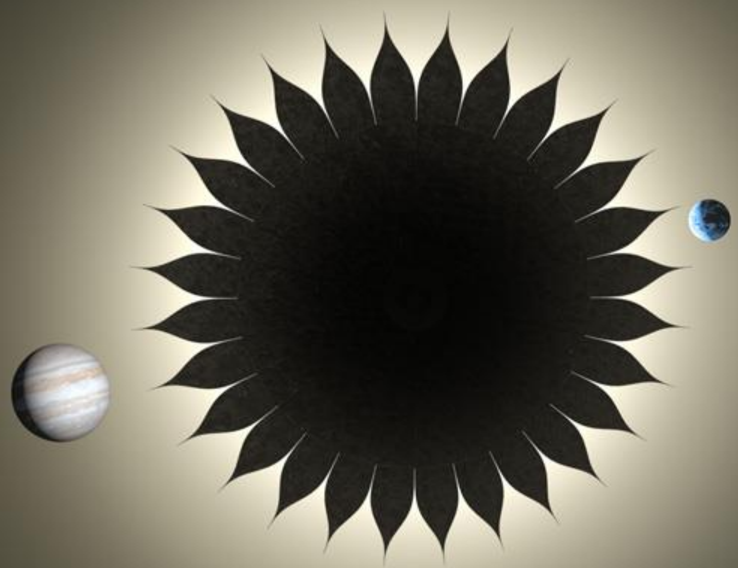
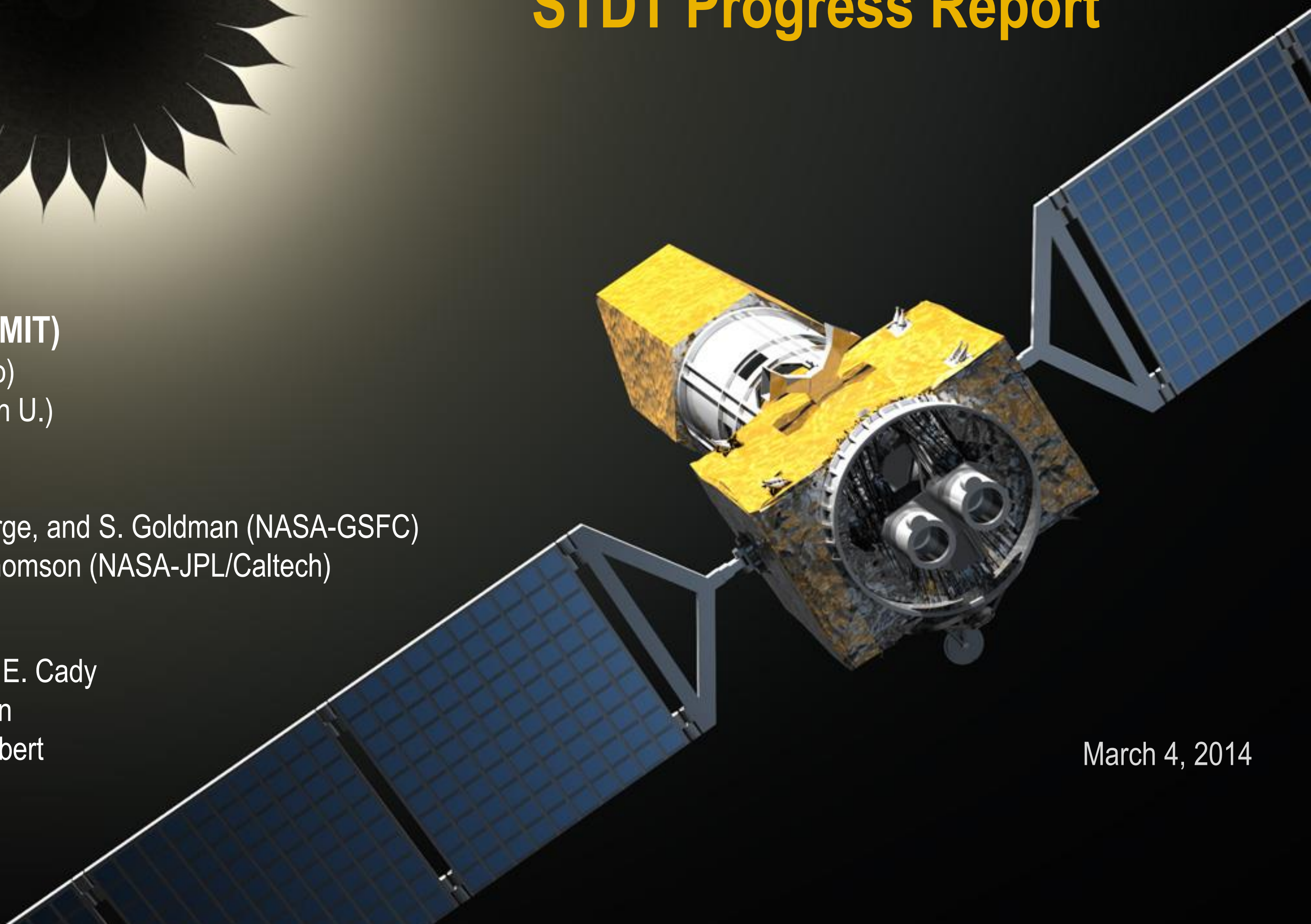


Probe Class Starshade Mission STDT Progress Report



Chair: S. Seager (MIT)

W. Cash (U. Colorado)

N.J. Kasdin (Princeton U.)

W. Sparks (STSci)

M. Turnbull (GCI)

M. Kuchner, A. Roberge, and S. Goldman (NASA-GSFC)

S. Shaklan and M. Thomson (NASA-JPL/Caltech)

JPL Design Team:

D. Lisman, S. Martin, E. Cady

D. Webb, J. Henrikson

D. Scharf, and R. Trabert

March 4, 2014

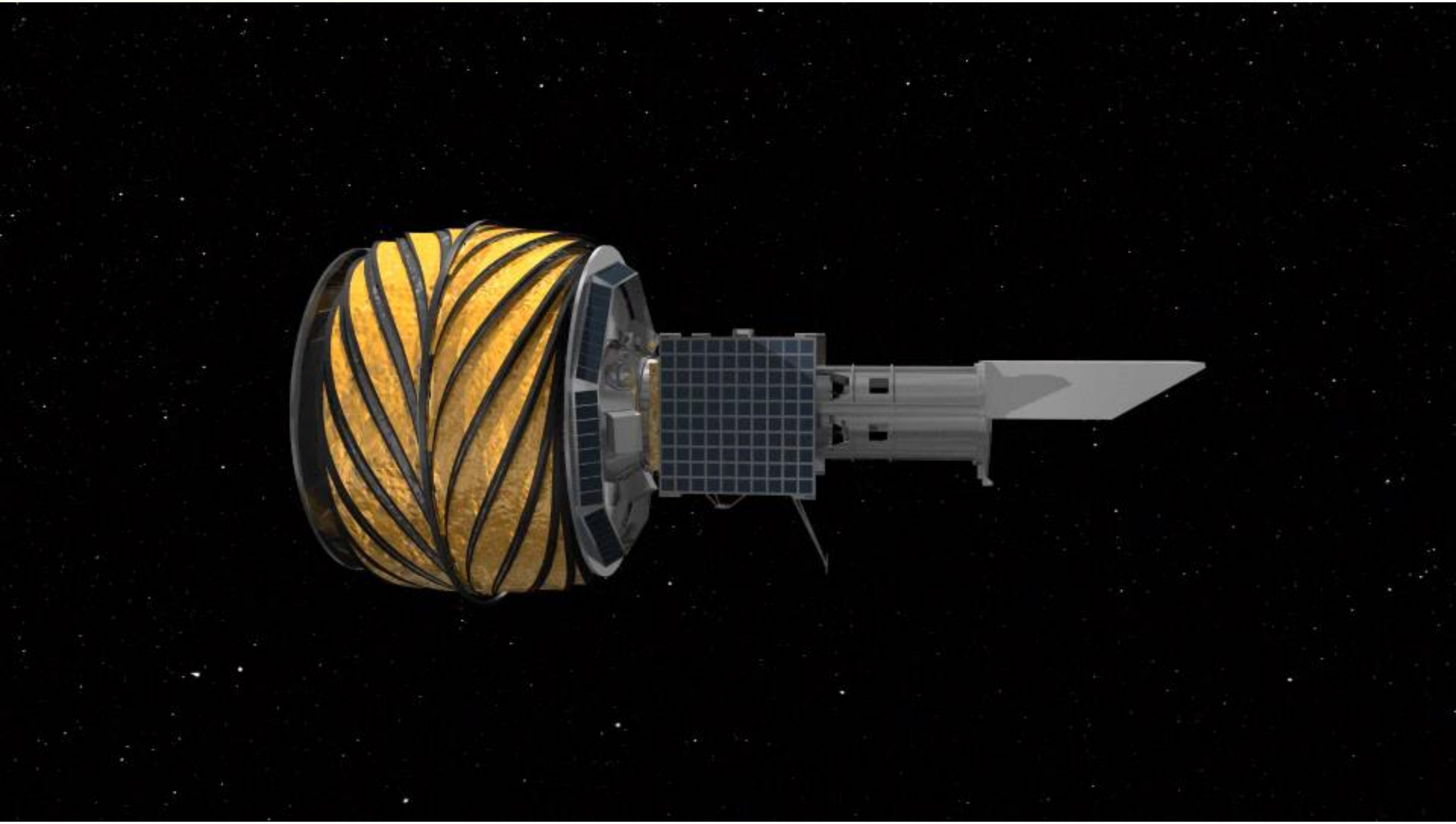
“Can we find another planet like Earth orbiting a nearby star? To find such a planet would complete the revolution, started by Copernicus nearly 500 years ago, that displaced Earth as the center of the universe. . . The observational challenge is great, but armed with new technologies. . . astronomers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

