Proponent's Technology Plan

Option 2b

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CTT Evaluation Criteria Items

DECIDE: Recommend a development strategy to enable a starshade science flight mission

		NOTES	Evaluation Team CTT	TMT	SCI
	MUSTS				
	Technical				
M1	Achieves TRL-6 by starshade KDP-C for the 3 critical technology areas	N=3 technology categories defined by Nick Siegler. Subcategories conditional upon the evolution of the design. The design has to work and meet error budget reqts for the observation. *N needs to be confirmed by sidebar group.*	x		
M2	Compatible with Rendezvous-Concept Study technical needs	CS = Concept Study in the Exo-S final report	x		
M3	Forward traceable to expected HabEx and LUVOIR technical needs				
M4	Likely to convince responsible critics at KDP-C	Must include engineering risk mitigation activities sensitivity analysis			
M5	Assumption: TRL5 by 2019	Reminder that we have to account for this assumption			
M6	Assumption: Parallel and adequate mission concept maturity	Assume future mission study			
	Schedule				
M7	Schedule-compatible with Rendezvous-CS launch within WFIRST prime mission	The Rendezvous option from final report. Assume WFIRST launch 2025, 6-year prime mission ends 2031. If R-CS LRD by 2028, *then KDPC is NLT…?(per CTT)* KDP-A NET 2022			
M8	SSWG completes recommendation by July 2016				
	Cost				
M9	Total cost of technology development strategy *< $100M*	*Derived as 10% of probe ($1B) category*			
	WANTS (DISCRIMINATORS)				
	Technical				
W1	Relative degree to which the strategy exceeds TRL-6 at KDP-C for the 3 critical technology areas	Pedigree	x		
W2	Admits enhancing technologies	Exceeds Must of N	x		
W3	Minimize the number of critical enabling technologies	Favor strategies/architectures that reduce the total enabling technologies	x		
	Schedule				
W4	Enables Earliest launch within WFIRST prime misssion				
W5	Exceed TRL gates at key intermediate milestones (2020 DS, KDP-A, KDP-B, KDP-C)	Maximize TRL prior to 2020 Decadal Survey. Ahead of the game			

Risks

Opportunities

Y/U/N (M1)

Y/U/N (M2)

Best, Small/Significant /Large Difference (W1–W3)

H/M/L (Risks)

H/M/L (Opportunities)

Description of Option Concept (1/2

Mission/systems:

- **2 Small sats launch as secondary payload and get placed into a GTO or GEO. Something similar to Millennium Space's Altair bus (http://www.millennium-space.com/platforms.html#altair) might work. These are each 30cm x 30cm x 30cm with a payload capacity of 50 kg**
- **one spacecraft can be called the "telescope spacecraft" or TSC. The other one is called the "occulter spacecraft" or OSC.**
- **OSC payload:**
  - Occulting disk that is approx 40 cm diam (slightly larger than the 30 cm side of the bus
  - RF comm link (commercial – e.g. L3's cadet radio) - provides range measurements through time of flight signals. Has ability to transfer state information
  - LEDs
  - Lasers
  - Thrusters for controlling relative position
- **TSC payload**
  - Commercial space-grade camera. Something similar to the GomSpace NanoCam would suffice. Use appropriate filters for imaging stellar objects in a certain band
  - RF comm link … same as above
  - Star tracker to image LEDs on OSC against background stars. Gives bearing angles. Filter combining bearing and Rf ranging measurement to give astrometric alignment and range.
  - Use commercial camera to image Galilean moons and laser on OSC. Detector in the camera needs to be modified so that only a part of the detector array is used for imaging the laser while the rest is used for imaging the science target. Another filter for determining lateral position offsets – x,y, positions

