Option 1a: Path to TRL-6

SSWG Telecon

J. Arenberg, T. Glassman, S. Warwick, D. Scharf and M.C. Noecker

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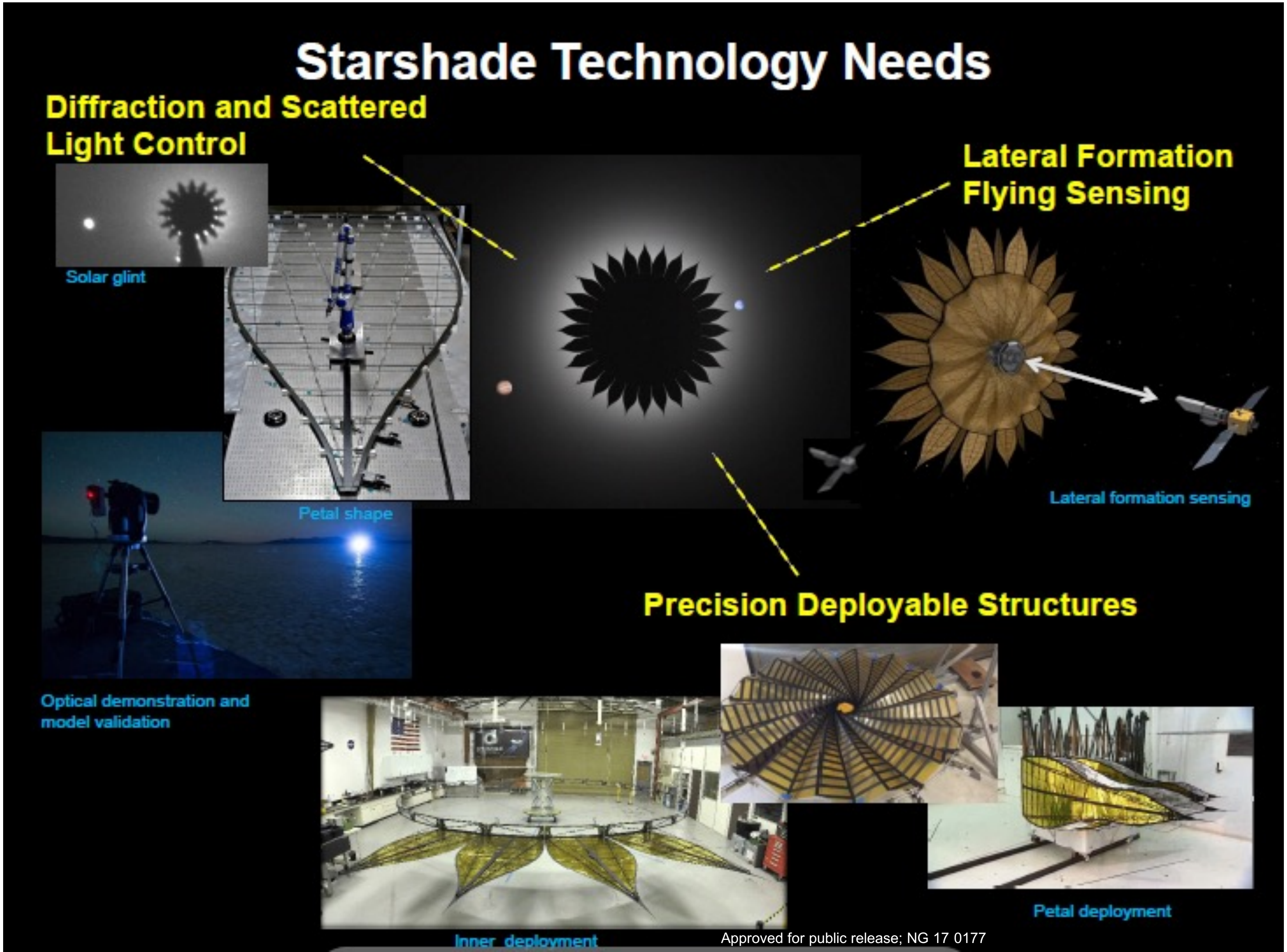
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Overview

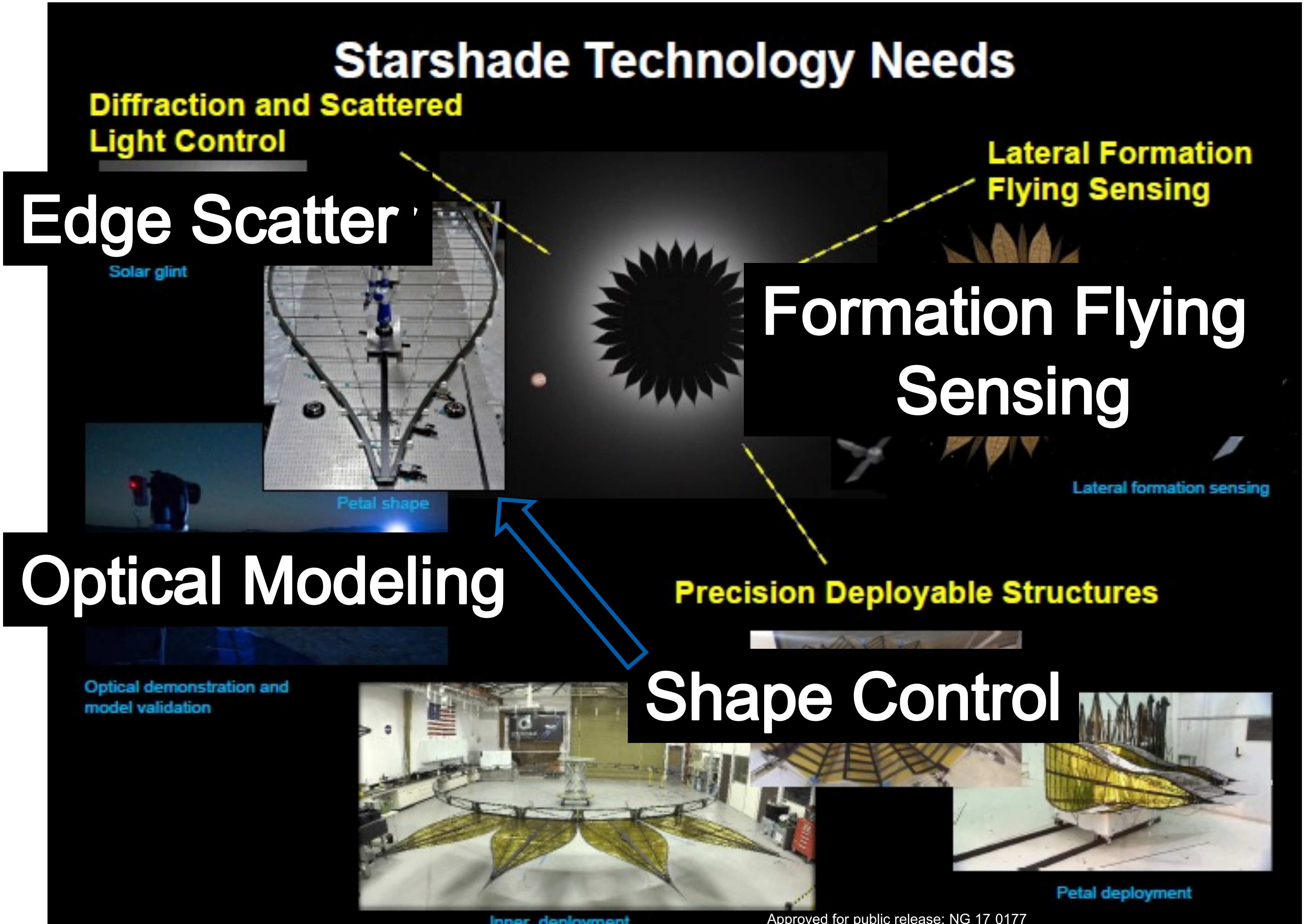
- This briefing will present a plan for technical readiness for the starshade addressing maturity across the swimlanes
- Each topic (swimlane) will be presented
- It will be shown that all of these tests can be accomplished on the ground without a flight experiment