–New Worlds, New Horizons, 2010

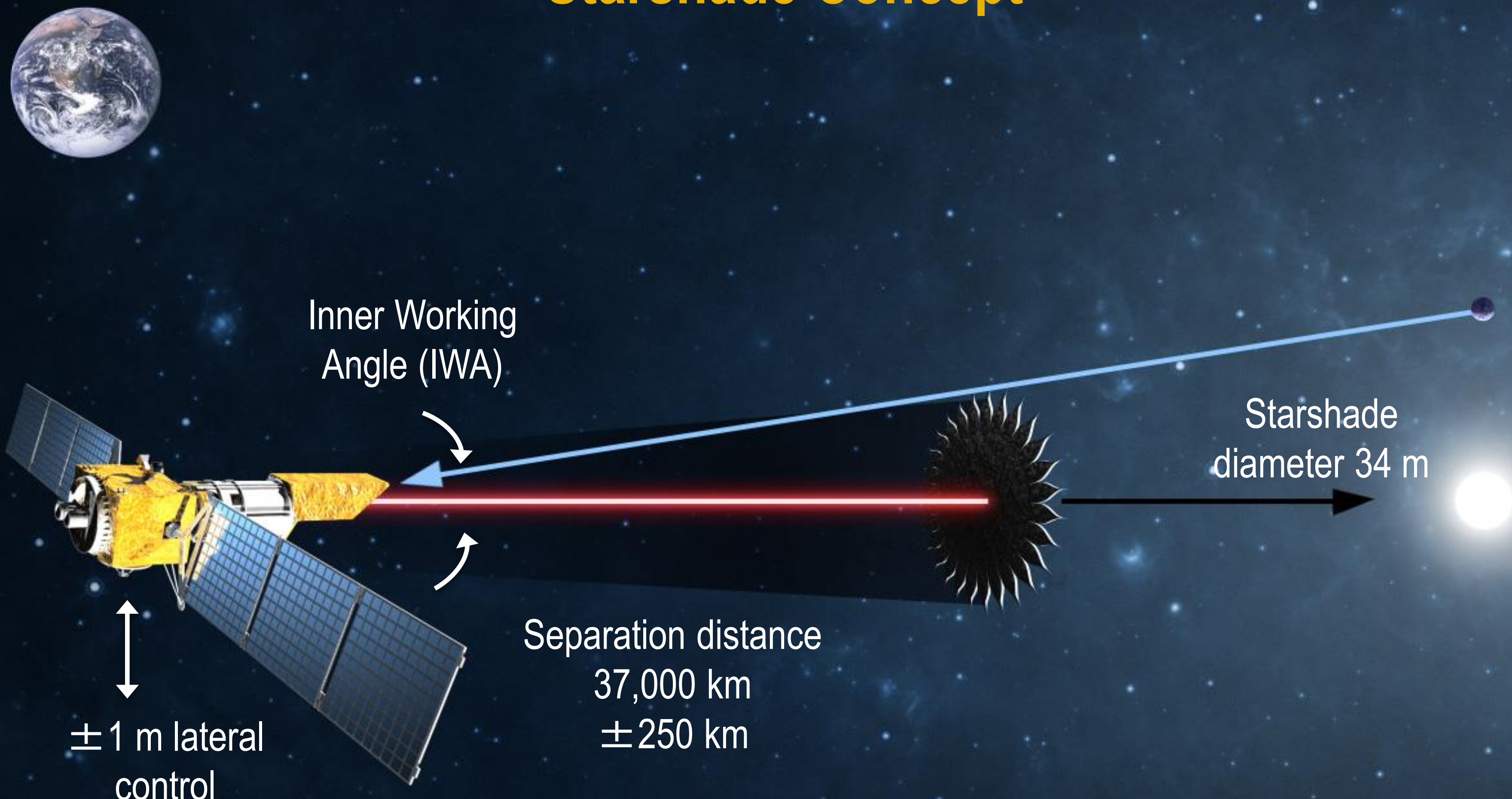
Starshade Study Context

- 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



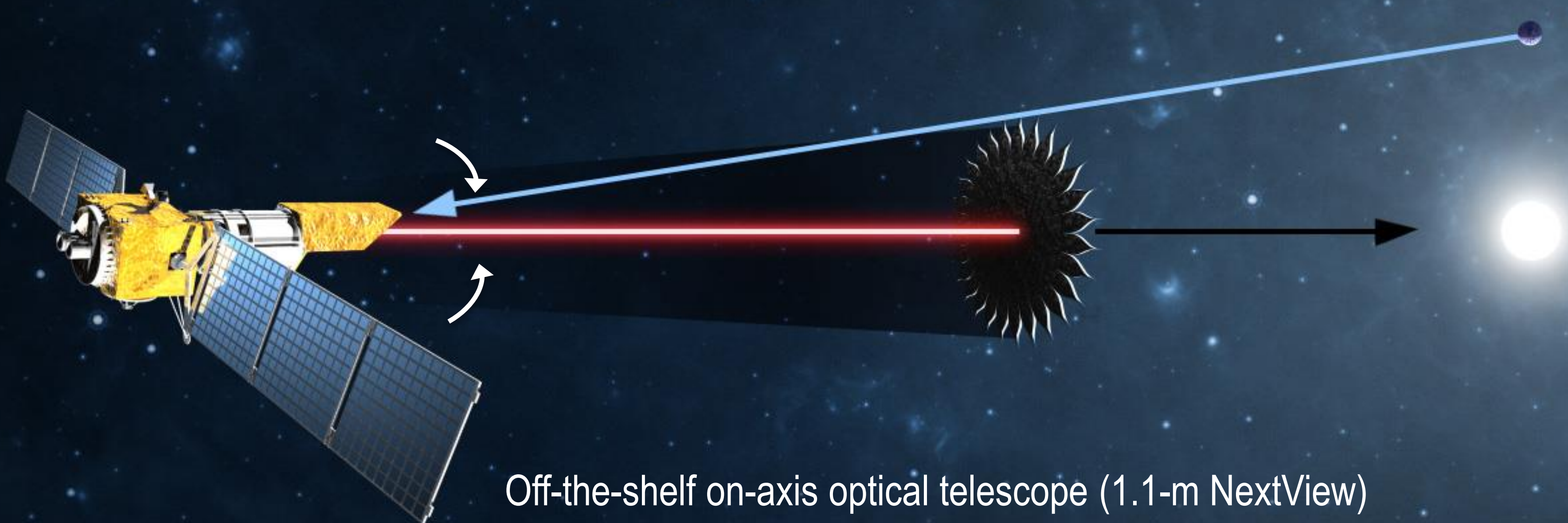
Starshade Concept



- 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

Exo-S Baseline Design Overview

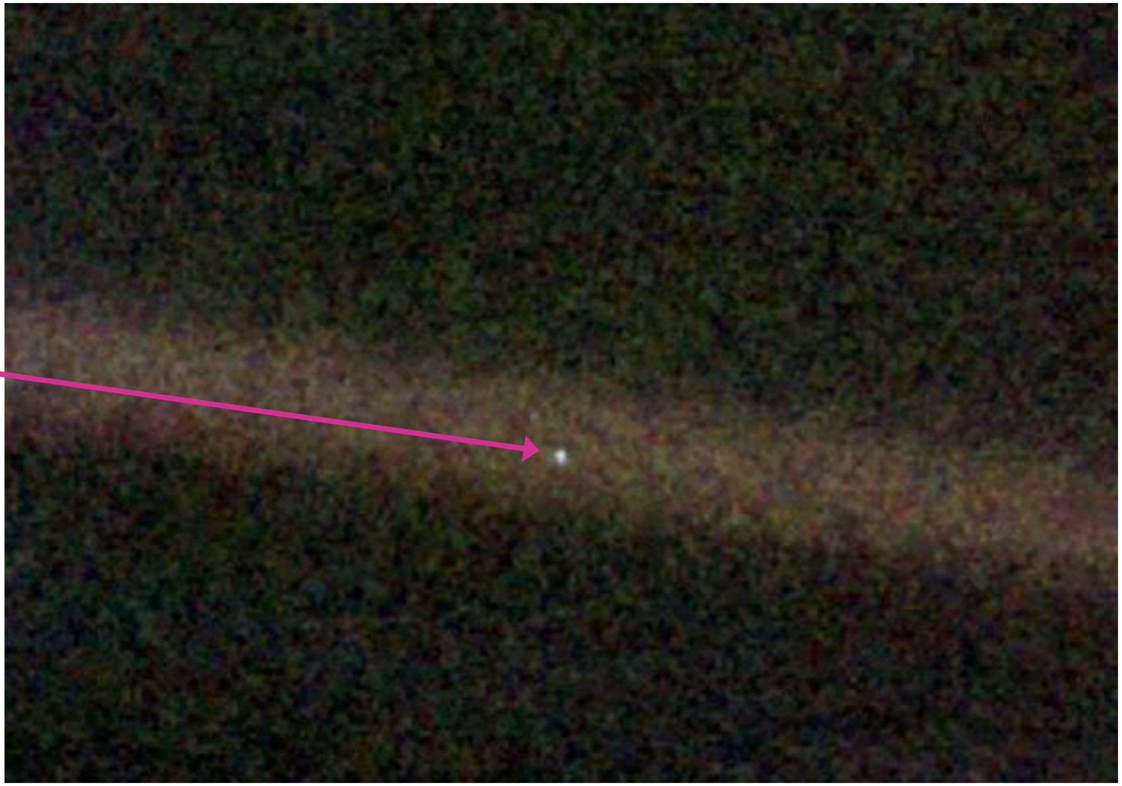
Band	Blue	Green	Red
Wavelengths (nm)	400–630	510–825	600–1,000
IWA (mas)	75	95	115
Separation (Mm)	47	37	30



- 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

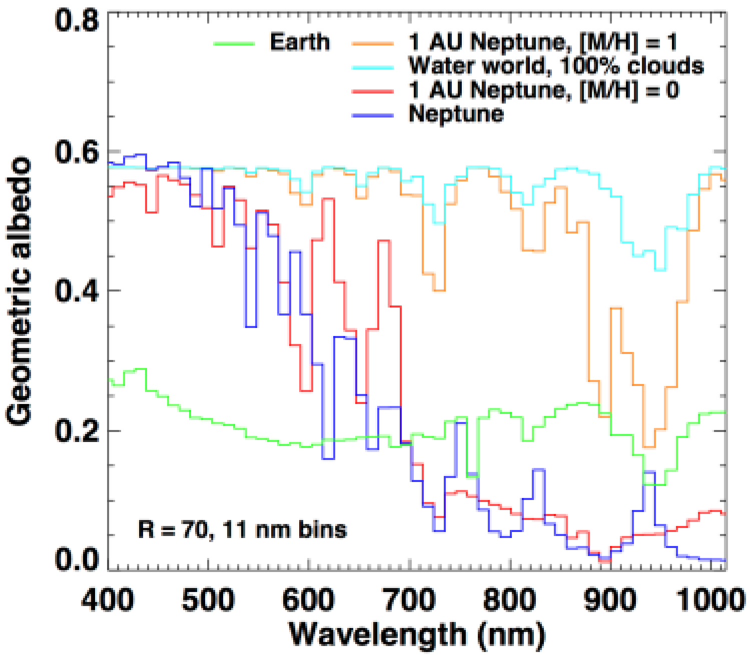
Science Goal #1:
Photometric Search for New Exoplanets

Earth as seen from Voyager I from 4 billion miles

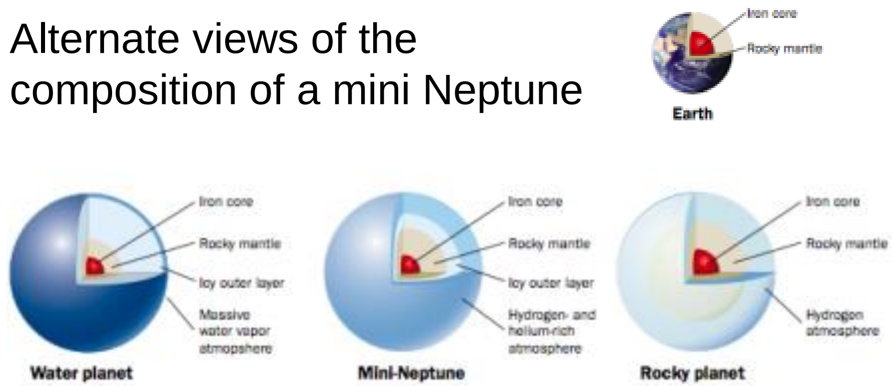


- Discover planets from Jupiter-like planets down to rocky planets orbiting nearby Sun-like stars
- Image rocky planets in a Sun-like star's habitable zone
- Discover multiple planets and circumstellar dust, around target stars

