Jet Propulsion Laboratory
California Institute of Technology

Starshade Compatibility

Briefing to the WFIRST Project

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June 6, 2016

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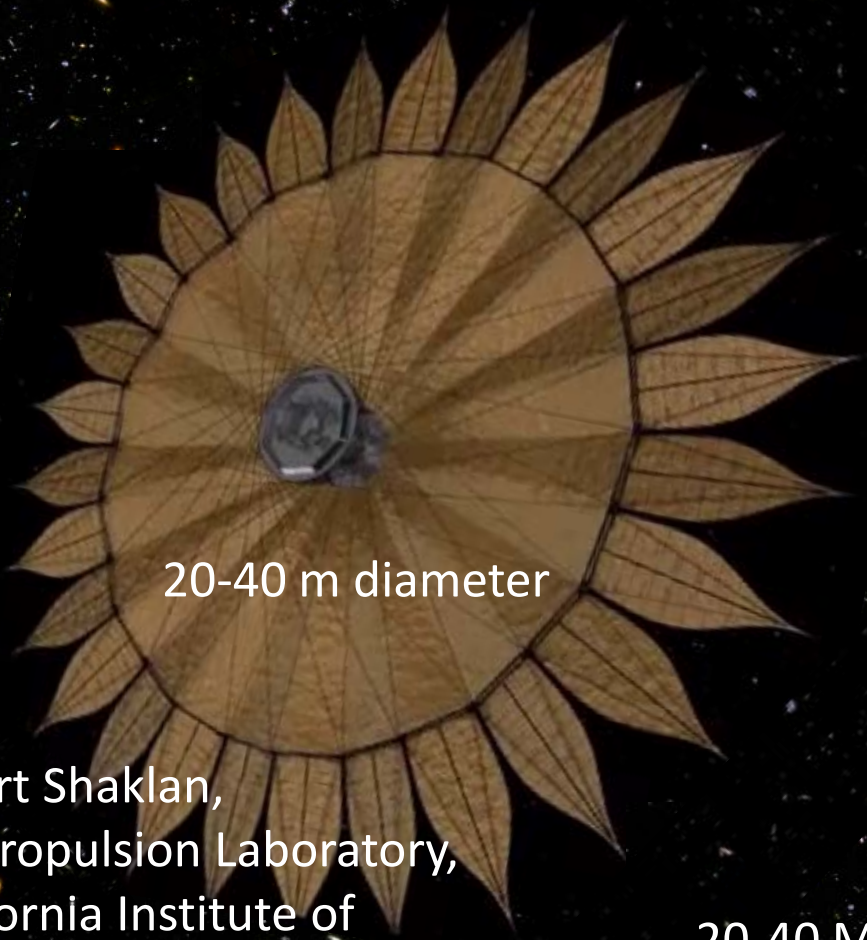
Briefing Agenda

1. Starshade Overview — Shaklan
2. Proposed Concept of Operations/ Requirements on the WFIRST Spacecraft — Lisman
3. Proposed Requirements/Modifications to the CGI — Martin

Starshade Overview for WFIRST Rendezvous



Earth-Sun L2 Orbit

2.4 m telescope

20-40 Mm separation

- Stuart Shaklan,
- Jet Propulsion Laboratory,
- California Institute of Technology

- June 6, 2016

Overview

- What is a starshade and how does it work?
- Brief History
- Exo-S Rendezvous Starshade (CS = Concept Study)
- Status

What is a Starshade?

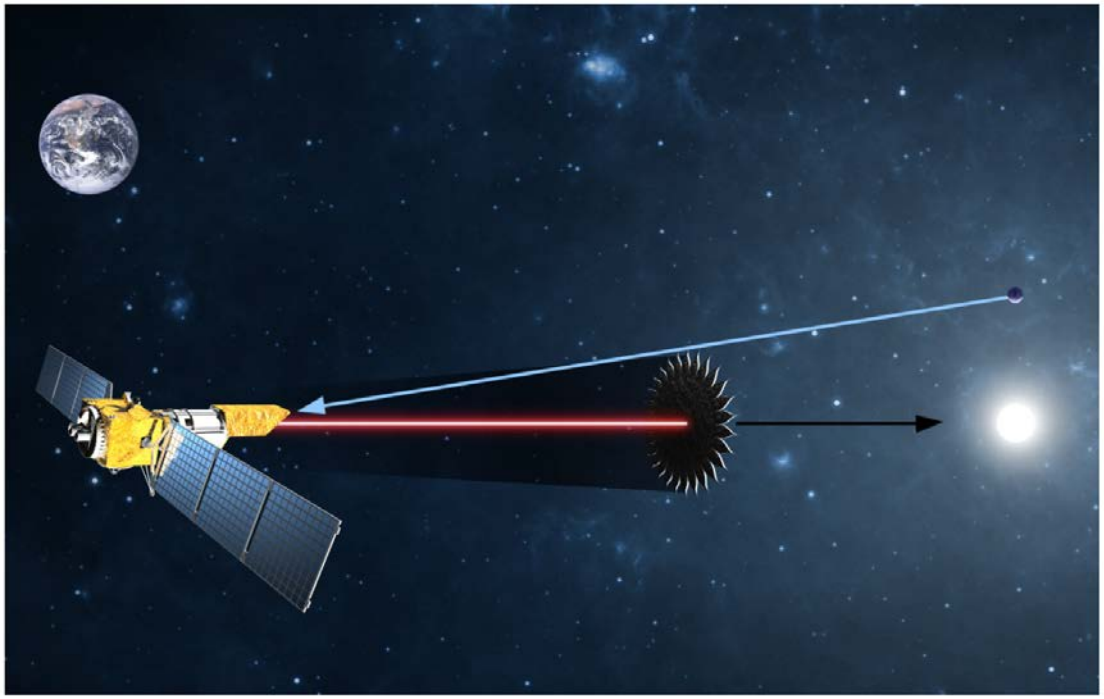
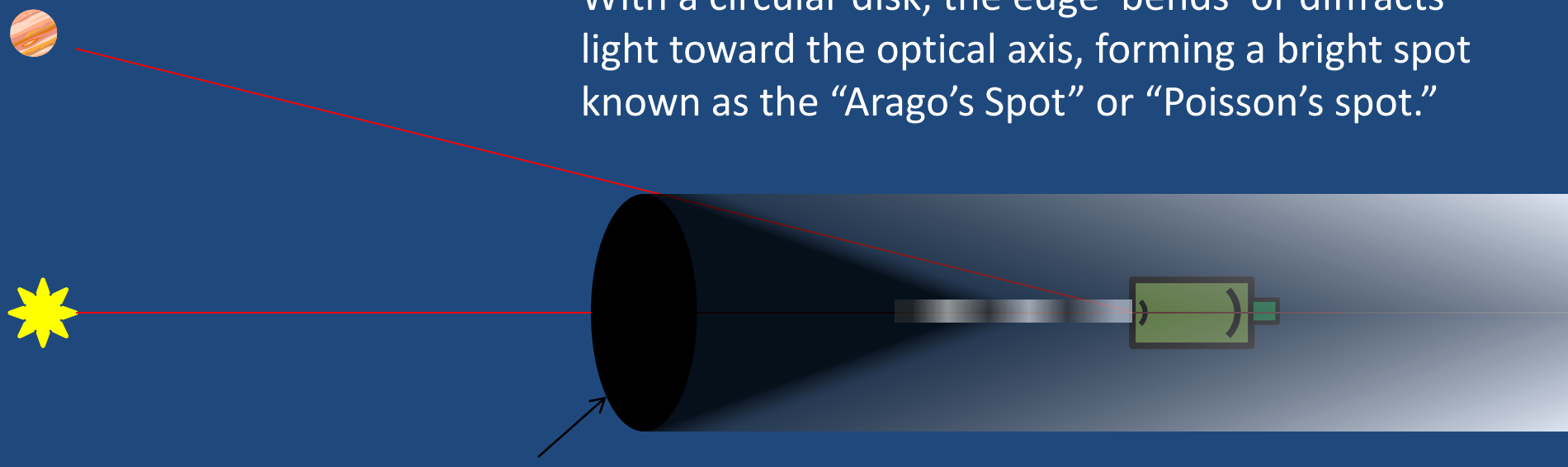


Figure ES-2. A starshade, also called an external occulter, is a precisely shaped screen that flies in formation with a telescope. The starshade blocks starlight to create a high-contrast shadow so that only planet light enters the telescope.

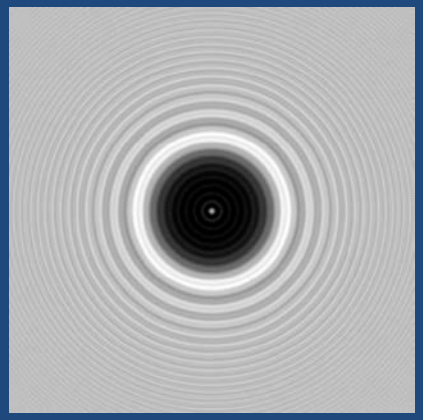
By blocking the light before it gets to the telescope, high-contrast imaging is achieved without imposing any stringent requirements on the telescope optics. Diffraction-limited imaging and few-milli-arcsecond pointing are sufficient.

Why is it shaped like a flower?

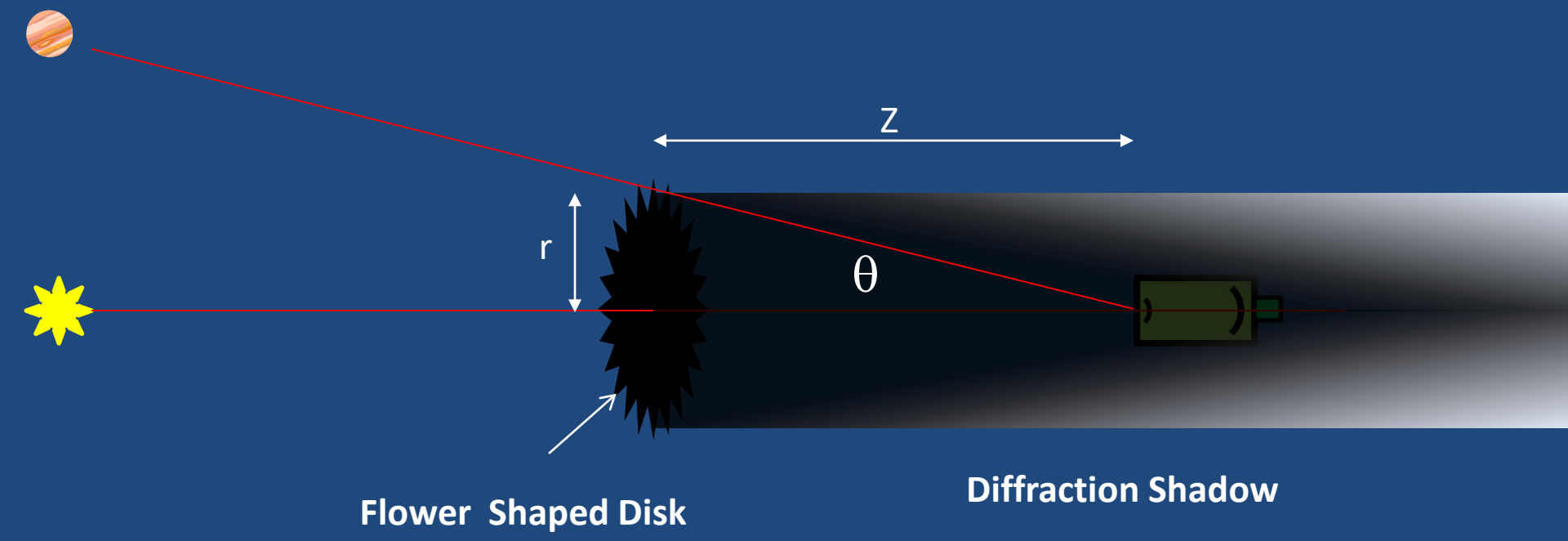
With a circular disk, the edge ‘bends’ or diffracts light toward the optical axis, forming a bright spot known as the “Arago’s Spot” or “Poisson’s spot.”

