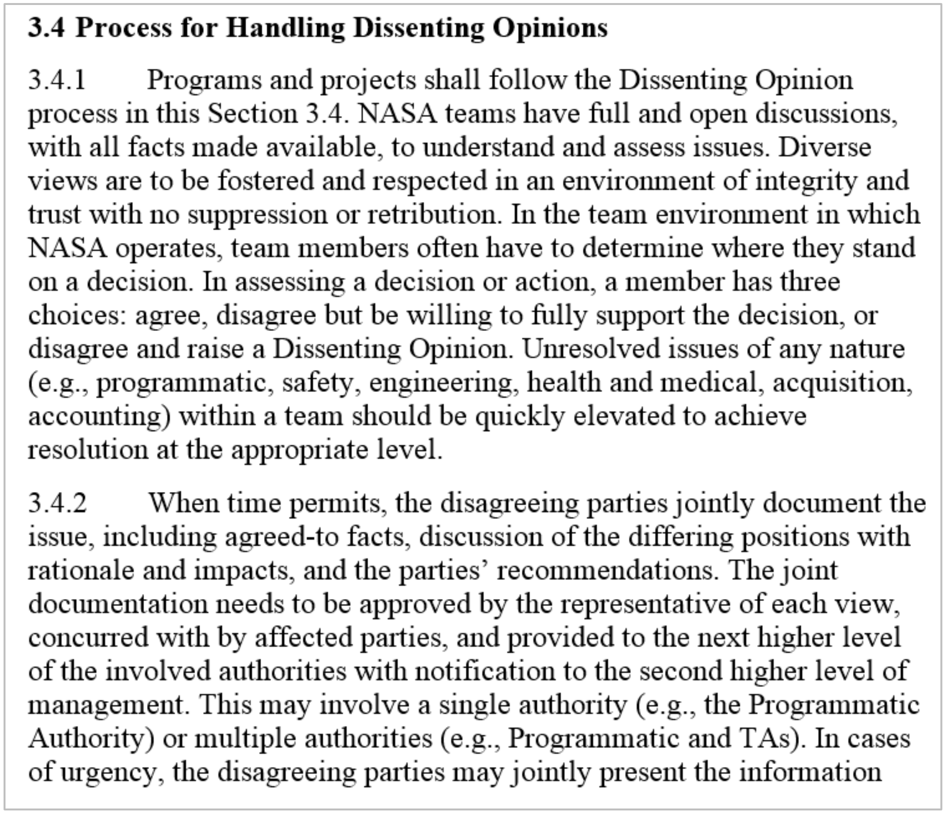
- **All NPR 7120.5 flight readiness requirements can be fully verified with a ground-based test program**

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

DISSENT DISCUSSION

Consensus and Dissent

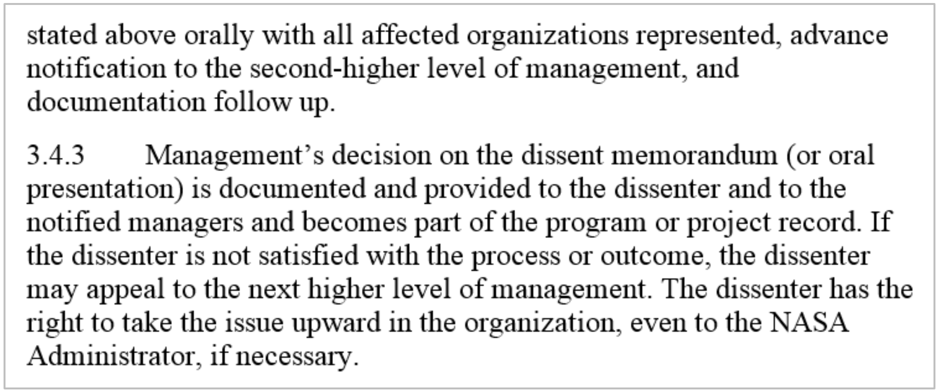
- We follow 7120.5E, Ch 3.4, “Process for Handling Dissenting Opinion”
  - Three options: (1) Agree, (2) Disagree but fully support the decision, (3) Disagree and raise a dissenting opinion
  - The SSWG treats (1) and (2) as consensus for the purposes of the recommendation
  - Dissents (3) will be documented and delivered to APD Director



3.4 Process for Handling Dissenting Opinions

3.4.1 Programs and projects shall follow the Dissenting Opinion process in this Section 3.4. NASA teams have full and open discussions, with all facts made available, to understand and assess issues. Diverse views are to be fostered and respected in an environment of integrity and trust with no suppression or retribution. In the team environment in which NASA operates, team members often have to determine where they stand on a decision. In assessing a decision or action, a member has three choices: agree, disagree but be willing to fully support the decision, or disagree and raise a Dissenting Opinion. Unresolved issues of any nature (e.g., programmatic, safety, engineering, health and medical, acquisition, accounting) within a team should be quickly elevated to achieve resolution at the appropriate level.

3.4.2 When time permits, the disagreeing parties jointly document the issue, including agreed-to facts, discussion of the differing positions with rationale and impacts, and the parties’ recommendations. The joint documentation needs to be approved by the representative of each view, concurred with by affected parties, and provided to the next higher level of the involved authorities with notification to the second higher level of management. This may involve a single authority (e.g., the Programmatic Authority) or multiple authorities (e.g., Programmatic and TAs). In cases of urgency, the disagreeing parties may jointly present the information stated above orally with all affected organizations represented, advance notification to the second-higher level of management, and documentation follow up.



3.4.3 Management’s decision on the dissent memorandum (or oral presentation) is documented and provided to the dissenter and to the notified managers and becomes part of the program or project record. If the dissenter is not satisfied with the process or outcome, the dissenter may appeal to the next higher level of management. The dissenter has the right to take the issue upward in the organization, even to the NASA Administrator, if necessary.