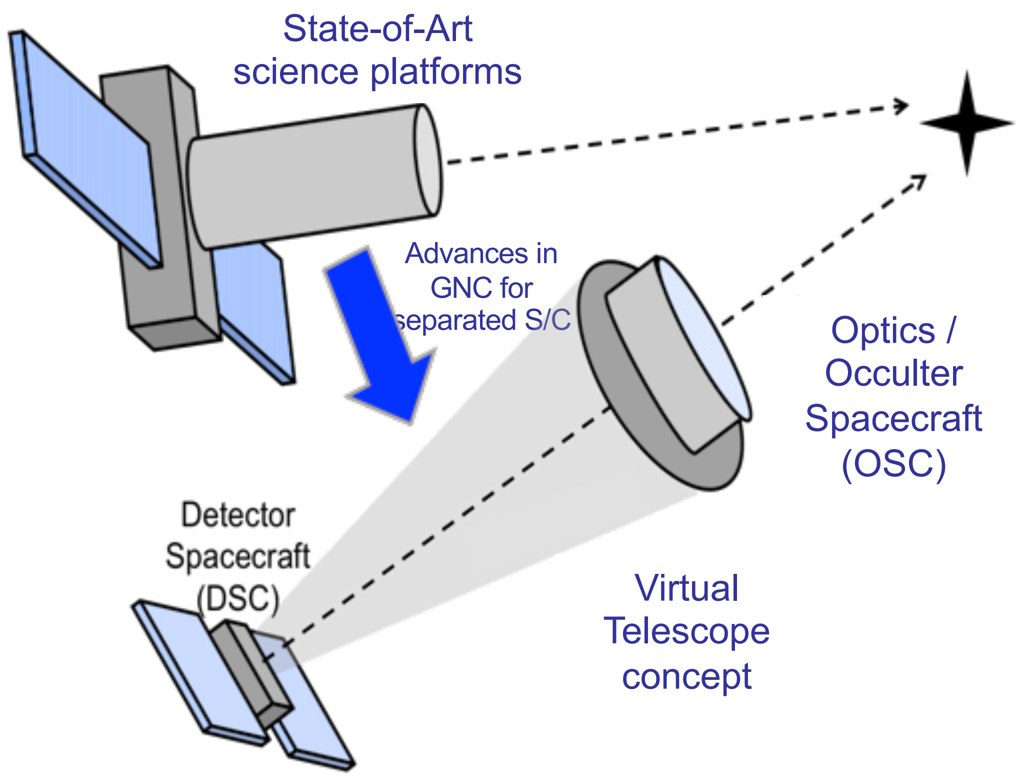
Description of Option Concept (2/2)

Concept of Operations:

- - 2 spacecraft launch as secondary payload to GTO or GEO
- - separation occurs
- - orient the two spacecraft towards jupiter. OSC blocks jupiter. TSC images moons.
- - *Experiment 1*: use differential drag and RF range/comm for transition and coarse relative position (mimics Rendezvous CS's Transition mode albeit with a different set of sensors and actuators being used); maneuver one or both. validate rel pos through ground nav
- - *Experiment 2*: begin acquisition. Use star tracker for astrometric alignment. Gets alignment to a certain box. Control OSC using thrusters, Validate using gps telemetry
- - *Experiment 3*: hand off to camera and laser system for finer acquisition. Should get you into a box that you can now collect images. Control with thrusters on OSC. Validate using gps telemetry and tracker-beacon solution
- - *Experiment 4*: hold alignment and collect images of Galilean moons. Validate with images from camera
-
- This is a system demo - the precision of the alignment is not the driver. It uses commercial components. What you get is a validation of each step of the gnc acquisition control modes. And then a final image that shows your alignment scheme worked.

NASA Science Requires Distributed "Virtual" Space Telescope

Many science investigations proposed by NASA require two spacecraft alignment across a long distance to form a distributed "virtual" space telescope.



Astrophysics:

- Milli Arc Second X-ray imaging
- Micro Arc Second X-ray imaging
- Calibration Telescope
- Starshade

Planetary:

- Exo-planet finder
- Near Earth Objects

Heliophysics:

- X-ray imaging of solar flares
- High-resolution UV/EUV imaging
- Next generation solar coronagraph

What's the Problem?

To pass KDP-C, and for credible science proposals ➔ TRL 6

- **<u>Perception:</u>**

1. Its been done already

➔ MMS, A-Train, GRAIL, PRISMA, CAN-X 4 5, EO-1, Hubble Servicing, etc.

We've studied this problem for over a decade

2. Precision formation alignment too risky

➔ Multiple launches, multiple spacecraft, never collected science

Concepts have been proposed and developed for over a decade. Not selected or canceled due to risk, feasibility, cost, etc.

