EXO-S FINAL REPORT PRESENTATION TO NASA APS

Aki Roberge
on behalf of the Exo-S Team
March 18, 2015

Exo-S: Starshade Probe-Class
Exoplanet Direct Imaging Mission Concept

Exoplanet Exploration Program
Jet Propulsion Laboratory, California Institute of Technology
Exo-S Study Charter

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

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

- Study also intended as a design input to the exoplanet community to help formulate ideas for the next Decadal Survey
Exo-S Team Members

STDT

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Two Cost Constrained Exo-S Concepts

- **Exo-S Dedicated Co-Launched Mission**
  - Starshade and telescope launch together to conserve cost
  - Telescope: low-cost commercial Earth observer, 1.1 m diameter aperture
  - Starshade: 30 m diameter
  - Orbit: heliocentric, Earth-leading, Earth-drift away
  - Retargeting: by the telescope spacecraft with solar-electric propulsion
  - Three year Class B mission

- **Exo-S Rendezvous Mission**
  - Starshade launches for a rendezvous with an existing telescope
  - Telescope: WFIRST/AFTA 2.4 m is adopted
  - Starshade: 34 m diameter
  - Orbit: Earth-Sun L2 (assumption for the purposes of the Exo-S study)
  - Retargeting: by the starshade spacecraft with chemical propulsion
  - Three year Class C mission
  - Minimal impact to current mission design
    - No stringent requirements are imposed on the WFIRST/AFTA spacecraft
    - No new instrument, only modification to the existing coronagraph
- Contrast and IWA decoupled from telescope aperture size
- No outer working angle
- High throughput, broad wavelength bandpass
- High quality telescope not required
  - Wavefront correction unnecessary
- Retargeting requires long starshade slews (days to weeks)
WFIRST/AFTA + Starshade
simulated image of
Beta Canum Venaticorum
plus solar system planets
(8.44 pc, G0V)

Earth

Venus

Jupiter

Saturn

Hypothetical dust ring
at 15 AU

Background
galaxy

Image credit: M. Kuchner
1. Discover new exoplanets from giants down to Earth size

2. Characterize new planets with R=10 to 70 spectra

3. Characterize known giant planets with R=70 spectra and constrain masses

4. Study planetary systems including circumstellar dust
   - Locate dust parent bodies
   - Evidence of unseen planets
   - Exozodi assessment for future missions

Simulated R=70 planet spectra for the Rendezvous mission, with three representative 10% error bars. Dedicated mission cannot reach R=70 on small planets.
### Key Capabilities

**Instruments:** Wide-Field Imager, Integral Field Spectrograph, Guide Camera

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Parameters</th>
<th>Observing Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Blue</td>
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<tr>
<td>Rendezvous Mission</td>
<td>Bandpass (nm)</td>
<td>425-602</td>
</tr>
<tr>
<td>20m inner disk</td>
<td>IWA (mas)</td>
<td>70</td>
</tr>
<tr>
<td>28 7m petals</td>
<td>Separation (Mm)</td>
<td>50</td>
</tr>
<tr>
<td>Dedicated Mission</td>
<td>Bandpass (nm)</td>
<td>400-647</td>
</tr>
<tr>
<td>16m inner disk</td>
<td>IWA (mas)</td>
<td>80</td>
</tr>
<tr>
<td>22 7m petals</td>
<td>Separation (Mm)</td>
<td>39</td>
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</tbody>
</table>

#### FoV (arcsec)

<table>
<thead>
<tr>
<th></th>
<th>Imager</th>
<th>IFS</th>
</tr>
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<tr>
<td>10</td>
<td>10</td>
<td>2</td>
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<tr>
<td>60</td>
<td>60</td>
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</table>

#### Throughput

<table>
<thead>
<tr>
<th></th>
<th>Imager</th>
<th>IFS</th>
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<tr>
<td>10</td>
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<tr>
<td>60</td>
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<td>3</td>
</tr>
</tbody>
</table>

Contrast at inner working angle consistent w/ error budget

- **Dedicated:** $5 \times 10^{-10}$
- **Rendezvous:** $1 \times 10^{-10}$
Design Reference Mission Strategies

- **Planet detection**
  - Green band observation with IFS
  - Divided into 3 channels for multi-color imaging
  - SNR = 4 per channel

- **Planet characterization**
  - SNR = 10, R=10 to 70 per spectral resolution element