Technology Chart From Chief Technologist



Technology Chart From Chief Technologist-Edited

ExoPlanet Exploration Program



Overview of Meeting TRL-6

ExoPlanet Exploration Program

TRL-6 Criteria	Optical Modeling	Edge Scatter	Fine Alignment Sensing	Shape Control: Deployment	Shape Control: Petal Shape
High Fidelity System/Component Prototype	Flight like shapes at flight light F#	Flight like edges (samples)	Breadboard sensor and algorithm	Near flight scale	Flight scale
Scaling	Show analytically and experimentally that F# and D_T/D_{SS} are proper NDV	Make enough samples to prove production process statistics	Flight like light levels	Near flight scale	Flight Scale
Relevant Environment	On orbit shapes predicted by use of modeling	Performance at EOL	Performance at EOL (degraded sensor and propulsion)	Offloaded deployment	Many analyses show environment al distortion tolerable
Demonstrate Operations	By analysis using validated model	By analysis using validated model	Loop closed under EOL conditions	Operated	Manufactured
Criteria	Ground test predictions match experiment Models agree in terms of performance and sensitivity Models predict by analysis acceptable on orbit performance	Small impact to effective IWA	Ability to sense ~1mas @EOL	Derived from error budget for deployment Many analyses show environment al distortion tolerable	Derived from error budget

TRL-6 Definition

ExoPlanet Exploration Program

NASA NPR 7123.1B Definitions

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

Optical Modeling

Two Ways

- Way 1: Completely(ALL parameters) scaled model tested to flight performance
  - Challenges for a terrestrial test
    - Very short wavelengths
    - Absolute tolerance
  - Focus is on mimicry of flight design before true flight design process has commenced
- Way 2: Scale selected parameters and develop validated model
  - Enables executable testing on the ground
  - Allows for targeted experiments to fully understand system performance
  - Typical of development for large complex missions

Optical Modeling: Scalar Diffraction

- Fundamental issue is validation that scalar diffraction is sufficient to design and verify the starshade
  - There are known areas where scalar approximation breaks down due to small features (corners, tip and valleys)
    - Scalar defect is small and can therefore be absorbed into the performance budget
- Applicability is shown by analysis of the diffraction equations
  - Analysis to show that F# and D_T/D_{SS} are the right non-dimensional parameters
- Scalar diffraction is shown to be correct within acceptable limits by comparison of experiments to models
  - Predicting starshade performance from measured scaled models of a flight like starshade
    - Varying wavelength, starshade size, and shade to telescope distance
    - Nominal shapes
    - Distorted shapes
- Computationally correct is shown by
  - Models shall be compared for predictions of absolute starshade performance
  - Models shall be compared for sensitivity of performance to various errors

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ExoPlanet Exploration Program

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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.

Measurements of Starshade Performance

ExoPlanet Exploration Program

- Goals are to show
  - G1. Starshade performance is predicable and acceptable (small scalar defect)
    - At least 2 fundamental shapes ($i \geq 2$)
  - G2. Scaling via F#
  - G3. D_T/D_{SS} is valid

Test Matrix-Shape i

			Performance	D_T	D_{SS}	λ	z (separation)	F#	
A	G1		Flight	T1	SS1	λ1, λ2, λ3, λ4, λ5	Separation appropriate for F# and λ		
B	G1								
C	G1	Distortions (4)	Flight	T1	SS1	λ1	z1	15	Same F#, vary shape
D	G2		Flight	T1	SS1	λ1	z2, z3, z4, z1, z5		
E	G2		Flight	T1	SS2	λ1	z2, z3, z4, z1, z5	8, 10, 12, 15, 18	
F	G3							8, 10, 12, 15, 18	
G	G3			T1,T2, T3, T4, T5	SS2	λ1			

Agreement Between Prediction and Measurement

- Experiment is very hard to make
  - Dimensional accuracy and its measurement of test shade at small size
- On the previous chart, ‘Flight’ is meant as the same performance level as the WFIRST starshade will have
  - Exact definition of performance to be defined (SAG18)
- Performance difference between experiment and model ~50%
- The experiment MUST have well quantified uncertainty budget

Agreement Among Models

- Verification by analysis requires one model to make a prediction and cross checking by at least one independent model
  - Model difference are treated as uncertainty to be accommodated
- Can calculate the mean local difference between model j and k as measure of agreement
- Determine the largest mean difference and use this as the model agreement uncertainty
- Goal is maximum model disagreement is less than 20% (of local suppression)
- Need tighter agreement about loss of contrast with individual error terms
  - If the loss of contrast with error is different among the models, additional performance is needed to accommodate this uncertainty
  - If we need to carry ~60 error terms in our budgets, then models must agree about the effect of each error to ~1%

Edge Scatter

Edge Scatter

- Edge scatter causes an increase in the IWA above the geometric value (D_{SS}/F)
  - IWA impact, ΔIWA, depends on D_T (telescope diameter) and distance F in addition to the optical properties of the edge

- The performance of the edge must be predictable over mission life so that its effects can be accommodated in the design of the starshade to achieve the necessary IWA

- Current gaps
  - Edge scatter efforts do not agree on performance, modeling
  - Samples are tiny compared to perimeter length for flight design
  - Manufacturing facilities need scaling to production level
  - Environmental exposure of coupons not fully flight like

- What is needed for TRL-6
  - Selection of edge coating/substrate system
  - Manufacturing process at flight scale
  - Production of samples
  - Flight like environmental exposures
  - Efficient test set
  - Determinative performance (scattering of sunlight into telescope aperture) from a representative sample for prototype manufacturing process at EOL
    - Maximum($+3\sigma$) level of scatter at EOL can be accommodated into design and meet IWA requirement

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  – Efficient test set
  – Determinative performance (scattering of sunlight into telescope aperture) from a representative sample for prototype manufacturing process at EOL
    - Maximum(+3σ) level of scatter at EOL can be accommodated into design and meet IWA requirement
      – Local scatter less than +32 M (TBR)

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.