Science Goal #2: *Spectral Characterization of New Exoplanets*



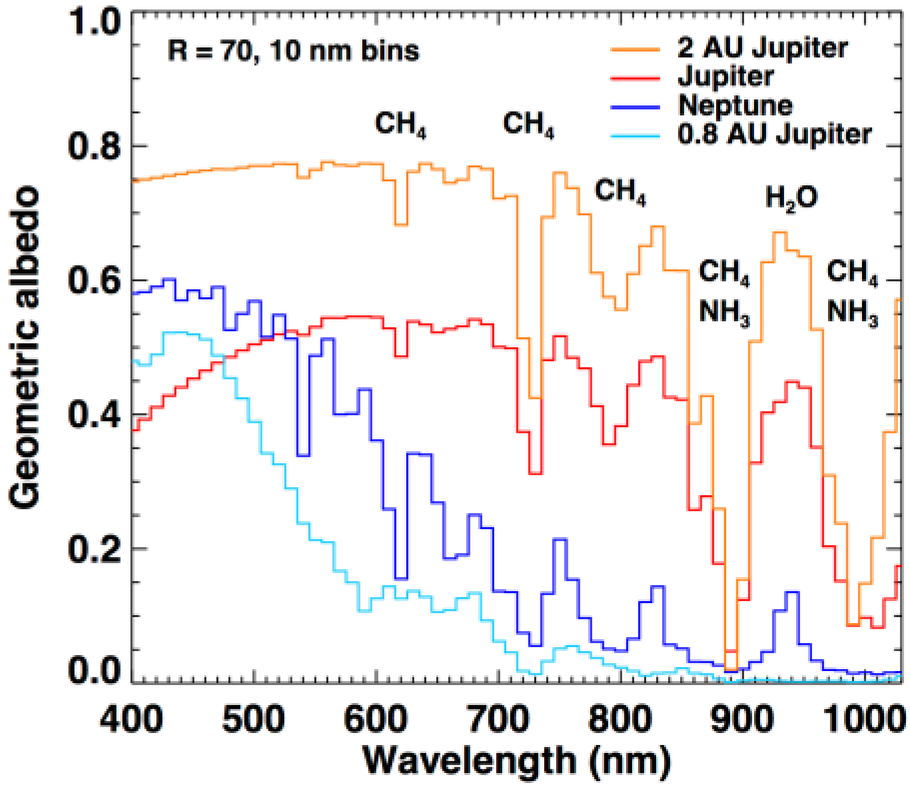
Alternate views of the composition of a mini Neptune



Credit: Science News 2010

- 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

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

Target		Target Angles (deg)			Durations (days)			ΔV (m/s) & Propellant Mass (kg)			
Obs. #	Hipparcos #	Longitude	Latitude	Slew Arc	Slew	On Target	Total Mission	Slew ΔV	Cumulative ΔV	Slew Prop	Cumulative Prop
1	57443	196.0	-37.9	0	0	9.201	9	0.0	0.0	0	0
2	64924	205.0	-9.3	29.7	12.4	7.171	29	55.8	55.8	1.80	1.8
3	69965	221.0	-11.3	15.9	9.4	1.667	40	48.3	104.1	1.55	3.3
4	75181	241.1	-28.8	25.6	10.0	1.667	52	48.5	152.7	1.56	4.9
5	80337	250.7	-17.3	14.4	7.3	1.667	60	38.9	191.5	1.25	6.2
6	86796	267.2	-28.4	18.8	8.6	4.518	74	41.3	232.9	1.32	7.5
7	89042	271.6	-38.6	10.8	6.1	1.667	81	35.4	268.3	1.13	8.6
8	26394	273.9	-76.0	37.4	11.5	5.284	98	63.7	332.0	2.04	10.6
9	29271	265.3	-81.8	6.0	5.4	12.72	116	19.9	351.9	0.63	11.3
10	99240	287.6	-44.7	37.8	13.6	1.667	131	48.3	400.2	1.54	12.8
11	105858	298.6	-47.0	8.0	5.4	3.221	140	29.3	429.5	0.93	13.8
12	113137	305.3	-55.5	9.5	5.3	5.642	151	40.2	469.8	1.28	15.0
13	1599	322.4	-57.7	9.6	5.9	3.263	160	32.5	502.2	1.03	16.1
14	7978	350.8	-57.3	15.2	8.0	4.102	172	35.2	537.4	1.12	17.2
15	5862	353.4	-48.1	9.3	5.9	1.667	180	30.7	568.1	0.97	18.2
16	2941	358.0	-26.3	22.1	8.6	1.667	190	52.7	620.8	1.67	19.8
17	8102	17.8	-24.8	17.9	7.2	1.667	199	57.7	678.5	1.83	21.7
18	9094	23.4	-20.8	6.5	4.2	6.692	210	39.9	718.4	1.26	22.9
19	15510	27.2	-58.1	37.4	12.3	3.406	225	55.8	774.2	1.76	24.7
20	23693	48.7	-78.9	21.9	9.4	6.827	242	65.9	840.1	2.08	26.8
21	16537	48.2	-27.7	51.2	15.2	1.881	259	71.8	911.9	2.26	29.0
22	17378	50.9	-28.7	2.6	2.7	1.667	263	22.2	934.1	0.70	29.7
23	19849	60.2	-28.4	8.2	7.0	4.384	274	63.0	997.1	1.98	31.7
24	27072	84.8	-45.8	26.1	9.7	1.667	286	78.3	1075.4	2.45	34.1
25	31592	101.7	-42.3	12.6	6.5	1.667	294	39.2	1114.6	1.23	35.4
26	37826	113.2	6.7	50.1	15.8	1.667	311	54.0	1168.6	1.69	37.1
27	44897	129.5	16.7	18.8	9.1	3.667	324	37.7	1206.3	1.17	38.2
28	47080	134.3	20.3	5.8	4.0	3.667	332	36.9	1243.2	1.15	39.4
29	49081	141.0	18.5	6.5	4.6	3.667	340	29.5	1272.7	0.92	40.3
30	53721	149.1	31.1	14.5	6.6	1.667	348	47.5	1320.2	1.48	41.8
31	61317	167.7	40.5	17.8	7.4	3.316	359	51.6	1371.8	1.60	43.4
32	62207	171.5	39.9	3.0	3.2	3.667	366	19.0	1390.8	0.59	44.0
33	64394	184.4	32.5	12.7	6.2	3.294	375	43.2	1434.1	1.34	45.3
34	72567	211.1	38.2	22.4	10.6	3.667	390	36.9	1470.9	1.14	46.4
35	71395	213.2	23.7	14.6	7.0	7.957	405	42.0	1512.9	1.30	47.7
36	77052	233.0	21.7	18.4	7.9	3.667	416	45.7	1558.6	1.41	49.2
37	77257	232.4	26.5	4.9	3.6	4.275	424	34.4	1593.0	1.06	50.2
38	84862	255.3	55.4	33.3	14.2	3.667	442	39.0	1632.1	1.20	51.4
39	86974	265.2	51.1	7.3	5.5	1.667	449	24.8	1656.8	0.76	52.2
40	88348	270.9	49.8	3.8	4.5	4.266	458	14.6	1671.5	0.45	52.6
41	90485	276.1	-6.5	56.5	14.9	5.087	478	67.7	1739.1	2.08	54.7
42	99825	300.0	-7.0	23.7	11.0	1.667	490	37.6	1776.7	1.15	55.9
43	95447	295.2	33.5	40.8	18.3	3.667	512	42.9	1819.6	1.32	57.2
44	98819	307.8	36.5	10.8	10.6	3.667	527	31.3	1850.9	0.96	58.1
45	98767	312.6	48.9	12.8	6.6	9.358	543	38.8	1889.7	1.19	59.3
46	100017	17.1	76.6	37.0	26.3	3.667	573	21.4	1911.1	0.66	60.0
47	96100	30.3	80.9	5.0	11.9	6.374	591	6.4	1917.5	0.20	60.2
48	3821	40.2	47.0	34.1	10.5	1.667	603	64.7	1982.2	1.98	62.2
49	7513	38.6	29.0	18.1	7.1	3.973	614	57.2	2039.4	1.75	63.9
50	7918	40.1	29.7	1.5	2.6	3.667	621	10.3	2049.7	0.31	64.2
51	12777	54.7	31.6	12.7	8.1	2.716	631	52.8	2102.5	1.61	65.8
52	14632	59.3	30.6	4.1	4.5	2.549	638	21.6	2124.1	0.66	66.5
53	116727	60.1	64.7	34.0	10.6	1.667	651	87.8	2211.9	2.67	69.2

Starshade Probe Mission: Targets in the Current DRM

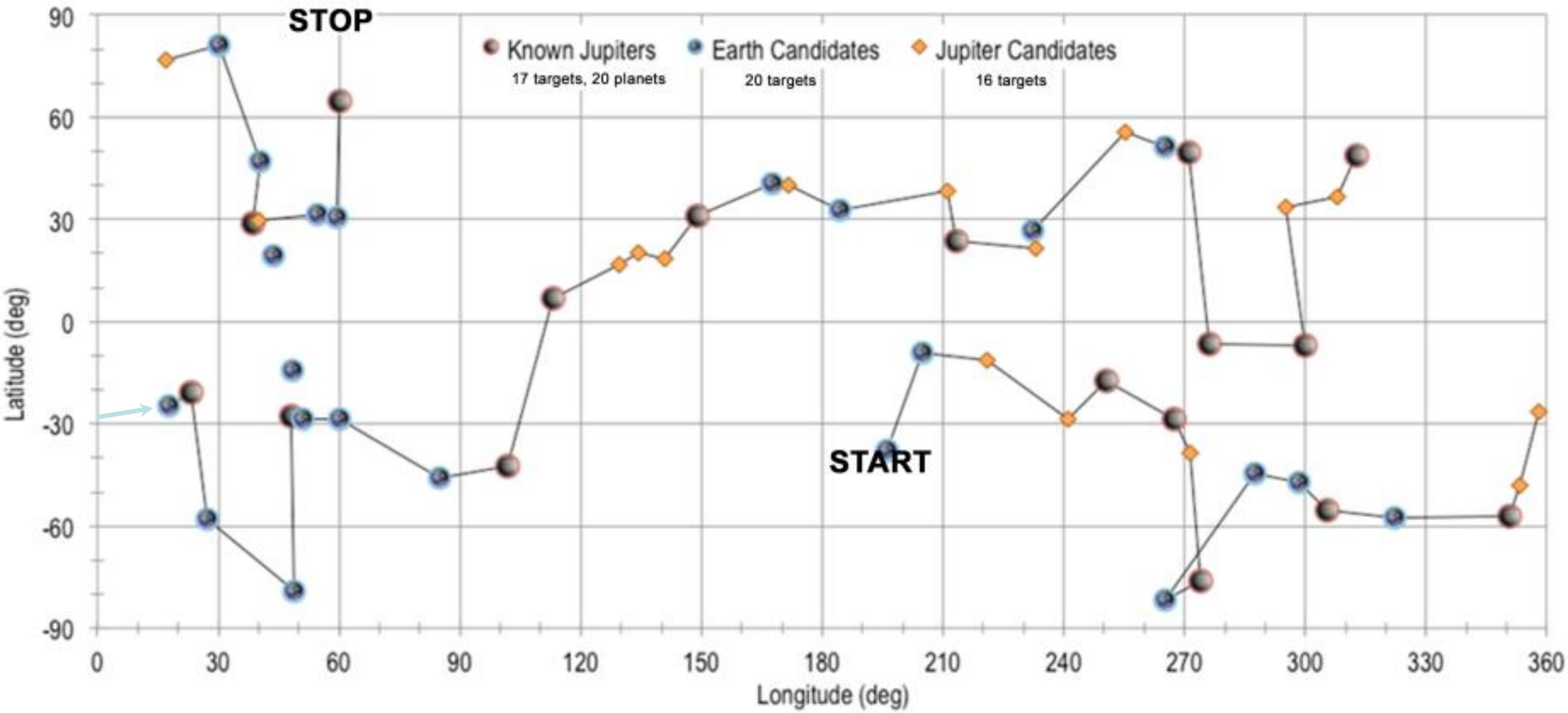
Name	d(pc)	$L(L_{sun})$	Spectral Type	Search Comp.	Known planets
τ Ceti	3.7	0.5	G8.5V	0.72	0
β CVn	8.4	1.3	G0V	0.36	0
δ Pav	6.1	1.3	G8IV	0.46	0
82 Eri	6.0	0.7	G8V	0.65	3
η Cas	5.9	1.3	G3V	0.37	0
…					
υ And d	13.5	3.6	F8V	1.00	4
47 Uma b, c	14.1	1.7	G0V	1.00	3
HD 128311 c	16.5	0.3	K3V	1.00	2
Pollux b	10.4	40.9	K0III	1.00	1
ε Eri b	3.2	0.4	K2V(k)	1.00	1?
…					

