ExoPlanet Exploration Program

Milestones and Performance Metrics for Occulters

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Technology Plan Appendix will be Revised in 2011

- *Exoplanet Exploration Program Technology Plan Appendix* released in April.
  - A reference document for SAT-TDEM proposals.
  - It provides a priority listing of milestones to be addressed by **coronagraphs**, taken from the TPF-C Technology Plan.
  - It suggests likely subject areas of milestones for **starshades**.
  - States that infrared interferometers are not candidate architectures for an architecture decision in 2015.
- Technology Plan will be revised before the end of 2011
- It will include a revised list of starshade milestones, negotiated with the stakeholders and approved by the Exoplanet Program.

http://exep.jpl.nasa.gov/files/exep/appendix_04_27_2011.pdf

Error Budgets and Tolerances are Implementation-specific

- *"Error budgeting and tolerancing of starshades for exoplanet detection,"* S. B. Shaklan et al., Proc. SPIE 7731 773112G (2010)
  - Proposed a standard set of starshade error sources
  - Demonstrated that independent diffraction modeling of starshades (NGAS & JPL) yielded the same sensitivities to errors for the same well-defined error sources.
  - Evaluated the tolerancing of an optimized occulter with 34-m tip-to-tip operating with a 2-m diameter telescope
  - Proposed an error budget for the example starshade.
- This was **not a trade study** between optimized and hypergaussian petal designs, nor between different methods of packaging and deployment
- Actual **error budgets and performance metrics will be implementation-specific**, and different from the example starshade
- Error budgets are subject to revision with changes in design and operations concepts, experience, and better engineering judgment

For example "A starshade petal error budget for exo-earth detection and characterization," Shaklan et al. SPIE Conf. 8151, Techniques and Instrumentation for Detection of Exoplanets V, 21-25 August 2011, San Diego, CA

Coronagraph demonstrations currently emphasize a single laboratory experiment

- Coronagraphs aim to demonstrate, through laboratory experiments in pre-Phase A, the ability to achieve 1 x 10^{-9} **contrast** at the inner working angle*, **
  - First monochromatically (**Milestone #1**).
  - Then broadband (**Milestone #2**).
- Also demonstrate experimentally that the sources of contrast degradation are well understood (**Milestone #3A**)
- And moreover demonstrate from experiments tied to a telescope model that the flight performance can be achieved (**Milestone #3B**)

- For a 4λ/D coronagraph, most other issues are left until Phase A***
  - Structural, thermal, and spacecraft technology
  - Coatings and mirror technology

- Almost everything hinges on laboratory demonstrations of contrast

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*As stipulated in the TPF-C Technology plan, the goal is to demonstrate 1 x 10^{-10}

**The goal should perhaps be "demonstrate the ability to achieve contrast sufficient to observe planets as faint as delta-mag = 26."

***We may want to revisit these assumptions if applied to 2λ/D coronagraphs

Starshade demonstrations would emphasize mechanical, thermal, and alignment technology

- You cannot demonstrate an end-to-end system validation of a **full-scale** starshade through laboratory experiments.
  - Proposed starshades are typically 10s of meters in diameter and 10s of thousands of km from the telescope.
  - The Earth's diameter is only ~13,000 km

- No single laboratory optical test will encapsulate the major design challenges or technology tall polls
  - Mechanical, thermal, and alignment demonstrations are necessary
  - The sensitivities to disturbances will be depend on the mechanical designs (petal shape and deployment method)
  - **Modeling and analysis will play a key role**

- The error budgets and performance goals are implementation-specific
  - No single performance metric will define a milestone goal.

Prospective Occulter Milestone Subjects

as listed in the Tech Plan Appendix 4/18/2011

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- Petal manufacturing. Demonstrate that a single petal can be manufactured to the design tolerances. A representative set of manufacturing tolerances shall be demonstrated that derive from known error budget allocations.
- ~~Petal~~ thermal deformation. Demonstrate that thermal deformations ~~of a petal~~ can be controlled within the budgeted tolerances for anticipated flight conditions of science operations.
- Edge scatter of sunlight. Demonstrate with a baseline external occulter design that the brightness of light scattered from the external occulter edges would be less than the brightness of exozodiacal light.
- ~~Petal~~ deployment. Demonstrate that t~~he petals of~~ a external occulter can be deployed to within the budgeted tolerances.
- Formation flying. Demonstrate that the guidance, navigation and control of a external occulter can be achieved with regard to the budgeted tolerances ~~of its lateral alignment with its telescope.~~
- Demonstrate, using the modeling approach validated against experimental results combined with appropriate telescope models and the current mission error budget, that a external occulter could achieve a baseline contrast of 1×10^{-10} over the required optical bandwidth necessary for detecting Earth-like planets, characterizing their properties and assessing habitability.