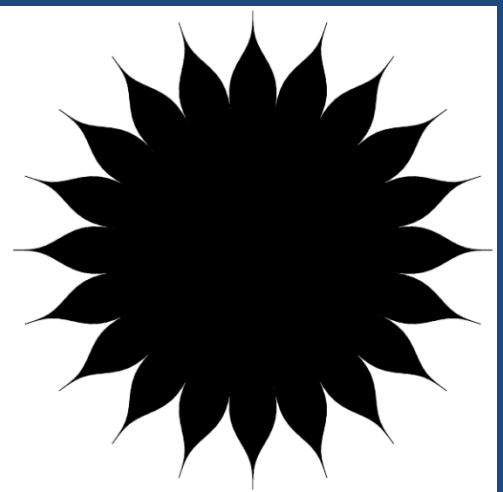


Circular Disk



The flower-shaped starshade has edges that diffract the light away from the axis. A deep shadow is formed without a bright axial spot.



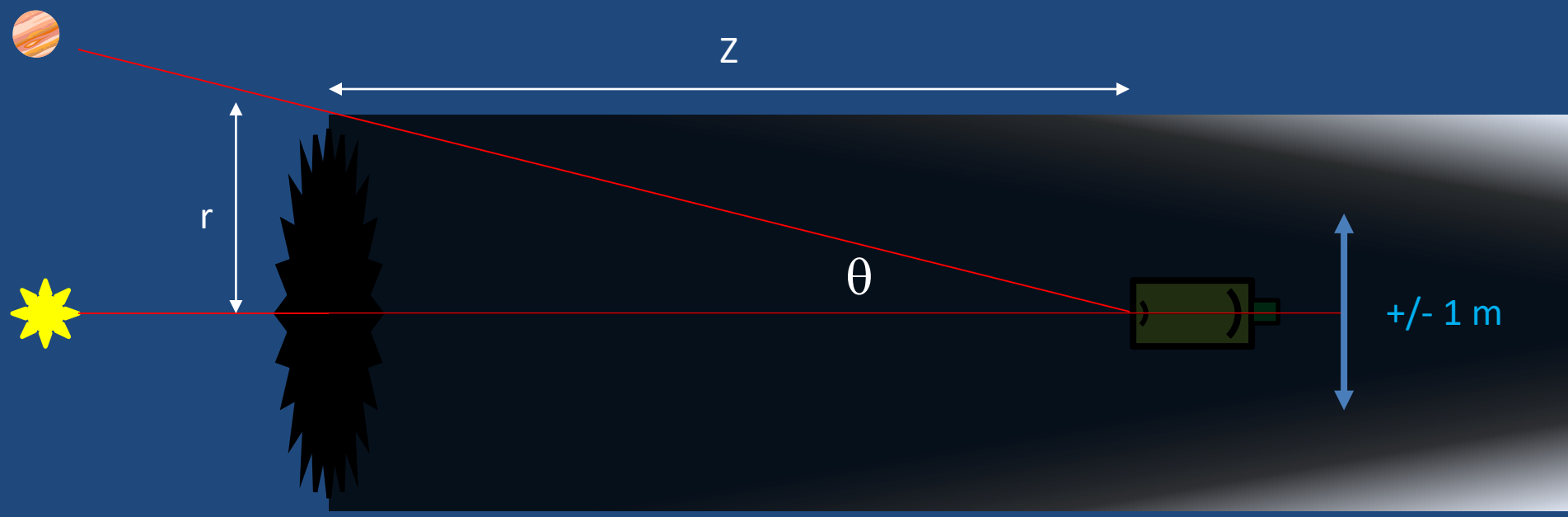


Angle to edge of starshade

$$\theta = r / Z$$

θ = 100 milli-arcsec for a star 10 pc from the sun and a star-planet separation = 1 AU.

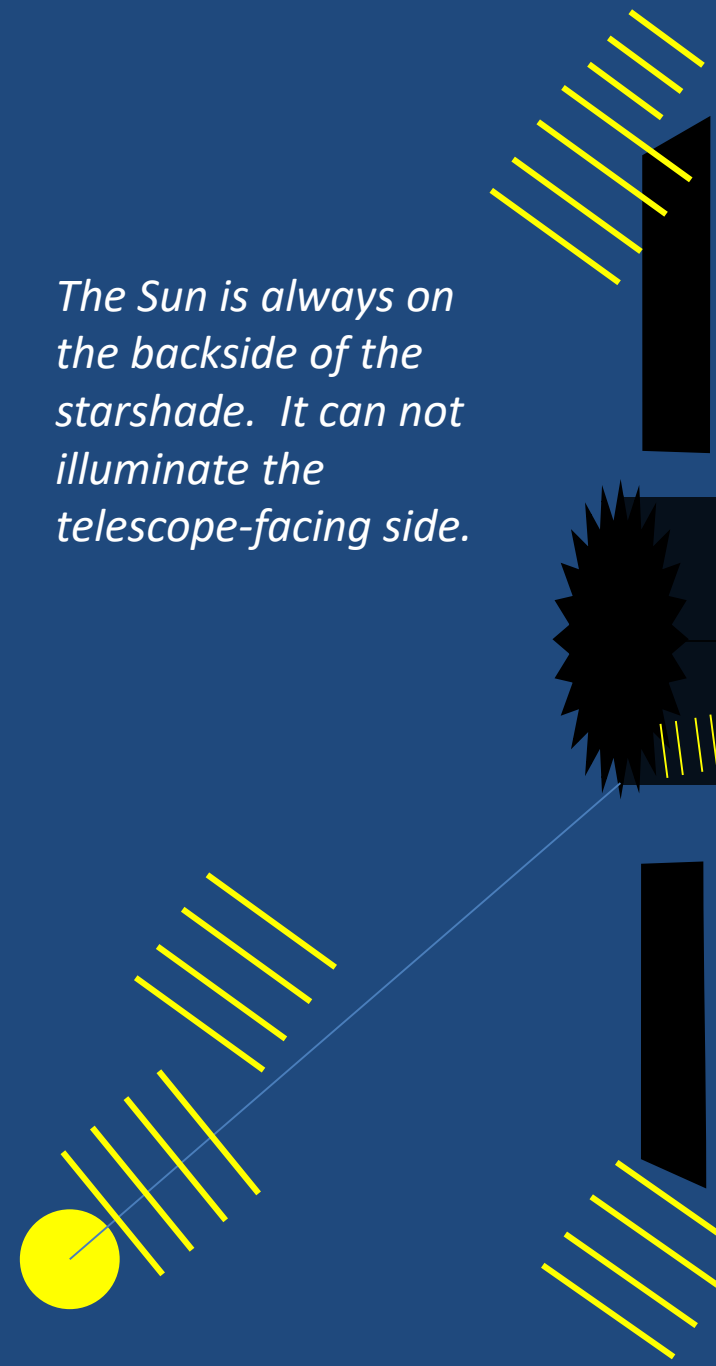
Oversizing the Shadow for Formation Flying



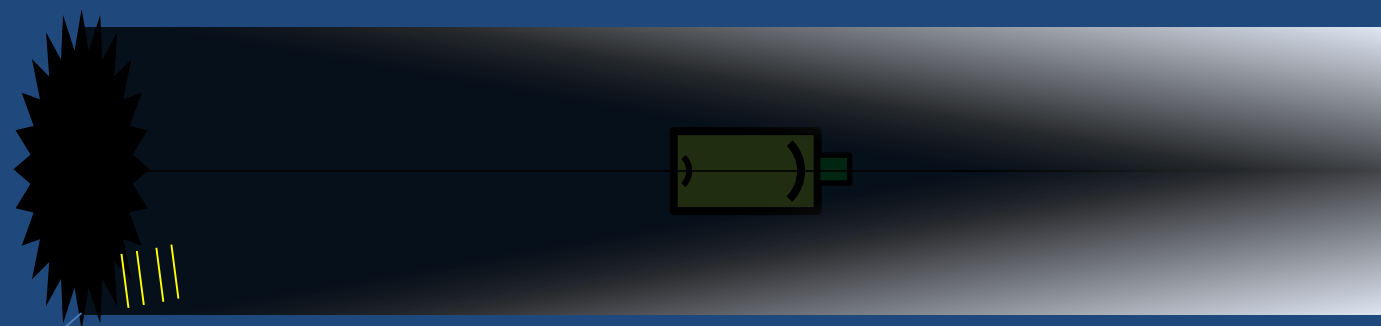
We want to find the smallest distance and smallest starshade that gives us a shadow large enough to cover the telescope with some room for drifting.

Solar Glint

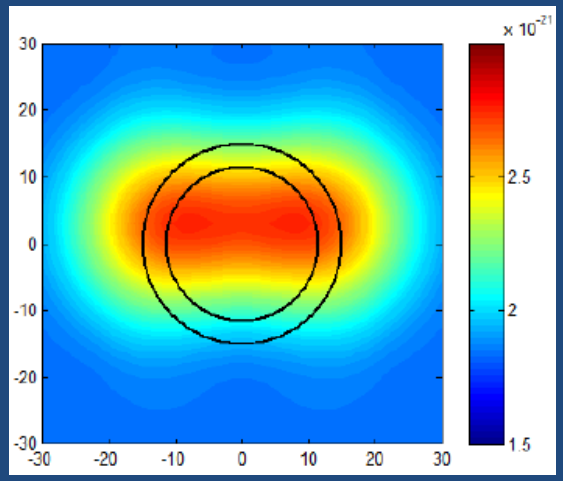
The Sun is always on the backside of the starshade. It can not illuminate the telescope-facing side.



The "trailing" edges are hidden from the sun.



The "leading" edges are exposed to direct sunlight.



Edge needs to be razor sharp

Starshade Design Through the Years

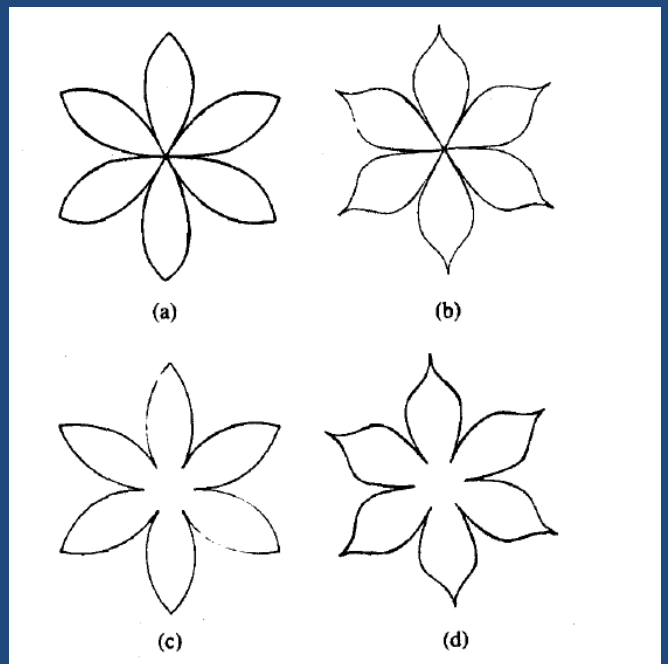
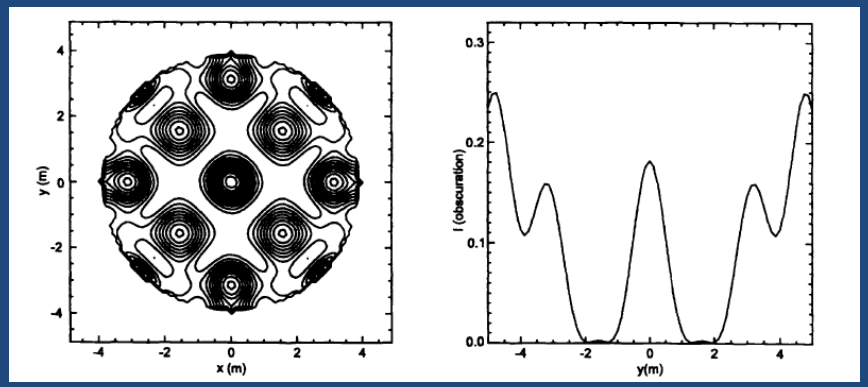


Fig. 4. The shape of some possible screens for various ψ functions. (a) $\psi = \psi_2$. (b) $\psi = \psi_3$. (c) $\psi = \psi_4$. (d) $\psi = \psi_5$.

