Proponent’s Technology Plan

Option # 2C

Long Baseline Facility

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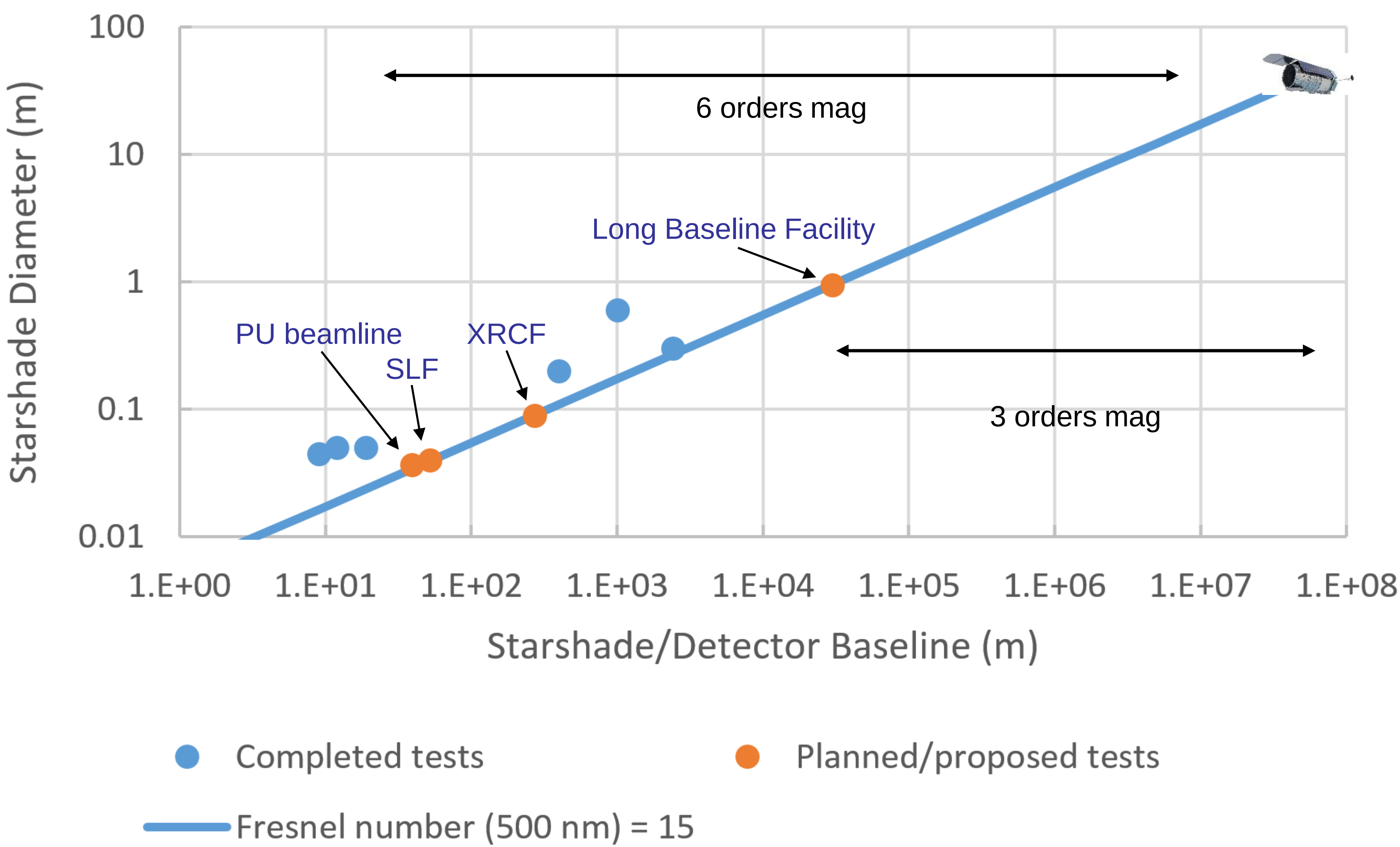
Overview

This strategy:

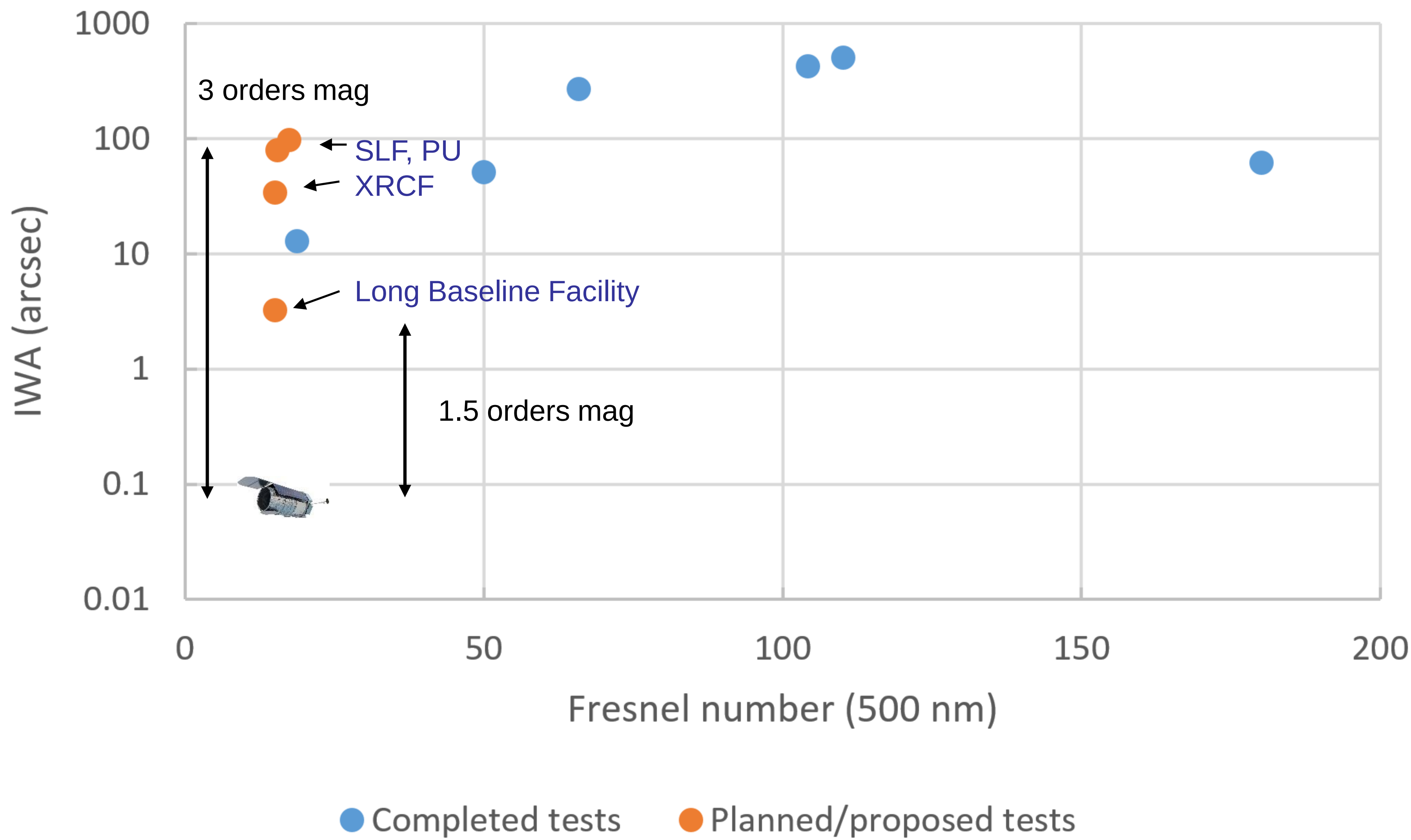
- **Addresses technology readiness of starshade system level issues, subsystem scaling gaps, and other problems that can be best examined over a long baseline and with larger starshades.**
- **Complements and expands upon Options 1a and 2d to address complicated scaling issues that cannot be addressed with existing testbeds.**
  - Starlight suppression, Optical modeling, Edge scatter, Formation flying sensing

A Long Baseline Facility will enable tests of a more representative system, further mitigating risk. Such a facility would be composed of a high quality flat mirror with siderostat mount, a starshade, and a telescope with hi-speed, low-noise detector. A variable baseline distance between the starshade and telescope up to 30km can be changed to suit a variety of functional tests. The ability to conduct optical tests with starlight or an artificial light source at large distances combines the capabilities and heritage of a siderostat and desert test into one facility.

Primary Motivation: Scaling



Primary Motivation: Scaling



Long Baseline Parameters

Parameter	Short Tests	Long Tests	Flight
Separation	10 km	30 km	50,000 km
Starshade Radius	0.25 m	0.45 m	20 m
Telescope Diameter	0.1 m	0.2 m	2.4 m
Fresnel # (at 0.5 μm)	15	15	15
Inner Working Angle	5"	3″	80 mas
Tel. Resolution (at 0.5 μm)	1.0″	0.5″	40 mas
# Res. Elements over SS	10	12	4

Why a Long Baseline?