?

Future milestones in Phase A would include additional topics related to formation flying. This would include demonstrating the required dynamical stability of the petals in flight and related spacecraft technology demonstrated at the component, subsystem, and system level.

What Milestones for 2015, 2020, and beyond?

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- What set of demonstrated technology Milestones are needed, as part of a larger review, to convince a review board that starshades are
  1. the architecture of choice for a New Worlds Mission? (by 2015)
  2. ready to enter Phase A? (prior to 2020)

Possible Milestone Subjects	Before architecture selection	Prior to Phase A start	Formulation: Phase A/B
Manufacturing (edges, tips, valleys)			
Deployment (design, repeatability)			
Shape stability/control (thermal, dynamic)			
Scattered light control (edges, transmission, stability)			
Occulter/telescope alignment (GN&C, sensors)			
Propulsion (number of targets)			
Laboratory starlight suppression demonstration			
On-sky system demonstration			
End-to-end modeling (optical, mechanical, thermal)			

Starshade Technology Roadmap →

Completed Activities

Develop reference design & analytical models

Build Proof of Concept Petal & demo deploy function

→

Current Activities including TDEM 1

Build breadboard petal

Demo manufacturing tolerance

Demo shape stability w/ stow/deploy

Demo edge scatter performance

Characterize CTE at coupon level

→

Future Activities at TDEM funding level

Demo thermal deformations

Characterize CTE at assy level

HW in-the-loop Stationkeeping

Precision metrology (if needed)

→

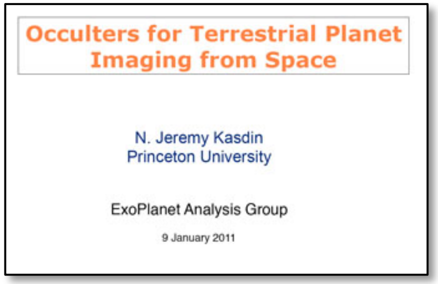
Future Activities at >> TDEM funding level (pre-Phase A)

Develop system prototype Including truss

Demo deployment accuracy

Validate structural model

Courtesy of N. J. Kasdin et al.
(D. Lisman, JPL/Caltech)


Occulters for Terrestrial Planet Imaging from Space

N. Jeremy Kasdin
Princeton University

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9 January 2011

NWO Starshade Technology Development Plan

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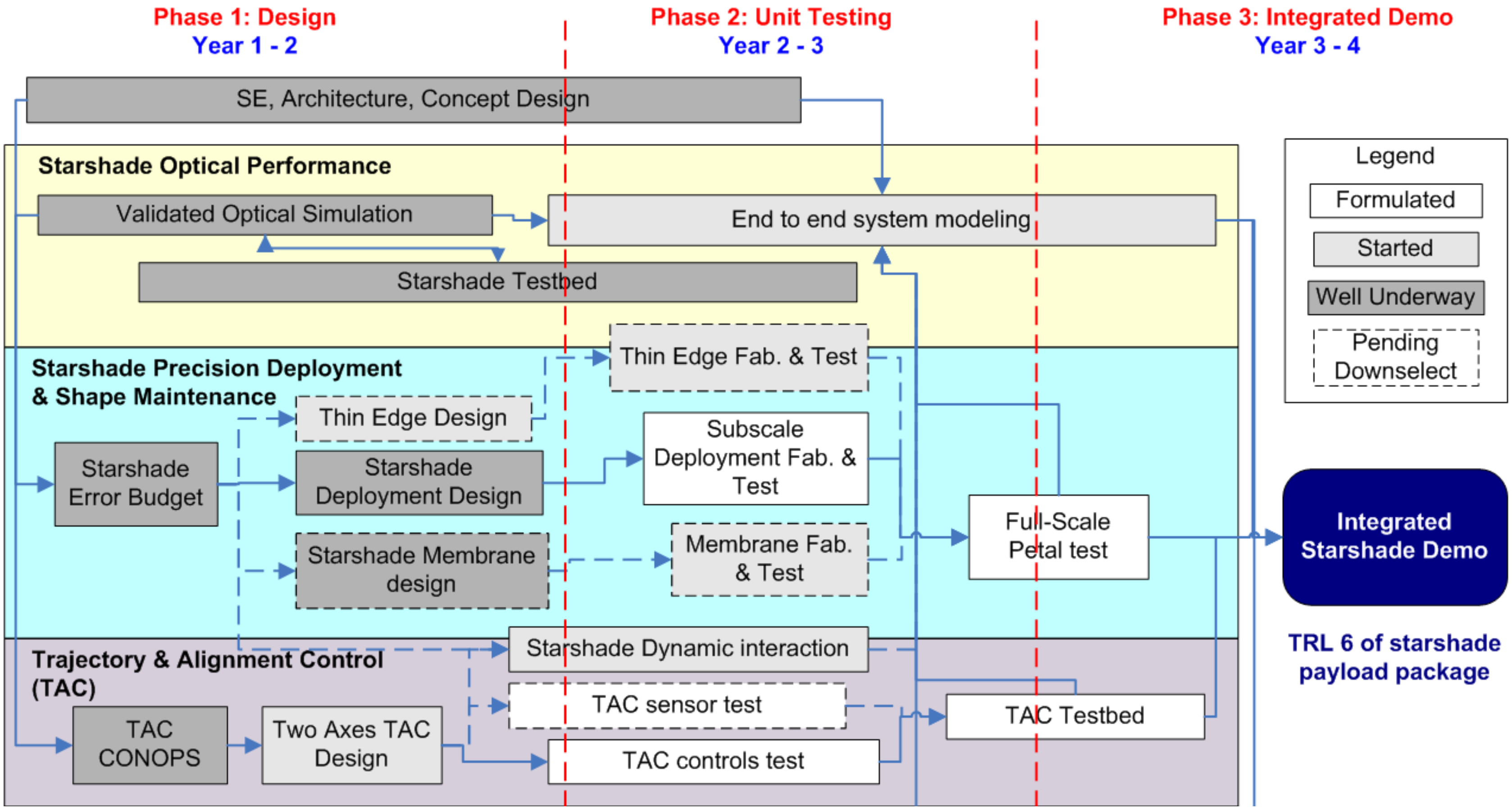