Dissent Discussion

- Professor Webster Cash, University of Colorado, dissents with the recommendation and premise of SSWG (using Exo-S Rendezvous concept study as the starting point)
  - Reports that he will not join the consensus recommendation of SSWG
  - Did not participate in the second face-to-face workshop nor in any consensus-building discussion with SSWG
  - Declined invitation to brief his dissent to the ExoTAC
  - States that he does not plan to voice his dissent in open forum to the APD Director, nor publicly document the dissent
  - States that he will privately deliver one paragraph non-technical dissent to the APD Director

- We open the floor now for any walk-on dissent

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 STATEMENTS

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

Acknowledgements

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SETI INSTITUTE

AMES RESEARCH CENTER

NASA Marshall Space Flight Center

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

DISCUSSION

BACKUP

Acknowledgements

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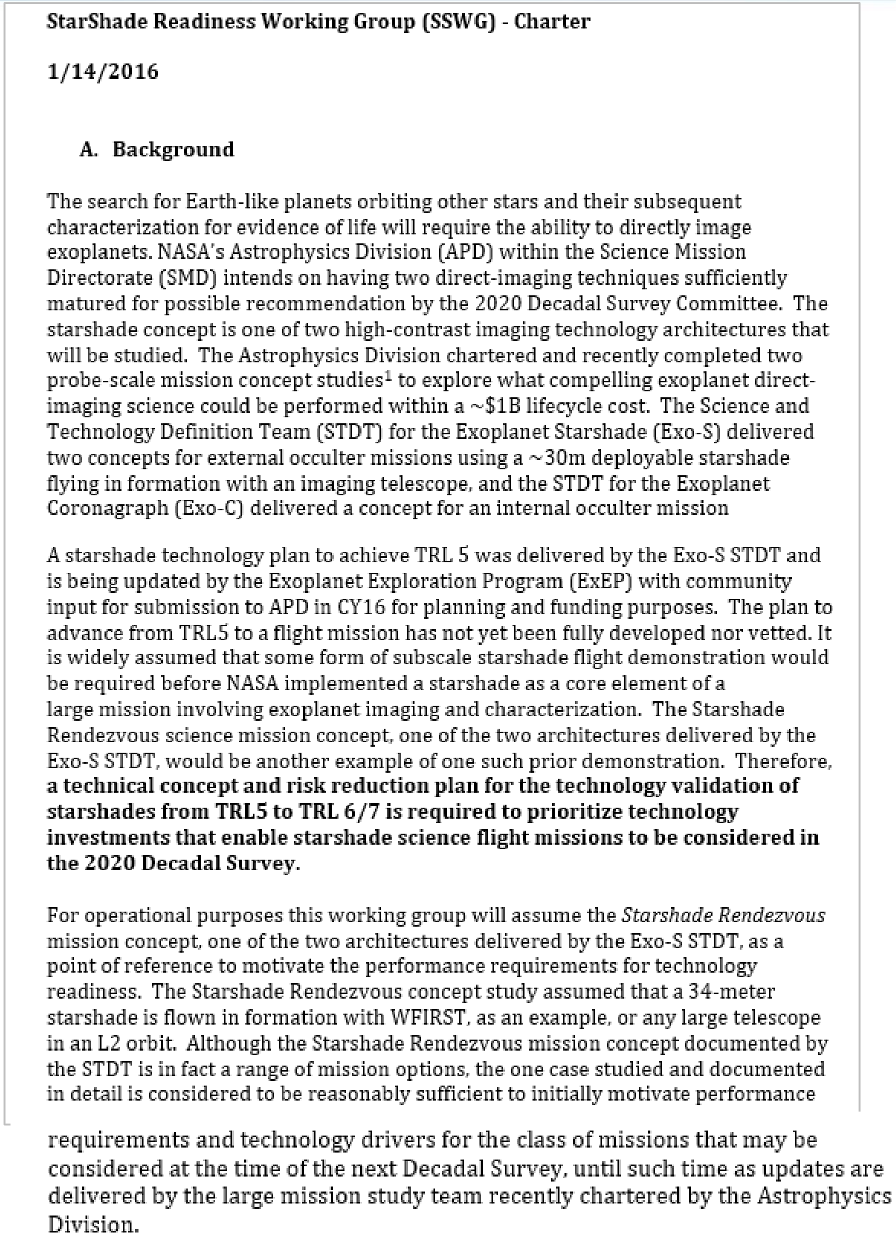
- The Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration. © 2016. All rights reserved.
- The Goddard Space Flight Center, the Ames Research Center, the Marshall Space Flight Center, the Space Telescope Science Institute, the Search for Extraterrestrial Intelligence Institute, the Massachusetts Institute of Technology, Princeton University, the University of Colorado, and the United States Air Force Academy
- 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

Charter (p1 of 2)



StarShade Readiness Working Group (SSWG) - Charter

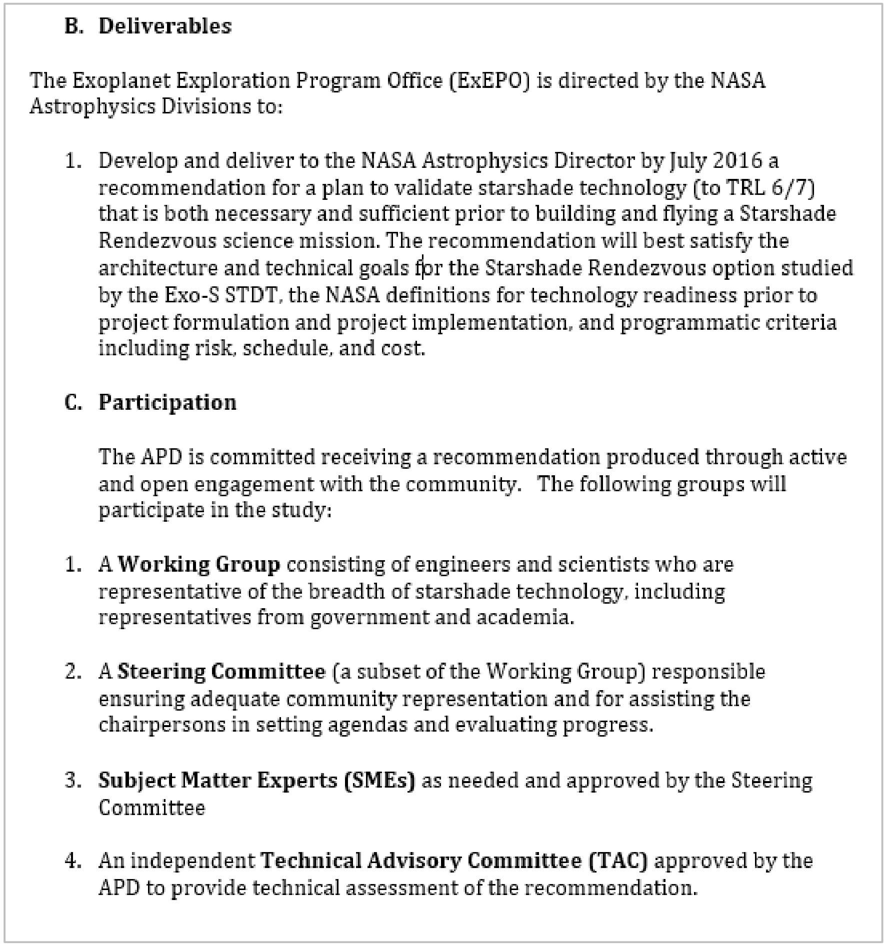
1/14/2016

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 requirements and technology drivers for the class of missions that may be considered at the time of the next Decadal Survey, until such time as updates are delivered by the large mission study team recently chartered by the Astrophysics Division.