- **We need to test a more representative flight-like system to fully understand complicated scaling issues**
  - We argue that Fresnel number is not the only relevant quantity
  - Our models may agree with recent experiments, but this is irrelevant if we are not testing the same physics and environment expected on orbit
  - There may be a hidden gremlin at larger scales
- **Order of magnitude increase in scale compared to current testbeds.**
- **Long baselines allow larger starshades to evaluate features that cannot functionally be scaled to a small size**
- **Appropriate aperture size to interface with scaled WFIRST instruments**
- **Parallel light to test in relevant environment (astronomical wavefronts)**
- **Versatile enough to push all optical technologies to TRL6+ before 2020 Decadal Survey**
- **Formation sensing (simulate coarse, medium, and fine sensing with autonomous control) with more relevant environment**
- **Look for non-Fresnel scaling issues**
  - Need to decompose Fresnel number into its 3 variables and test scalability of each

$$F = \frac{a^2}{\lambda L}$$

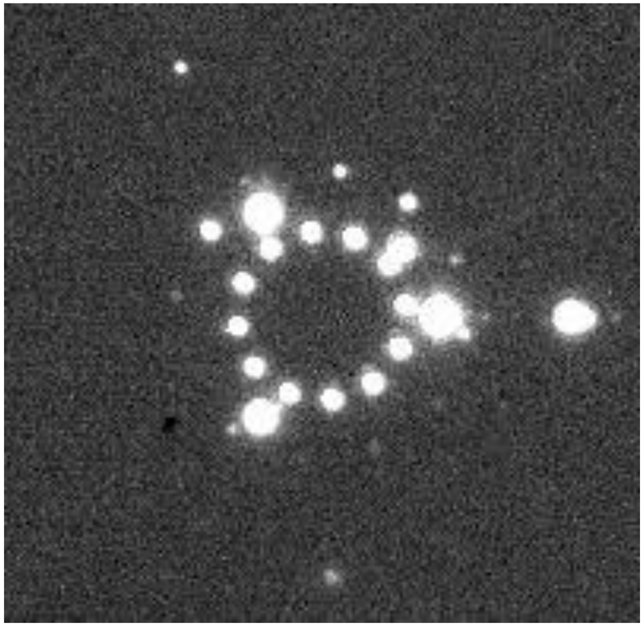
- **Reduce IWA**

Starlight Suppression: Limitation of Current Testbeds

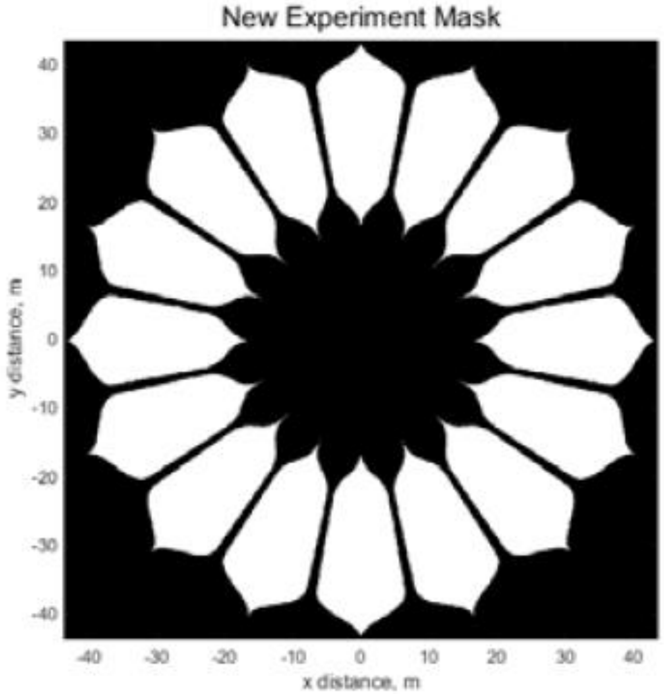
- **Starshade feature sizes approach wavelength size**
  - Feature sizes are < 0.5 microns
  - Scalar diffraction theory has a possibility to break down at these size scales
    - Polarization may become an issue
  - There is a possibility that these small size scales are helping with light suppression
    - e.g., could induce a current in a conducting petal edge that absorbs energy away from EM wave
    - Serve as a waveguide?
    - How does charging change starshade performance?
- **Limitations of fabrication tolerances**
  - Cannot fabricate features small enough to be at the proper scale
  - How does diffraction at petal bases, joints and edges in deployment features, micrometeroite perforations, material degradation, etc. scale?
- **Limited dynamic range of observations**
  - Testing size scales over 5 orders of magnitudes, when in flight these scales could cover 8 orders of mag
  - For example: how do we simulate effect of micrometeorite punctures if we cannot create holes at the appropriate scale relative to the size of the starshade?
  - Are we sure these features scale up in our favor?
- **Testing at too large IWA**
  - Forward scattering is a strong function of angle
  - We may have seen limited forward scattering due to the large IWA of current test setups