Marchal, 1985
Babinet's Principle
Petals, central disk
Hundreds of meters

Schultz,1999
Square screen

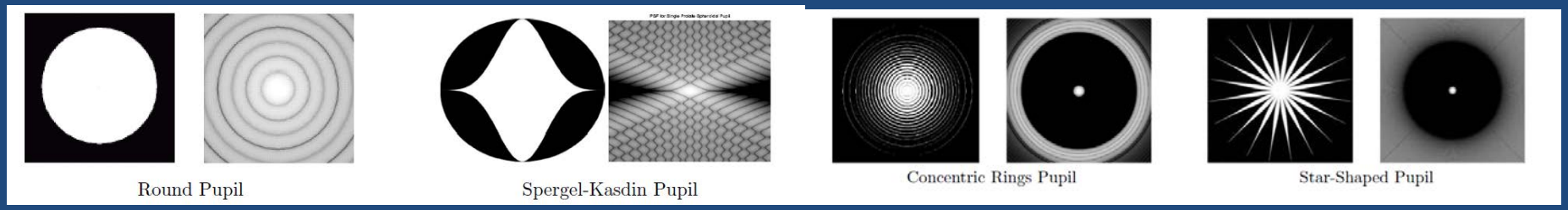


Starshade Design Through the Years

Kasdin, Vanderbei, and Spergel (Princeton) and Cash (U Colo), 2004

Coronagraph Apodization masks:

Pinhole Starshade



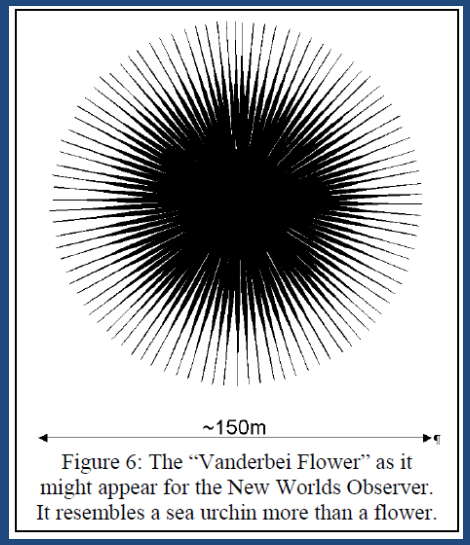


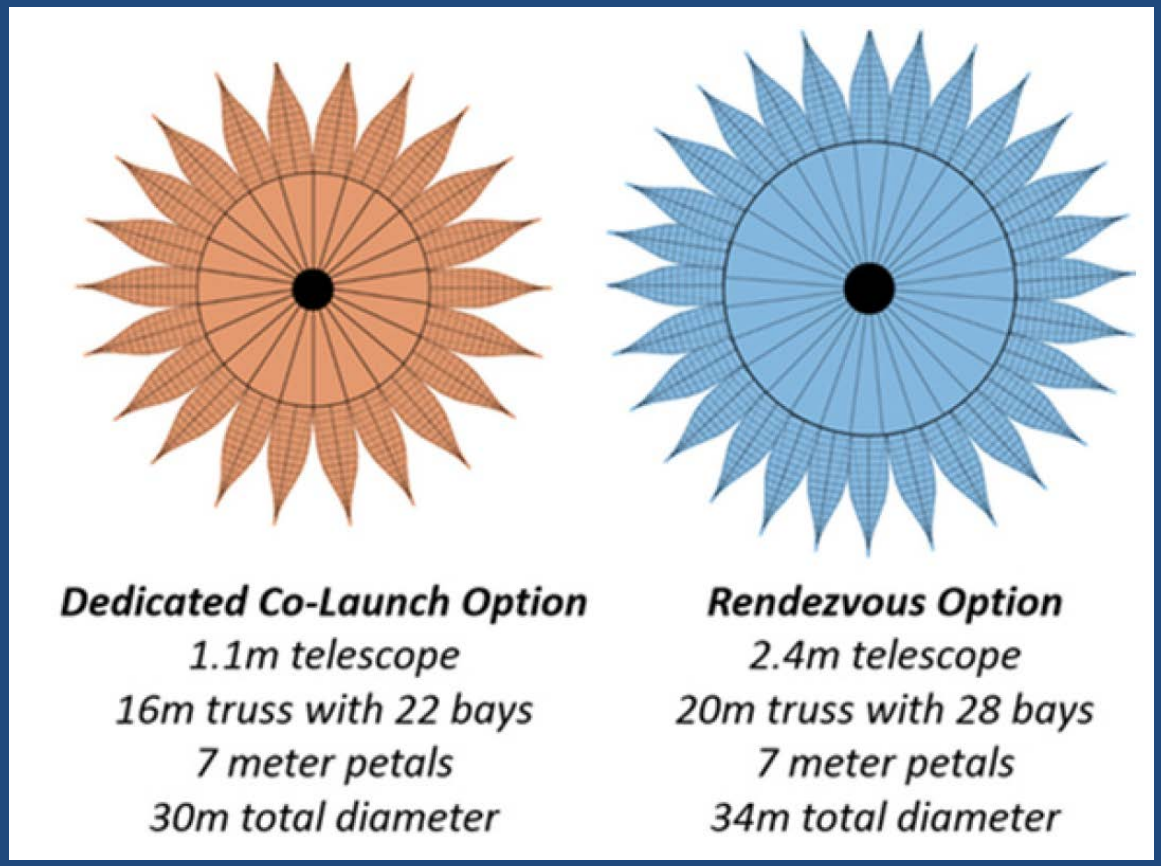
Figure 6: The "Vanderbei Flower" as it might appear for the New Worlds Observer. It resembles a sea urchin more than a flower.

Cash & Kasdin, 2005
300 m, many petals

Cash, 2006, "New Worlds Observer"
First practical design.
60 m, 10^{-10} suppression

Starshade Design Through the Years

Vanderbei, Cady, Kasdin (2007)
Optimized Design
Constrain tips, valleys, diameter…



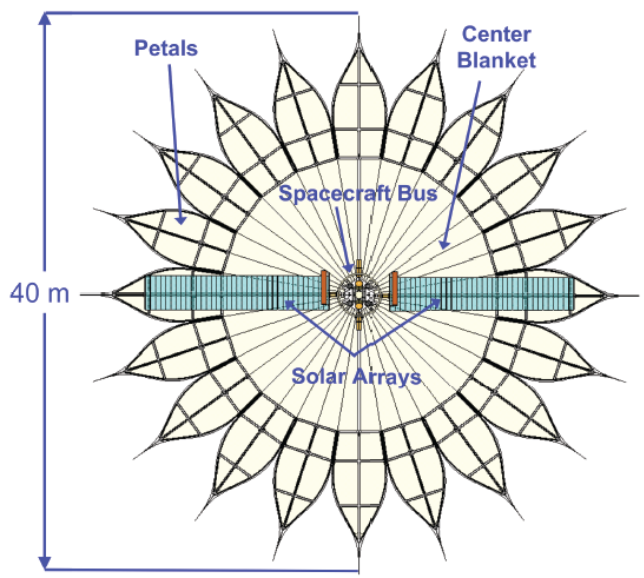
Seager et al, 2015
Exo-S Final Report

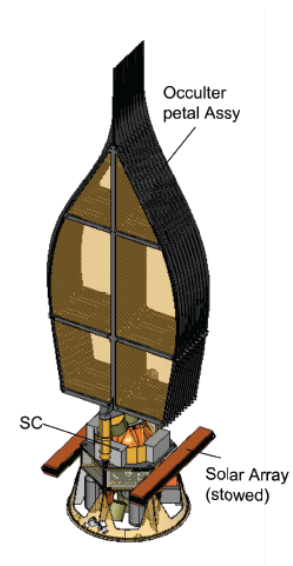
THEIA Mission Concept

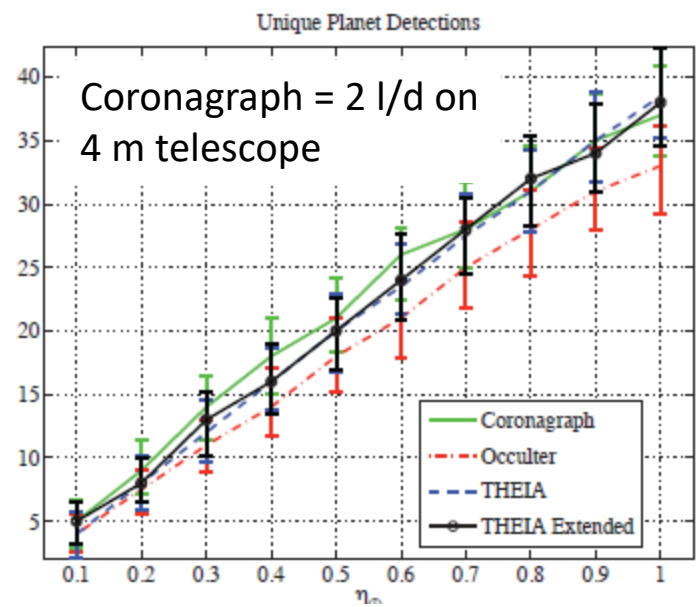
ASMCS 2009 (Spergel)

- 4 m off-axis telescope
- 40 m diameter occulter at 55,000 km
- 250-1000 nm bandpass
- Multi-band/IFS detector for exoplanets
- Wide-field UV camera
- UV spectrometer

Petal Position or Shape Error	Allocation
r.m.s shape ($1/f^2$ power law)	100 μm
Proportional shape	80 μm at max width
Length clipping at tip	1 cm
Azimuthal position	0.003 deg (1 mm at tip)
Radial position	1 mm
In-plane rotation about base	0.06 deg (1 cm at tip)
In-plane bending (r^2 deviation)	5 cm
Out-plane bending (r^2 deviation)	50 cm
Cross-track occulter position	75 cm







New Worlds Observer

ASMCS 2009 (Cash)

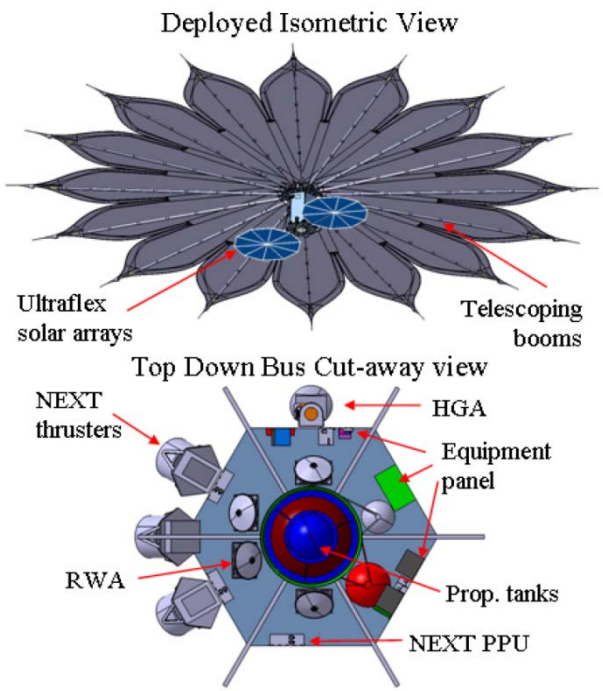


Figure 10: The starshade is a passive payload. The spacecraft bus provides high ΔV with the NEXT electric propulsion system.

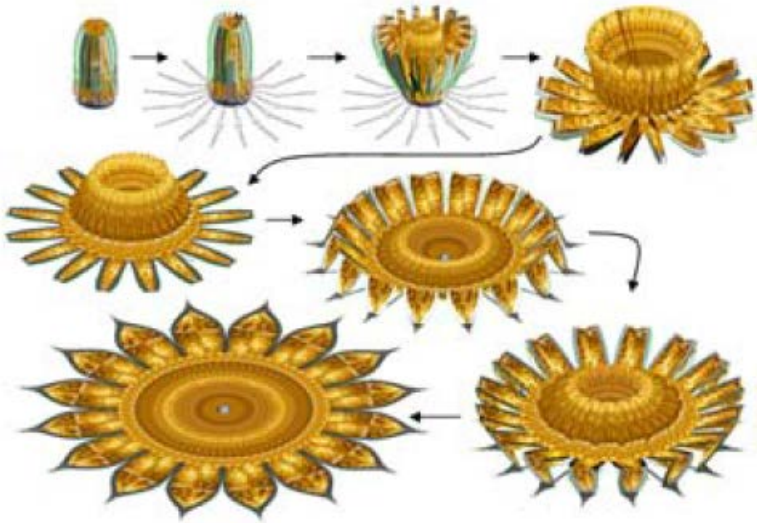


Figure 16: The stowed starshade has a high compaction ratio to fit inside the 5 m EELVs. The starshade deployment uses a single powered mechanism for each petal.

