Probe Class Starshade Mission
STDT Progress Report

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“Can we find another planet like Earth orbiting a nearby star? To find such a planet would complete the revolution, started by Copernicus nearly 500 years ago, that displaced Earth as the center of the universe. . . The observational challenge is great, but armed with new technologies. . . astronomers are poised to rise to it.”

–New Worlds, New Horizons, 2010
Starshade Study Context

• The discovery of ExoEarths, via a space-based direct imaging mission, is a long-term priority for space astrophysics (Astro 2010)

• Exo-S is an 18-month NASA HQ-funded study of a starshade and telescope “probe” space mission (5/2013 to 1/2015)
  – Total mission cost: <$1B (FY15 dollars)
  – Technical readiness: TRL 5 by end of Phase A, TRL 6 by end of Phase B
  – New start in 2017, launch in 2024
  – Science must be beyond the expected ground capability at end of mission

• This is the first time NASA has formed an STDT to study the starshade

• Although presently a “back up” to AFTA/WFIRST, the team considers the study a key formulation in the path to identifying Earth-like exoplanets
Starshade Concept

- Contrast and inner working angle are decoupled from the telescope aperture size
  - A simple space telescope can be used
  - No wavefront correction is needed
- No outer working angle

Separation distance
- 37,000 km
- ±250 km

±1 m lateral control

Telescope diameter 1.1 m

Starshade diameter 34 m
Exo-S Baseline Design Overview

<table>
<thead>
<tr>
<th>Band</th>
<th>Blue</th>
<th>Green</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelengths (nm)</td>
<td>400–630</td>
<td>510–825</td>
<td>600–1,000</td>
</tr>
<tr>
<td>IWA (mas)</td>
<td>75</td>
<td>95</td>
<td>115</td>
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<tr>
<td>Separation (Mm)</td>
<td>47</td>
<td>37</td>
<td>30</td>
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</tbody>
</table>

Off-the-shelf on-axis optical telescope (1.1-m NextView)
Heliocentric, Earth-drift away orbit (Earth-Sun L2 is also a possibility)
Move telescope, not starshade for retargeting
Instrumentation: imager and low-resolution spectrograph
Science Goal #1: Photometric Search for New Exoplanets

- Discover planets from Jupiter-like planets down to rocky planets orbiting nearby Sun-like stars
- Image rocky planets in a Sun-like star’s habitable zone
- Discover multiple planets and circumstellar dust, around target stars

Earth as seen from Voyager I from 4 billion miles
Science Goal #2: Spectral Characterization of New Exoplanets

- Spectra of newly discovered planets from 400–1000 nm, with a spectral resolution $R = 70$
- Spectra of mini Neptunes to ascertain the very nature of the low-density, extremely common, yet mysterious planets
- Potential for rocky planet spectra, for a handful of favorable target stars

Credit: Science News 2010
Science Goal #3: Spectroscopy of Known Jupiters

- Spectra of 17 known Jupiter-mass exoplanets
- Spectral characterization from 400–1000 nm, with a spectral resolution $R = 70$
- Molecular composition and presence of clouds or haze will inform us of the diversity of giant planet atmospheres
- Comparative planetology with a variety of Jupiter-type exoplanets

The known Jupiters are detectable by virtue of extrapolated position in 2024 timeframe
### Target Stars in the Preliminary DRM

<table>
<thead>
<tr>
<th>Target</th>
<th>Target Angles (deg)</th>
<th>Durations (days)</th>
<th>∆V (m/s) &amp; Propellant Mass (kg)</th>
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<tbody>
<tr>
<td></td>
<td>Longitude</td>
<td>Latitude</td>
<td>Slew</td>
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<td>Longitud #</td>
<td>Latitutde</td>
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### Additional Information

- This document has been cleared for public release. Release CL#14-0952
- Target Stars in the Preliminary DRM
- ExoPlanet Exploration Program
- Starshade STDT Progress Report
### Starshade Probe Mission: Targets in the Current DRM