Edge Scatter Narrative

- Need to get one story for the scatter of sun light from starshade edges
- The EOL properties of the edge must be known on a statistically significant sample that comes from a presentative manufacturing process
- Need to make sure materials search is complete (don't want to miss good candidates)
- No clear definition of environment to do initial screening
  - Determine complete L2 environment and required thermal cycling
    - Use JWST EV spec as template for L2 environment
    - Use existing thermal model for rotating shade to estimate number of cycles and depth
    - Perform scatter measurement on BOTH test sets
- Down select to 1 or 2 high probability materials
- Develop scaled manufacturing process
  - Make samples, understand yield and performance variance
  - Produce sufficient samples to prove consistency in manufacturing
- Then we can do TRL-6 testing and qualification
- Needed data is confident upper limits on scatter
  - Let the design accommodate results

Tasks for Qualification of Edges

TRL	Task/Gap	Action	Size
5	Scatter results and models do not agree	Reconcile measurements and models	TDEM
5	Environmental exposures not a complete set of L2 stimuli	Define standard L2 environment for testing	S
5	Test more materials and more sample	Expand candidate materials and get better handle on performance statistics	M
6	TRL-6 Testing Plan	From mission requirements define performance level of edge and sampling plans	S/M
6	TRL-6 Testing Plan	Select candidates	M
6	TRL-6 Testing Plan	Scale production facilities	L-VL
6	TRL-6 Testing Plan	Make samples	L
6	TRL-6 Testing Plan	Make measurements more efficient	L-M
6	TRL-6 Testing Plan	Environmental exposures	M
6	TRL-6 Testing Plan	Measure samples	M
6	TRL-6 Testing Plan	Analyze and report	M

Size is a Jon WAG at cost in log10(Cost) S=4, M=5, L=6, VL=7

Edges Summary

- Edges are the big gap
  - Understanding
  - Best candidates
  - What is the test qualification environment
  - What is the performance of production processes
    - Need to develop production processes
  - Need increased efficiency in measurement of scatter performance

Formation Flying Sensing

Introduction

- Option1: Proceed from TRL 6 to Science Flight Mission

  From S. Seager's Jan 28, 2016 package

  A. Get to TRL 5&6 and do *NOT* do a flight demo

  B. Path to TRL 6 is made in pieces and not as an integrated unit, **need a strong story for this approach**

  C. Define technologies, each with plan to get to TRL 6

- Identified Technology Gap S-3: ***Lateral Formation Flying Sensing***
  - "Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow."

    From N. Siegler's Jan 15, 2016 package
  - Formation flying itself as a technology? Part of "strong story" (next)
- Purpose here: propose quantitative path to TRL 6 for Tech Gap S-3
  - Need to introduce lateral formation sensing concepts at deeper level
  - Define relevant environment, critical performance, interface issues, relevant & operational environments, and example experiments

Formation Flying in General

- **Two-spacecraft, “Leader-Follower” formations have flown = TRL 9**
  - Russia (Soyuz)
  - JAXA (ETS-VII, HTV)
  - DARPA (Orbital Express)
  - NASA (DART)
  - University of Toronto (CanX-4 & 5)
  - USAF (XSS-11)
  - ESA (ATV, Proba-3 (2018))
  - DLR (TanDEM-X)
  - SSC, CNES, DLR, DTU (PRISMA)
- **Counter-point: “Devil is in the details”**
  - Degree and duration of autonomy?
    - DART fully autonomous (failure due to rushed engineering), PRISMA SAFE experiments, CanX-4/5 autonomous experiments
  - Operational complexity including relative-sensor hand-offs?
    - Orbital Express handed-off between far, medium, and close range sensors (believed autonomous: published info omits some details)
  - Fault modes?
    - Starshade has no collision risk, can fall back on DSN (cost risk)

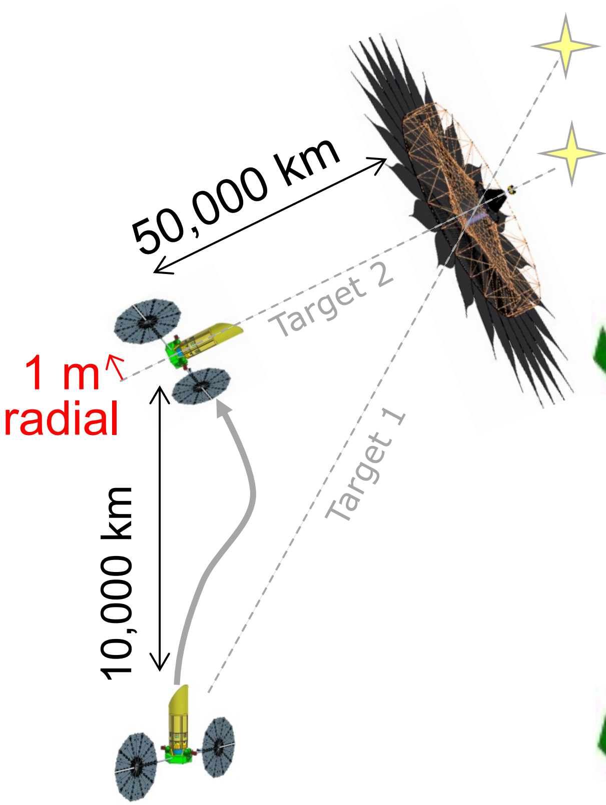
Formation Flying in General

- Not saying formation flying easy or even standard, but are arguing that the last decade of tech demo missions (and even science missions: TanDEM-X) make it difficult to say formation flying as a whole is an unproven technology

- So what aspects of Starshade formation flying are not covered by previous formation tech demo missions?

Starshade Formation-Flying Guidance, Navigation, and Control

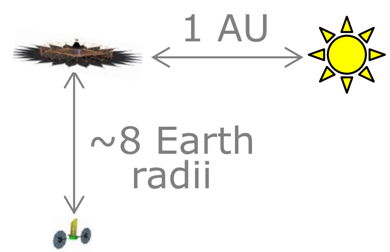
- **Just looks hard:** two spacecraft, 50,000 km separation, zooming around 10,000 km between observations, and then controlling to 1 m/50 Mm = 20 nrad (4 mas)



- **In reality, argue *easier* than routinely done autonomous docking…**

  …if we can sense accurately enough

Dynamics

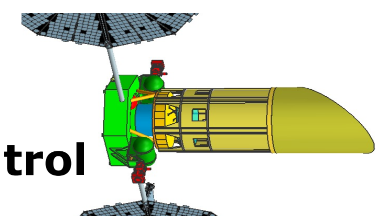


Gravity gradient
at 50 Mm in heliocentric orbit

=

Gravity gradient
at 1.5 m in LEO

Control



2 m

0.3 m

Controlling 2 metric ton
starshade to ±1 m

~10x Easier

Controlling 7 metric ton
spacecraft to ±0.15 m

Graphics from Exo-S Dedicated Mission: for Rendezvous Mission, Starshade would maneuver.