20 targets with high HZ completeness to search for Earth analogs

17 targets with 19 <u>known giant planets</u> at favorable elongation for characterization

- 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
- α Cen is not included (bright binary, large projected diameters)

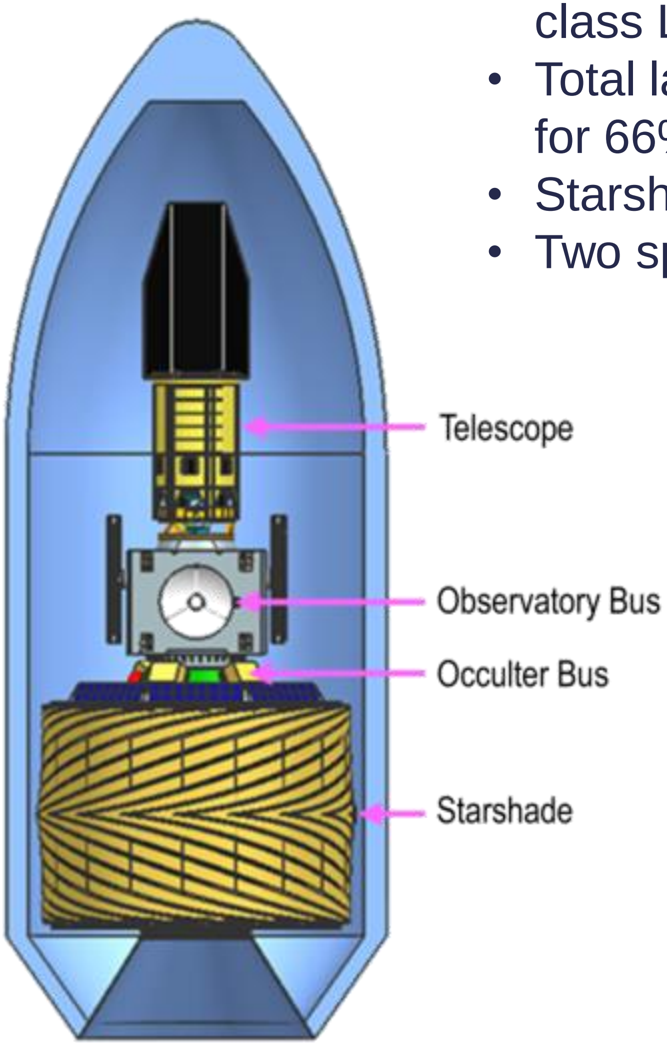
Preliminary Observing Strategy

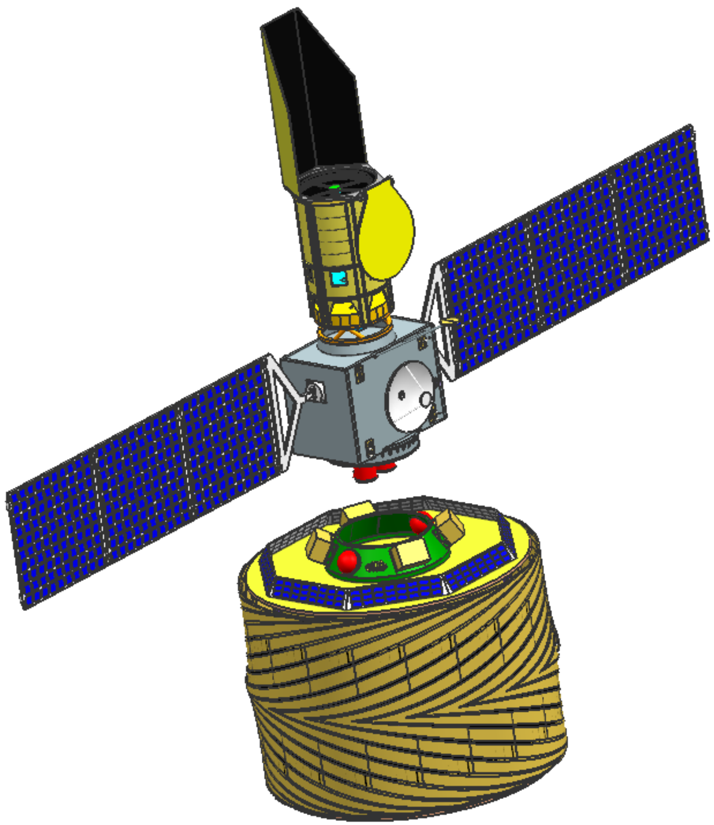


- The prime mission is 3 years; a 22 month example observing schedule is shown with targets sequential in longitude; an additional year is available for revisits and spectroscopy
- Observation times are approximately 1 to 5 days and retargeting times are about one week
- Observations include multi-color 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