B. Deliverables

The Exoplanet Exploration Program Office (ExEPO) is directed by the NASA Astrophysics Divisions to:

1. Develop and deliver to the NASA Astrophysics Director by July 2016 a recommendation for a plan to validate starshade technology (to TRL 6/7) that is both necessary and sufficient prior to building and flying a Starshade Rendezvous science mission. The recommendation will best satisfy the architecture and technical goals for the Starshade Rendezvous option studied by the Exo-S STDT, the NASA definitions for technology readiness prior to project formulation and project implementation, and programmatic criteria including risk, schedule, and cost.

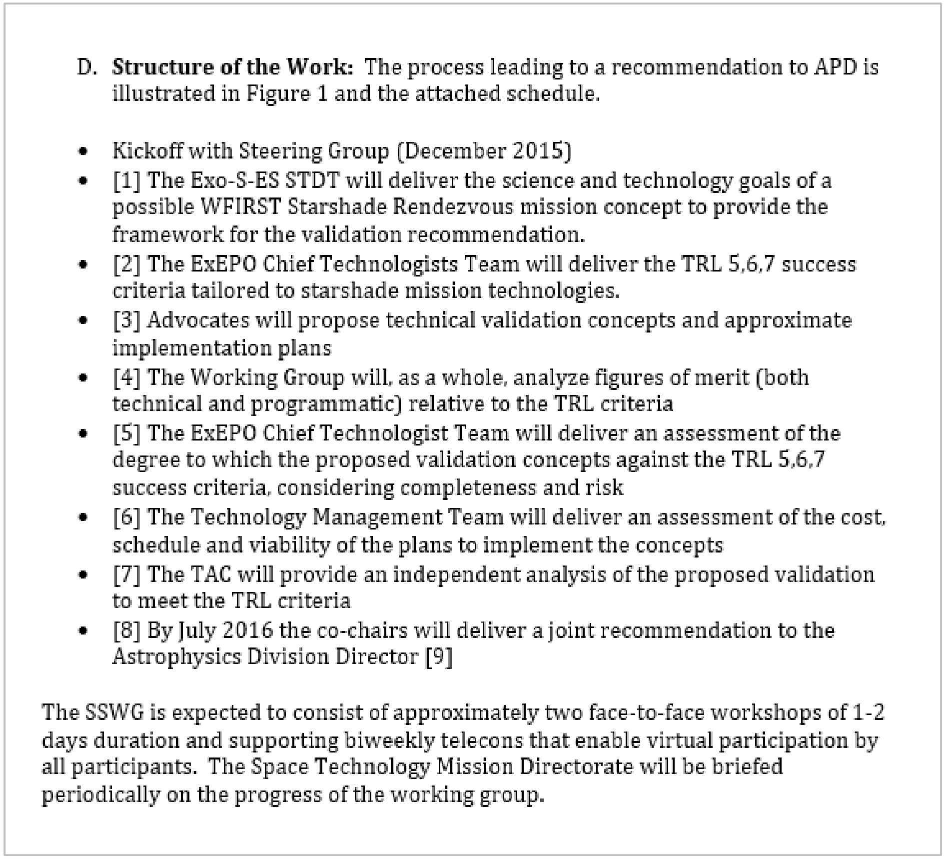
C. Participation

The APD is committed receiving a recommendation produced through active and open engagement with the community. The following groups will participate in the study:

1. A **Working Group** consisting of engineers and scientists who are representative of the breadth of starshade technology, including representatives from government and academia.
2. A **Steering Committee** (a subset of the Working Group) responsible ensuring adequate community representation and for assisting the chairpersons in setting agendas and evaluating progress.
3. **Subject Matter Experts (SMEs)** as needed and approved by the Steering Committee
4. An independent **Technical Advisory Committee (TAC)** approved by the APD to provide technical assessment of the recommendation.

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

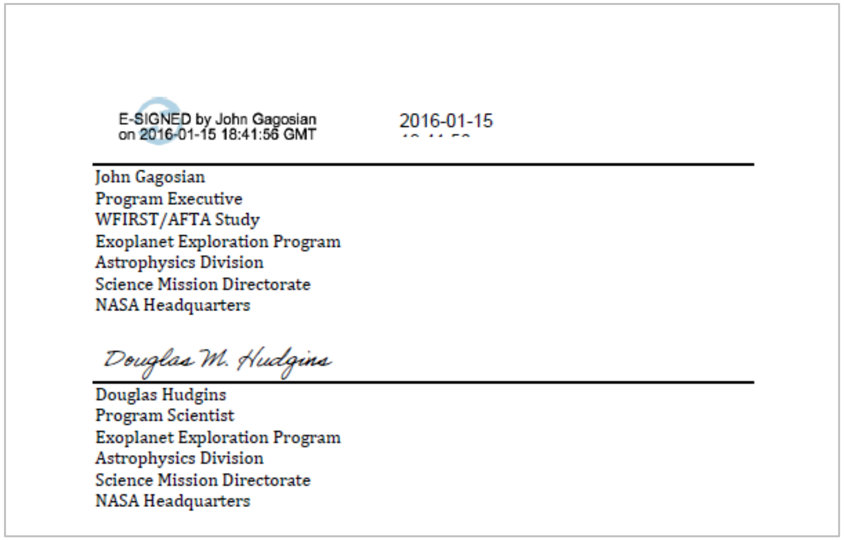
Charter (p2 of 2)



D. **Structure of the Work:** The process leading to a recommendation to APD is illustrated in Figure 1 and the attached schedule.

- Kickoff with Steering Group (December 2015)
- [1] The Exo-S-ES STDT will deliver the science and technology goals of a possible WFIRST Starshade Rendezvous mission concept to provide the framework for the validation recommendation.
- [2] The ExEPO Chief Technologists Team will deliver the TRL 5,6,7 success criteria tailored to starshade mission technologies.
- [3] Advocates will propose technical validation concepts and approximate implementation plans
- [4] The Working Group will, as a whole, analyze figures of merit (both technical and programmatic) relative to the TRL criteria
- [5] The ExEPO Chief Technologist Team will deliver an assessment of the degree to which the proposed validation concepts against the TRL 5,6,7 success criteria, considering completeness and risk
- [6] The Technology Management Team will deliver an assessment of the cost, schedule and viability of the plans to implement the concepts
- [7] The TAC will provide an independent analysis of the proposed validation to meet the TRL criteria
- [8] By July 2016 the co-chairs will deliver a joint recommendation to the Astrophysics Division Director [9]

The SSWG is expected to consist of approximately two face-to-face workshops of 1-2 days duration and supporting biweekly telecons that enable virtual participation by all participants. The Space Technology Mission Directorate will be briefed periodically on the progress of the working group.