- **<u>Gap:</u>**
  - Component technologies have been developed (some being developed) and tested (some still to be tested)
  - Relative spacecraft navigation and control demonstrated (albeit at varying levels of precision)
  - Never formed a virtual science instrument and made a science measurement
  - **End-to-End System-level capability currently at TRL 4 → *Need a system demo***

Approach

- **Assume Technology area (1) Contrast and (2) Deployment Accuracy and Shape Stability matured to TRL 6 by other options (e.g., 4a+4b, or 6a+6b, etc.)**
- **Assume ExEp matures Technology area (3) Formation sensing through currently funded efforts by Kasdin.**
- **Remaining Technology Gaps within Technology Area (3) … assumed:**
  - Formation acquisition and transition between sensing and control modes
  - Formation control
  - Closed loop system demonstration (currently @ TRL 4)
- ***Demonstrate remaining areas with a science-agnostic end-to-end system-level low-cost small sat-class pathfinder mission***

Final Thoughts

1. **Tech Demos that try to "do it all" get cancelled (paraphrase Chip Barnes presentation to SSWG on 2/11)**

2. **Formation flying for over 50 years, but no one has ever built a formation flying science instrument**
   - No mission has made a science measurement using a "virtual" space telescope

3. **Seeking to reduce risk through a SmallSat pathfinder mission.**

M1: Achieves TRL-6 for the Three Key Technology Areas by KDP-C

Explain how your plan matures the three technology areas to reach TRL-6 assuming the TRL-5 initial condition (first two slides in the Appendix). This can be spread out over multiple slides.

1. ~~**Contrast**~~
   a) ~~Starlight diffraction~~
   b) ~~Sunlight scatter~~

2. ~~**Deployment Accuracy and Shape Stability**~~
   a) ~~Petal shape and stability~~
   b) ~~Petal positioning accuracy~~

3. **Formation Sensing Accuracy**
   - **CANYVAL-X to demonstrate navigation and control algorithms to achieve and maintain alignment with an inertial source**
   - **Science-agnostic pathfinder mission to demonstrate end-to-end system to TRL 7/8**

➢ **See first note on next page**

M1 Comments

- **Please note, for this exercise, the TRL-5 and -6 performance requirements are the same and are assumed to meet the flight requirements.**
  - See slides 10 and 11 in the Appendix
- **What changes between the TRLs is the:**
  - fit/form/function goes from mid-fidelity with respect to the flight hardware to high-fidelity (flight-like)
    - It's a system/software maturation. If you fly it you mature the algorithms and "distributed space telescope system" to TRL 7+
  - the scaling issues must be well understood but TRL-6 does not have to be full-scale
    - Use covariance-error analysis to show improved performance with higher performing sensors/actuators
  - required performance at TRL-6 is achieved with the critical interfaces
- **If there is a current SSWG option that has a plan that meets TRL-6 that you want to piggy-back on please identify the Option #.**
  - This strategy may allow you to focus on portions of their plan that you feel may be lacking or carries high risk.
  - Assume Technology area (1) Contrast and (2) Deployment Accuracy and Shape Stability matured to TRL 6 by other options (e.g., 4a+4b, or 6a+6b, etc.)

Opportunities

- List any opportunities your approach offers.

Multiple partnering opportunities:

- Astrophysics interested in distributed space telescope
- Astrophysics interested in interferometry
- Heliophysics interested in solar science using distributed space telescopes
- Interest from international institutions.

Concerns and Risks

- **List any concerns or risks regarding your approach.**

  Not targeting a specific science instrument. Instead focusing on a generic capability development effort.

  Not achieving the tech performance needed for rendezvous-cs

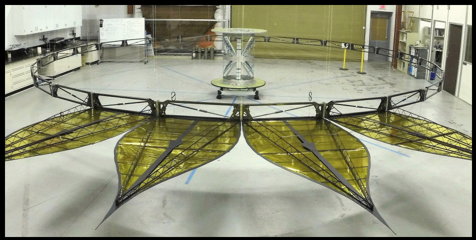
  Schedule may not meet WFIRST starshade development time horizon