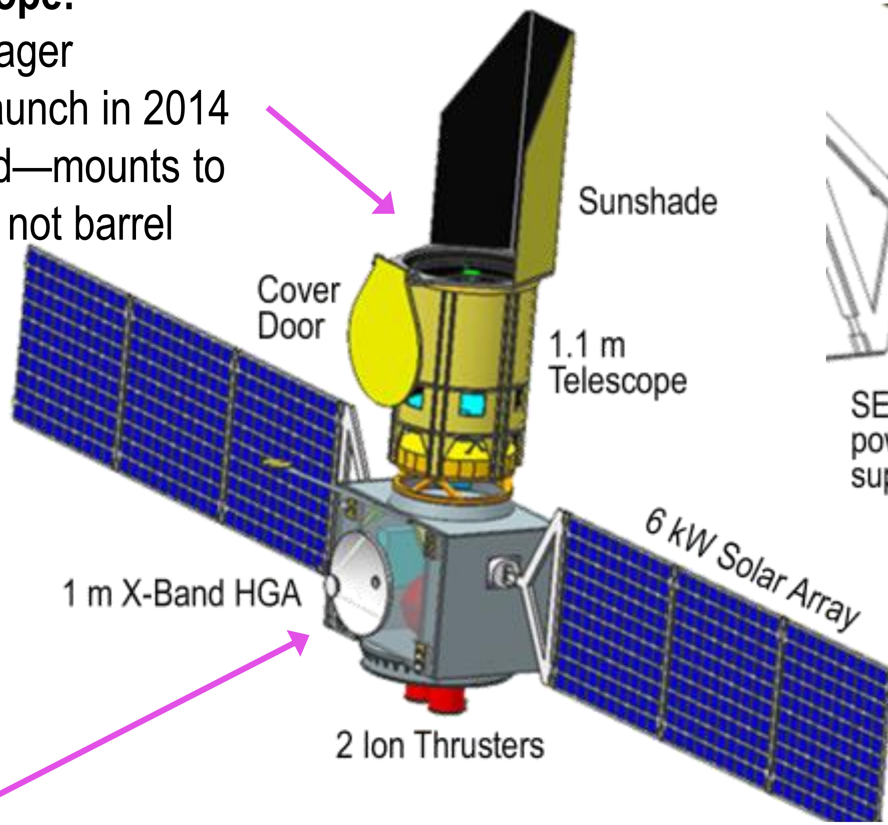


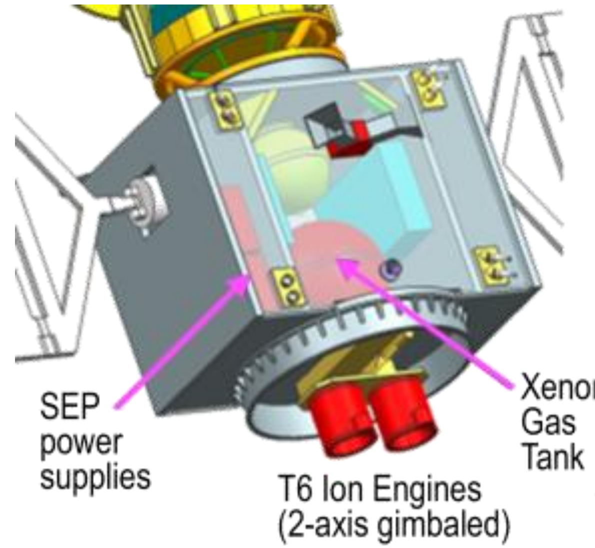


Fully Deployed Observatory

ExoPlanet Exploration Program

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

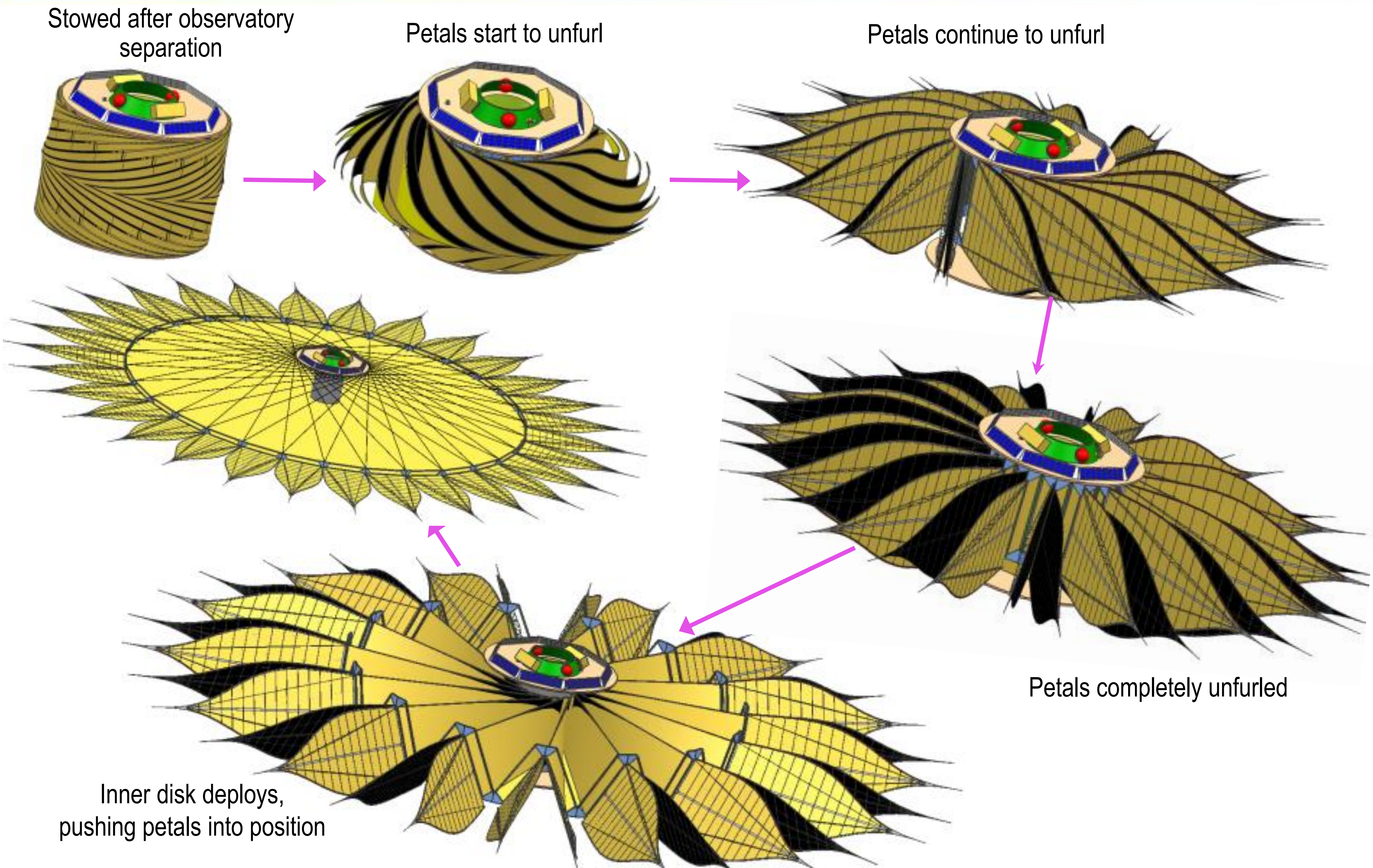




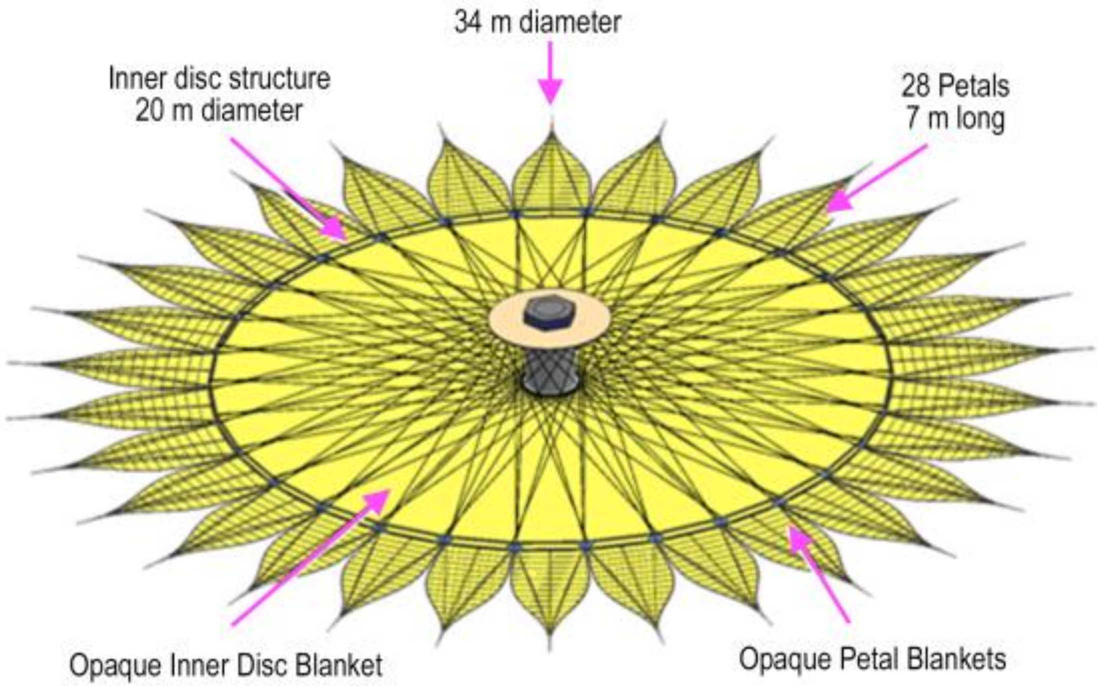
PROBA-3 Bus:
Commercial bus
In dev. For external occulter mission formation-flying demo
Planned launch is 2017
Primary mod is to add electric propulsion
Also add: HGA, X-band, larger RWs

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

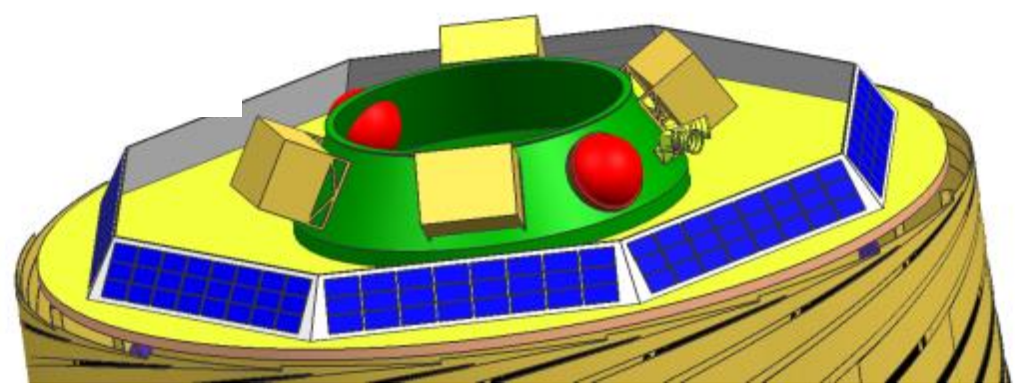


Deployed Starshade

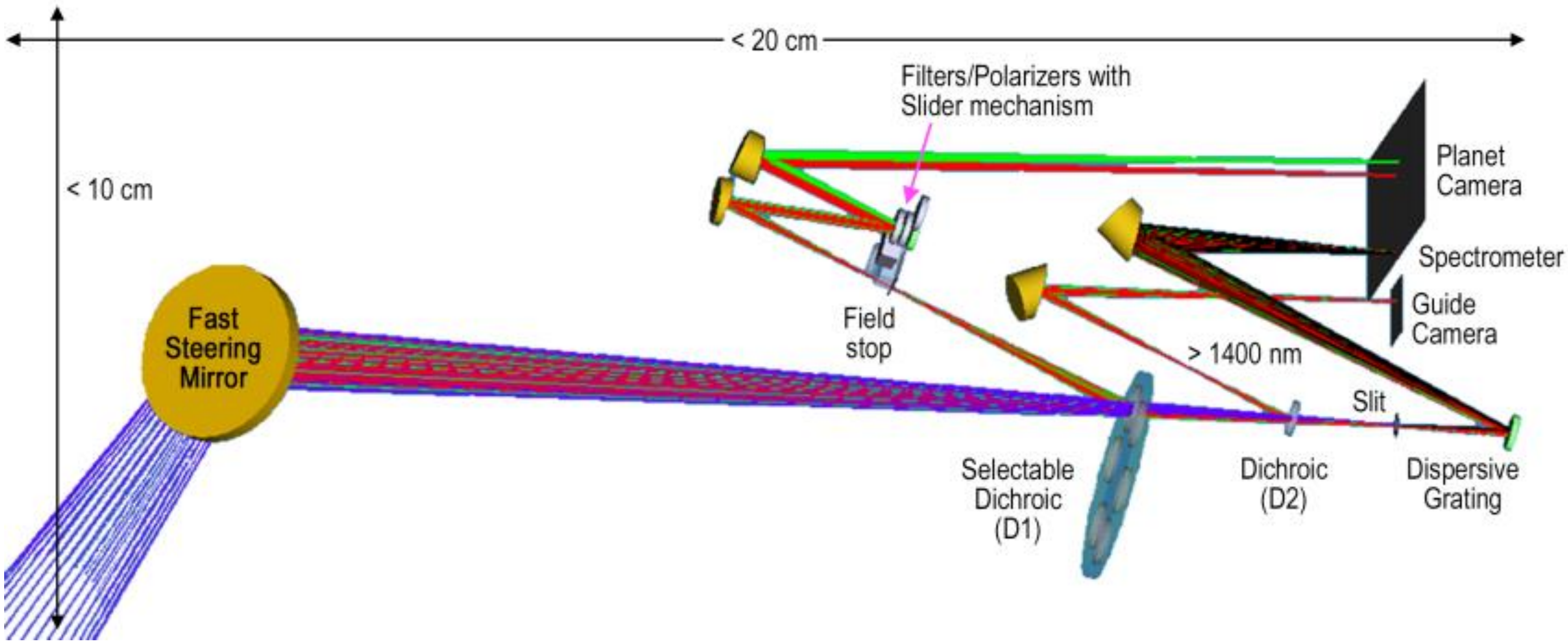


Starshade System:
Spins (3-min period) for improved planet detection
Blankets are Black Kapton, with spaced layers to limit direct light paths to telescope from micrometeoroid holes

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

Proba III

(image credit: ESA)