Table 1: NWO Science Instruments

Name	Primary Use	FOV	# pixels	Bandpass	Focus	Notes
ExoCam	Detecting/ Imaging Exoplanets	26″ x 26″	4 x 2k x 2k	0.25-1.7 μm	Cass.	photon-counting CCDs, 6 bands simultaneously
ExoSpec	Spectroscopy of Exoplanets	10″ x 3″	500 x 150 x 728	0.25-1.7 μm	Cass.	R=100, integral field
Shadow Sensor	Fine alignment control	N/A	256 x 256	1.7-3 μm	Cass.	Pupil plane mapping
WF Camera	GA, Fine Guider	10′×20′	92k x 46k	0.4-0.9 μm	TMA	3′×3′ req. for FG
UVSpec	GA UV Spectroscopy	< 1″	16k x 256	0.12-0.5 μm	Cass.	R=30,000 – 100,000

New Worlds Observer Precursor Mission

Chuck Lillie, Amy Lo, Dean Dailey, Tiffany Glassman
Northrop Grumman Space Technology

Spirit of Lyot meeting, Berkeley, 2007

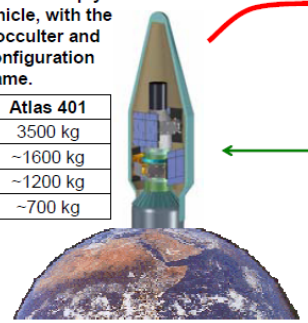
ABSTRACT

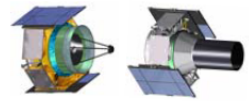
The New Worlds Observer Precusor mission is a mission concept capable of directly imaging gas giant planets, as well as terrestrial planets around stars closer than 10 pc. This mission uses a 1.1 meter telescope with a 14 meter occulter, and is targeted for NASA's "medium" mission class, estimated at a $500M mission cap with launch vehicle costs included. This precursor mission contains all the elements of the NWO Terrestrial Planet Finder architecture: deployable occulter, solar electric propulsion, and a separate telescope spacecraft. This precursor mission is designed to demonstrate the major NWO technologies, including formation flying, occulter deployment, occulter-telescope alignment, and occulter slewing, as well as validate the occulter optical performance.

Mission Concept

Occulter and telescope launched in a 2 stack configuration on an Atlas 401.
The full scale NWO mission simply uses a larger launch vehicle, with the corresponding larger occulter and telescope. Launch configuration remains the same.

Assumed LV	Atlas 401
Launch Mass to L2	3500 kg
Occulter S/C	~1600 kg
Telescope S/C	~1200 kg
Launch Margin	~700 kg

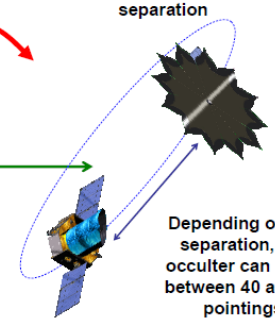




Occulter and telescope deploy shortly after launch. Check out and calibration occurs en route to L2 (3 month transit)

Earth to L2 = 1.5 million km

Orbit injection into an L2 Halo orbit. Occulter and Telescope have same orbit, but have the required separation

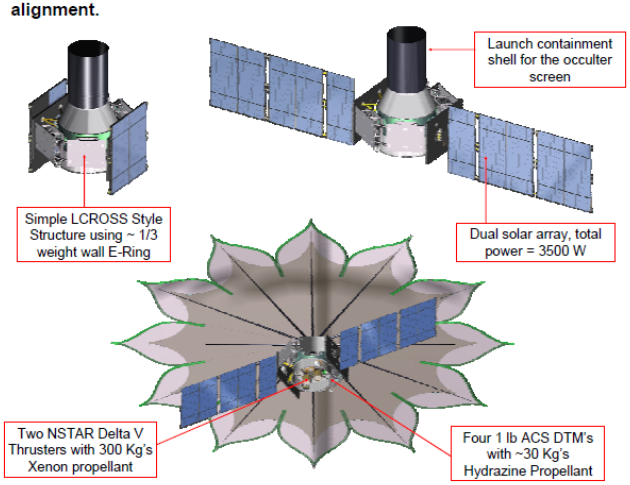


Depending on the separation, the occulter can make between 40 and 80 pointings

Science Performance			
Separation	*Contrast*	*IWA (mas)*	*Detection*
8,000 km	10^{-9}	150	Earths @ <10pc
10,000 km	10^{-8}	120	Neptunes
12,000 km	10^{-8}	100	Saturns/Jupiters

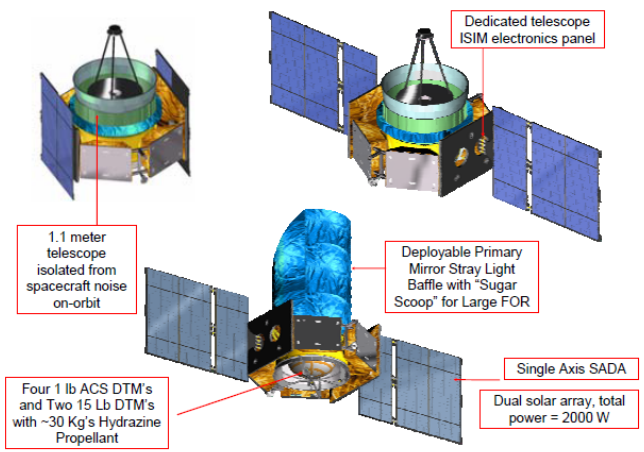
Occulter Spacecraft

The occulter is 14 meters in diameter. A 15 cm aspect camera is mounted in the forward cone for astrometry and telescope alignment. This inexpensive ESPA-derived spacecraft bus has 6 panels for modularity. Dual propulsion with 300 kg Xenon and ACS thrusters for alignment.



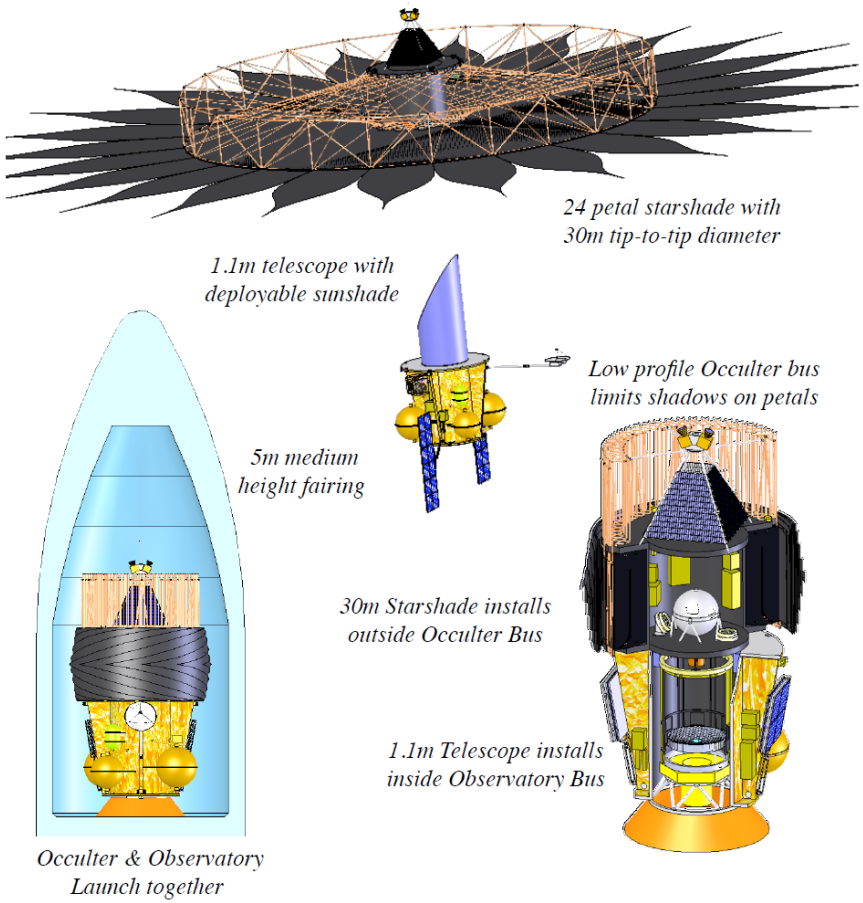
Telescope Spacecraft

Telescope is "off the shelf" 1.1 m aperture with fixed secondary. A deployable sugar scoop baffle enables observations within 45 degrees of the sun. Same structure as the occulter (ESPA ring) but no lightweighting necessary, unless required by launch vehicle constraints



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/or Caltech.

Occulting Ozone Observatory (O3)



Mission and System Design

- 4 year prime mission at Earth-Sun L2
- Single Atlas V launch from Cape Canaveral
- Occulter launches atop Observatory & separates at L2
- Observatory performs formation sensing/control & retargeting
- 2.5 km/s ΔV including 30% contingency
- Conventional propulsion: Observatory-biprop, Occulter-monoprop
- Conventional solar arrays: Observatory-1 axis gimbals, Occulter-fixed
- S-Band DTE & Inter-spacecraft com, Ka-Band science downlink
- Mass contingency is 43% busses, 50% starshade, 30% Observatory payload

Parameter	Value
Occulter tip diameter (m)	30
Telescope aperture diameter (m)	1.1
Number of occulter petals	24
Length of occulter petals (m)	7.5
Planet contrast sensitivity (Δmag)	26
Occulter tip working angle (mas)	75/150
Occulter distance (Mm)	41.25/20.625
Blue passband (nm)	250-550
Red passband (nm)	500-1100

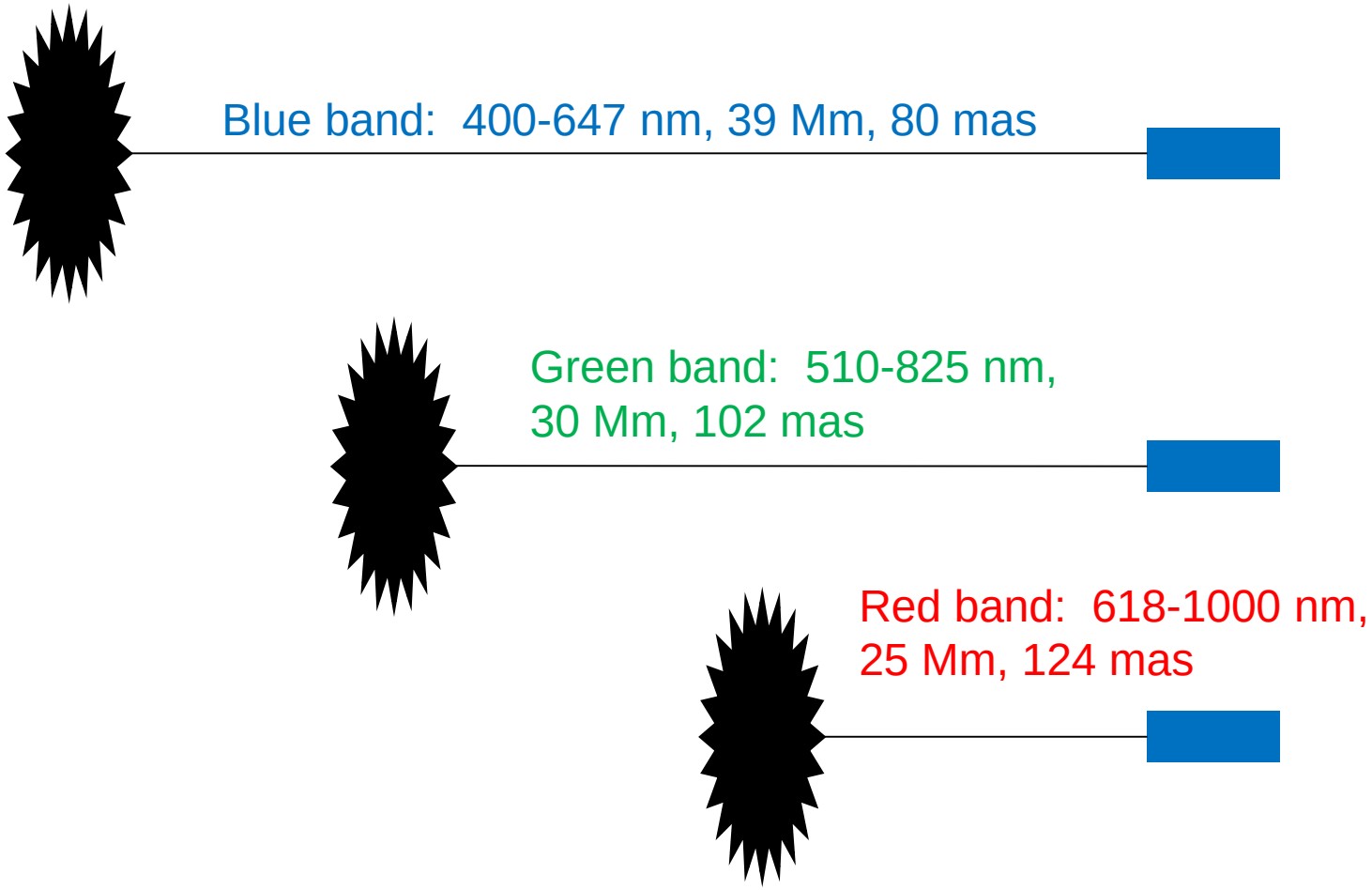
Missions Considered in Exo-S Report

Table 4.1-1. Starshade mission options, including two case study missions (1A & 2C) detailed in this report.