Appendix

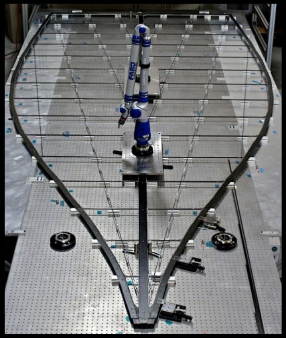
A Proposed TRL-5 Starshade by End FY19

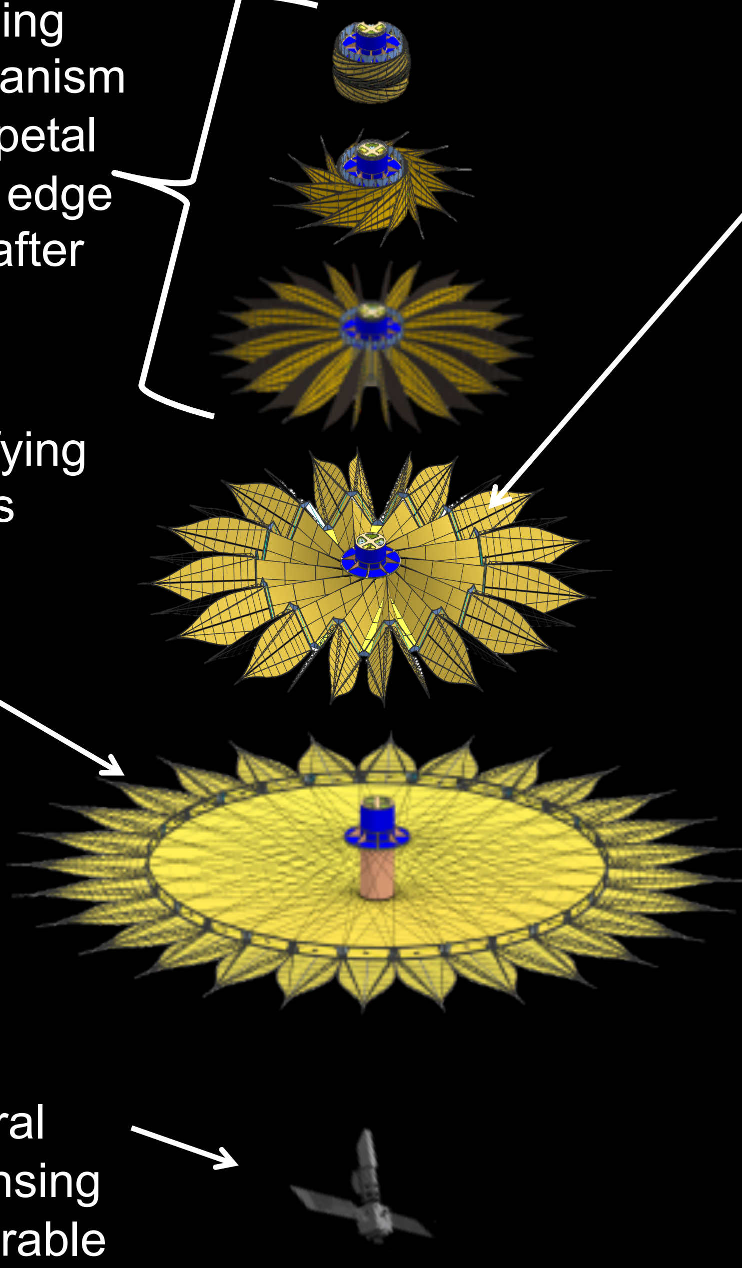
(2) 10-m scale latching and unfolding mechanism verifying controlled petal deployment with no edge contact during and after launch

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



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





(4) Sub-scale test demonstrating lateral formation flying sensing accuracy at comparable bearing angle

Key models and analyses predicting:

(5) Optical performance and validate optical model based on Princeton 78 m and NGAS 2 km demonstrations

(6) Maximum micro-meteoroid hole area

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

(8) Dynamic and thermal stability modeling

The TRL-6 Success Criteria that the SSWG Options Need to Meet

Technology Area	Key Performance Tolerances (3σ)	TRL-6 End-State Fidelity (Prototype): Fit	Form	Function	Tested in Relevant Environment; Life Testing	Performance Verification	Model Validation
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						
	Supression (test): $\leq 1\text{x}10^{-9}$ Contrast (modeling): $\leq 1\text{x}10^{-10}$ (validted 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