Courtesy of W. Cash et al.
(A. Lo, NGAS)

Combined Starshade Roadmap (version 3.1)

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	Work to Date	Year 1 (2011-12)*	Year 2 (2012-13)*	≥ Year 3 (≥ 2013-14)*
System Engineering	Concept design, error budget & tolerancing	Concept design, error budget & tolerancing	End-to-end system modeling	End-to-end system modeling
Optical	Optical simulations Thin edge design,	Validated optical simulations, Demo edge scatter	Thin edge fab & test	
Mechanical	Deployment design, Proof of concept petal & demo deployment	Build breadboard petal, Demo manufacturing tolerances, Demo shape stability stow/deploy, Membrane design	Subscale deployment fab & test, Membrane fab & test	Integrated starshade demo, full-scale prototype including truss, Demo deployment accuracy, Validate structural model
Thermal		Characterize CTE at coupon level	Demo thermal deformations, Characterize CTE @ assembly level	
Formation Alignment & Control	Trajectory & alignment control CONOPS	Two-axes alignment control	Starshade dynamical interactions, sensor tests, Precision metrology, HW in the loop station-keeping,	HW in the loop station-keeping

*Approximate timeline

Perspective

- Lawson will propose a series of telecons and/or meetings to arrive at a prioritized list of milestones before the end of October 2011
- The discussions will be announced through the ExoPAG email list
- All members of the community are invited to participate
- The updated milestone list will be included in the revised Technology Plan Appendix, to be released before the end of 2011.

Backup

N. J. Kasdin et al.
Starshade Technology

Occulters for Terrestrial Planet Imaging from Space

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Princeton University

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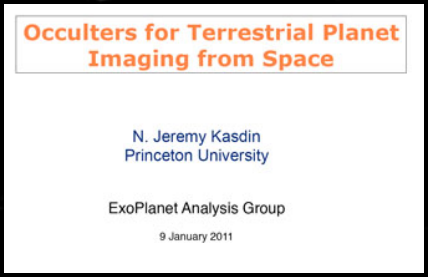
Technology Challenges

To design and build an occulter that satisfies the requirements and constraints:

- Precision edge shape
- Deployment accuracy
- Validated optical models (software and lab)
- Sensing and Formation control
- Thermal variations
- Dynamic stability
- Solar Glint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. . . and develop verification and validation aproaches.