Starlight Suppression: Limitation of Current Testbeds

Laboratory mounting conditions complicate proper testing of form



Schindhelm et al., 2007



Kim et al., 2015

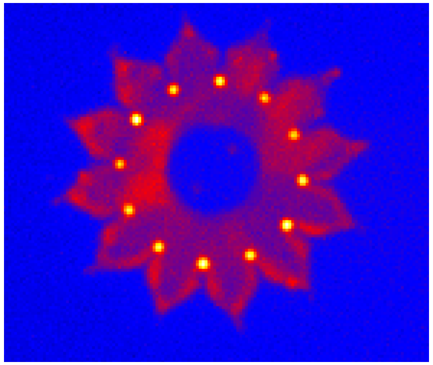
Starlight Suppression: Long Baseline Facility

- **TRL-6 requires a high-fidelity system/subsystem that addresses *all* scaling and interface issues**
  - We argue that the proposed advancements of Option 1a do not reach TRL-6 as they do not fully address the complicated scaling issues
  - We argue that the small scale tests are not representative of a flight system
  - If we are only experimenting in parameter space that maintains Fresnel number, our scalar diffraction models may agree, but don't necessarily tell us what to expect in flight
- **We need to address all critical scaling issues and demonstrate by analysis**
  - Validate models and predict diffractive behavior in a large dynamic range of size scales
    - Model validation occurs at all stages
  - Test at representative size scales
  - Test with parallel astronomical wavefronts, a more relevant environment

Edge Scatter

- **Option 1a addresses the technical development needed to answer important questions regarding this issue and its potential effect on starshade system performance. This option expands on Option 1a test strategies:**

- **Higher waveguide "scatter" at petal bases in short baseline testbeds biases starshade design studies.**
  - Flight design has mm (or even cm) petal bases vs micron for scaled versions in lab testbeds
  - European flag scaling must be understood on larger starshades
- **Scatter effects only quantifiable with large-scale starshades include**
  - Scatter off deployment features (e.g., edge joints) and simulated micrometeoroid damage is only possible on large starshades
  - High-angle diffraction and waveguide scatter of solar photons through petal bases
- **Longer baselines allow**
  - Forward scatter at closer to flight-like IWA
  - Tests of larger portions of full scale petals



Formation Sensing

- **Address technology gap S3 for precision sensing for lateral formation flying**
- **Evaluate pupil and focal plane FF sensors simultaneously with starlight suppression**

- **We need to understand critical scaling issues by testing at a more representative configuration**
  - Need larger features that are properly scaled for longer wavelength operation
  - We propose to test at 3 orders of magnitude from flight, instead of 5
- **Integrate handoff between coarse, medium, and fine sensing into system with starlight suppression**
- **Test a more representative system by incorporating WFIRST instrumentation (i.e., coronagraph optics) into formation sensing**
  - It's necessary to understand the critical interface between starshade and sensors to reach TRL-6

Formation Sensing Tests

- **Realistic parameters**
  - Stars
  - Parallel light
  - Spectral response
  - Realistic backgrounds
- **Relevant environment**
  - Long baseline
  - SNR
  - Fresnel #'s at min and max separation
- **Use intrinsic starshade performance features to develop fine control sensing**
  - Ring = residual suppression
  - Visible petal bases for direct position sensing
  - Handoff between coarse, medium and fine sensing with autonomous control
- **Petal base brightness**
  - Is the change in relative brightness sufficient for guidance?
  - Does decreased waveguide efficiency push the European flag effect into the noise?
  - Do waved petal edges significantly affect petal base brightness at full scale?
- **Spot of Arago**
  - Measure intensity of Spot of Arago with broadband starlight to simulate mission performance.
  - Employ coarse, medium and fine sensing methods simultaneously