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on 2016-01-15 18:41:56 GMT

2016-01-15

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

Threshold Science
(as defined by Exo-S final report for Rendezvous-CS)

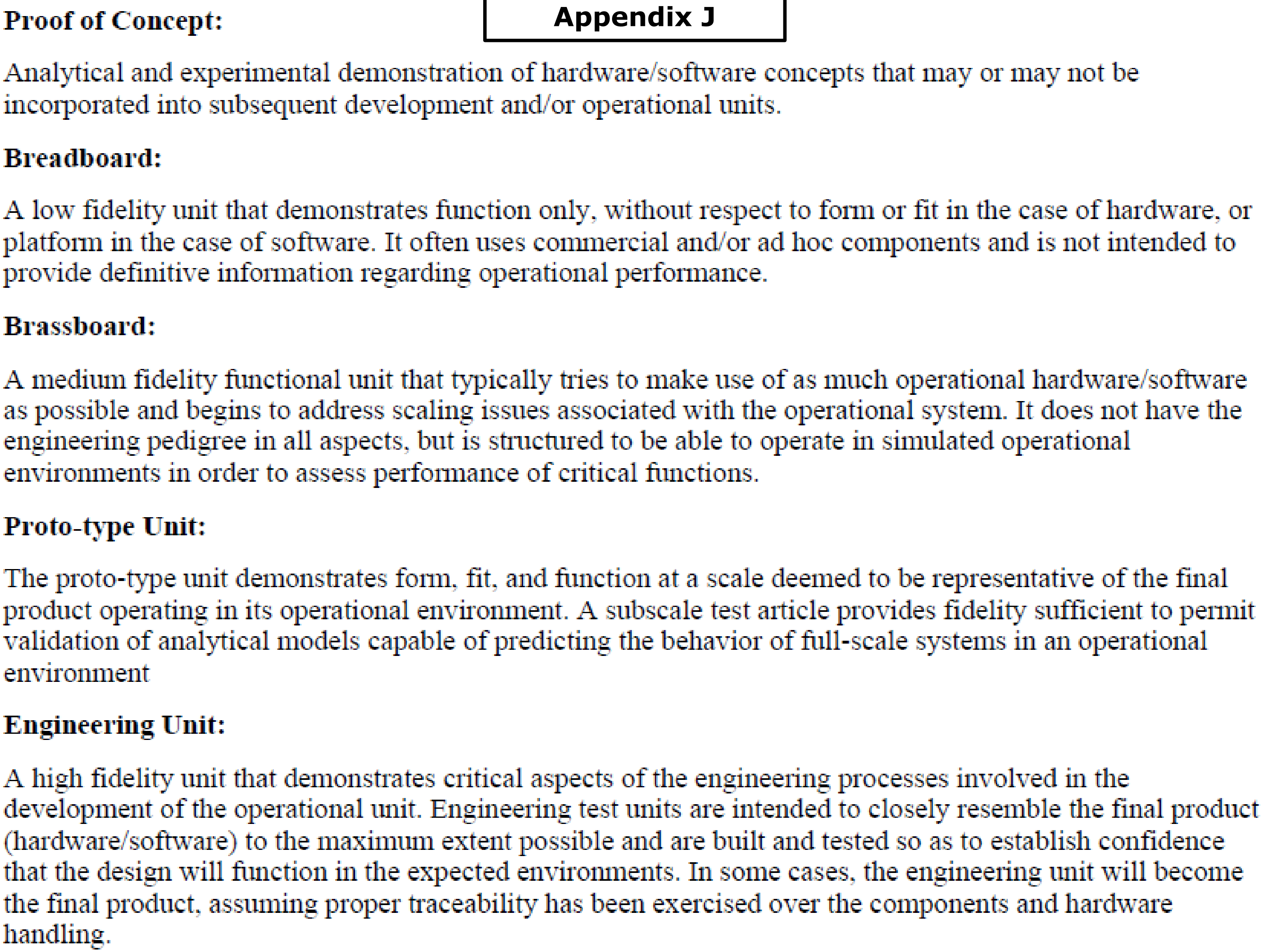
- Science goals will emphasize RV planet spectroscopy and searching for small planets around the nearest bright stars
- WFIRST Starshade Rendezvous Concept Study (CS) science yield depends on the inner working angle (smaller is better), number of maneuvers that can be executed (more is better), and the bandpass accessible at a single starshade-telescope separation (more is better).
- The baseline Design Reference Mission (DRM) is partly defined by Case 3 in Chapter 5 of the Exo-S STDT final report, to be modified for complementarity to the DRM of the WFIRST-CGI instrument. The DRM for follow-up observations of discovered planets (multi-color photometry, multi-epoch astrometry) is still to be defined.
- The threshold science is defined as a survey of 10 HZs with 25% completeness and spectral characterization of 10 known RV planets.

What Happened to Options 3 and 5?

- These were ideas that came from the initial brainstorming session
- Option 3: the former label for Option 1b (recast Rendezvous Concept Study as technology demo version of 1a)
  - Option 3 became Option 1a
  - Option 3 label retired
- 5 was “ride-along” – the piggyback on another (non-ISS) flight mission
  - No concepts developed further
  - Option 5 retired

Technology Development Terminology (1/2)

NPR 7120.8
Appendix J



Proof of Concept:

Analytical and experimental demonstration of hardware/software concepts that may or may not be incorporated into subsequent development and/or operational units.

Breadboard:

A low fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.

Brassboard:

A medium fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects, but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.

Proto-type Unit:

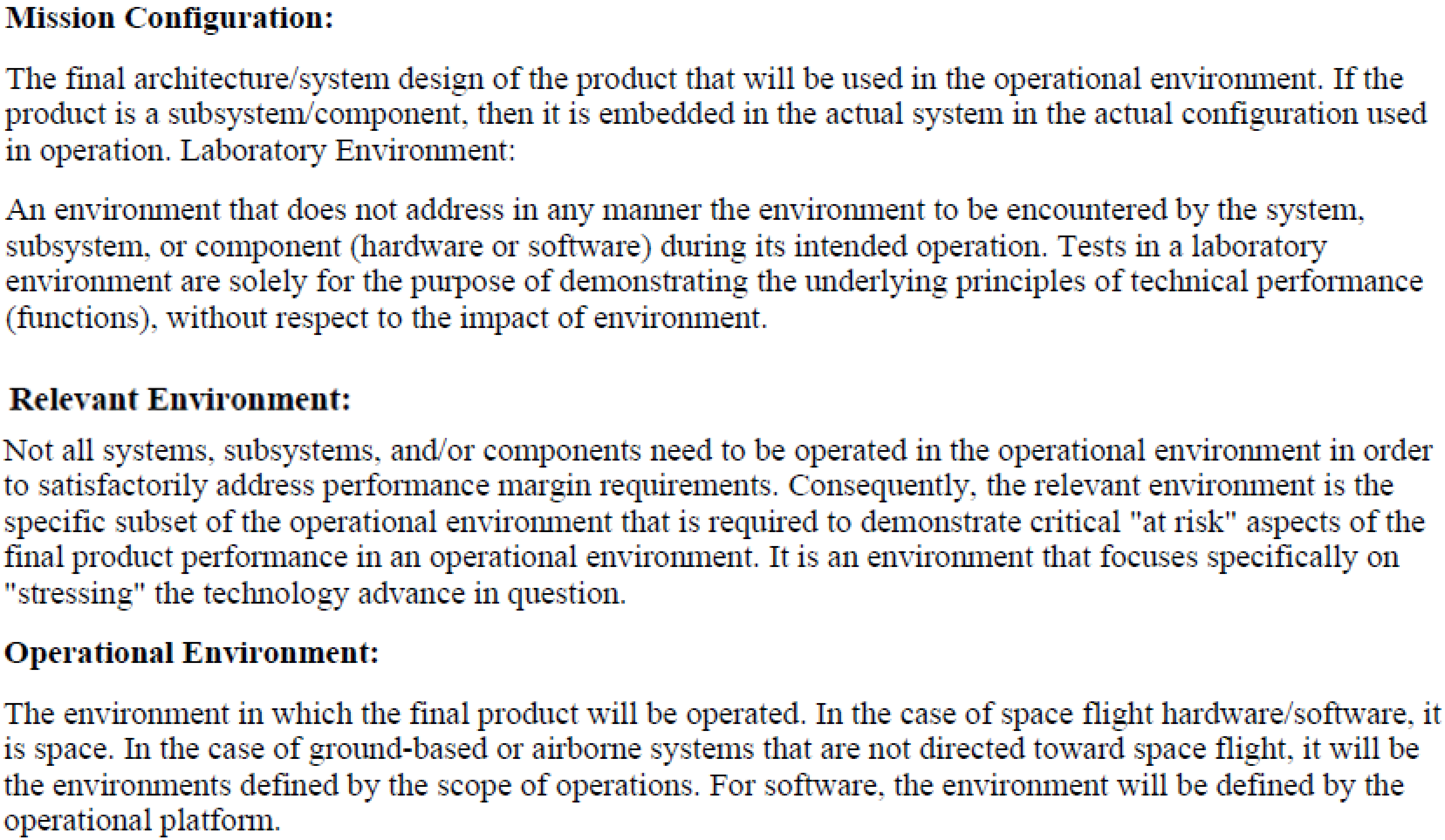
The proto-type unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment

Engineering Unit:

A high fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the final product, assuming proper traceability has been exercised over the components and hardware handling.

Technology Development Terminology (2/2)

NPR 7120.8
Appendix J



Mission Configuration:

The final architecture/system design of the product that will be used in the operational environment. If the product is a subsystem/component, then it is embedded in the actual system in the actual configuration used in operation. Laboratory Environment:

An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions), without respect to the impact of environment.

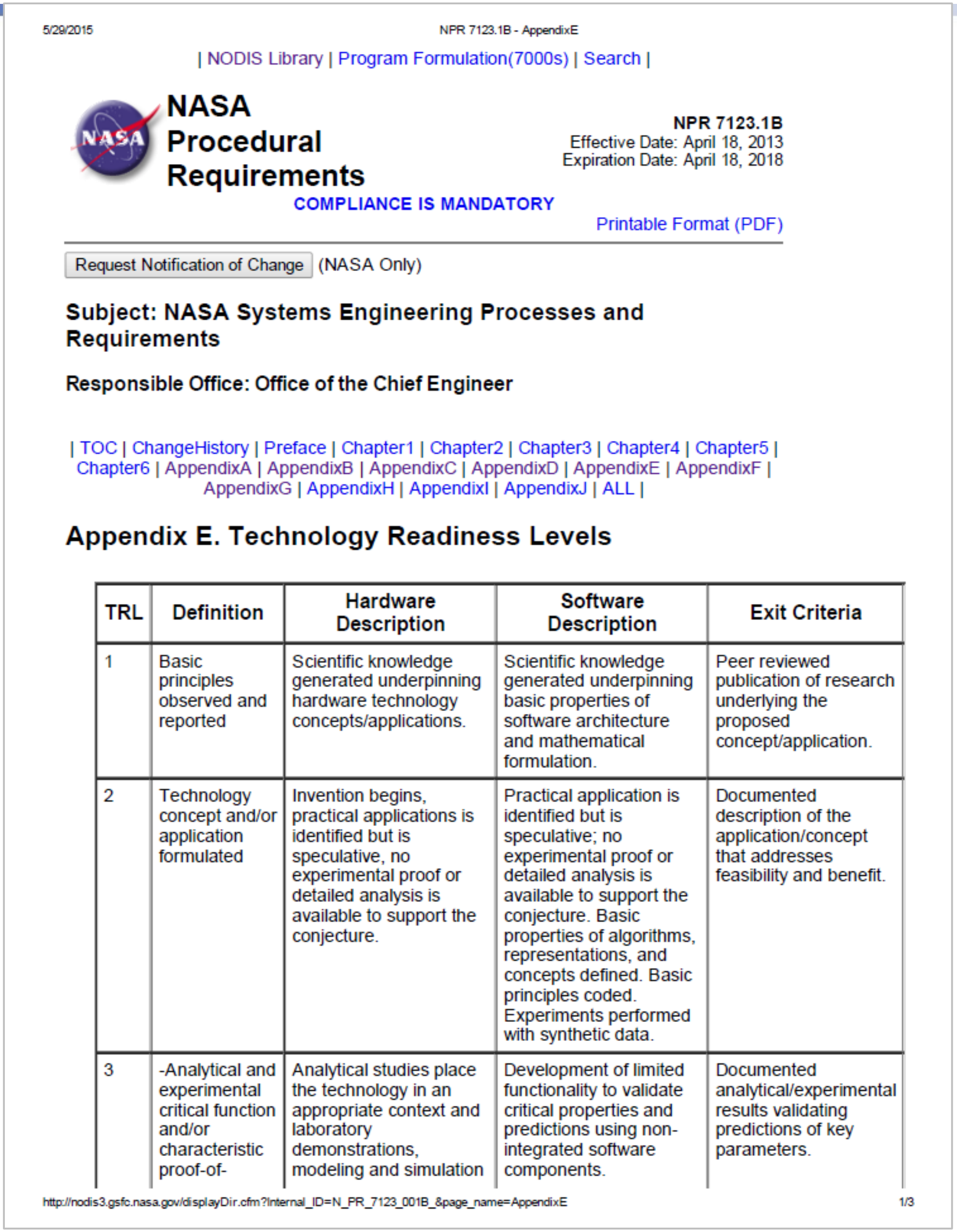
Relevant Environment:

Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "at risk" aspects of the final product performance in an operational environment. It is an environment that focuses specifically on "stressing" the technology advance in question.