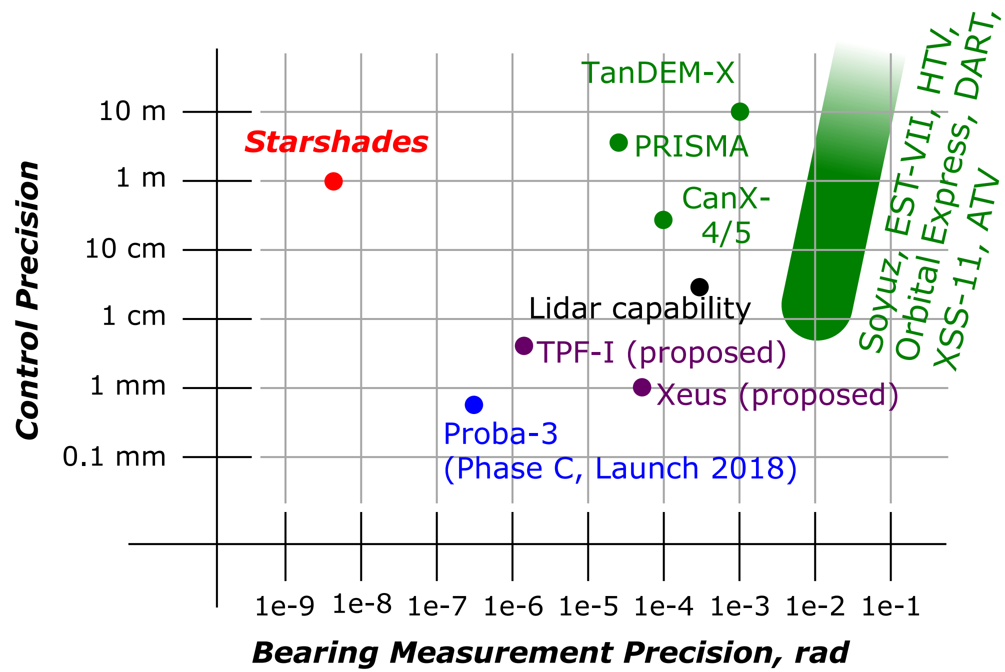
Deadband drift duration for science engineering issue, e.g., sizing thrusters

Starshade Formation Flying Challenge: Sensing

- What has *not* been done before is sensing sub-meter relative position at tens-of-megameters
  - **Starshade Technology Gap S-3: Lateral Formation Flying Sensing**

- For lateral control requirement of ~1 m in Science mode, assume need to sense to ~0.3 m (estimator further improves knowledge), which is 1.2 mas at 50 Mm

- For cost reasons, also want autonomous relative navigation during Transition/Re-targeting and Acquisition



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Main Argument (1 of 3)

- Contend that two-spacecraft, Leader-Follower formation flying has been demonstrated to TRL-6 by previous tech demo and autonomous rendezvous and docking missions...
  - With more challenging relative dynamics in LEO,
  - With tighter control requirements, and
  - With at least comparable operational complexity in terms of sensor hand-offs (Orbital Express)
- ...but none with a sensor suite that operates over 10-50 Mm
  - So evaluate sensors for starshade formation flying for technology risks
- Proposed coarse sensor is inertial-navigation plus an LED beacon array on the starshade viewed by a star tracker on WFIRST
  - Space-qualified LEDs and power converters available, standard optics, star trackers mature
  - Coarse sensor not considered a technology risk

Main Argument (2 of 3)

- Proposed medium sensor is a diffuse laser beacon on the starshade seen by a "guide camera" on WFIRST
  - Space-qualified diode lasers (e.g., NuSTAR 100-mW 810-nm laser) exist, standard optics
  - Does assume centroiding to < 3.5 mas 1-sigma on sky
    - For Exo-S, 2.5-arcmin FOV with 1024x1024 detector, so 1/40th of a pixel compared to 1/100th SOA
    - WFIRST coronagraph's 5x10-arcsec FOV should be no problem (TBC)
      - Steady-state bearing knowledge on coarse sensor ~9 arcsec 3-sigma, so may need minimal, 1-DOF scan to acquire laser beacon
  - Medium sensor not considered a technology risk
- Leaves the fine sensor: fine sensor proposals rely on details of the diffraction pattern that must be mathematically predicted beforehand
  - They also fit images to predicts, and so detector SNR could be a concern

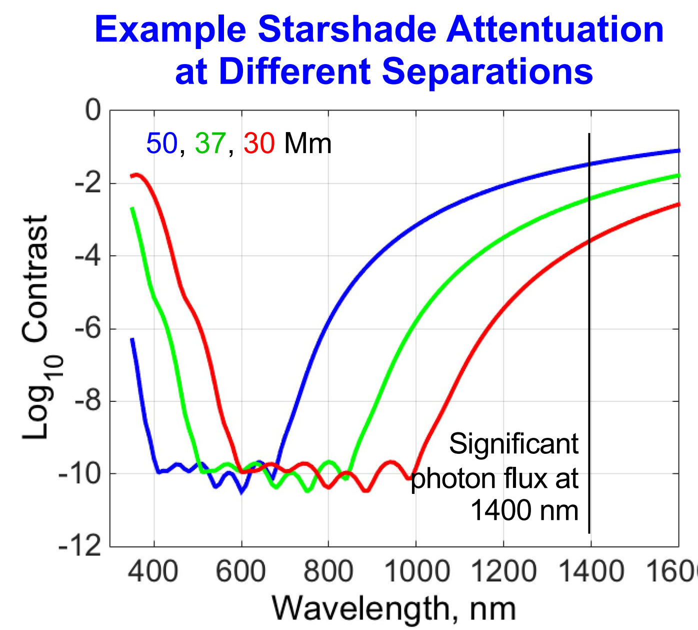
Main Argument (3 of 3)