System Level Performance

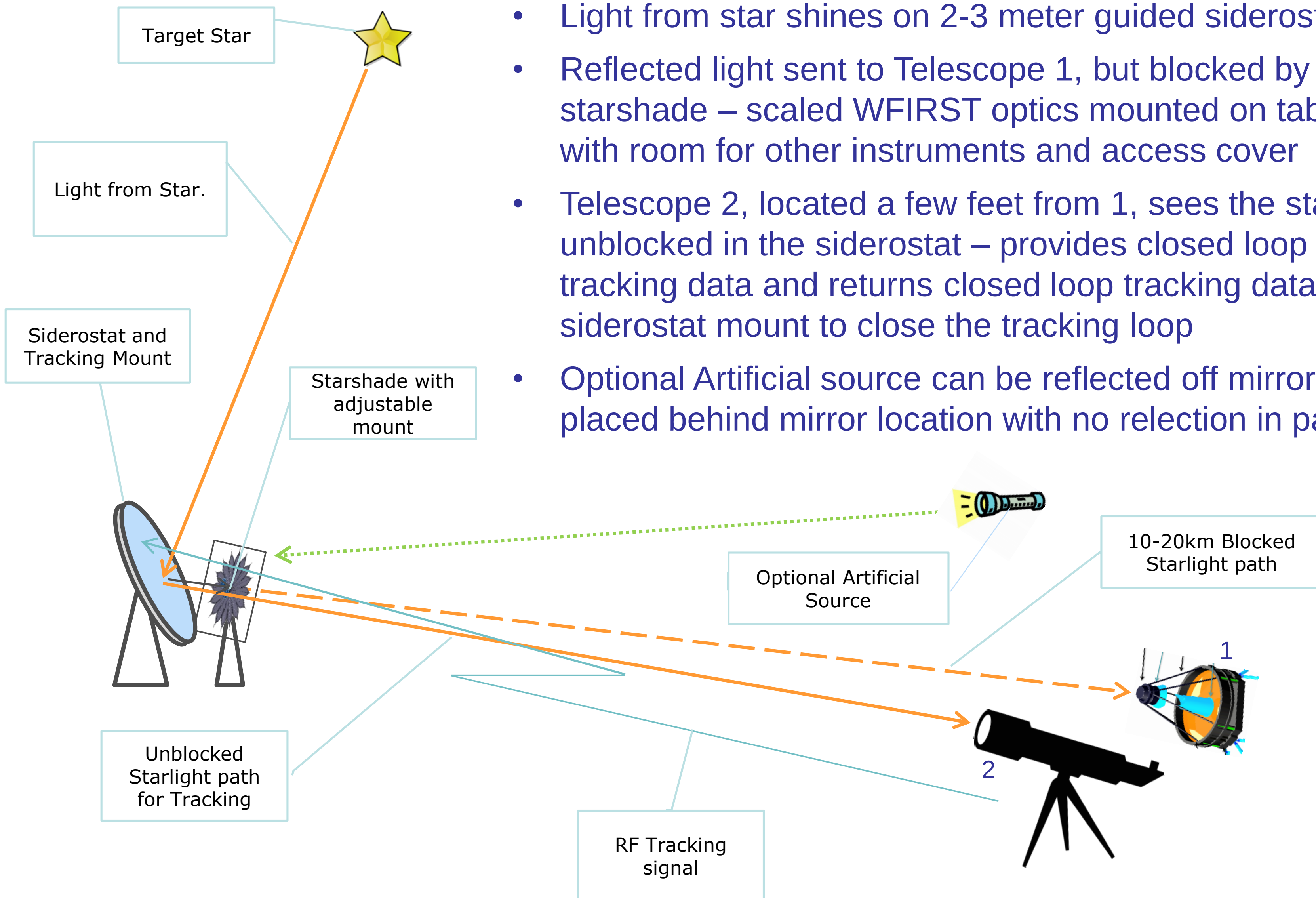
- **This is a new technology that needs system level testing to understand nuances.**
  - Discrete subsystems don’t automatically play nice
  - Increased system fidelity mitigates risk
- **Representative flight-like configuration for system level validation**
  - Need to demonstrate pieces interface effectively to reach TRL-6
- **Integrate with scaled WFIRST architecture**
  - Optical path, detector, filters, sensing equipment, stray light control, spectrograph, etc.…
- **Test, model, and validate performance of full system:**
  - At low Fresnel #
  - With full bandpass
  - With correct spectral response
  - With realistic S/N
  - WFIRST optical components (detectors, filters)
  - Parallel light from astronomical wavefronts
  - Realistic backgrounds (stars)
  - Low IWA

Long Baseline Facility Description

- **Semi-permanent/semi-portable**
  - Stable mount but with variable baselines to understand scaling
- **High quality flat mirror**
- **Siderostat mount with remote control**
- **White light source with remote control adjustable mount**
- **Infrared source**
- **Starshade mount – adjustable, remote position and angle control, accepts a variety of starshade sizes and shapes**
- **Filter wheel (UV to near IR, ND filters)**
- **Telescope – similar scaled version of WFIRST (3 mirror astigmatic). Components mounted on an optics table that can accept other components/instruments with access panel through cover.**
- **Detector(s)**
  - Optical (low noise)
  - Infrared
- **Guide camera**
- **Formation sensing equipment with feedback loop**

Long Baseline Facility

- Light from star shines on 2-3 meter guided siderostat
- Reflected light sent to Telescope 1, but blocked by the starshade – scaled WFIRST optics mounted on table with room for other instruments and access cover
- Telescope 2, located a few feet from 1, sees the star unblocked in the siderostat – provides closed loop tracking data and returns closed loop tracking data to siderostat mount to close the tracking loop
- Optional Artificial source can be reflected off mirror or placed behind mirror location with no relection in path