Mission					Telescope/Starshade			Instrumentation		
Orbit	#	Case Name	Mission Class/ Duration	Cost ($M FY15)	Tele-scope	Retarget Prop. Responsibility/ Technology	Starshade	Implementation	FOV	Optical Thru-put
Earth Leading	**1A**	**Dedicated Case Study**	**B 3 years**	**~1100**	1.1-m NextView	Telescope SEP	16-m disk 22 7-m petals	Dedicated IFS Dedicated Imager	30 arcsec 60 arcsec	42% 51%
	1B	Dedicated Downgrade	C 3 years	~950						
	1C	Dedicated Tech Demo	D 1 year	~750	0.6-m QuickBird	Telescope Small Biprop	16-m disk 22 6-m petals			
Earth-Sun L2	2A	Rendezvous Hi Performance	B 5 years	~800	2.4-m WFIRST/ AFTA	Starshade SEP*	20-m disk 22 9-m petals	Dedicated IFS Dedicated Imager	30 arcsec 60 arcsec	42% 51%
	2B	Rendezvous Upgrade	C 3 years	~640		Starshade Large Biprop	20-m disk 28 7-m petals			
	2C	**Rendezvous Case Study**	**C 3 years**	**~630**				Coronagraph IFS Coronagraph Imager	2 arcsec 10 arcsec	22% 28%
	2D	Rendezvous Tech Demo	D 1 year	~400		Starshade Small Biprop				

One Starshade, Multiple IWA and Bandpass

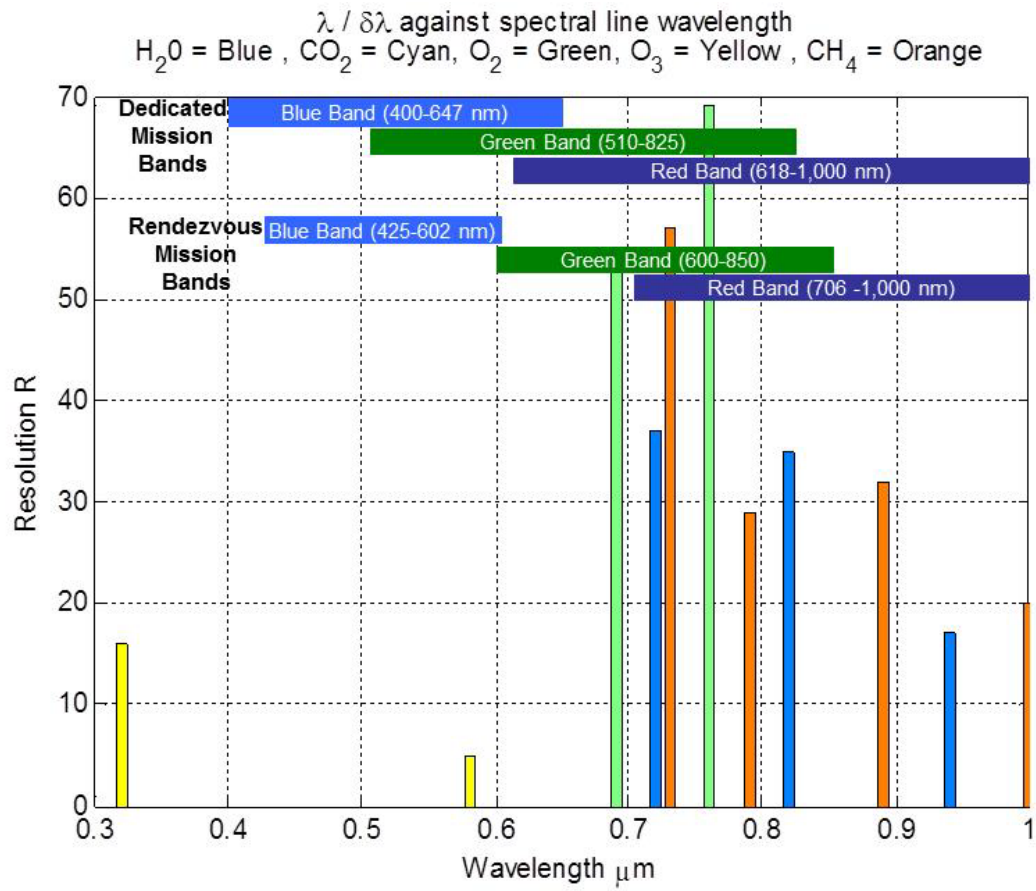
- The starshade is designed to form a dark shadow over a finite bandpass.
- The bandpass shifts as the distance to the starshade shifts.



Dedicated and Rendezvous Design Bands

Table 4.4-1. Summary of case study parameters.

Case Study	Parameters	Observing Bands		
		Blue	Green	Red
Rendezvous Mission	Bandpass (nm)	425–602	600–850	706–1000
20-m inner disk	IWA (mas)	71	100	118
28 7-m petals	Separation (Mm)	50	35	30
Dedicated Mission	Bandpass (nm)	400–647	510–825	618–1000
16-m inner disk	IWA (mas)	80	102	124
22 7-m petals	Separation (Mm)	39	30	25

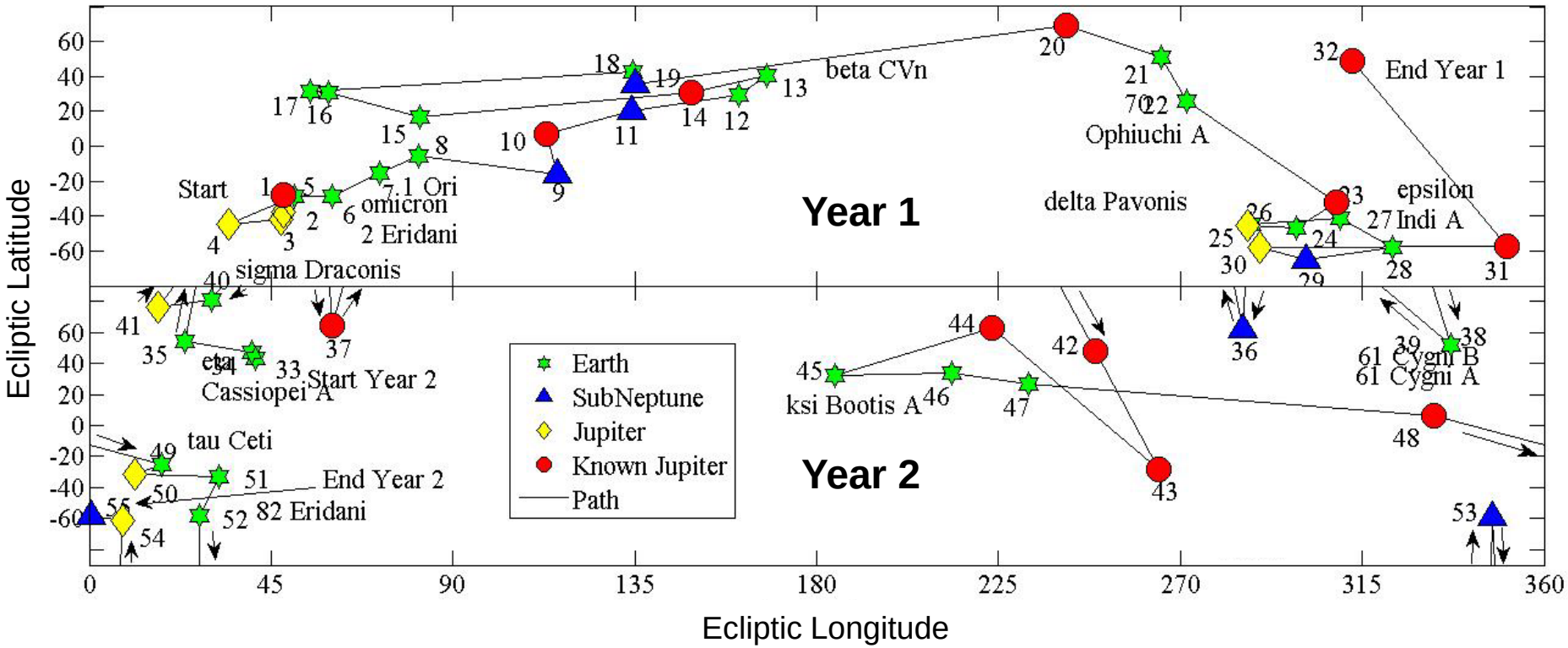


Final designs have 7 m long petals, 16 m truss (Dedicated), 20 m truss (Rendezvous), and work in 3 bands, each 46% wide (Dedicated) and 32% wide (Rendezvous). The workhorse "Green" band measures key spectral features.

Observing Sequence: Rendezvous Mission (Case 3)

This is a 2-year sequence, 55 targets, ΔV = 1266 m/s

Targets: 12 known RVs, 28 Earth twins, 7 sub-Neptune, 8 Jupiters



Telescope Time Utilized: **9%**. This was a strategic decision to maximize the number of targets while still getting many spectra of giant planets.

For the Dedicated mission, telescope utilization is **25%** (Cases 1 and 2).

The program is consistent with low overall utilization of the telescope allowing other science to be performed.