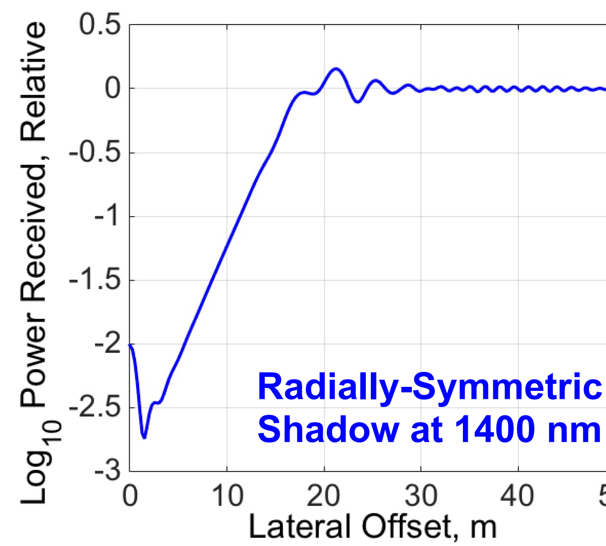
- Proposition: If
  - The fine sensor concepts are demonstrated to TRL 6, and
  - A high-fidelity simulation of formation flying demonstrates initialization from DSN through two science modes using validated sensor models

  the formation flying aspects of Starshade Rendezvous are at TRL 6
- Now review the two fine sensor concepts (next slides). Contend
  - Can test in stand alone environments
  - Can test in open-loop with representative closed-loop motions (from simulation)
- Concepts rely on 1) predicting diffracted images and 2) "fitting" actual images to predicts
- So to demonstrate fine sensors to TRL-6, need to
  - Demonstrate ability to predict diffracted images
  - Demonstrate ability to fit images to required performance with expected SNR and pixel-size

Two Concepts for Lateral Sensing in Science Mode

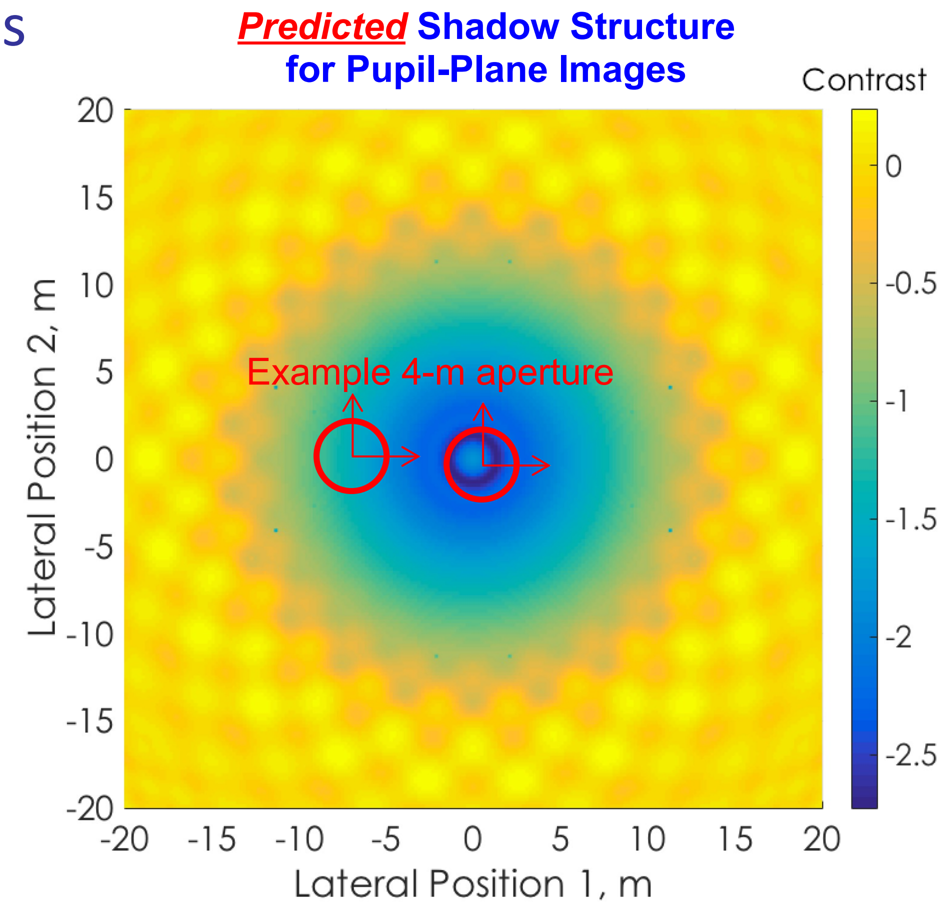
- Two concepts: **pupil plane (PP)** and **focal plane (FP)** fine sensors
  - Pros and cons to both, both being matured
- Both use “leaked” light from the target star outside the science bands
- For technology maturation, both concepts ***rely on mathematically predicting the shape/structure of the starshade diffraction pattern at the 10⁻³ level***
  - NOT the Science 10^{-10} level





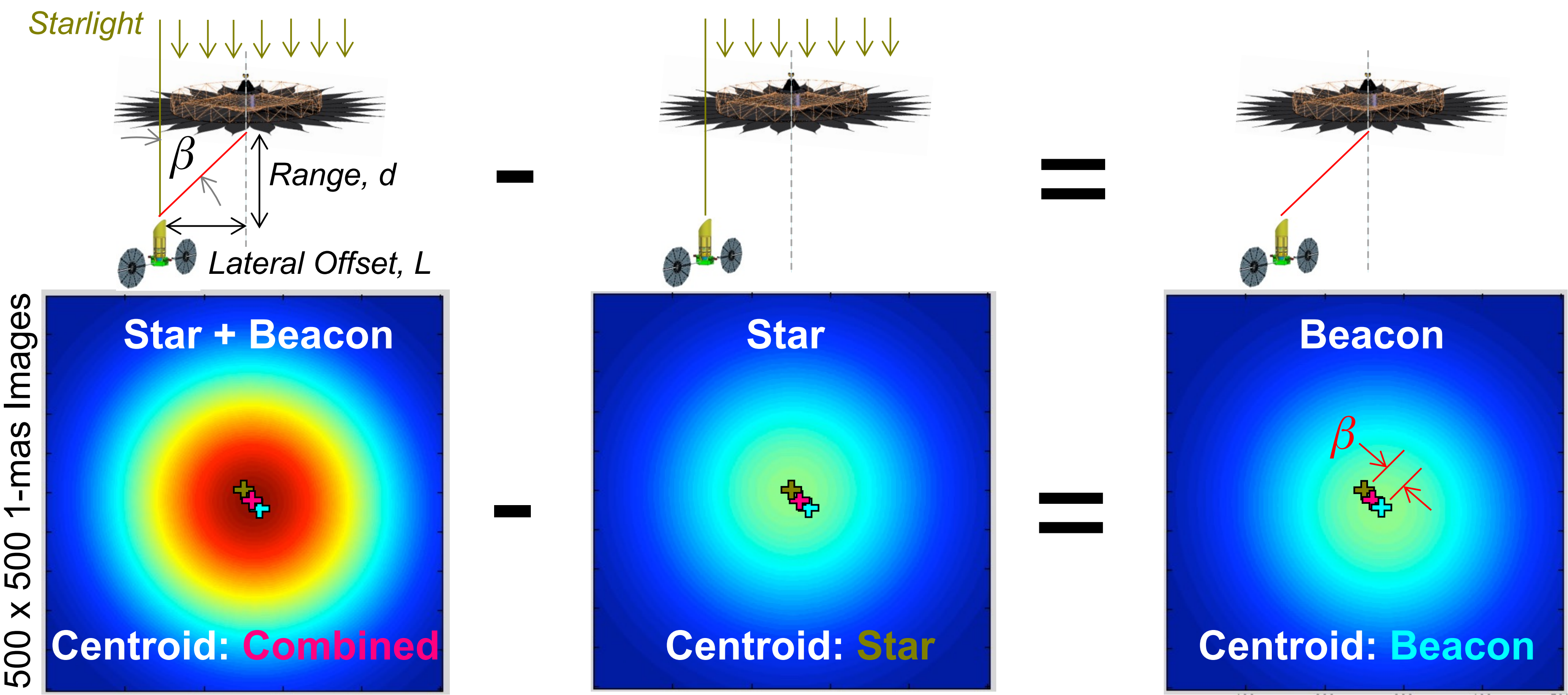
Pupil-Plane Fine Sensor: Concept and Dependence on Prediction