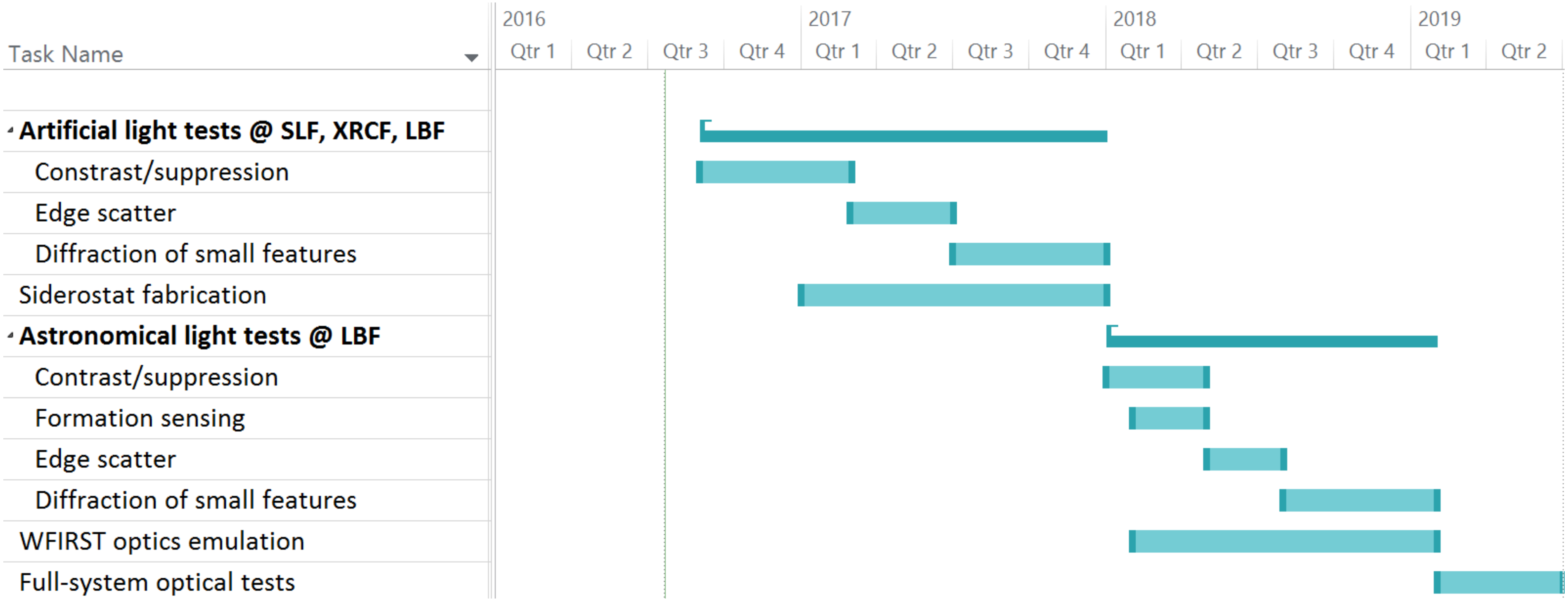


*Slide from Option 2d – edited

List of Tests

- **To properly understand scaling relations, contrast and formation sensing tests should be done with at least three configurations:**
  - Short baselines of 10s of meters (PU, HAO, SLF)
  - Medium baselines of 100s to 1000s of meters (XRCF, McMath)
  - Long baselines of 10s of km (LBF)
- **LBF allows unique tests that can only be done with large starshades and at long baselines**
  - Edge/waveguide/small feature scatter
    - Micrometeoroids
    - Petal bases
    - Deployment joints
    - Low-angle forward scatter at small IWA
  - Full-scale starshade segments (bases, tips)
  - Large-angle solar scatter and diffraction
  - System-level (scaled down WFIRST optics)

Test Timeline



Summary of Opportunities

- **O1: Scaling**
  - Varying long baselines
  - Varying starshade sizes
  - Varying wavelengths
  - Identify factors that do not scale with Fresnel number
    - Petal base feature –waveguide vs. diffraction contribution
  - Confidence in scaling partial derivatives
- **O2: Representative flight-like configuration for system level validation**
- **O3: Parallel light from astronomical wavefronts**
- **O4: Flexible testbed with rapid turnaround for technology risk retirement**
  - Model validation of various flawed shapes.
  - Tolerance testing
  - Edge scatter testing
- **O5: Combines siderostat and desert testing heritage and capabilities.**
- **O6: Opportunity to interface with WFIRST instrumentation**

Concerns and Risks

- **R1: Difficult to model external environmental effects can complicate interpretation of results.**
  - Atmospheric turbulence
  - Stray light
    - Dust and mirror scatter
- **R2: Duty cycle**
  - Weather