- **If dust level high, obtain wide-field image then move on**

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**Three target prioritization strategies studied**

<table>
<thead>
<tr>
<th>Study Case</th>
<th>Theme</th>
<th>Mission</th>
<th>Propulsion</th>
<th>Defining Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>&quot;Earths in HZ&quot;</td>
<td>1.1 m Dedicated</td>
<td>SEP</td>
<td>Efficient observations based on Stellar Luminosity</td>
</tr>
<tr>
<td>Case 2</td>
<td>&quot;Maximum Planet Diversity&quot;</td>
<td>1.1 m Dedicated</td>
<td>SEP</td>
<td>Observe all stars to limiting sensitivity ( \text{lim} \Delta \text{mag}=26 ) (contrast of 4e-11)</td>
</tr>
<tr>
<td>Case 3</td>
<td>&quot;Earths in HZ&quot;</td>
<td>2.4 m Rendezvous</td>
<td>Bi-prop</td>
<td>Efficient observations based on Stellar Luminosity</td>
</tr>
</tbody>
</table>
Observing Sequence

1. Schedule known giant planet observations
2. Fill in gaps on sky with highest priority blind search target
3. Repeat with lower priority targets until fuel or time limit reached
4. Reserve 3rd year for follow-up / additional characterization revisits

Rendezvous mission, 2-year sequence, 55 stars visited, $\Delta v = 1266$ m/s

12 known giant planets. Blind search targets: 28 Earths, 7 sub-Neptunes, 8 Jupiters
DRM Yield Summaries

Completeness is the probability of detecting a planet if it's there, summed over all stars.

Multiply completeness by planet frequency ($\eta$) to get expected yield.

Assumed $\eta = 16\%$ for Earths, $\eta = 10\%$ for all other planets.

Large Planet Characterization

Number of stars for which $R=X$ spectra of Jupiters and sub-Neptunes can be acquired.
Yield By Planet Type & Temperature

Exo-S 2.4-m Planet Discovery Yield
"Habitable Zones" Program
<N> = 26 Total New Planets in 2 years
Hot -- Warm -- Cold

Plus 12 known RV planets characterized at up to R~70

For Planet Occurrence Rates:
Hot/Warm/Cold Earths, 16%
All Others, 10%
R = 9, SNR = 7, 600-850nm
Starshade Mechanical Design Overview

- Starshade stows compactly, fits in 5m launch fairings, can carry a telescope on top, and can carry propellant in central cylinder.
- Inner disk draws heritage from Astromesh Antenna (Thuraya), but is greatly simplified and tailored to accommodate petals.
## Starshade Error Budget

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Dedicated Mission (1.1m telescope)</th>
<th>Rendezvous Mission (2.4m telescope)</th>
<th>Demonstrated Performance</th>
<th>Demo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tolerance Allocation</td>
<td>Contrast $\times 10^{-11}$</td>
<td>Tolerance Allocation</td>
<td>Contrast $\times 10^{-11}$</td>
</tr>
<tr>
<td>Manufacture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petal Segment Shape (Bias)</td>
<td>14 $\mu$m</td>
<td>1.4</td>
<td>22 $\mu$m</td>
<td>0.4</td>
</tr>
<tr>
<td>Petal Segment Shape (Random)</td>
<td>68 $\mu$m</td>
<td>0.3</td>
<td>68 $\mu$m</td>
<td>0.1</td>
</tr>
<tr>
<td>Petal Segment Placement (Bias)</td>
<td>4 $\mu$m</td>
<td>0.7</td>
<td>7 $\mu$m</td>
<td>0.1</td>
</tr>
<tr>
<td>Petal Segment Placement (Random)</td>
<td>45 $\mu$m</td>
<td>0.6</td>
<td>53 $\mu$m</td>
<td>0.5</td>
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<tr>
<td><strong>Pre-Launch Deployment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petal Radial Position (Bias)</td>
<td>150 $\mu$m</td>
<td>6.0</td>
<td>200 $\mu$m</td>
<td>0.15</td>
</tr>
<tr>
<td>Petal Radial Position (Random)</td>
<td>450 $\mu$m</td>
<td>0.6</td>
<td>450 $\mu$m</td>
<td>0.1</td>
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<tr>
<td><strong>Post-Launch Deployment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petal Radial Position (Bias)</td>
<td>100 $\mu$m</td>
<td>2.7</td>
<td>250 $\mu$m</td>
<td>0.23</td>
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<tr>
<td>Petal Radial Position (Random)</td>
<td>350 $\mu$m</td>
<td>0.4</td>
<td>375 $\mu$m</td>
<td>0.06</td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disk-Petal Differential Strain (Bias)</td>
<td>20 ppm</td>
<td>6.0</td>
<td>40 ppm</td>
<td>0.6</td>
</tr>
<tr>
<td>1-5 cycle/petal width (Bias)</td>
<td>10 ppm</td>
<td>1.0</td>
<td>30 ppm</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Formation Flying</strong></td>
<td></td>
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<td></td>
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<tr>
<td>Lateral Displacement</td>
<td>1 m</td>
<td>2.9</td>
<td>1 m</td>
<td>1.1</td>
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<tr>
<td>Longitudinal Displacement</td>
<td>250 km</td>
<td>2.5</td>
<td>250 km</td>
<td>0.43</td>
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<tr>
<td><strong>Total Photometric Error</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Photometric Allocation</td>
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<td>10</td>
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<tr>
<td><strong>Total Systematic Error</strong></td>
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<tr>
<td>Systematic Allocation</td>
<td>4</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