<table>
<thead>
<tr>
<th>Name</th>
<th>d(pc)</th>
<th>L(L$_{\text{sun}}$)</th>
<th>Spectral Type</th>
<th>Search Comp.</th>
<th>Known planets</th>
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<tbody>
<tr>
<td>$\tau$ Ceti</td>
<td>3.7</td>
<td>0.5</td>
<td>G8.5V</td>
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<td>$\beta$ CVn</td>
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<td>$\delta$ Pav</td>
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<td>G8IV</td>
<td>0.46</td>
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<tr>
<td>82 Eri</td>
<td>6.0</td>
<td>0.7</td>
<td>G8V</td>
<td>0.65</td>
<td>3</td>
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<tr>
<td>$\eta$ Cas</td>
<td>5.9</td>
<td>1.3</td>
<td>G3V</td>
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<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>u And d</td>
<td>13.5</td>
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<td>F8V</td>
<td>1.00</td>
<td>4</td>
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<tr>
<td>47 Uma b, c</td>
<td>14.1</td>
<td>1.7</td>
<td>G0V</td>
<td>1.00</td>
<td>3</td>
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<tr>
<td>HD 128311 c</td>
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<td>Pollux b</td>
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<td>$\epsilon$ Eri b</td>
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<td>0.4</td>
<td>K2V(k)</td>
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<td>1?</td>
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- 16 additional “Jupiter search” targets for a total of 53 stellar systems explored in 22 months
- Targets span a range in spectral types: F, G, K, even a few giants
- Targets span a range of ages: 1–10 Gyr
- Targets span a range of metallicity: -0.5 < [Fe/H] < +0.3
- Several “classic favorites” with bright nearby companions are *not* included
- $\alpha$ Cen is not included (bright binary, large projected diameters)

20 targets with high HZ completeness to search for Earth analogs

17 targets with 19 known giant planets at favorable elongation for characterization
Preliminary Observing Strategy

- The prime mission is 3 years; a 22 month example observing schedule is shown with targets sequential in longitude; an additional year is available for revisits and spectroscopy
- Observation times are approximately 1 to 5 days and retargeting times are about one week
- Observations include multi-color imaging to identify planet candidates and spectroscopy for known Jupiters and newly discovered planets
- Disk science and search for Jupiter analogs around all stars
- The observing schedule is adaptable to real-time discoveries
Launch Configuration

- Telescope and starshade fit in the low cost intermediate-class L/V 5-m fairing
- Total launch mass is 2,140 kg vs. 3,550-kg launch capacity for 66% launch margin
- Starshade carries loads through existing central cylinder
- Two spacecraft separate on-orbit
FULLY DEPLOYED OBSERVATORY

OFF-THE-SHELF TELESCOPE:
Commercial Earth Imager
4 operational, 5th to launch in 2014
Sunshade is only mod—mounts to cover door assembly, not barrel

PROBA-3 BUS:
Commercial bus
In dev. For external occulter mission
formation-flying demo
Planned launch is 2017
Primary mod is to add electric propulsion
Also add: HGA, X-band, larger RWs

ELECTRIC PROPULSION:
Provides 5 km/s ΔV for retargeting
Redundant T6 ion thrusters by bus vendor
(3,800s Isp, 254 mN thrust, 4.5 kW power)
All SEP components are heritage from ESA’s Bepi Colombo mission to Mercury
Starshade Deployment

Stowed after observatory separation

Petals start to unfurl

Petals continue to unfurl

Inner disk deploys, pushing petals into position

Petals completely unfurled
**Deployed Starshade**

**Starshade System:**
Spins (3-min period) for improved planet detection
Blankets are Black Kapton, with spaced layers to limit direct light paths to telescope from micrometeoroid holes

**Starshade Bus:**
Simplified copy of telescope bus, with repackaged avionics
Conical structure transfers loads from observatory to starshade
Fixed solar panels mount to starshade deck
Instrument Design

- Exo-S instrument is small and simple
- Integrates 3 functions (planet camera, guide camera, and spectrometer) on 2 detectors on a single focal plane
- Planet camera includes capability for 3 color measurement ($R = 7$) and 1 of 2 polarizers
- Throughput is high (~50% cameras, ~40% spectrometer)
- Fast steering mirror provides pointing stability at >1 Hz and aligns slit on selected planet
  - Control loop is closed around guide camera
Preliminary Cost Estimate

- Exo-S concept meets the Charter’s requirement of a total mission cost below $1B
- Existing capability is highly leveraged for existence-proof baseline design*
  - Observatory and starshade spacecraft buses are based on designs used by ESA for their formation-flying solar occulting mission Proba III
  - The telescope is the fifth build of a 1.1m commercial design
  - The ground system and operations will follow the Kepler model
- CATE Plans
  - Aerospace Corp. will provide an independent cost estimate through the Cost and Technical Evaluation (CATE) process
  - The Design Team will hold meetings with the CATE team to review key design issues in detail this month
  - CATE team will provide 3 estimates over the next year
    - The STDT will iterate the concept design based on these estimates

*Bus and telescope designs are for existence-proof demonstration only. Flight selection will be made through competitive bid.
Basis for Preliminary Cost Estimate