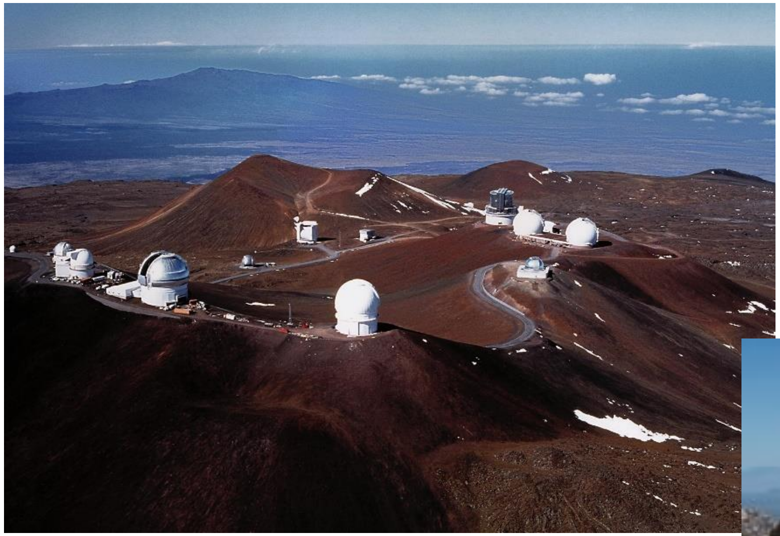
The TRL-6 Success Criteria that the SSWG Options Need to Meet

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

Appendix

Operations and Alignment Plan

- Site selection
- Facility design
- Facility fabrication
- Initial Stray Light Facility and XRCF tests (parallel effort during construction)
- Alignment plan details
- Facility operations



Existing Options

Stray-light Test Facility

CLASS 10K CLEAN ROOM AND CHAMBER

OPPOSITE: END OF ROOM TUBE

MAIN CHAMBER AND PREP AREA

- 3 by12-m test volume for baffle or mirror
- 1.3-m diameter, 82-m long section
- 1.5-m diameter, 10-m isolatable section
- Pumped with cryo-pump: $<10^{-7}$ torr
- Measured baffle rejection ratios up to 10^{15}
- Use to test x-ray optics up to 1-m dia

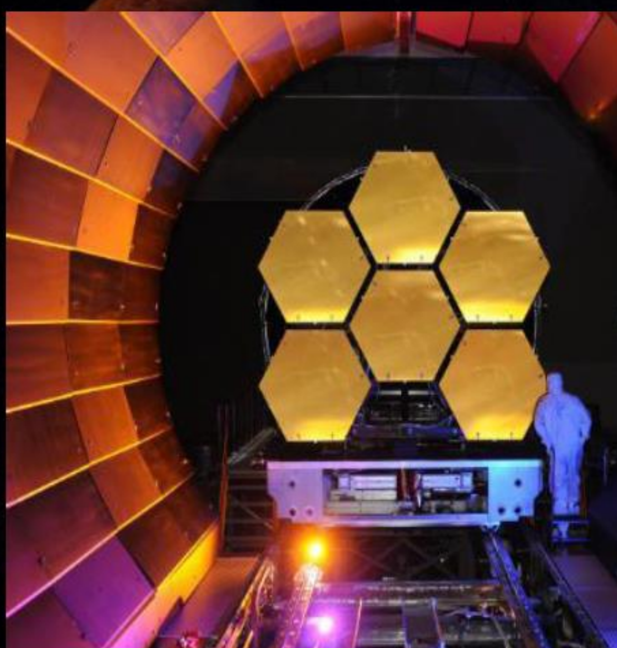
Existing Facilities

X-Ray and Cryogenic Facility (XRCF)

James Webb Space Telescope flight mirror segments were tested in the (XRCF), the same facility that tested the Chandra X-ray telescope at MSFC. The test chamber offers the unique capability for simulating a space environment with low temperature and pressure.

Vacuum Chamber

- 7.3 x 22.8 m Polished Stainless Steel 10-7 Torr Vacuum Chamber
- Full 155 to 355K Thermal Shroud – Helium shroud to 20K
- Vibration Isolated via Seismic Mass
- 5DOF Remote Controlled Test Stand



CTT Evaluation Criteria Items

	DECIDE: Recommend a development strategy to enable a starshade science flight mission		Evaluation Team		
		NOTES	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)

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

Explain how your plan matures the three technology areas listed below 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**

➢ ***Important: See notes 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)
  - the scaling issues must be well understood but TRL-6 does not have to be full-scale
  - required performance at TRL-6 is achieved with understanding of 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 that Option #.**
  - This strategy may allow you to focus on portions of their plan that you feel may be lacking or carries high risk and your Option can mitigate.