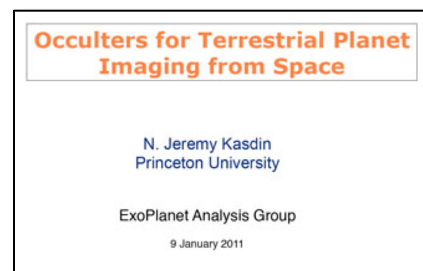
Starshade Technology Tall Poles

Tallest Poles

- Petal manufacturing tolerance = ± 25 μm in width for max width of 2.5m
- Petal thermal deformation tolerance = ± 25 μm in width for ΔT up to 100 °C
  - Need CTE of ± 0.1 ppm/°C, stock material gives ± 0.16 ppm
- Edge scatter of sunlight ≤ Exo-zodi, expect radius of curvature < 50 μm

Poles of Lesser Stature

- Petal deployment tolerance = ± 1mm at root and ± 2.5 cm at tip
  - Inner disk truss controls root position & heritage antennas have demonstrated this capability
- Occulter alignment with telescope = ± 1.5 m (excess shadow relative to aperture)
  - Occulter position error is sensed by dedicated channel of exoplanet camera, at long wavelengths, and transmitted to occulter
  - Control loop time is long (typically > 200s) for μg differential gravity between spacecraft
- In-plane dynamic deformations
  - Short transients are OK and truss quickly damps transients from bus (e.g., thruster firings)
  - Petals are stiff relative to truss and do not participate in system modes
- Petal shape stability with stow/deploy cycles
  - Members that control width are not stressed in stowed configuration



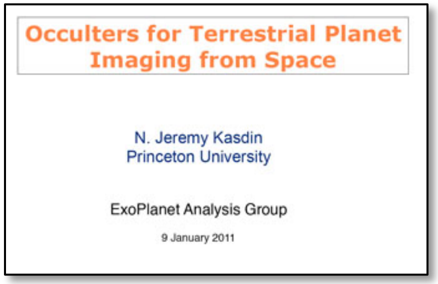
Why we should worry about "downselecting" too early . . .

Or, what keeps me up at night . . . it is not about losing.

- It may be impossible to find a combination of materials with low enough CTE for an occulter to maintain its shape over wide swings in temperature and thermal gradients.

- It may be impossible to achieve the picometer precision needed on a DM to get ~ 10^{-11} contrast (laws of physics might work against us)

- It may be impossible to make a ≥ 4 m telescope stable enough to maintain contrast between corrections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W. Cash et al.
Starshade Technology

NWO Tall Poles

- Deployment of 50m shade to cm class tolerances
- Acquiring and holding line of sight
- Fuel usage, orbits and number of targets
- Stray Light – particularly solar

NWO Starshade Critical Technology

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Enabling Technologies

Precision Shape Control
•Maintain edge position
•Maintain structure shape

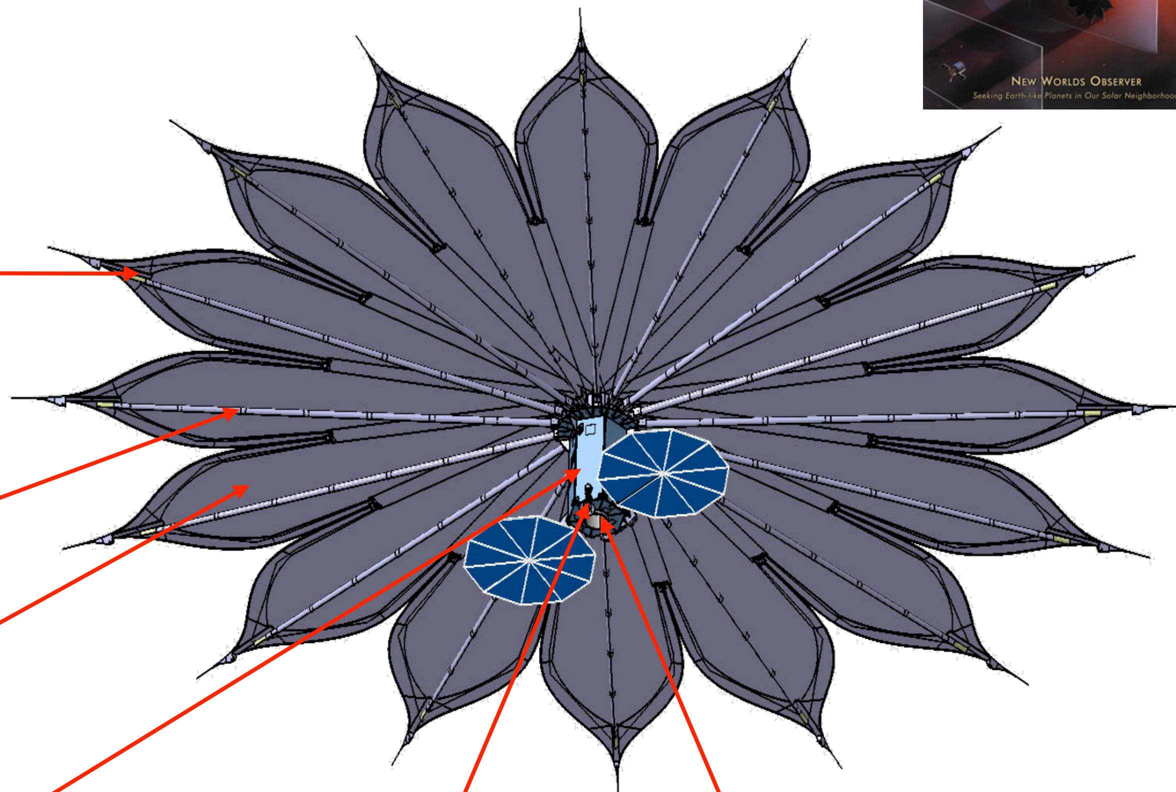
Thin Edge Treatment
•Maintain edge stability
•Minimize stray light