Rendezvous Planet Yield Estimate

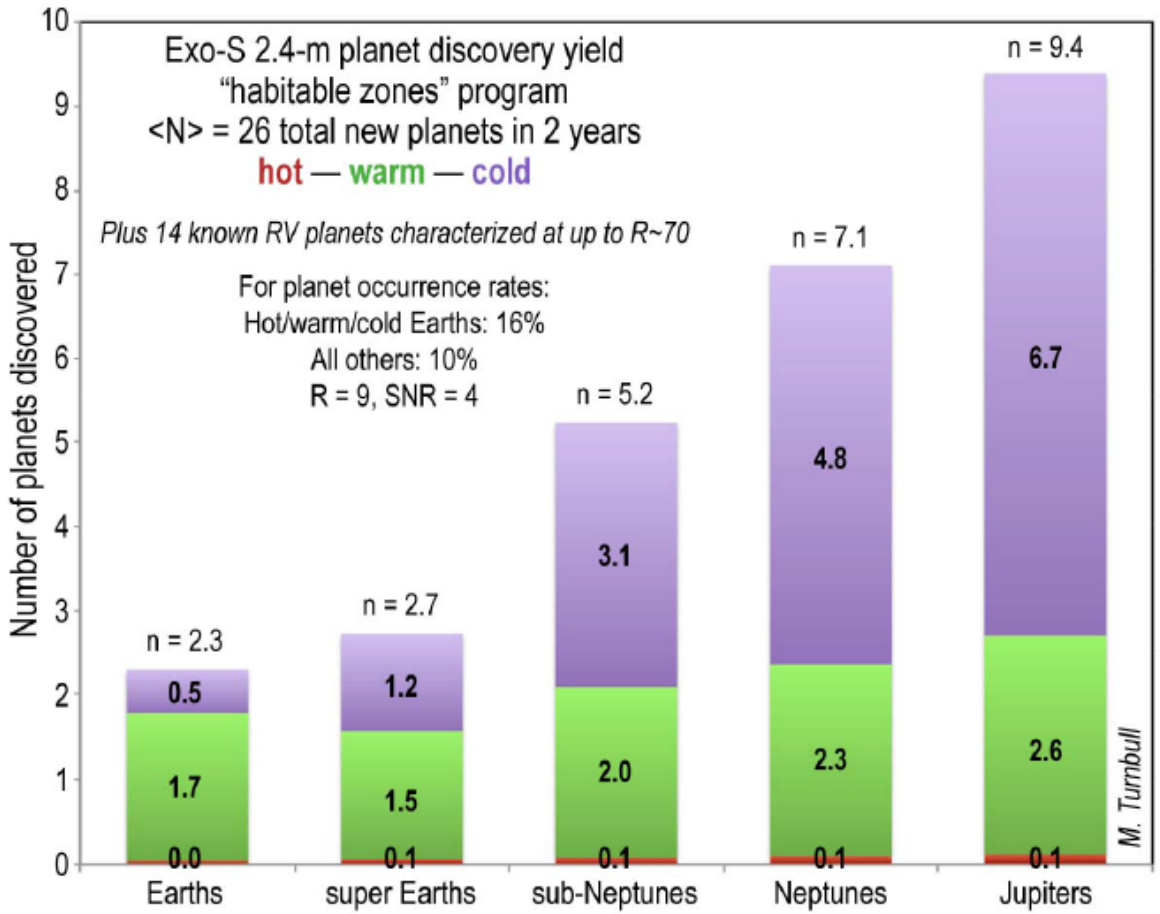
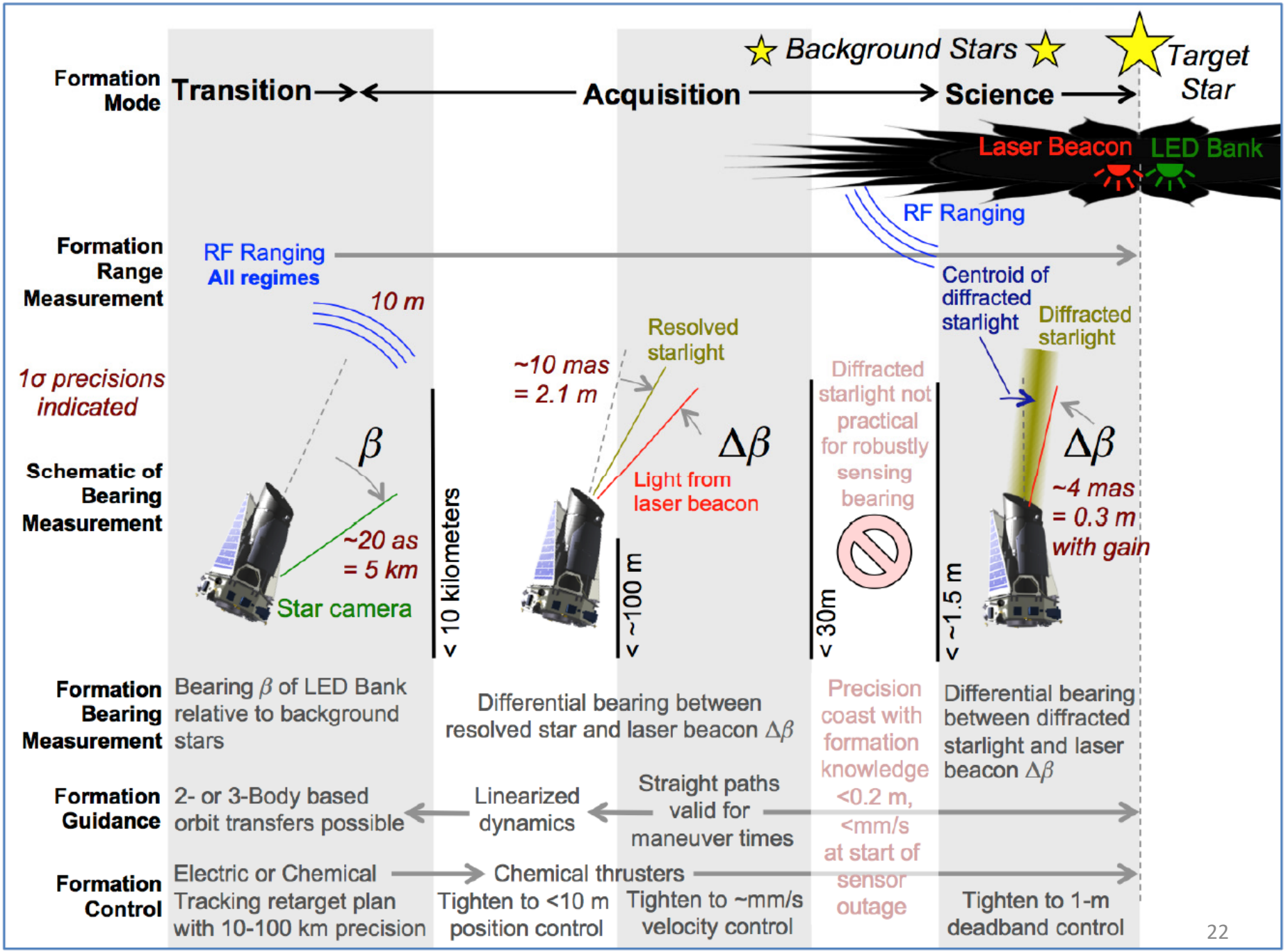


Figure 2.6-3. The predicted Exo-S 2.4-m planet discovery yield in the first two years of operations, for the Case 3 target selection scenario designed in part to maximize the discovery of habitable zone Earths.


Formation Mode
Transition
Acquisition
Science
Background Stars
Target Star
Laser Beacon
LED Bank
RF Ranging
Formation Range Measurement
RF Ranging
All regimes
10 m
Centroid of diffracted starlight
Diffracted starlight
1σ precisions indicated
Resolved starlight
~10 mas = 2.1 m
Diffracted starlight not practical for robustly sensing bearing
Schematic of Bearing Measurement
β
~20 as = 5 km
Star camera
< 10 kilometers
Light from laser beacon
Δβ
< ~100 m
< 30m
Δβ
~4 mas = 0.3 m with gain
< ~1.5 m
Formation Bearing Measurement
Bearing β of LED Bank relative to background stars
Differential bearing between resolved star and laser beacon Δβ
Precision coast with formation knowledge <0.2 m, <mm/s at start of sensor outage
Differential bearing between diffracted starlight and laser beacon Δβ
Formation Guidance
2- or 3-Body based orbit transfers possible
Linearized dynamics
Straight paths valid for maneuver times
Formation Control
Electric or Chemical Tracking retarget plan with 10-100 km precision
Chemical thrusters
Tighten to <10 m position control
Tighten to ~mm/s velocity control
Tighten to 1-m deadband control

Key Requirements: No Showstoppers

Table 6.4-3. Key requirements for the error budget. Values are 3-sigma tolerances.

	Dedicated 1.1 m	Contrast × 10^{-11}	Rendezvous 2.4 m	Contrast × 10^{-11}
Manufacture				
Petal Segment Shape (Bias)	14 µm	1.4	22 µm	0.37
Petal Segment Shape (Random)	71 µm	0.5	71 µm	0.26
Petal Segment Placement (Bias)	4 µm	0.7	7 µm	0.07
Petal Segment Placement (Random)	45 µm	0.6	53 µm	0.47
Pre-Launch Deployment				
Petal Radial Position (Bias)	150 µm	6.0	200 µm	0.15
Petal Radial Position (Random)	450 µm	0.6	450 µm	0.1
Post-Launch Deployment				
Petal Radial Position (Bias)	100 µm	2.7	250 µm	0.23
Petal Radial Position (Random)	350 µm	0.4	375 µm	0.06
Thermal				
Disk-Petal Differential Strain (Bias)	20 ppm	6.0	40 ppm	0.6
1–5 Cycle/Petal Width (Bias)	10 ppm	1.0	30 ppm	0.2
Formation Flying				
Lateral Displacement	1 m	2.9	1 m	1.1
Longitudinal Displacement	250 km	2.5	250 km	0.43

Error Budget Requirements and Allocations

Table 6.4-2. Starshade contrast requirements.

Requirement	Dedicated 1.1 m	Rendezvous 2.4 m
Photometric Floor	5×10^{-10}	1×10^{-10}
Systematic Floor	4×10^{-11}	4×10^{-11}

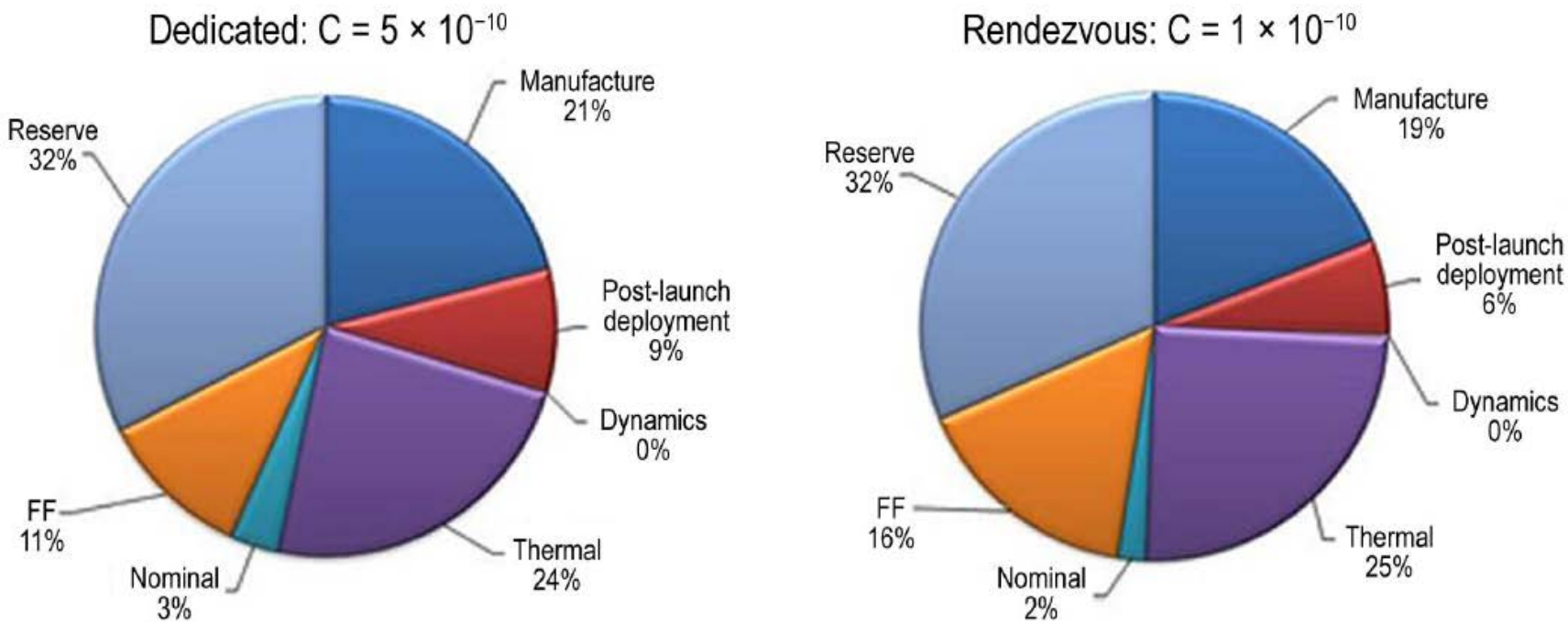


Figure 6.4-3. Overall photometric error budget for the Dedicated and Rendezvous missions.