Operational Environment:

The environment in which the final product will be operated. In the case of space flight hardware/software, it is space. In the case of ground-based or airborne systems that are not directed toward space flight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform.

NPR 7123.1B Appendix E (1/2)



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NASA Procedural Requirements

NPR 7123.1B
Effective Date: April 18, 2013
Expiration Date: April 18, 2018

COMPLIANCE IS MANDATORY

Printable Format (PDF)

Request Notification of Change (NASA Only)

Subject: NASA Systems Engineering Processes and Requirements

Responsible Office: Office of the Chief Engineer

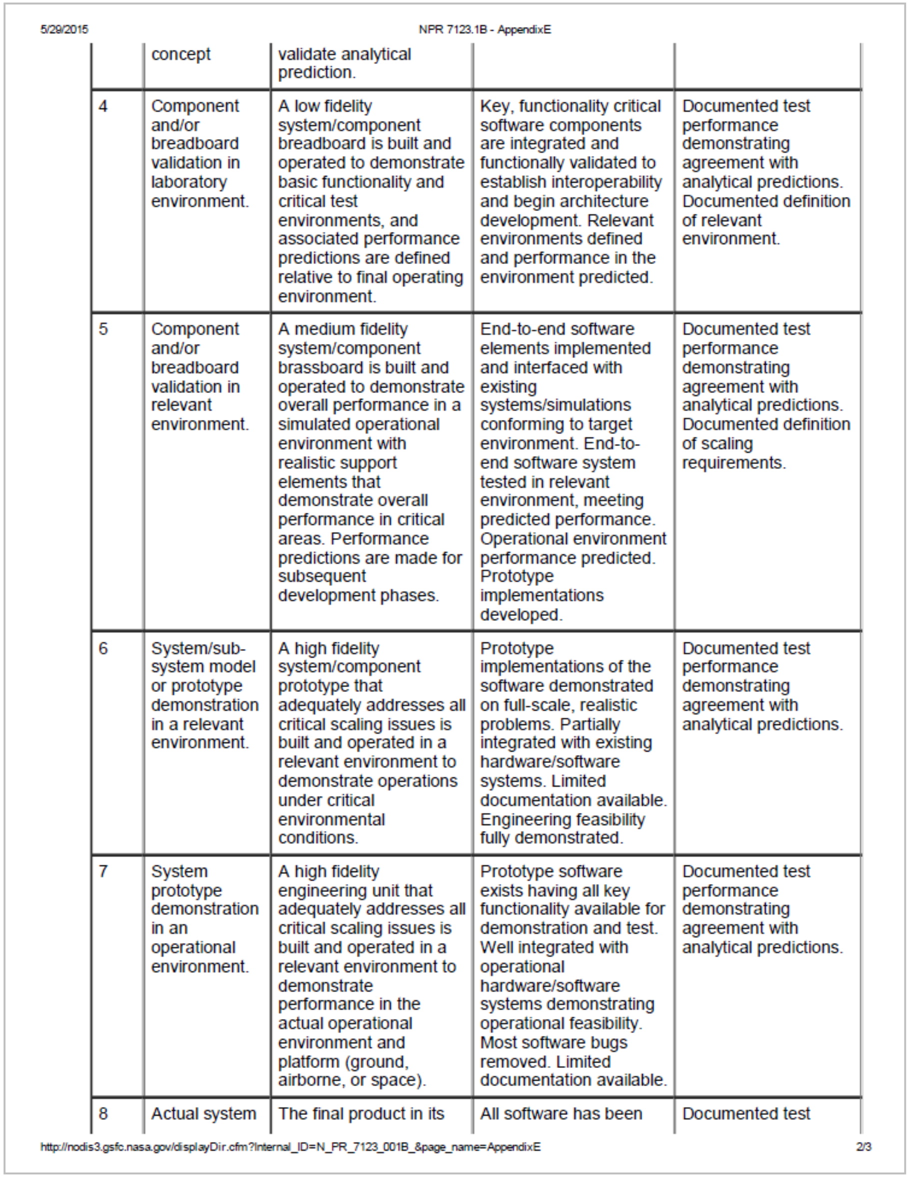
| TOC | ChangeHistory | Preface | Chapter1 | Chapter2 | Chapter3 | Chapter4 | Chapter5 | Chapter6 | AppendixA | AppendixB | AppendixC | AppendixD | AppendixE | AppendixF | AppendixG | AppendixH | AppendixI | AppendixJ | ALL |

Appendix E. Technology Readiness Levels

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated	Invention begins, practical applications is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations, and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	-Analytical and experimental critical function and/or characteristic proof-of-	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.

NPR 7123.1B Appendix E (2/2)

ExoPlanet Exploration Program



5/29/2015 NPR 7123.1B - AppendixE

	concept	validate analytical prediction.		
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to final operating environment.	Key, functionality critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant 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.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in a relevant environment.	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.	Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit 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).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system	The final product in its	All software has been	Documented test