Precision Deployment
•Minimize jitter
•Maintain petal location

Opaque Membrane
•Maintain opacity
•Lightweight

2 Axes Formation Flying
•Maintain 1m alignment
•Minimize jitter

Enhancing Technologies



Solar Electric Propulsion
•NEXT engine
•Increase observable targets
•Reduce propellant mass

Lightweight S/C Structures
•Increase observable targets
•Reduce overall mass

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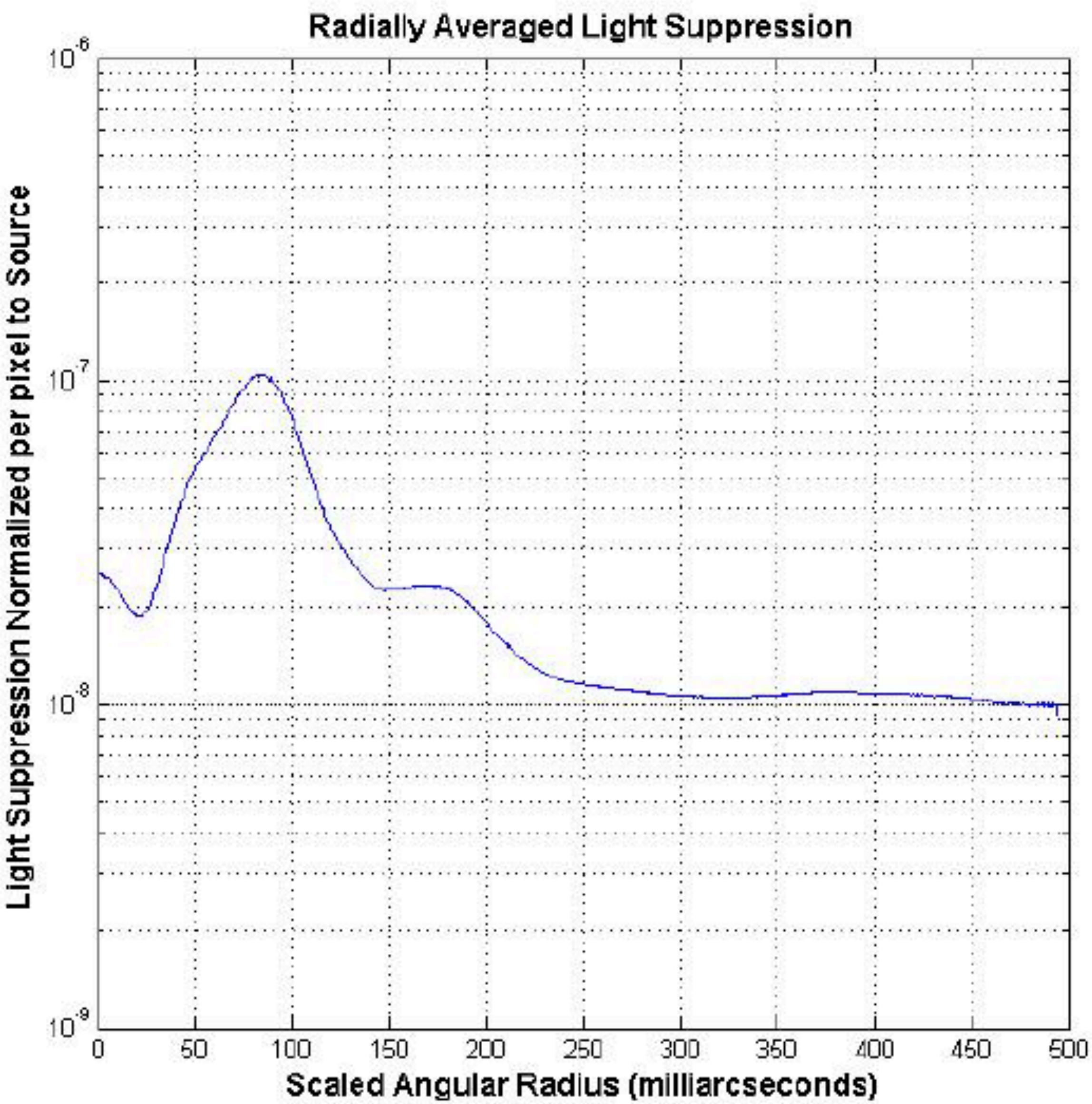
Selected Experimental Results