Experiment vs. Requirement

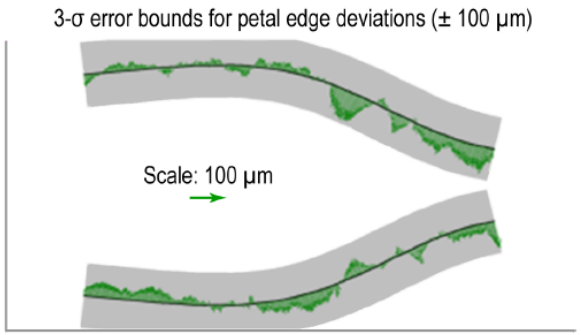
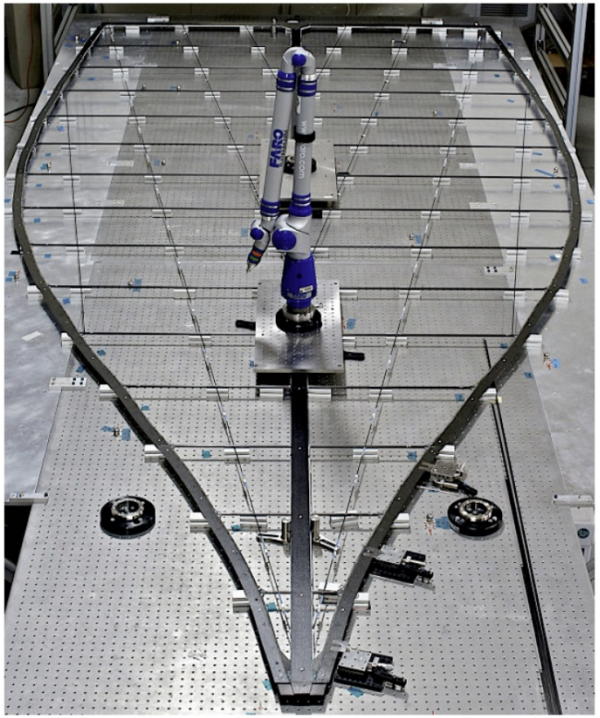


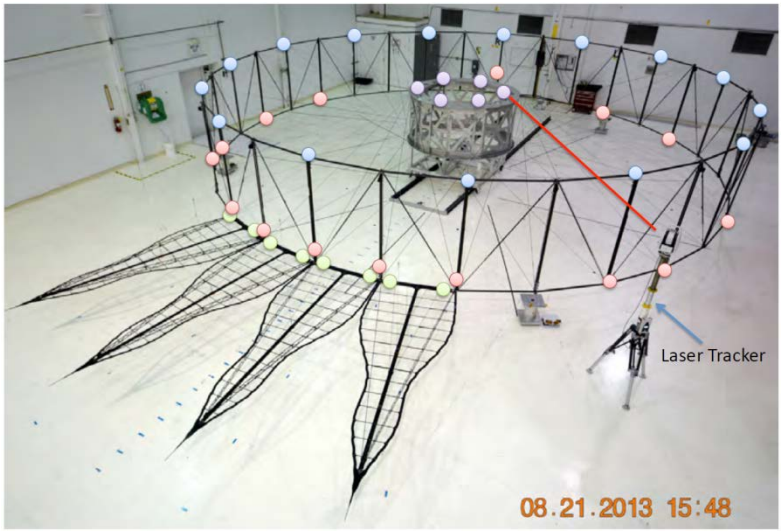
Figure 9.4-2. Measured petal shape error (green arrows) vs. 100 μm tolerance for 1×10^{-10} imaging (gray band) shows full compliance with the allocated tolerance.

Table 6.4-4. Comparison of TDEM results with Exo-S requirements.

Key Technology	Demonstra-tion	Achieved Tolerance	Required Tolerance
Petal Segment Shape (Random)	TDEM-09	±45 μm	±68 μm
Petal Segment Position (Random)	TDEM-09	±45 μm	±45 μm
Radial Petal Position (Bias)	TDEM-10	±100 μm	±150 μm



Kasdin TDEM-10 Final Report



Kasdin TDEM-11 Final Report

Take Aways

- Rendezvous Starshade will be 20-40 m in diameter, depending on science/technology goals and budget.
- It will be sensitive enough to detect Exo-Earths in the habitable zone.
- We are marching toward TRL-5.
- It will not drive any optical requirements on the telescope or wide-field instrument.

Starshade Ready Briefing to WFIRST Project

Concept Requirements

Doug Lisman

June 6, 2016

Agenda

- Mission overview
- Previous trade studies that shape the concept of operations
- Proposed concept of operations
- Proposed requirements on the WFIRST spacecraft

WFIRST Rendezvous Mission Options

Option #	Option Name	Approximate Starshade Size	Approximate Telescope Separation	Mission Class & Duration	Retarget Propulsion	Attitude Stabilization
0	Hi Performance	40 m	70 Mm	5 yr - Class B	SEP	3-axis
1	Exo-S Concept Study	34 m	50 Mm	3 yr - Class C	Biprop	Spin
2	Exo-S Extended Study	20 m	20 Mm	3 yr - Class C	Biprop	3-axis
3	Tech Demo	20 m	20 Mm	1 yr - Class D	Monoprop	3-axis

Option 1 is detailed in the Exo-S STDT Report, of March 2015. Updates need to be flagged to avoid confusion.

Option 2 is the most current design with new petal unfurling approach that should be folded back into the other options.

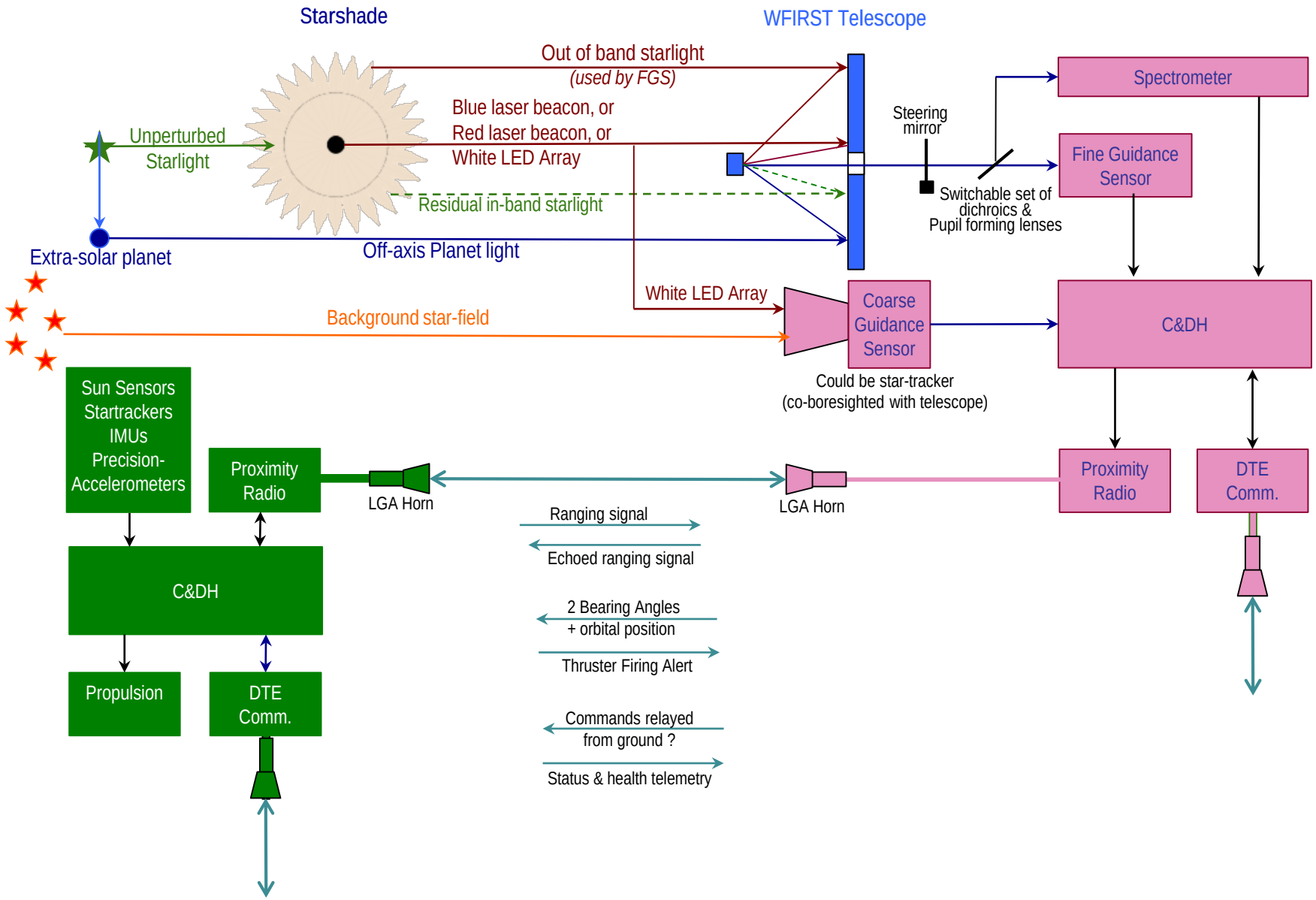
Starshade Reference Mission Overview

- Falcon-9 launch on direct trajectory to E-S L2 to rendezvous with WFIRST
- 3 year Class C mission with 34 m starshade, per case study in Exo-S STDT report
  - Other mission options are under study as shown on next chart
  - Design continues to evolve and some out of date information in the Exo-S STDT report can be confusing
  - A list of these incidences is included here as a backup chart
- Exoplanet observations with the starshade utilize < 10 to 20% of telescope time
  - Performed with the Coronagraph IFU
  - Wide Field Camera can observe the available field in parallel
- Lateral formation error is sensed with the Coronagraph DI at out of band wavelengths
- Starshade to Telescope communications are via S-Band proximity radio link that also measures the range between the two spacecraft

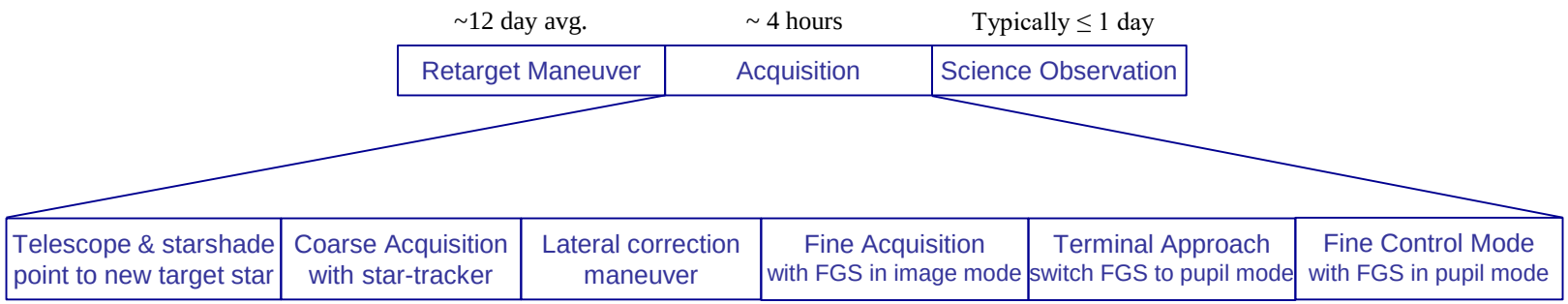
Summary of Previous Trade Studies that shape the concept of operations

Trade Study Conclusions	Rationale
1. Telescope performs lateral formation sensing.	Avoid starshade complexity of sensing lateral error with a large dual aperture telescope and dichroic to image both telescope and star on same focal plane.
2. Telescope performs lateral formation sensing in both image plane and pupil plane modes, with a switch built into the acquisition process.	Hybrid approach makes acquisition robust. Initial acquisition requires image mode, but signal is ambiguous as starshade transitions from first contact to fine control mode. Switching to pupil mode avoids dead reckoning process.
3. Starshade performs lateral formation control.	Avoid telescope complexity of applying lateral ΔV with minimal torque and longer data outages for telescope damping.
4. Starshade performs retarget maneuvers.	Avoid telescope complexity of adding propulsion capability. Avoid losing observation time for other experiments.
5. Starshade performs retarget maneuvers with no telescope tracking to calibrate the trajectory.	Avoid operational complexity and lost obs. time. Starshade execution accuracy with precision accels is sufficient to correct error with reasonable fuel and time, with telescope acquisition about 4 hours before start of obs..
6. Starshade is “leader” for measuring range over RF link with telescope “echo” of ranging signal.	Avoid telescope complexity, albeit minimal
7. Starshade exoplanet obs. and formation guiding is performed by the coronagraph instrument.	Avoid telescope complexity with no new focal planes. Wide Field Camera not appropriate because of pixel scale, not co-boresighted with IFU and no filter wheels convenient to add starshade bandpass filters.