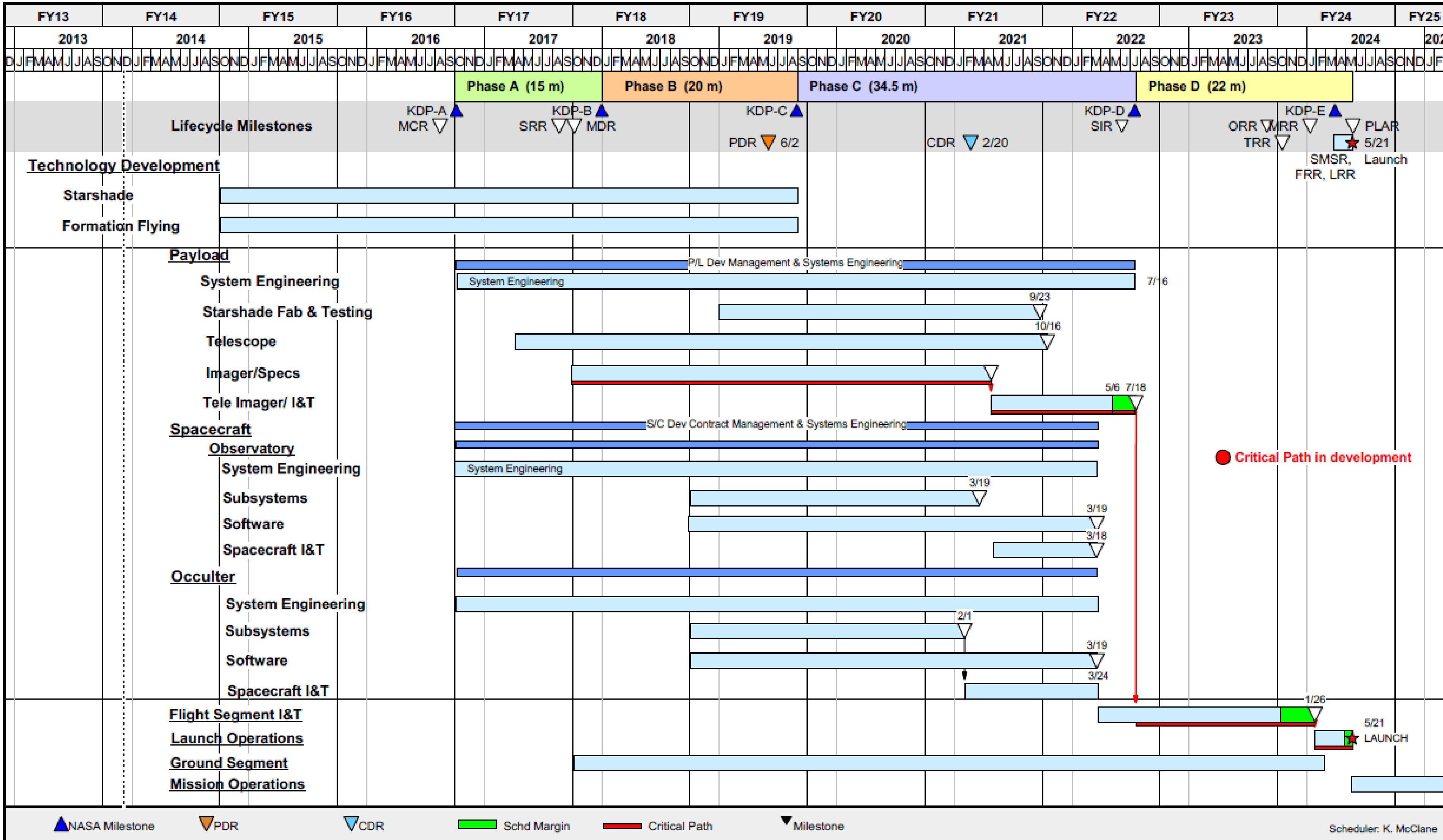
*Bus and telescope designs are for existence-proof demonstration only. Flight selection will be made through competitive bid.

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

Preliminary Schedule

ExoPlanet Exploration Program



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

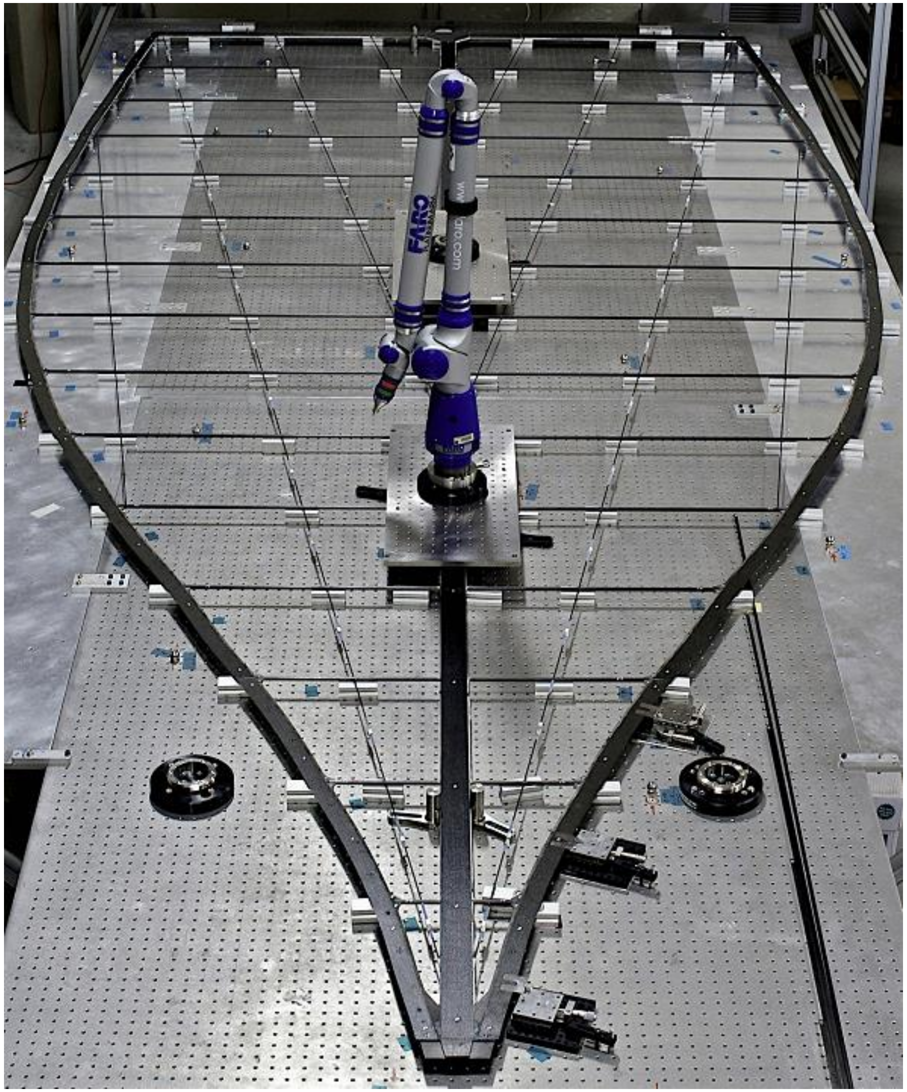
- Build structure that meets shape requirements
- Deploy accurately and with high reliability
- Maintain shape during on-orbit disturbances such as jitter and thermal gradients

Long Distance Formation Flying

- Sense cross-track alignment errors between starshade and telescope
- Control relative position of starshade and telescope line of sight

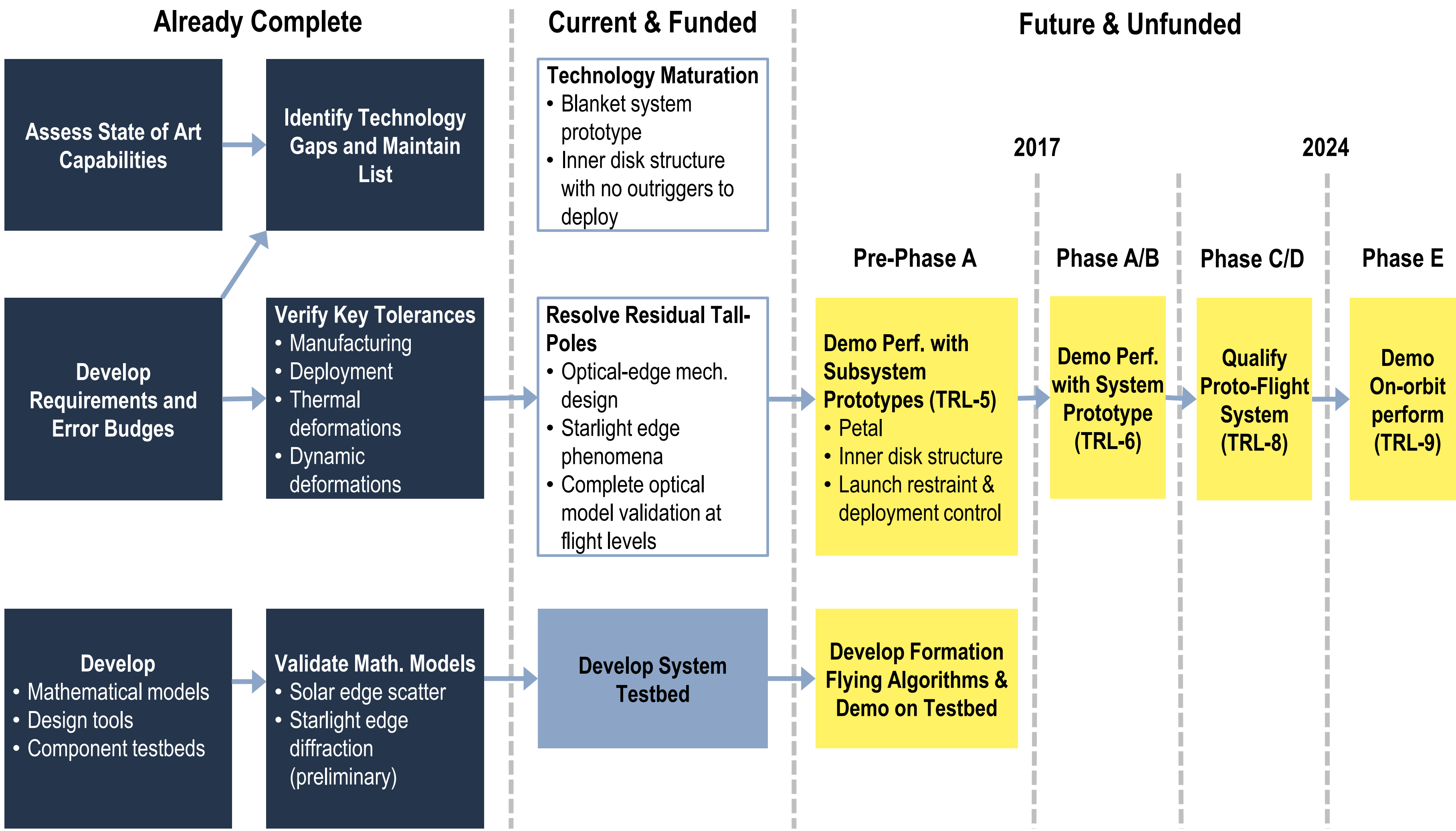
Stray Light Control

- Mitigate scattering of sunlight off edge of starshade petals
- Control transmission of sunlight and starlight through membrane



Starshade Technology Readiness Plan

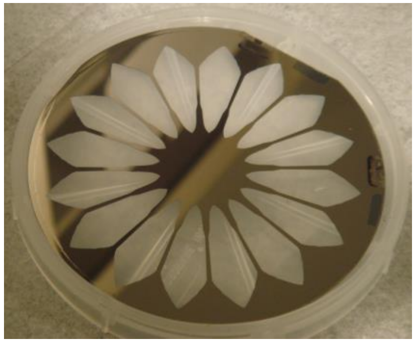
ExoPlanet Exploration Program



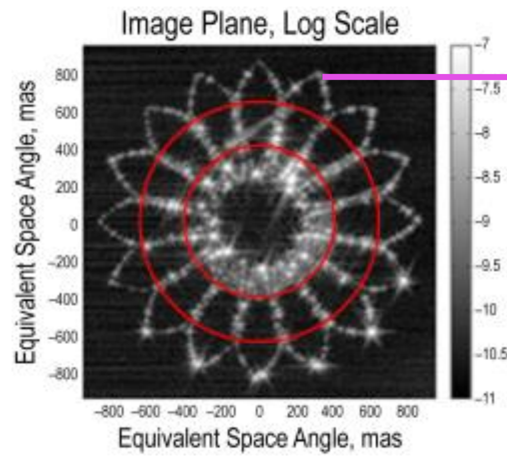
This document has been cleared for public release. Release CL#14-0952