- A pupil-plane image is the intensity across the aperture
  - Example images at right in apertures
- Can pre-compute intensity images on 2D grid of lateral positions...
  - Quad-cells, 8-sector gradients, or say, 8x8 image
- Then find best match between actual and pre-computed images
  - Gives lateral position to ±0.35 m for 4-m aperture
- Once aperture includes Poisson spot, can fit this feature
  - Lateral position to sub-cm for 4-m aperture within meters of alignment
  - Can also use image gradient to move towards center (rather than fitting)



Focal-Plane Fine Sensor: Concept

- Put "dispersed" laser beacon on starshade and measure bearing between it and the centroid of the diffracted target star
  - Nearing alignment, point spread functions of star and beacon overlap
- To resolve: blink beacon, taking two images, subtract, and calculate difference between centroids (RF link used to synch starshade time to telescope to 10s of ms)
  - Star+Beacon – Star-only = Beacon-only

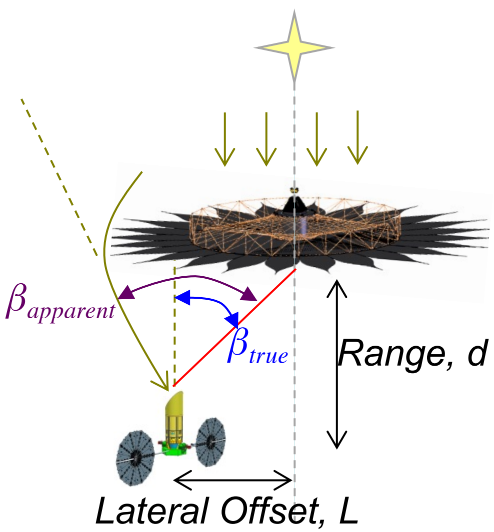


Focal-Plane Fine Sensor: Dependence on Prediction

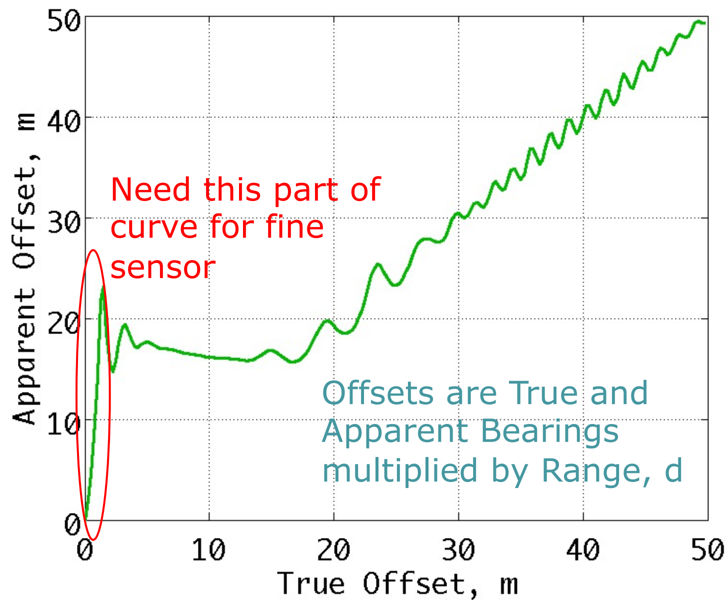
- Target star diffracted, so apparent bearing between beacon and star needs to be translated into actual bearing

- Relationship predicted from diffraction mathematics

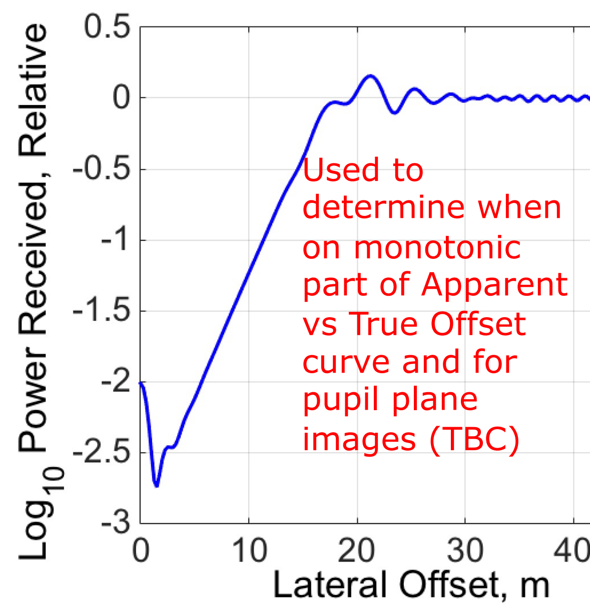
Diffraction Shifts Apparent Centroid of Target Star



Predicted **Diffraction-Based Relation Between True and Apparent Offsets**



Predicted **Shadow for Photometry/Pupil Plane**



TRL 5&6 for Fine Sensors: Overview

- S-3: “Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade’s dark shadow.”
- Fine sensors consist of
  - Pupil plane image on detector
  - Focal-plane image on detector
  - Laser beacon (20-mW diode, +/-1.2 deg FOV)
    - Physics of laser and imaging optics not tech issues
  - **“Fitting”** detector images to **predicted diffracted images**
- **Relevant Environments:**
  - **Predicting Images**: same as relevant env. for S-2: Optical Perf Demo and Model Validation
  - **Fitting Images**: images on detectors with representative noise, pixel size, point-spread functions, and photon flux