Assumed TRL-5 Starting Point for SSWG Options

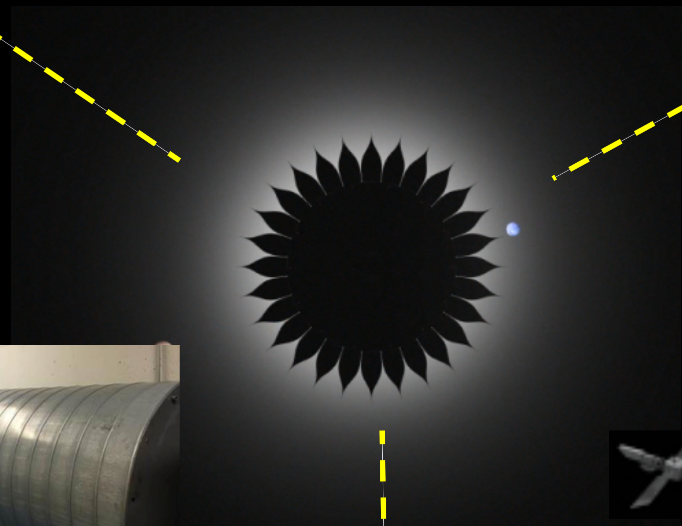
Technology Area	Key Performance Tolerances (3σ)	Proposed End-State Fidelity (TRL-5+)			Tested in Relevant Environment; Designed to Meet Life Rqmt	Performance Verification	Model Validation
		Fit	Form	Function			
Deployment Accuracy and Shape Stability	**Petal Shape and Stability**						
	In-plane envelope: ± 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						
	Supression (test): ≤ 1x10-9 Contrast (modeling): ≤ 1x10-10 (validted 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 an independent TAC at the end of Starshade Technology Project Formulation)

The Three Key Technology Areas for a Starshade

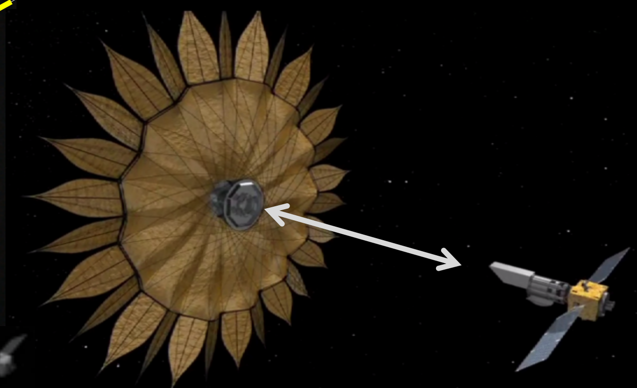
(1) Contrast

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



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

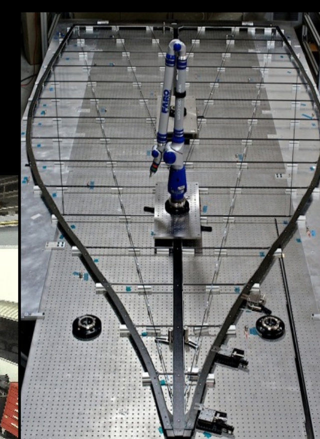
(3) Formation Sensing and Control



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

(2) Deployment Accuracy and Shape Stability

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



Fabricating the petal to high precision (S-4)

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

	TRL-5	TRL-6	TRL-7
NASA NPR 7123.1B Definitions	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.	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.	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).
SSWG operational interpretation	Demonstrate by tests in relevant environments the critical performance of medium-fidelity subsystem/assembly brassboards that begin to address all critical scaling issues and demonstrate by analysis of relevant environments the system performance with validated models	Demonstrate by tests in relevant environments the critical performance of high-fidelity system/subsystem prototype(s) that addresses all critical scaling and interface issues and demonstrate by analysis of operational environments the system performance with validated models	Demonstrate by operating in a **space environment** the required performance of high-fidelity system/subsystem prototypes/engineering units that addresses targeted scaling and interface issues of **a key technology (or all key technologies)** and demonstrate by analysis of operational environments the system performance with validated models

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

TRL 5 for a Starshade

TRL-5

Demonstrate by tests
in **relevant environments**
the **critical performance** of

medium-fidelity subsystem/assembly
brassboards* that begin to address
all critical scaling issues

and
demonstrate by analysis
of relevant environments the
system performance with validated models

N.Shah - The critical performance metric here is the angle you can sense and control to.