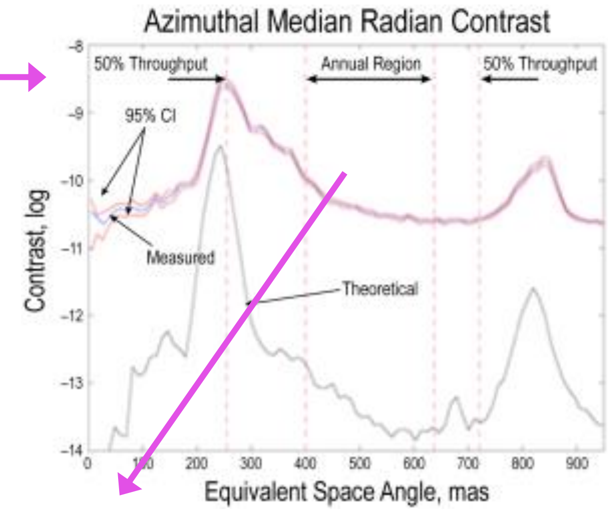
Optical Model Validation

ExoPlanet Exploration Program

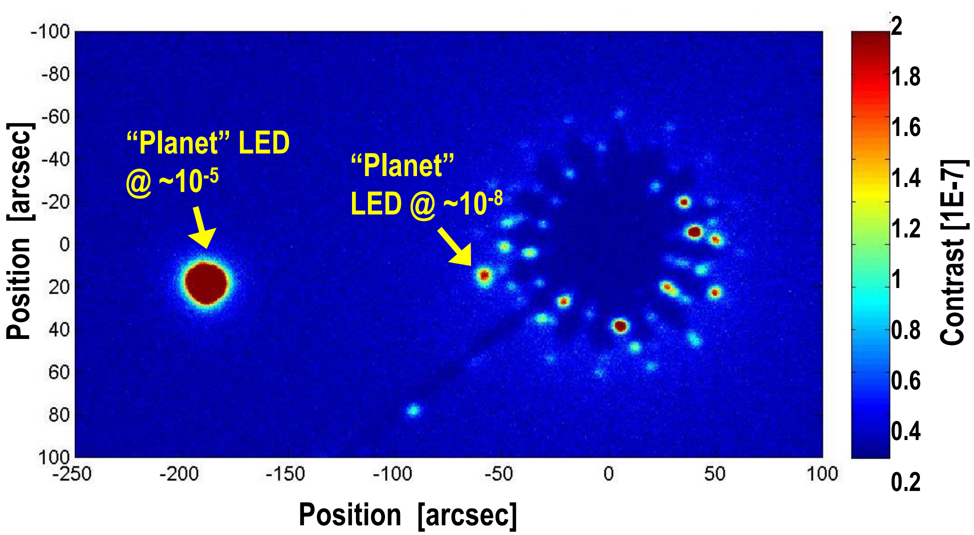


Lab experiments at Princeton and NGST have demonstrated contrasts close to flight levels for large flight versions





< 10^{-10} contrast at 400 mas equivalent

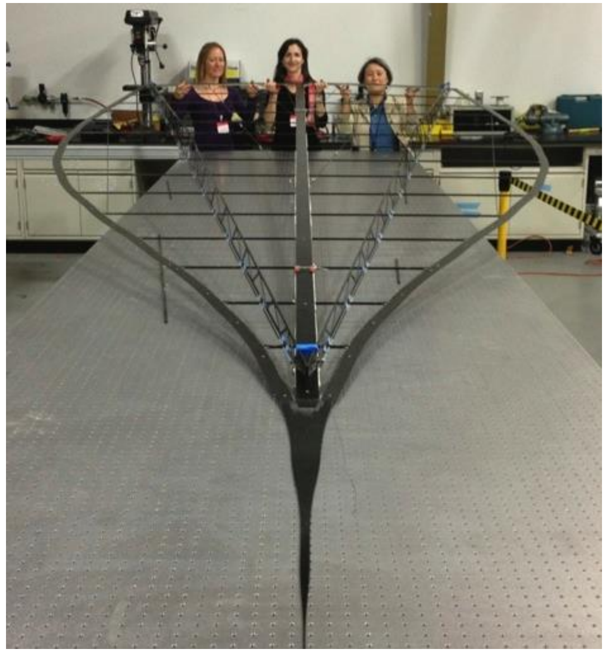


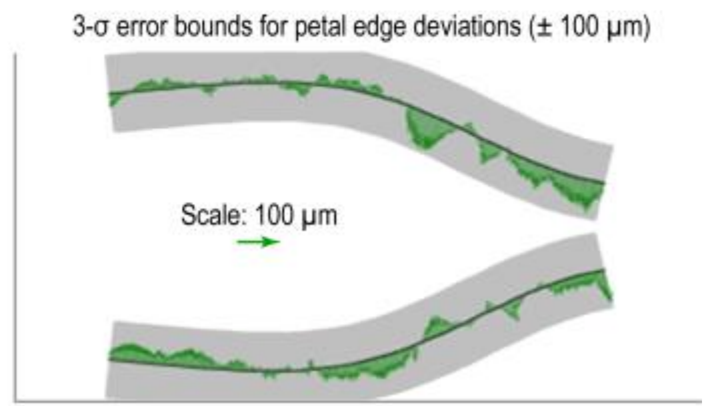
Desert field testing at 1% scale has demonstrated contrasts at 10^{-7}; Glassman et al. 2013

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

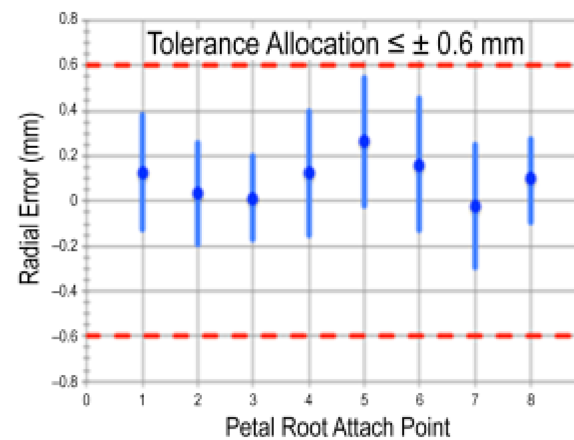
Petal Prototype and Deployment

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

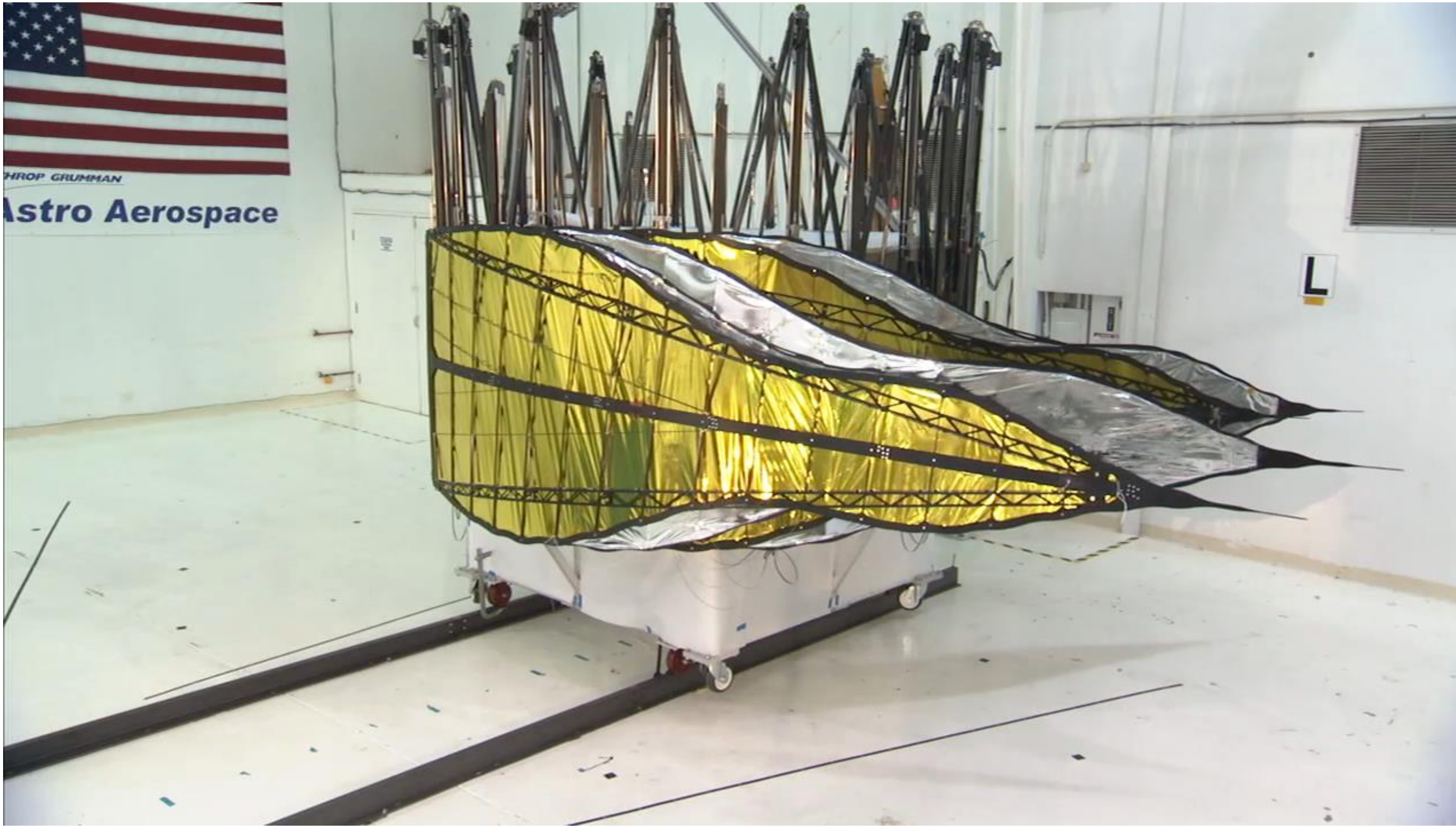




Subscale (2/3) partial starshade prototype. 25 deployment cycles demonstrated deployed positions to within required tolerances. NGC facility.