- Most of the estimate is based on objective models and Kepler actual costs:
  - Instrument cost – NASA Instrument Cost Model v5 (NICM)
  - Telescope cost – Luedtke and Stahl telescope cost model published in SPIE’s *Optical Engineering* in 2012 and 2013
  - Spacecraft and ATLO costs – The Aerospace Corp. Small Satellite Cost Model 2010 (SSCM10)
    - Grass root electric propulsion estimate added to SSCM10. SSCM10 lacks EP estimate capability
  - Science, ground system, and most of operations came from Kepler actual costs as reported by NASA
- The starshade lacks direct analogies – its estimate is based on expert judgment drawing from large deployable antenna development efforts
  - A grassroots estimate and a Price-H model estimate of the starshade will be developed for the final report
- Exo-S is holding 30% reserves
Probe studies are directed to be based on a Phase A start at the beginning of FY17, project PDR in FY19, and a launch no later than 12/31/2024. The schedule includes funded schedule reserves per JPL Design Principles.
Summary of Critical Technologies

**Optical Model Validation**
- Experimentally demonstrate that models predict performance to $10^{-11}$ contrast

**Precision Deployment and Shape Control**
- Build structure that meets shape requirements
- Deploy accurately and with high reliability
- Maintain shape during on-orbit disturbances such as jitter and thermal gradients

**Long Distance Formation Flying**
- Sense cross-track alignment errors between starshade and telescope
- Control relative position of starshade and telescope line of sight

**Stray Light Control**
- Mitigate scattering of sunlight off edge of starshade petals
- Control transmission of sunlight and starlight through membrane
Starshade Technology Readiness Plan

**Already Complete**
- Assess State of Art Capabilities
- Identify Technology Gaps and Maintain List
- Develop Requirements and Error Budgets
- Develop Mathematical models
- Design tools
- Component testbeds
- Validate Math. Models
- Solar edge scatter
- Starlight edge diffraction (preliminary)
- Develop System Testbed

**Current & Funded**
- Technology Maturation
  - Blanket system prototype
  - Inner disk structure with no outriggers to deploy
- Resolve Residual Tall-Poles
  - Optical-edge mech. design
  - Starlight edge phenomena
  - Complete optical model validation at flight levels
- Develop System Testbed
- Develop Formation Flying Algorithms & Demo on Testbed

**Future & Unfunded**

2017:
- Pre-Phase A
  - Demo Perf. with Subsystem Prototypes (TRL-5)
    - Petal
    - Inner disk structure
    - Launch restraint & deployment control

2024:
- Phase A/B
  - Demo Perf. with System Prototype (TRL-6)
- Phase C/D
  - Qualify Proto-Flight System (TRL-8)
- Phase E
  - Demo On-orbit perform (TRL-9)
Lab experiments at Princeton and NGST have demonstrated contrasts close to flight levels for large flight versions.

Contrasts have been demonstrated at 1% scale: Glassman et al. 2013.

Desert field testing has demonstrated contrasts at $10^{-7}$: Glassman et al. 2013.

NASA funded effort is directed at larger-scale experiments closer to flight geometry and in broadband light to completely verify the propagation models.
Petal Prototype and Deployment

Full-scale petal prototype with the petal width profile manufactured to required tolerances. JPL facility.

Subscale (2/3) partial starshade prototype. 25 deployment cycles demonstrated deployed positions to within required tolerances. NGC facility.
Starshade Stowage and Deployment
STDT Next Steps

Baseline Probe Design
- Refine Design Reference Mission and science yield simulations
- Complete trades for the baseline design of starshade + telescope system

“Starshade Ready” Design
- Starshade design for a future or existing telescope (e.g., NRO)
- Starshade readiness of telescope

Technology Development
- Priorities recommended by STDT
- Where technology development will continue by the community through competed NASA technology programs; some STDT members participating

Occulter with 2.4-m NRO telescope stacked on top
The starshade probe-class mission is the only way to reach down to rocky exoplanets with a relatively small space telescope.

The planet-star flux contrast and IWA are nearly independent from the telescope aperture size.

Technology progress is on track for a new start in 2017.
ExoPlanet Exploration Program

Starshade Technology “Gap List”

Table A.4 Starshade Technology Gaps Listed in Priority Order.