-Full error budget accounts for 200 separate perturbation sources
-Will repeat early demos with more flight-like prototypes for TRL-5
-32% of total allocation is unallocated reserve

Compliance is demonstrated via TDEMs for several key requirements
Starshade Technology Development Overview

The STDT identified 5 technology gaps. Resolution plans in place to establish TRL-5 by 2017

<table>
<thead>
<tr>
<th>Technology Gap</th>
<th>Resolution Plan</th>
<th>Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Control edge scattered Sunlight</td>
<td>Additional modeling</td>
<td>TDEM-12, NGAS</td>
</tr>
<tr>
<td></td>
<td>Testbed</td>
<td>ExEP modeling, infrastructure</td>
</tr>
<tr>
<td></td>
<td>Prototype edge segment</td>
<td>JPL internal R&amp;T&amp;D</td>
</tr>
<tr>
<td></td>
<td>Flight-like edges part of TRL-5 petal</td>
<td>TDEM-12, Princeton</td>
</tr>
<tr>
<td>2. Verify optical performance at subscale</td>
<td>Modeling</td>
<td>ExEP modeling, infrastructure</td>
</tr>
<tr>
<td></td>
<td>Desert testbed</td>
<td>TDEM-12, NGAS</td>
</tr>
<tr>
<td></td>
<td>Laboratory testbed</td>
<td>TDEM-12, Princeton</td>
</tr>
<tr>
<td>3. Demo. formation flying sensing perf.</td>
<td>Design, simulations, algorithm dev., Optical testbed</td>
<td>TDEM-13, Princeton</td>
</tr>
<tr>
<td>4. Mature petal design to TRL-5</td>
<td>Flight-like full-scale petal with: all truss I/Fs, optical edges, optical shield, etc.</td>
<td>TDEM-12, Princeton</td>
</tr>
<tr>
<td>5. Mature inner disk design to TRL-5</td>
<td>Flight-like half-scale inner disk with: all petal I/Fs, optical shield, launch restraint</td>
<td>TBD</td>
</tr>
</tbody>
</table>

All efforts to TRL-5 are fully funded, except Gap #5

Exo-S Final Report to NASA APS - March 18, 2015
Starshade-Ready WFIRST/AFTA

- Minimal modifications needed
  - Earth-Sun L2 orbit
  - Use existing coronagraph IFS for science, imager for formation guidance
  - Rotate coronagraph masks out of path, add bandpass filters to existing wheel
  - Add proximity radio with 2-way ranging to bus telecom system
  - IFS FOV reduced to accommodate broader bandpass, but mitigated by adding detectors for bigger focal plane (improves coronagraph FOV as well)
Cost Estimates

- Cost estimates from Exo-S Team, JPL Team X, and Aerospace CATE
- Dedicated mission went slightly over $1B cap
- Rendezvous mission Phase A – F cost: $627M
- Exo-S team estimates close to CATE, except for “threats”
- CATE raised no issues with schedule

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and Caltech.
WFIRST/AFTA can be leveraged for a unique and timely opportunity

- Rendezvous Mission can access up to 50 unique target stars for exoEarths in the habitable zone
- Minimal modification needed for starshade readiness
- Starshade technology is on track for TRL-5 by 2017 and for new start by 2018, but not fully funded
- Mission cost ~ $627M