Starshade testbed results: Samuele et al. NGAS 2009



Samuele et al, "Starlight Suppression from the starshade testbed at NGAS," Proc. SPIE 7440, 744004 (2009)

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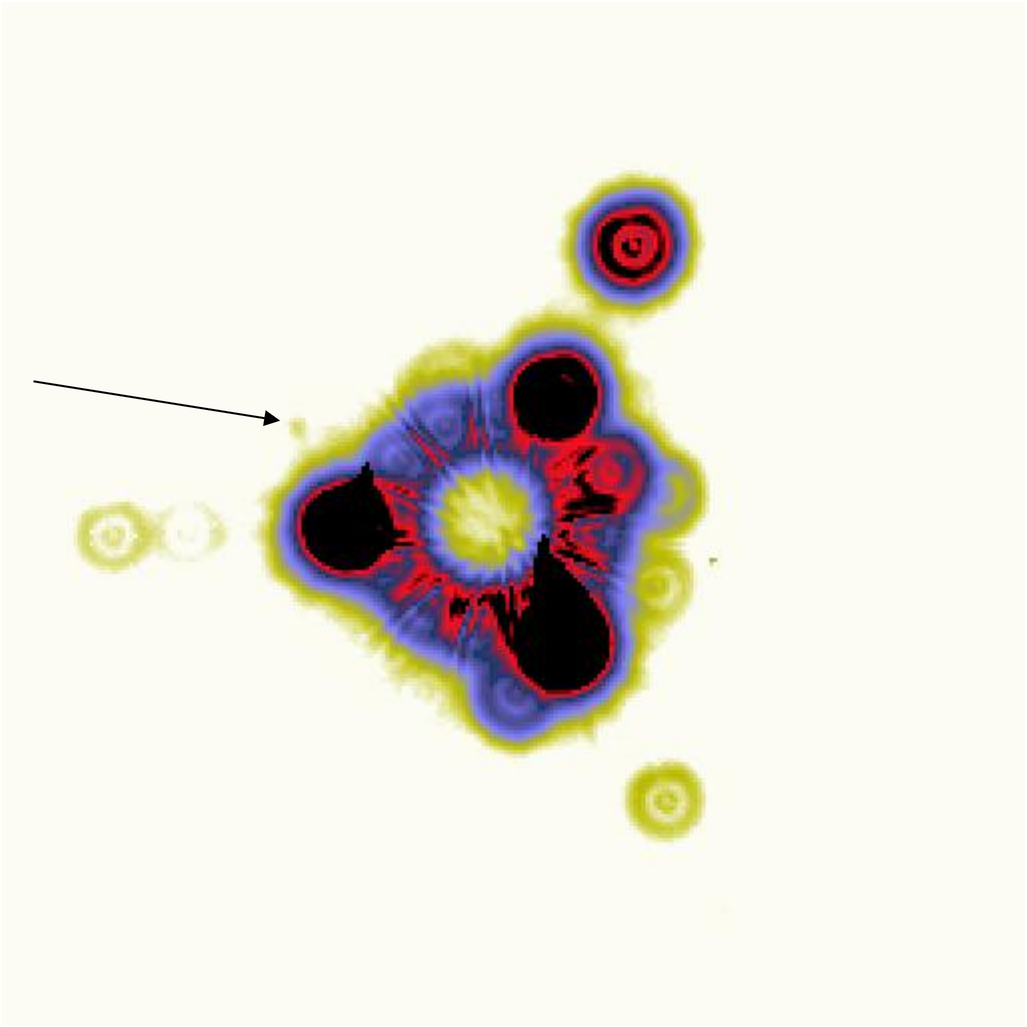
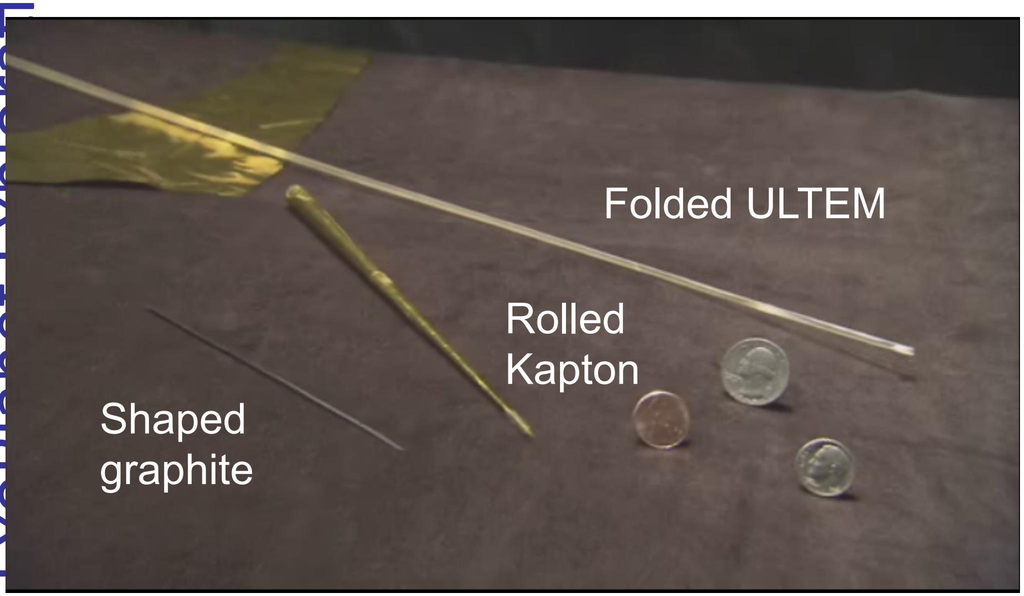
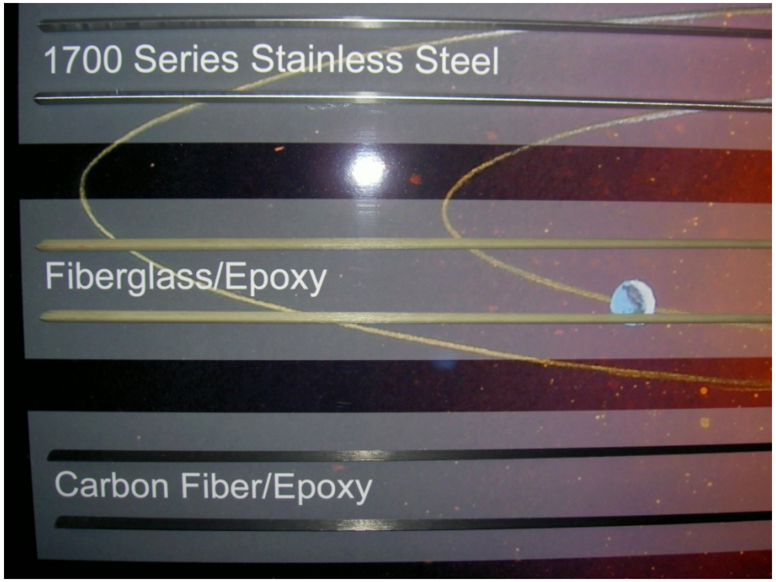