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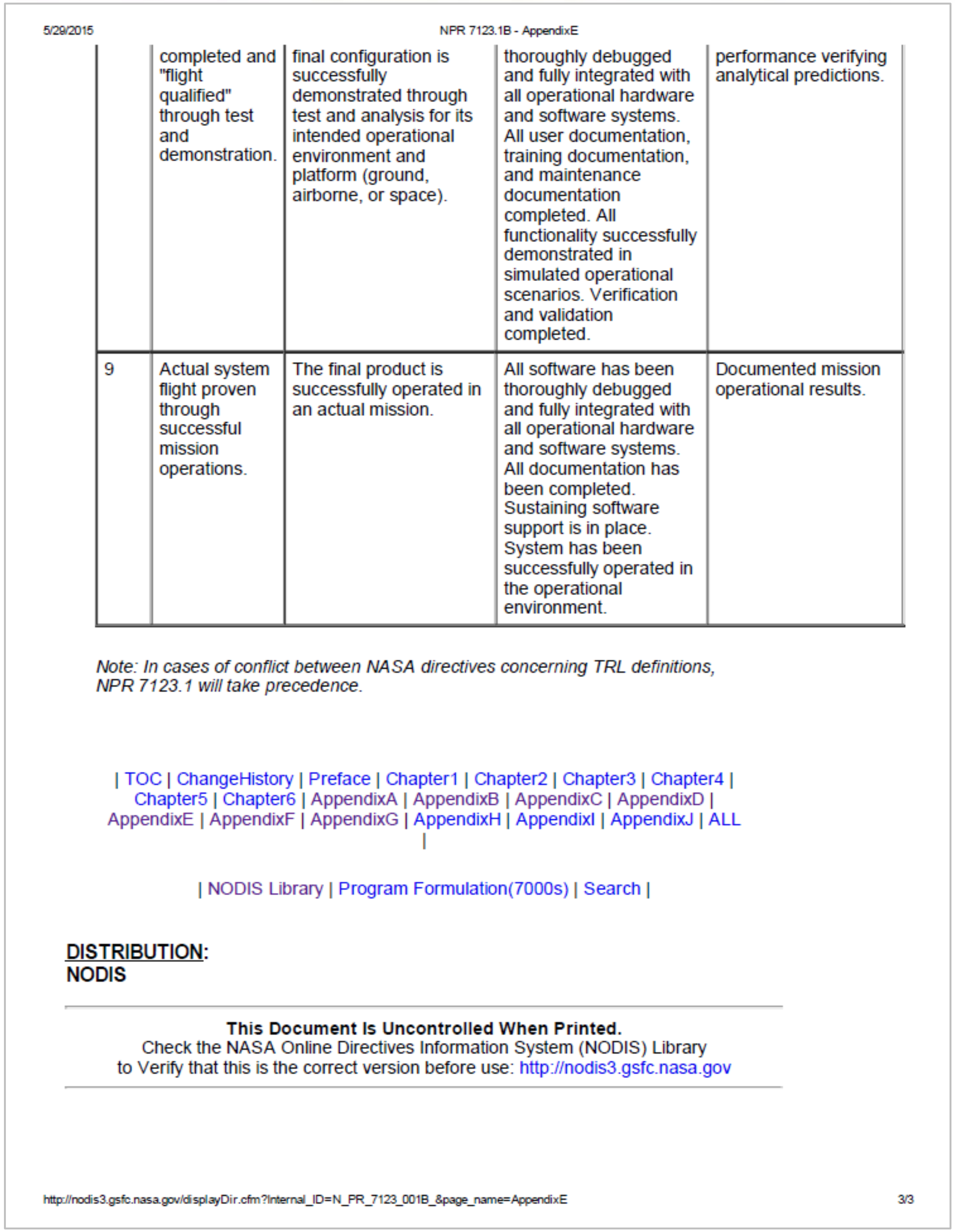

5/29/2015 NPR 7123.1B - AppendixE

	completed and "flight qualified" through test and demonstration.	final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and validation completed.	performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All documentation has been completed. Sustaining software support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

Note: In cases of conflict between NASA directives concerning TRL definitions, NPR 7123.1 will take precedence.

| TOC | ChangeHistory | Preface | Chapter1 | Chapter2 | Chapter3 | Chapter4 | Chapter5 | Chapter6 | AppendixA | AppendixB | AppendixC | AppendixD | AppendixE | AppendixF | AppendixG | AppendixH | AppendixI | AppendixJ | ALL |

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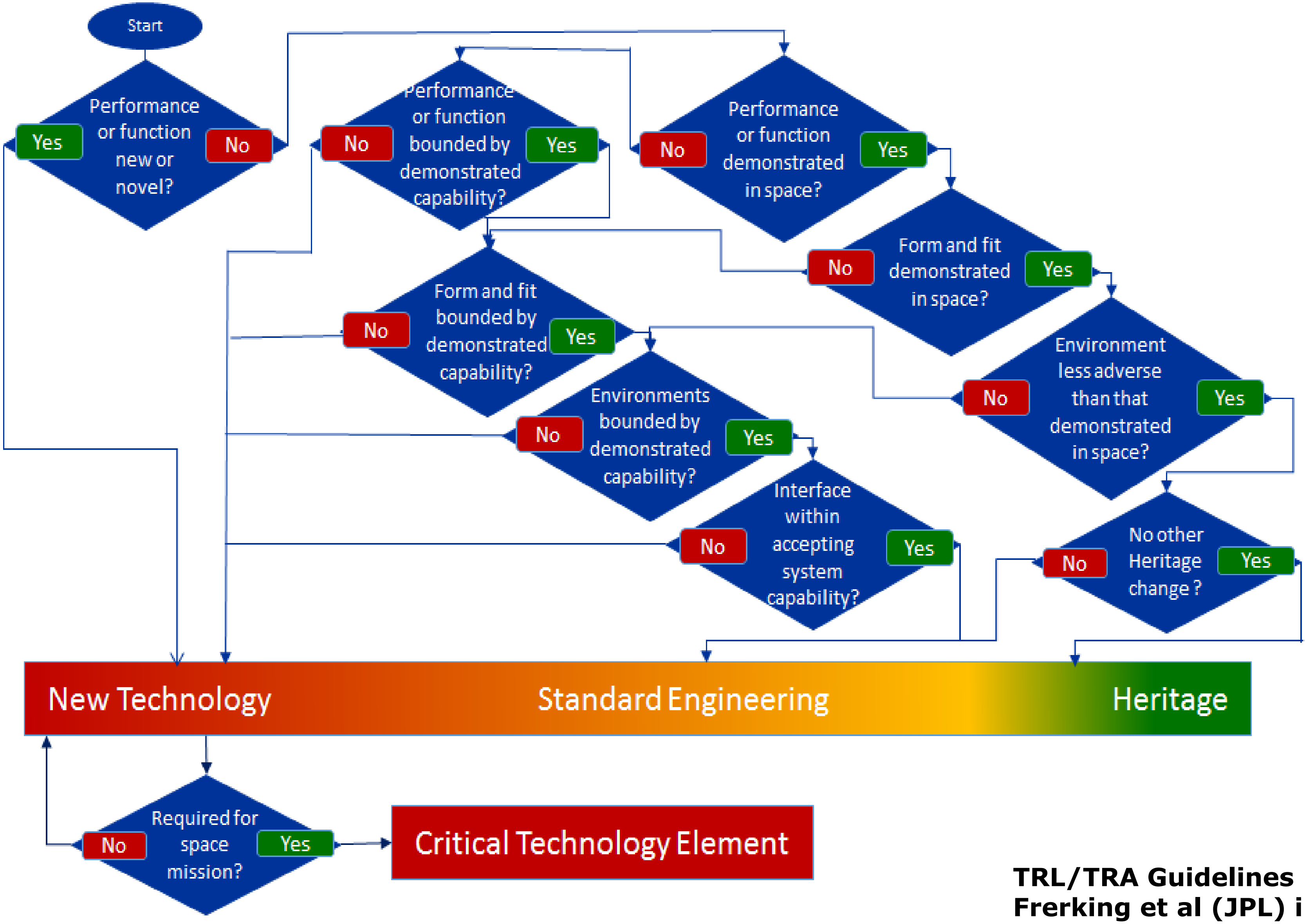
Technology or Engineering?