<table>
<thead>
<tr>
<th>ID</th>
<th>Title</th>
<th>Description</th>
<th>Current</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1</td>
<td>Control of Sunlight Scattered from Starshade</td>
<td>Sunlight scattered from starshade edges and surfaces risk being the dominant source of measurement noise.</td>
<td>Several preliminary designs of edge shapes have been studied through laboratory tests having edge radius ( \geq 10 , \mu m ).</td>
<td>Edges manufactured of high flexural strength material with edge radius ( \leq 1 , \mu m ).</td>
</tr>
<tr>
<td>S-2</td>
<td>Validation of Starshade Optical Models</td>
<td>Experimentally validate the equations that predict the contrasts achievable with a starshade.</td>
<td>Experiments have validated optical diffraction models at Fresnel number of ( \sim 100 ) to contrasts of ( 4 \times 10^{-19} ), but with poor agreement near petal valleys and tips.</td>
<td>Experimentally validate models of starlight suppression to ( \leq 1 \times 10^{-11} ), and perturbation intensities to 20% at Fresnel number of 10-20.</td>
</tr>
<tr>
<td>S-3</td>
<td>Starshade Deployment</td>
<td>Demonstrate that a starshade can be deployed to within the budgeted tolerances.</td>
<td>Millimeter-wave mesh antennas have been deployed in space with diameters up to 17m x 19m and a out-of-plane accuracy of 2.4-mm.</td>
<td>Demonstrate using a half-scale or larger prototype the budgeted in-plane deployment tolerances, which are millimeter to sub-millimeter depending on the specific error terms.</td>
</tr>
<tr>
<td>S-4</td>
<td>Petal Prototype Demonstration</td>
<td>Demonstrate a high-fidelity prototype starshade petal.</td>
<td>Low-fidelity petals have been assembled and precision petal manufacturing has been demonstrated.</td>
<td>Demonstrate a fully integrated petal, including blankets, edges, and deployment control interfaces.</td>
</tr>
<tr>
<td>S-5</td>
<td>Formation Flying G&amp;C</td>
<td>Demonstrate that the G&amp;C system for an occulter will enable the required slew from star to star and positional stability for science observations.</td>
<td>Simulations have shown that sensing and G&amp;C is tractable, though sensing demonstrations of lateral control has not yet been performed.</td>
<td>Sensors demonstrated with errors ( \leq 0.25 , m ). Control algorithms demonstrated with lateral control errors ( \leq 1 , m ).</td>
</tr>
</tbody>
</table>


This document has been cleared for public release. Release CI #14-0952
## Mission Options

<table>
<thead>
<tr>
<th>Option</th>
<th>Telescope</th>
<th>Launch Config. &amp; Vehicle</th>
<th>Orbit</th>
<th>Propulsion Responsibility*</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Small dedicated (1.1-m Telescope)</td>
<td>Occulter + Telescope on low cost intermediate-class L/V</td>
<td>Earth Leading</td>
<td>Telescope System</td>
<td>Baseline for Interim Report</td>
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<tr>
<td>2</td>
<td>Larger shared existing telescope</td>
<td>Occulter separately on low cost intermediate-class L/V, rendezvous with telescope</td>
<td>Earth-Sun L2</td>
<td>Occulter</td>
<td>Deferred to Final Report</td>
</tr>
<tr>
<td>3</td>
<td>Larger shared existing telescope</td>
<td>Occulter + Telescope on intermediate-class L/V</td>
<td>Earth-Sun L2</td>
<td>Occulter</td>
<td>Deferred to Final Report, studied briefly for SALSO RFI</td>
</tr>
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* For retargeting maneuvers and formation control

Options 2 and 3 require telescope to launch “starshade ready”, with instrument, guide camera, and radio system for inter-spacecraft communications
# Error Budget

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<th>Error Source</th>
<th>Tolerance Allocation</th>
<th>Contrast Allocation</th>
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<td><strong>Petal Manufacture</strong></td>
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<tr>
<td>Segment Placement</td>
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<td>1.00E-11</td>
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<tr>
<td>Segment Shape</td>
<td>+/- 80 um</td>
<td>1.00E-11</td>
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<td><strong>Petal Deployed Position</strong></td>
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<td>Radial (common to all petals)</td>
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<td>Random Radial</td>
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<td>Tangential</td>
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<td>Elliptical truss deformation</td>
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<td><strong>Thermal Deformations</strong></td>
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<td>Monotonic gradients</td>
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<td>Semi-Random errors</td>
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<td><strong>Formation flying</strong></td>
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<td>+/− 1 m lateral</td>
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<td><strong>Glint and Leakage</strong></td>
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<td>Solar glint calibration residual</td>
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<td>Micrometeoroid transmission</td>
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<td><strong>TOTAL</strong></td>
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