*a medium fidelity unit that 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 with scaling factors understood
Form is approximate with scaling factors understood
Functionality demonstrates performance

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

Demonstrate by tests
in **relevant environments**
the **critical performance** of

high-fidelity system/subsystem
prototype(s)* that addresses
all critical scaling and **interface issues**
and
demonstrate by analysis
of operational environments the
system performance with validated models

*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

Critical performance

Same as TRL-5

High Fidelity

Fit is representative with scaling factors understood
Form is representative with scaling factors understood
Functionality is tested to meet performance requirements

Relevant Environments

- Same as TRL-5 plus
- Petal Restraint
  - ❑ Dynamic testing
- Petal Shape:
  - ❑ Moisture absorption and loss (de-gassing)
  - ❑ Long-term stowed bending strain
- Solar Glint:
  - ❑ Dust in laboratory and launch fairing

Interfaces to be demonstrated and exercised

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 Guide Camera

TRL-6 is a necessary milestone.

TRL 7 Starshade Success Criteria

TRL-7

Demonstrate by operating
in a **space environment** the required
performance of

high-fidelity system/subsystem
prototypes/engineering units that addresses
targeted
scaling and interface issues of **a key technology (or all key technologies)**

and
demonstrate by analysis
of operational environments the
system performance with validated models

Operational Environments (including space)

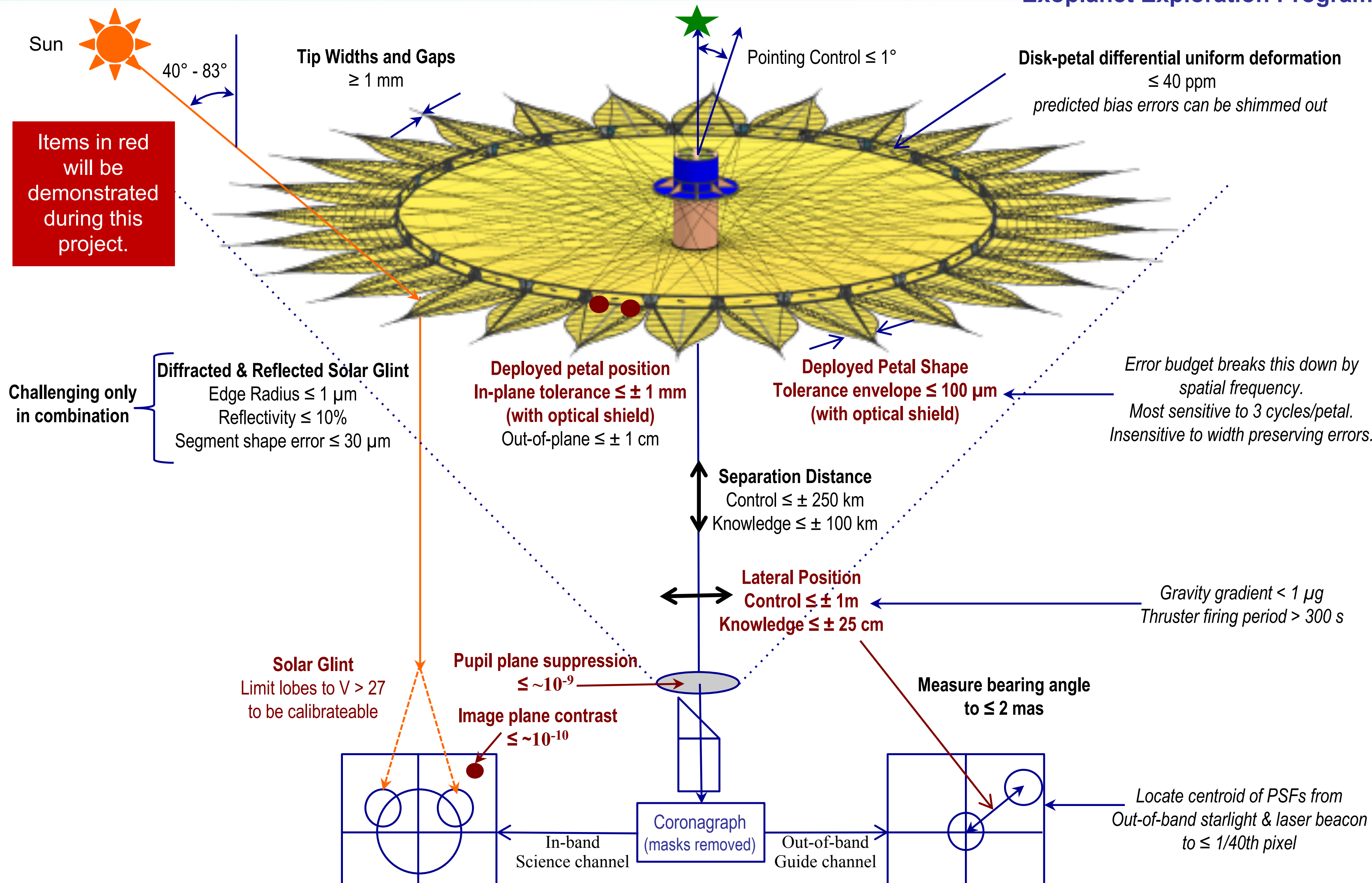
- Ground handling and transportation
- Long-term stowage
- Launch vibration
- Ascent venting
- Dust
- Vacuum
- 0-g
- Moisture absorption/loss
- Thermal
- Sun-target angles
- Space charging
- Micrometeoroids