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

TRL-6

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

TRL 5&6 for Fine Sensors: Overview

- **Critical Performance:**
  - Sense lateral offset of Starshade relative to Star-Telescope line to ≤ 1.2 mas 1-sigma for spacecraft separations from 10 to 50 Mm
    - Estimator and low disturbance environment can turn this sensing level into centimeter-level knowledge
- **Medium-Fidelity Brassboard (TRL-5)**
  - **Predicting Images:** same as TRL-6
  - **Fitting Images:** same as TRL-6
- **High-Fidelity Subsystem (TRL-6)**
  - **Predicting Images:** same as for S-2 (diffraction testbed) but detector sensitive outside of science band and with precision motion stage to move detector across shadow; better than flight images
  - **Fitting Images:** separate testbed with mask, source, and representative detector (similar noise, pixel size); for FP, add beacon; for PP match aperture size and mask out footprint of secondary

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

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TRL-6

Demonstrate by tests
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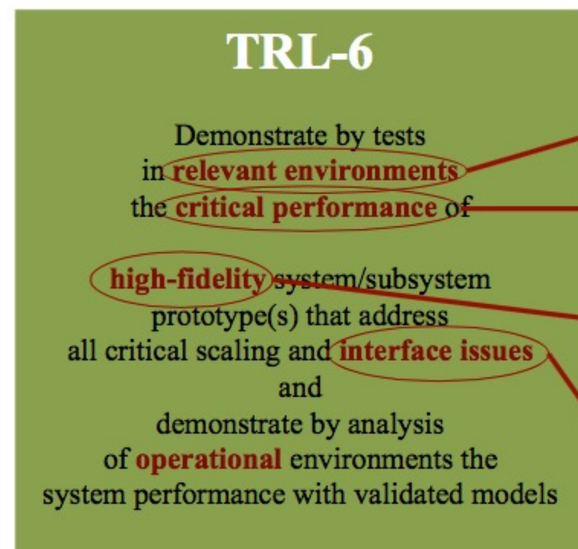
TRL 5&6 for Fine Sensors: Overview

- **Interface Issues and Operational Environments**
  - Fine sensor concepts compartmentalized
  - Create sensor models validated with test data from standalone fine sensor TRL maturation tests
  - Simulate in high-fidelity GNC environment end-to-end formation flying for re-targeting
    - Validated fine sensor models
      - For FP, effects of jitter analyzed and added to images as bearing shift
    - Sensor and actuator misalignments and noises
    - 6DOF rigid body models of spacecraft
    - Full ACS on each spacecraft
    - Sensor handoffs and estimator convergence
    - "Putting" to acquire focal-plane sensor

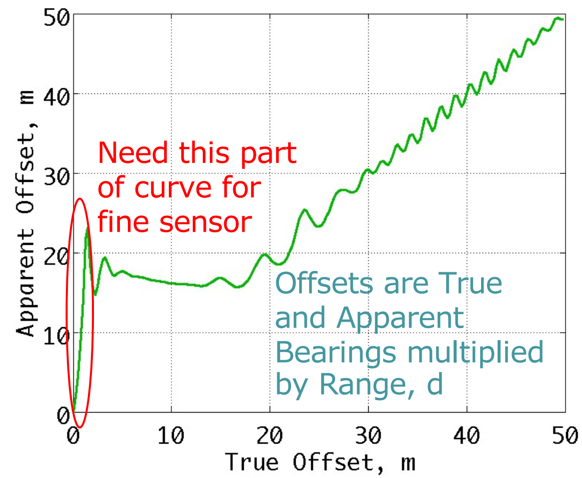


Specific TRL 5/6 Demonstration Experiments

ExoPlanet Exploration Program

- For **predicting images** for PP and FP fine sensors
  - For 3 representative masks (capture manufacturing and design variability)
  - Move detector across shadow, collecting focal and pupil plane images
    - Do **not** match flight pixel-size and SNR, but should be factors better to compare to mathematical predict
    - Images covering at least 3 lines; can be through the middle if FOV large enough
  - Do tests at Fresnel numbers corresponding to minimum and maximum spacecraft separations
  - Show predicts match images to <1% RMS (TBR)
    - Contend feedback should work with errors of this size

Predicted **Diffraction-Based Relation Between True and Apparent Offsets**



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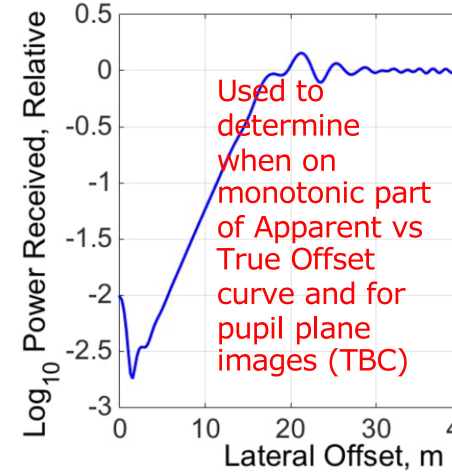
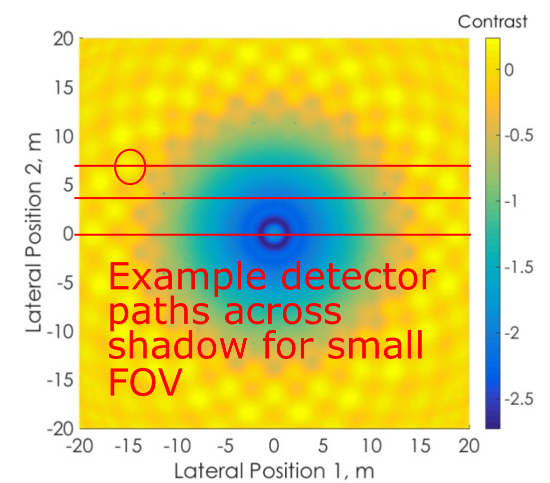




Specific TRL 5/6 Demonstration Experiments

- For **fitting images** for FP sensor,
  - Using possibly different testbed with representative photon flux from source and diffracted point spread function from mask that provides 10^{-4} contrast, and
    - Beacon on starshade (e.g., dot reflecting laser by detector) with representative flux at detector
    - Detector with representative noise and pixel-on-sky mounted on motion stage
  - Collect images with and without beacon for 20 (TBR) two-dimensional detector positions within monotonic portion of Apparent-vs-True bearing curve
  - Calculate true angular offset from differenced-and-centroided images and compare to actual angular offset of detector from motion stage
  - Show calculated true offset matches actual offset to <1.2 mas 1-sigma