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

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

	TRL-5 Component and/or breadboard validation in relevant environment.		TRL-7 System prototype demonstration in an operational environment.
NASA NPR 7123.1B Definitions	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	A high fidelity engineering unit/prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).
	TRL-5		**TRL-7**
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

*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

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)

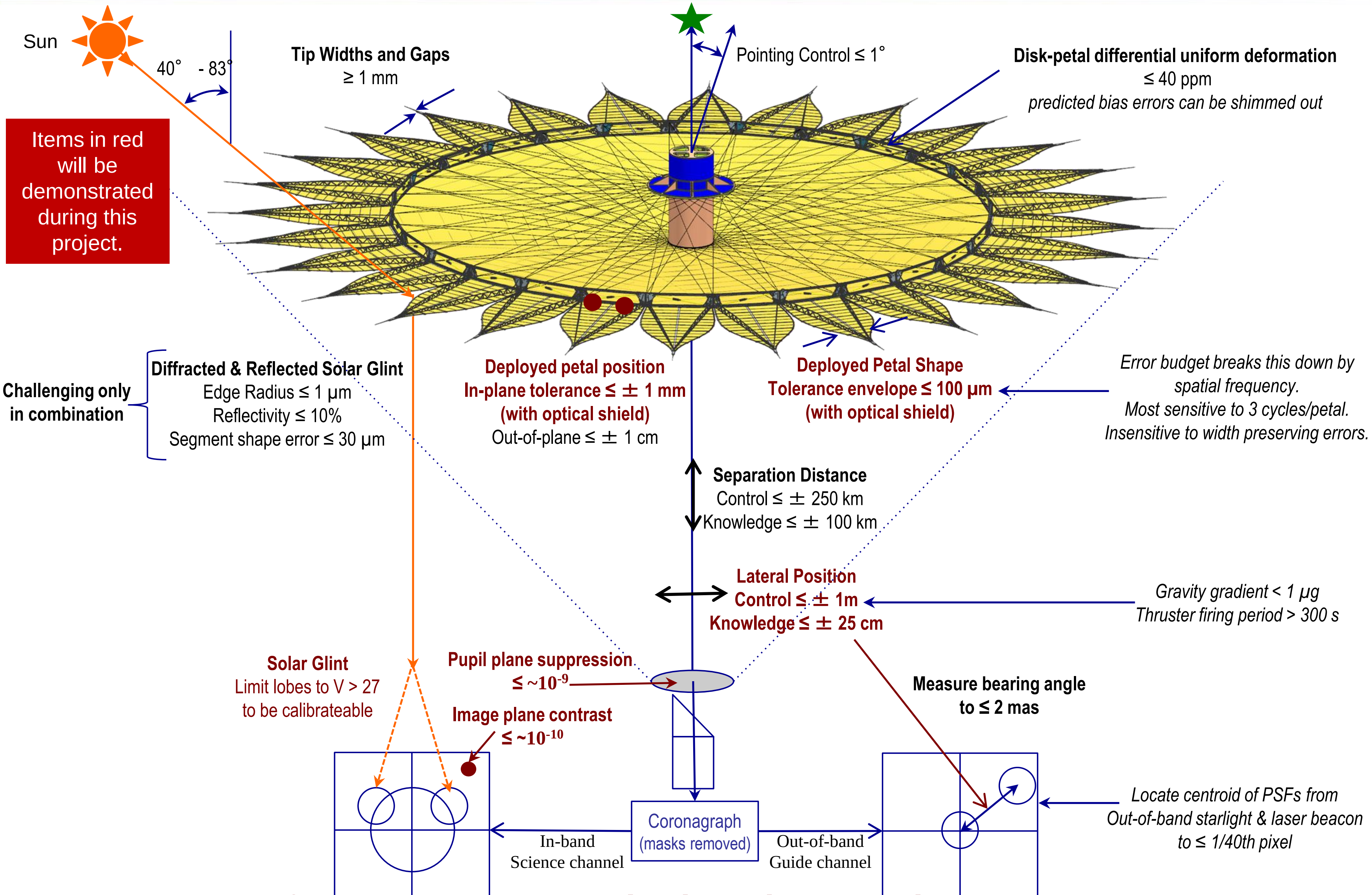
- Ground handling and transportation
- Long-term stowage
- Launch vibration
- Ascent venting
- Dust
- Vacuum
- 0-g
- Moisture absorption/loss
- Thermal
- Sun-target angles
- Space charging
- Micrometeoroids

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

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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
	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
	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
	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
	Flight Unit	Final Product	Tested to meet performance/ function requirements	Exact	Tested to meet flight qualification environmental requirements	Full
	Flight Spare	Final Product	Tested to meet performance/ function requirements	Exact	Tested to meet flight qualification environmental requirements	Full

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