Starshade Stowage and Deployment



STDT Next Steps

ExoPlanet Exploration Program

Baseline Probe Design

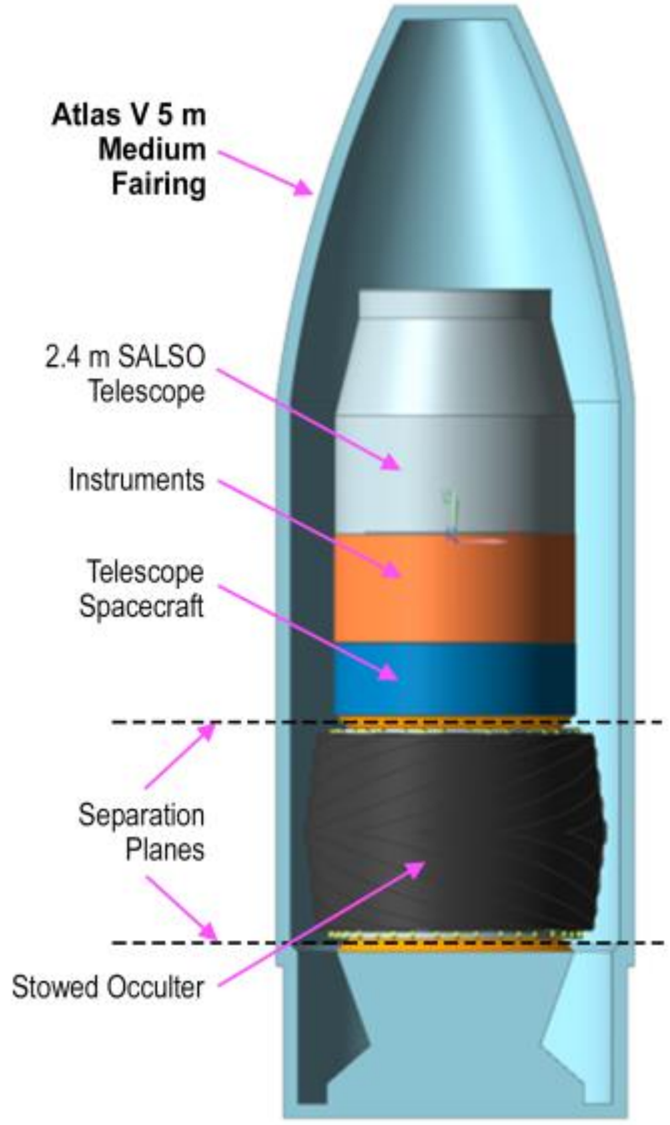
- Refine Design Reference Mission and science yield simulations
- Complete trades for the baseline design of starshade + telescope system

"Starshade Ready" Design

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

Technology Development

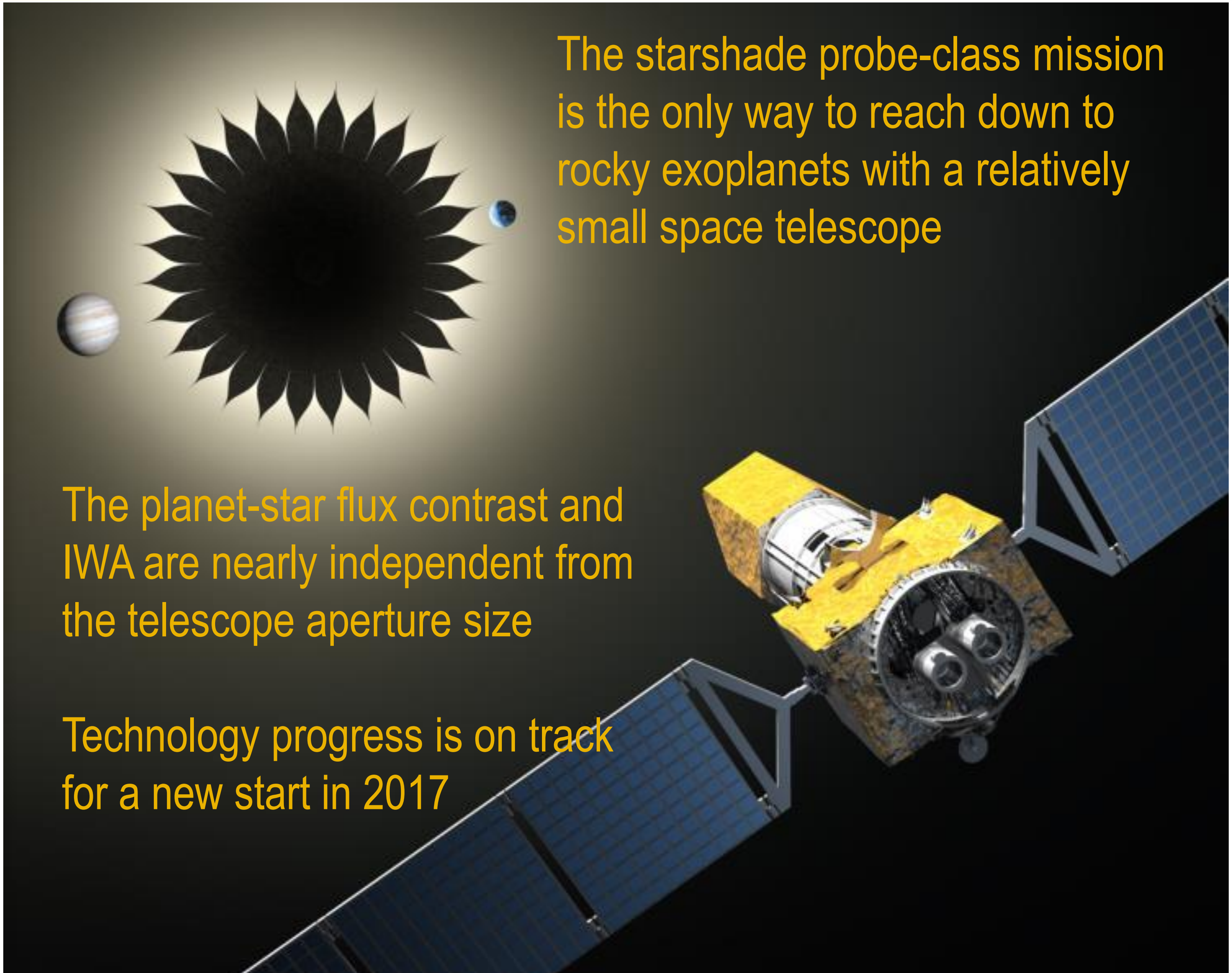
- Priorities recommended by STDT
- Where technology development will continue by the community through competed NASA technology programs; some STDT members participating



Occulter with 2.4-m NRO telescope stacked on top

Starshade Summary

ExoPlanet Exploration Program



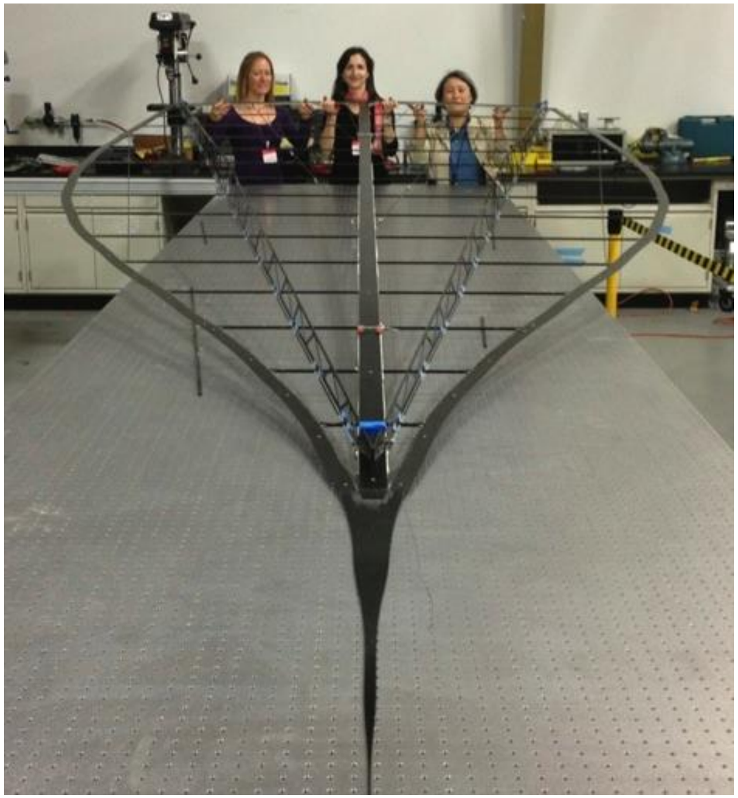
The starshade probe-class mission is the only way to reach down to rocky exoplanets with a relatively small space telescope

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

Backup

Starshade Technology "Gap List"



- ExEP Technology Plan Appendix: http://exep.jpl.nasa.gov/technology/

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

ID	Title	Description	Current	Required
S-1	Control of Scattered Sunlight	Sunlight scattered from starshade edges and surfaces risk being the dominant source of measurement noise.	Several preliminary designs of edge shapes have been studied through laboratory tests having edge radius ≥ 10 µm.	Edges manufactured of high flexural strength material with edge radius ≤ 1 µm.
S-2	Validation of starshade optical models	Experimentally validate the equations that predict the contrasts achievable with a starshade.	Experiments have validated optical diffraction models at Fresnel number of ~100 to contrasts of 4×10^{-10}, but with poor agreement near petal valleys and tips.	Experimentally validate models of starlight suppression to $\leq 1 \times 10^{-11}$, and perturbation intensities to 20% at Fresnel number of 10–20.
S-3	Starshade Deployment	Demonstrate that a starshade can be deployed to within the budgeted tolerances.	Millimeter-wave mesh antennas have been deployed in space with diameters up to 17m × 19m and a out-of-plane accuracy of 2.4-mm.	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.
S-4	Petal Prototype Demonstration	Demonstrate a high-fidelity prototype starshade petal.	Low-fidelity petals have been assembled and precision petal manufacturing has been demonstrated.	Demonstrate a fully integrated petal, including blankets, edges, and deployment control interfaces.
S-5	Formation Flying GN&C	Demonstrate that the GN&C system for an occulter will enable the required slew from star to star and positional stability for science observations.	Simulations have shown that sensing and GN&C is tractable, though sensing demonstrations of lateral control has not yet been performed.	Sensors demonstrated with errors ≤ 0.25 m. Control algorithms demonstrated with lateral control errors ≤ 1m.

This document has been cleared for public release. Release CL #14-0952

Mission Options

Option	Telescope	Launch Config. & Vehicle	Orbit	Propulsion Responsibility*	Status
1	Small dedicated (1.1-m Telescope)	Occulter + Telescope on low cost intermediate-class L/V	Earth Leading	Telescope System	Baseline for Interim Report
2	Larger shared existing telescope	Occulter separately on low cost intermediate-class L/V, rendezvous with telescope	Earth-Sun L2	Occulter	Deferred to Final Report
3	Larger shared existing telescope	Occulter + Telescope on intermediate-class L/V	Earth-Sun L2	Occulter	Deferred to Final Report, studied briefly for SALSO RFI

* 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

Error Source	Tolerance Allocation	Contrast Allocation
Petal Manufacture		
Segment Placement	+/- 60 um	1.00E-11
Segment Shape	+/- 80 um	1.00E-11
Petal Deployed Position		
Radial (common to all petals)	+/- 0.25 mm	4.50E-12
Random Radial	+/- 0.6 mm	1.40E-12
Tangential	+/- 0.5 mm	2.00E-12
Elliptical truss deformation	1 mm	5.00E-13
Thermal Deformations		
Uniform	n/a	
Monotonic gradients	+/- 35 ppm	9.00E-12
Semi-Random errors	+/- 7.5 ppm	7.00E-13
Formation flying	+/- 1 m lateral	1.00E-11
Glint and Leakage		
Solar glint calibration residual	1 um radius	1.00E-11
Micrometeoroid transmission	< 1 cm^2	1.00E-11
TOTAL		6.81E-11