TRL-7 Interpretations

- "pathfinder"
  - In some cases it is desirable to demonstrate a new technology in space prior to incorporation in the flight program.
  - Doesn't have to be a full system
- "targeted 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.

Preliminary Key Performance Parameters



KPPs stem from a system error budget that translates errors to contrast

TRL-5 and -6 Definitions Decomposed

TRL	Definition from NPR 7123.1e	Completion Criteria from NPR 7123.1e	Mission Req.	Performance/ Function	Fidelity of Analysis	Fidelity of Build	Level of Integration	Environment Verification
5	Component and/or brass-board validated in relevant environment	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.	Generic or specific class of missions	Basic functionality/ performance maintained	Medium fidelity: to predict key performance parameters and life limiting factors as a function of relevant environments	Medium fidelity: brass-board with realistic support elements	Component / Assembly	Tested in relevant environments Characterize physics of life-limiting mechanisms and failure modes.
6	System/ subsystem model or prototype demonstrated in a relevant environment	Documented test performance demonstrating agreement with analytical predictions	Specific mission	Required functionality/ performance demonstrated	Medium fidelity: to predict key performance parameters and life limiting factors as a function of operational environments	High fidelity: prototype that addresses all critical scaling issues	Subsystem/ System	Tested in relevant environments. Verify by test that the technology is resilient to the effects of life-limiting mechanisms

Frerking et al. in process

Fidelity of Build

	Unit	Purpose	Performance/ Function	Form and Fit/ Scaling	Environmental Requirements	Pedigree
New Technology	Breadboard	Proof-of-concept for a potential design	Demonstrate performance/ function	Not required, e.g. laid out flat on lab table	Tested in a laboratory environment	NA
New Technology	Brassboard	Demonstrate feasibility of form and fit, environments	Demonstrate performance/ function	Approximate (not flat) with scaling factors understood	Designed to meet relevant environmental requirements	NA
New Technology	Prototype	Representative design; pathfinder; demonstrator	Tested to meet performance/ function requirements	Representative with scaling factors understood	Tested to meet relevant environmental requirements	NA, but may be partial or full
Engineering Development	Engineering Unit	Finalize detailed design	Tested to meet performance/ function requirements	Exact as known at time of build	Tested to meet relevant environmental requirements	NA, but may be partial or full
Engineering Development	Qualification Unit	Qualify design	Tested to meet performance/ function requirements	Exact as known at time of build	Tested to meet flight qualification environmental requirements	Full
Engineering Development	Flight Unit	Final Product	Tested to meet performance/ function requirements	Exact	Tested to meet flight qualification environmental requirements	Full
Engineering Development	Flight Spare	Final Product	Tested to meet performance/ function requirements	Exact	Tested to meet flight qualification environmental requirements	Full

Frerking et al. in process