NGAS Starshade Petal Tips

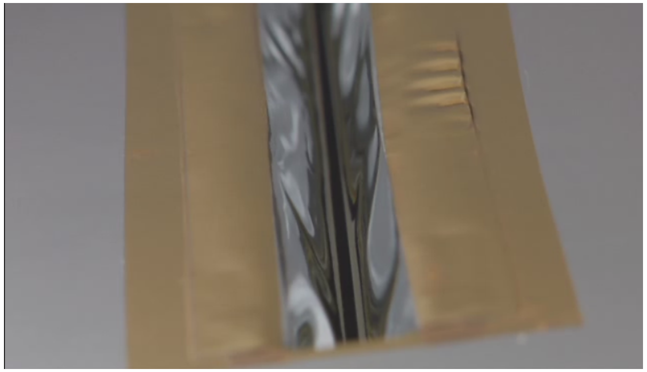
- Thinnest component of starshade, with hypergaussian taper to 100µm
- Design needs to survive handling, integration & test, stowing, launch, and deployment
- Primary focus is to investigate:
  - Range of materials that will meet tip requirements
  - Manufacturing processes

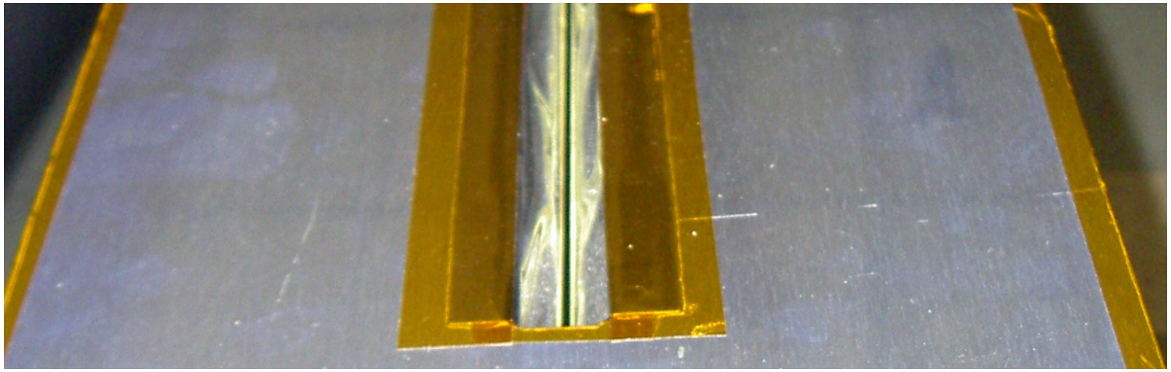




NGAS Starshade Valleys

- Starshade petals come together to form the valley, a negative of the tip
- Focus on maintaining a hypergaussian separation between petals
- We plan to investigate affects such as thermal expansion and material stress deformation





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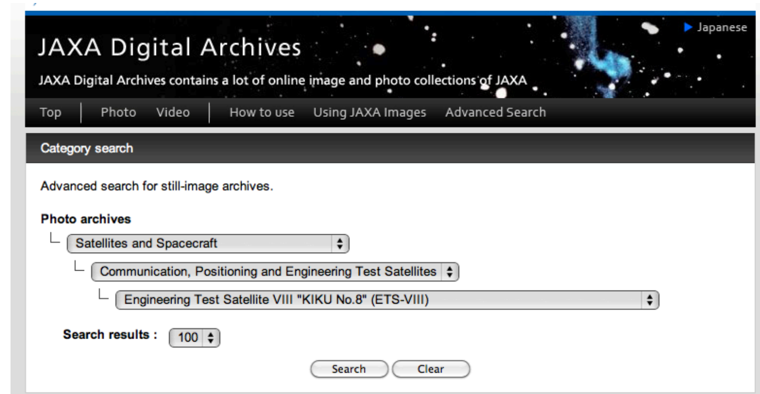
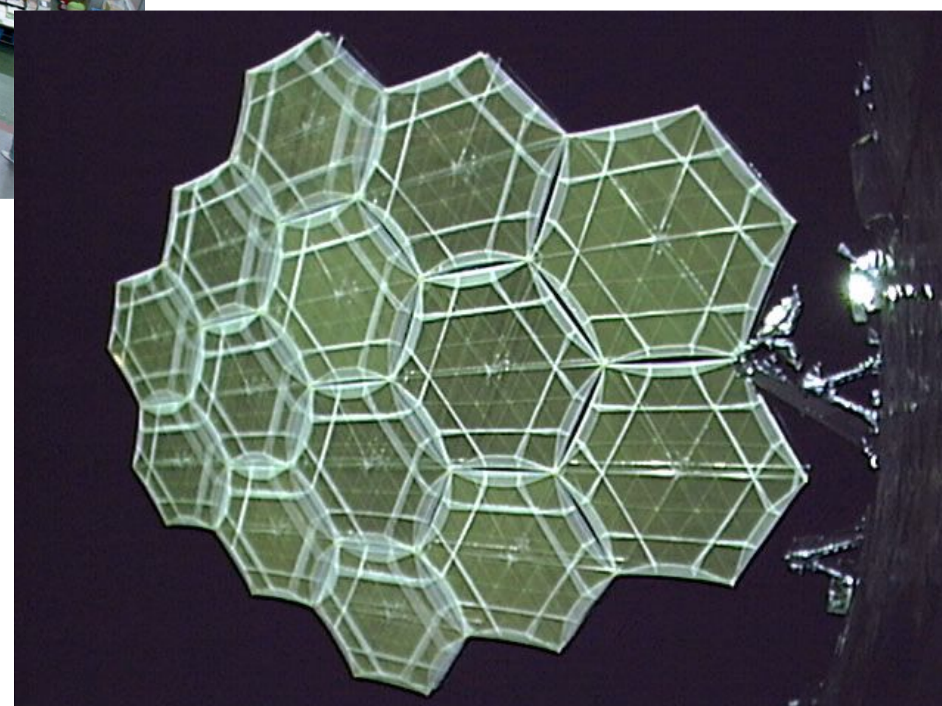
JAXA Engineering Test Satellite VIII "KIKU No. 8"





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http://jda.jaxa.jp/

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