TRL/TRA Guidelines Frerking et al (JPL) in review

TRL-5 for a Starshade

TRL-5

Component and/or breadboard validation in relevant 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 medium fidelity demonstrates performance and function as well as feasibility of form and fit.

Critical Performance Items

Optical contrast performance near a flight Fresnel #; validated optical model
Solar glint measurements contribute less than contrast requirements
Full-scale petal fabricated to shape tolerances
Full-scale petal deployment mechanism
Deploying and positioning petals to in-plane tolerance
Scaled lateral formation sensing tolerances met
Thermal and dynamic modeling, error budget

Medium Fidelity

Fit is approximate
Form is approximate
Functionality is partial, but includes all critical functions

Relevant Environments

Petal Positioning and Optical Shield Deployment
- Vacuum
- 0-g
- Deployment and handling cycles (during ground testing)

Petal Shape
- Thermal cycles
- Deployment and handling cycles (during ground testing)
- Optical shield thermal deformation

Solar Glint
- Sun-target angles

Formation Sensing Accuracy
- 30,000-50,000 km separations between two spacecrafts

Optical Performance
- Micrometeoroids, space

TRL-6 Starshade Success Criteria

TRL-6

System/subsystem model or prototype demonstration in a relevant environment.

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 unit demonstrates performance as well as form, fit, and function at a scale deemed to be representative of the final product operating in its operational env't

Relevant Environments

Same as TRL-5

Critical performance

Same as TRL-5

Fidelity

Form is flight-like
Fit is representative with scaling issues understood
Functionality is flight-like with all interfaces addressed

Interfaces

Petal – Petal Latch – Unfurling System
- Launch restraint unlatch
- Quasi-static unfurling mechanism

Petal – Inner Disk
- Precision hinges
- Full deploy latch

Optical Shield – Inner Disk

Starshade Beacon – Telescope Sensor

TRL 6 is a necessary milestone on the path to flight

TRL 7 Starshade Success Criteria

TRL-7

System prototype demonstration in an operational environment.

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).

Operational Environments (including Space)

- Ground handling and transportation
- Long-term stowage
- Launch vibration
- Ascent venting
- Dust
- Vacuum
- 0-g
- Moisture absorption/loss
- Thermal
- Sun-target angles
- Space charging
- Micrometeoroids

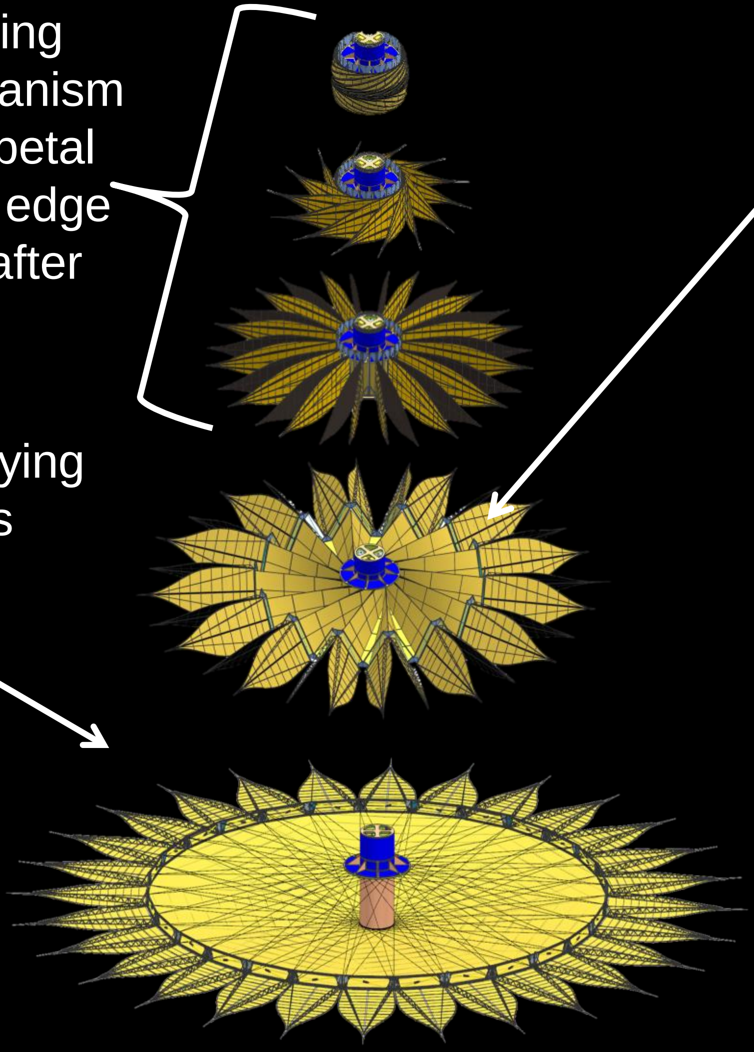
TRL-7 Interpretations

- "pathfinder"
  - Can demonstrate one or more critical technologies
  - Doesn't have to be a full system or "build-to-print"
- "prototype in an operational environment"
- "risk reducer"
- "will enable a science mission to become possible and achievable"

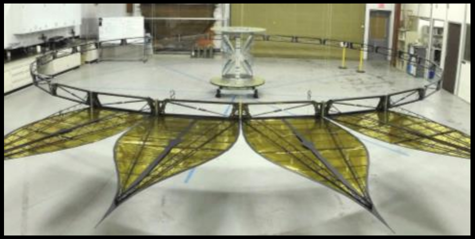
TRL 7 is not a necessary milestone, however, in some cases it may play an important role in technology maturation and risk mitigation.

Proposed Steps to Starshade TRL-5 Demo

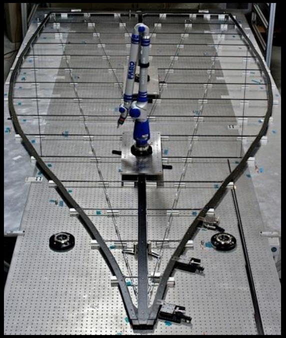
(2) 10-m scale latching and unfolding mechanism verifying controlled petal deployment with no edge contact during and after launch S-5



(3) 10-m scale inner disk verifying deployment and petal positioning tolerances S-5



(1) 5-m scale petal verifying optical shape tolerances and edge scatter performance S-4



Key models and analyses predicting:

(5) Optical performance and validate optical model based on Princeton and NGAS demonstrations S-1 S-2

(6) Maximum micro-meteoroid hole area

(7) Error budget and draft requirements for a possible mission concept

(8) Dynamic and thermal stability modeling

(4) Sub-scale test demonstrating lateral formation flying sensing accuracy S-3

Note: the deployment architecture remains an open trade at this time