Specific TRL 5/6 Demonstration Experiments

- For **fitting images** for PP sensor,
  - Contend that do not need experimental demonstration, instead...
  - For 3 masks with different simulated shape errors consistent with flight requirements; and for a 4th mask without a pronounced Poisson spot
  - Select 20 (TBR) random positions within the applicable part of the shadow
  - Generate pupil plane images from now validated math
  - Apply representative detector noises to predicted image
  - Add footprint of secondary to image
  - Apply fitting algorithm and show calculated position matches true position to <1.2 mas 1-sigma

Shape Control

Other Important Stuff: Engineering not Technology But Shown Viable

- Key to starshade performance the realization of the optical prescription on orbit
  - Petal manufacture
  - Deployment
  - Stability over environment
- Previous TDEMs have demonstrated sufficient performance to meet flight requirements
- Design aspects that are design dependent or have multiple paths to solution however important they might be are not technologies

Shape Control Demonstration

- Current starshade demonstrator is certainly a high prototype design at near flight scale with representative interfaces
  - Scaling from subscale to flight is small
- Performance of petal manufacturing and deployment measured and shown to be of sufficient accuracy
  - Don't believe me, read the TDEM reports
- Starshade shape will be affected by the flight environment, these effects have been budgeted and analyzed by many efforts by multiple groups (references next slide)
- The degradation of performance due to flight environment has been shown to be tolerable for multiple concepts of operations

Add picture of JPL Shade

TRL-6

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

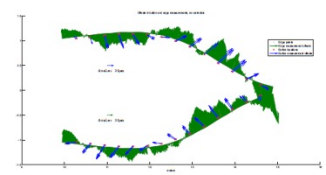
A high fidelity system/component prototype that adequately addresses all critical scaling issues

is built and operated in a relevant environment

to demonstrate operations under critical environmental conditions.

From TDEM Funded Work

- TDEM for petal development “Starshades for Exoplanet Imaging and Characterization: Key Technology Development” 2009



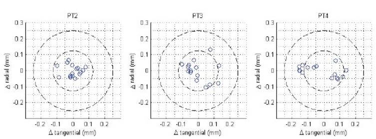
ADVANCING TECHNOLOGY FOR STARLIGHT SUPPRESSION VIA AN EXTERNAL OCCULTER 41

9. Conclusions, Lessons Learned and Future Work

As shown in this report, we exceeded our milestone goal by 30% in contrast at the worst case wavelength and closest inner working angle for the conservative case of a single set of global errors on all petals equal to that on our measured as-built petal. For the more realistic case of an occulter with random errors on each petal consistent with those seen on the as-built petal we achieved a calculated mean contrast at the inner working angle more than an order of magnitude better than the milestone (more than a factor of 5 better at the 95% confidence level). We have shown that it is possible to build an occulter petal to the stringent shape requirements for a terrestrial planet finding mission.[6]

- TDEM for deployment “Verifying Deployment Tolerances of an External Occulter for Starlight Suppression”

8. Conclusions



This report shows that we successfully met our milestone of repeated deployments with ± 0.95 and 1.6 mm accuracy in the radial and tangential directions, respectively, corresponding to a 3σ contrast of 10^{-9}. In fact, we did better than this by a substantial margin, achieving an equivalent contrast of better than 10^{-12} due to deployment errors. A system with more control over the tangential position we would achieve an even better contrast. While the experiment employed a central truss that is not the same design as an eventual flight system and didn’t allow the continuous unfurling and deploying of the petals and starshade, it did demonstrate the feasibility of meeting the stringent deployment requirements with existing mechanical systems. This retires a major technology element of starshade manufacture.

Partial List of Tolerance and Shape Control Works

- 2016 SPIE, 9904, 71, Glassman et al. Starshade starlight-suppression performance with a deployable structure
- 2015 SPIE, 905E, 2ES, Sirbu et al. Scaling relation for occulter manufacturing errors
- 2015, SPIE\\, 9605E, 0ZS, Shaklan et al. Error budgets for the Exoplanet Starshade (Exo-S) probe-class mission study
- 2014, PIE, 9151E, 1PW, Webb et al. Successful Starshade petal deployment tolerance verification in support of NASA's technology development for exoplanet mission
- 2012, SPIE, 8442E, 0AK, Kasdin et al. Technology demonstration of starshade manufacturing for NASA's Exoplanet mission program
- 2011, SPIE, 8151E, 13S, Shaklan et al. A starshade petal error budget for exo-earth detection and characterization
- 2010, SPIE, 7731, 161, Glassman, et al. Error analysis on the NWO starshade
- 2010, SPIE, 7731, 75, Shaklan et al. Error budgeting and tolerancing of starshades for exoplanet detection
- And more into the mists of the early days of starshade

Review of Meeting TRL-6

ExoPlanet Exploration Program

TRL-6 Criteria	Optical Modeling	Edge Scatter	Fine Alignment Sensing	Shape Control	
				Deployment	Petal Shape
High Fidelity System/Component Prototype	Flight like shapes at flight light F#	Flight like edges (samples)	Breadboard sensor and algorithm	Near flight scale	Flight scale
Scaling	Show analytically and experimentally that F# and D_T/D_{SS} are proper NDV	Make enough samples to prove production process statistics	Flight like light levels	Near flight scale	Flight Scale
Relevant Environment	On orbit shapes predicted by use of modeling	Performance at EOL	Performance at EOL (degraded sensor and propulsion)	Offloaded deployment	Many analyses show environment al distortion tolerable
Demonstrate Operations	By analysis using validated model	By analysis using validated model	Loop closed under EOL conditions	Operated	Manufactured
Criteria	Ground test predictions match experiment Models agree in terms of performance and sensitivity Models predict by analysis acceptable on orbit performance	Small impact to effective IWA	Ability to sense ~1mas @EOL	Derived from error budget for deployment Many analyses show environment al distortion tolerable	Derived from error budget

All Test Facilities Needed are on Earth

TRL-6 Criteria	Optical Modeling Princeton, XRCF etc	Edge Scatter NG, JPL	Fine Alignment Sensing PU, JPL, CU	Shape Control	
				Deployment Completed	Petal Shape Completed
High Fidelity System/Component Prototype	Flight like shapes at flight light F#	Flight like edges (samples)	Breadboard sensor and algorithm	Near flight scale	Flight scale
Scaling	Show analytically and experimentally that F# and D_T/D_{SS} are proper NDV	Make enough samples to prove production process statistics	Flight like light levels	Near flight scale	Flight Scale
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Summary: Option 1a

- Tests for Optical Modeling, Edge Scatter and Fine Sensing to achieve TRL-6 defined
  - Shape control adequately demonstrated by TDEMS on 2009, 2010 and analysis
- All proposed testing can be accomplished on the ground
- Area of most significant resource need is in edge scatter
- Current test facilities (or with modest investment or copy) can meet needs for Optical Model and Fine Sensing
  - If improvements in optical test facilities are needed back up option defined (see Noecker 9 June 2016 Presentation)

Summary: Option 1a

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On to L2!