System Block Diagram



Concept of Operations – 1 of 2



Retarget Mode

- Starshade receives a new executable sequence from the ground for the next target
- Starshade autonomously executes a retarget maneuver with precision accelerometers to within ± 10 km
- Starshade points to the new target star, turns on it's LED array starts computing range

Acquisition Mode

- Telescope points to new target, acquires starshade with CGS and starts sending inertial bearing angles
- Starshade autonomously executes a correction maneuver, closing loop around bearing angles
- Telescope acquires starshade with FGS, using FSM, and starts sending more accurate bearing angles
- Starshade switches from LED array to laser beacon (blue or red)
- As starshade starts to diffract starlight, telescope switches FGS to pupil plane mode for final acquisition
- Telescope and starshade enter fine control mode and transition to Science Mode

Concept of Operations – 2 of 2

Science Mode

- Telescope measures lateral formation bearing angles and radios them starshade
- Starshade measures axial separation distance and computes lateral position error
- Starshade controls lateral position, sending thruster firing warnings beforehand
- Telescope stops reading out detectors for a specified time after each thruster firing warning
- Telescope periodically downlinks exo-planet science data as coronagraph data packets

Telescope Functional Requirements

- The telescope shall provide a science camera(s) for exoplanet detection and spectral characterization.
- The telescope shall provide a fine guidance camera (FGC) to measure bearing angles between a starshade laser beacon and out of band starlight.
- The telescope shall provide complimentary bandpass filters that simultaneously feed the co-boresighted science camera and FGC.
- The telescope shall provide for operating the FGC in either image plane or pupil plane modes.
- The telescope shall provide a coarse guidance camera (CGC) to measure inertial bearing angles
- The telescope shall provide a proximity radio for communications with the starshade and to echo a range-finding signal from the starshade

Key Performance Requirements

Starshade

- Retarget accuracy ≤ ± 10 km
- Range knowledge ≤ ± 1 km
- Range control ≤ ± 250 km
- Lateral position knowledge ≤ 25 cm
- Lateral position control ≤ 1 m

Telescope

- Bearing angle knowledge accuracy ≤ ± 1 mas
- Field of regard relative to Sun at least 54° to 83° (goal is 40° to 83°)
- Coarse guidance sensor accuracy ≤ 25 arc-sec, consistent with the FGS capture range using the FSM
- Science bandpass ≥ 30%
- 3 observing wavelength bands (see Stefan Martin's presentation below)
- FOV consistent with observing a Jupiter twin at ≥ 10 parsecs

Starshade Optics Interface to WFIRST

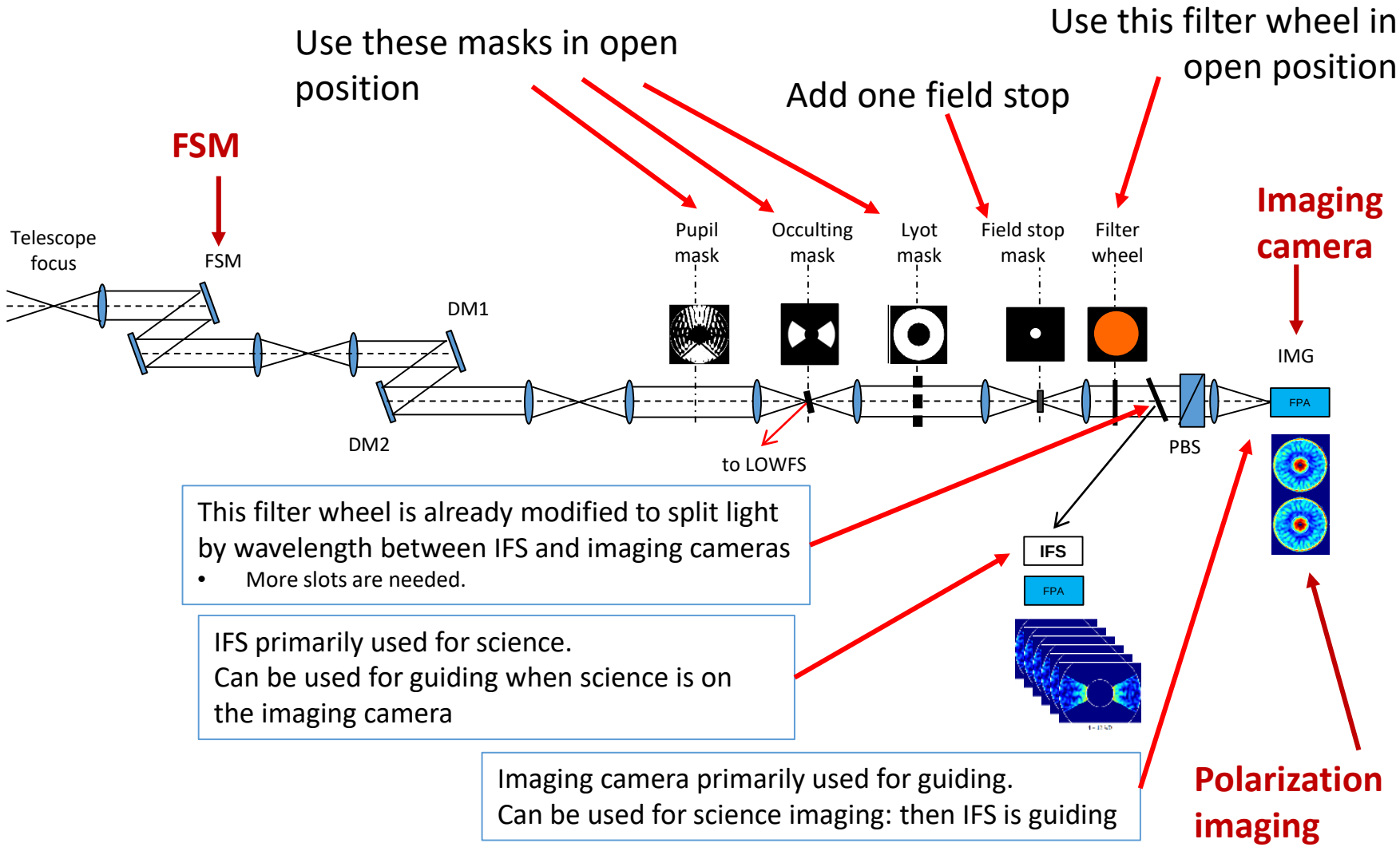
Stefan Martin

JPL

Starshade Optical System Summary

- Science Instruments
  - Imaging:
    - A field camera for imaging the target planetary system
  - Spectroscopy:
    - A integral field spectrometer with spectral resolution of 70
- Formation Flying
  - Star tracker
    - Tracks LED beacon on starshade during retargeting maneuvers
  - Guide camera
    - Tracks laser beacon on starshade and light from the target star
  - Communications system
    - Starshade range obtained from telescope-starshade communications link

WFIRST Coronagraph beamtrain



Coronagraph Mechanisms

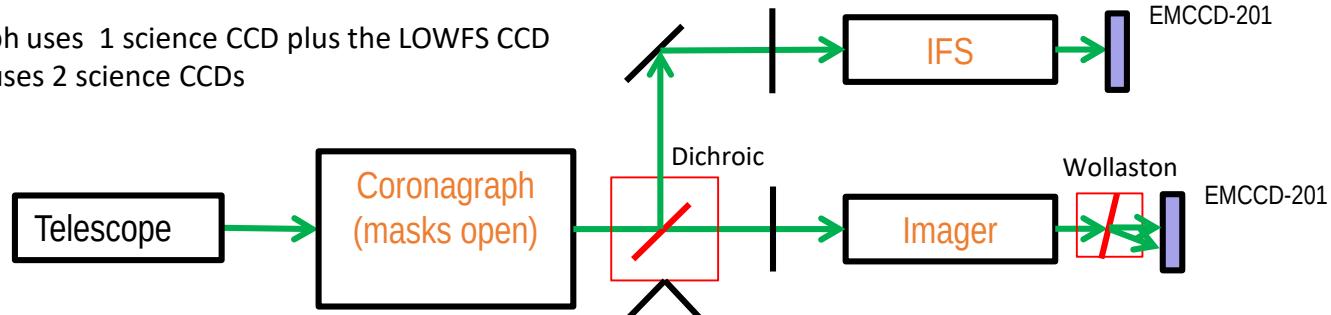
9 mechanisms, 6 of which are identical designs

Mechanism	Description
Fast Steering Mirror	Tip and tilt at pupil (PM conjugate) Operates at up to 1 KHz based on feedback from low-order wave-front sensor (LOWFS) Dynamic range = 30 as / 60 mas = 500 (TBR) Resolution of 60 mas (TBR) (to correct telescope pointing to 1mas = 120mas in coronagraph = 60mas in mirror angle.) ✓ Feedback from guide channel (~ 1Hz)
Shaped Pupil Mask Changer	5 positions (4 SP masks, 1HL flat mirror) ✓
Focal Plane (occulting) Mask Changer	14 positions (11 SP masks, 2 HL masks, 1 open) ✓
Lyot Stop Changer	3 positions (1 SP mask, 1 HL mask, 1 open) ✓
Field Stop Changer	3 positions (1 SP open, 2 HL stops, 1 starshade imaging stop) ✓ Add one slot for wider FOV
Color Filter Changer	12 positions ([4] 5% filters, [3] 10% filters, [3] 18% filters, 1 open, 1 dark) ✓
Camera Selector Changer	N positions (1 lens for IMG cam, 1 fold mirror for IFS, 1 lens for pupil image on IMG cam)
Focus Mirror Adjust	Continuous positioning for focus adjustment ✓
MLA rotator/switcher	Rotates or swaps out microlens array to suit starshade or coronagraph: new mechanism

Additional positions for dichroics to partition light between guide and science channels

Camera Selector Modes

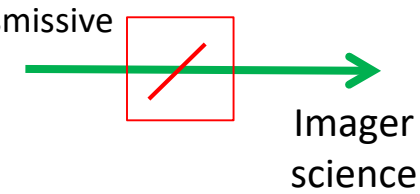
Coronagraph uses 1 science CCD plus the LOWFS CCD
Starshade uses 2 science CCDs



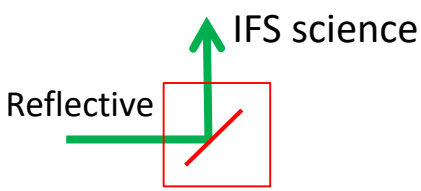
Performance
20% throughput
18% bandpass
0.7 arc-sec FOV

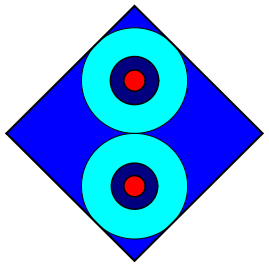
Coronagraph Mode

Imaging Mode



Spectroscopy Mode

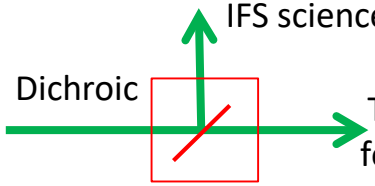




Arrangement of polarization images on guide CCD for larger starshade FOV

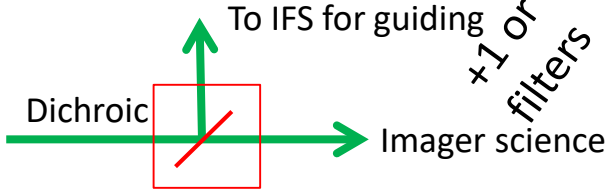
Starshade Mode

Spectroscopy Mode



+3 filters

Wide Field Imaging Mode



+1 or more filters

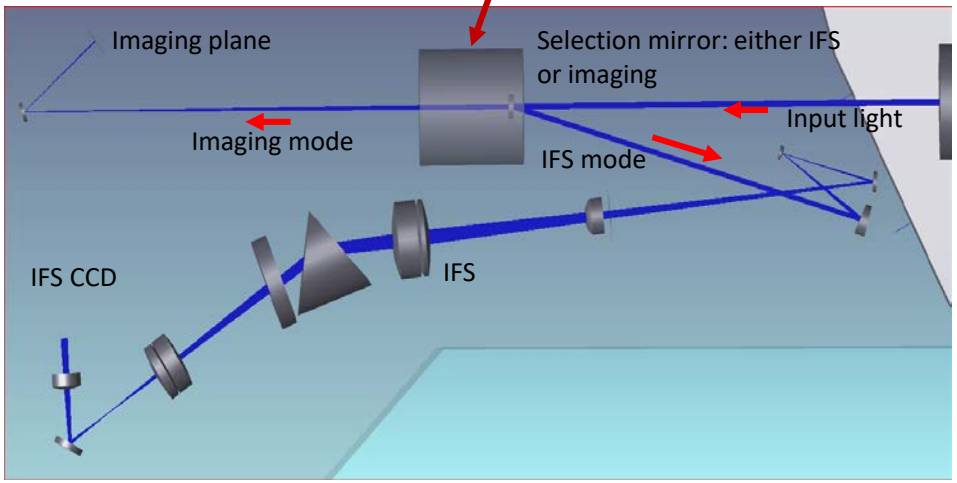
Add dichroic BP filters to existing wheel

Starshade using WFIRST Coronagraph Instrument

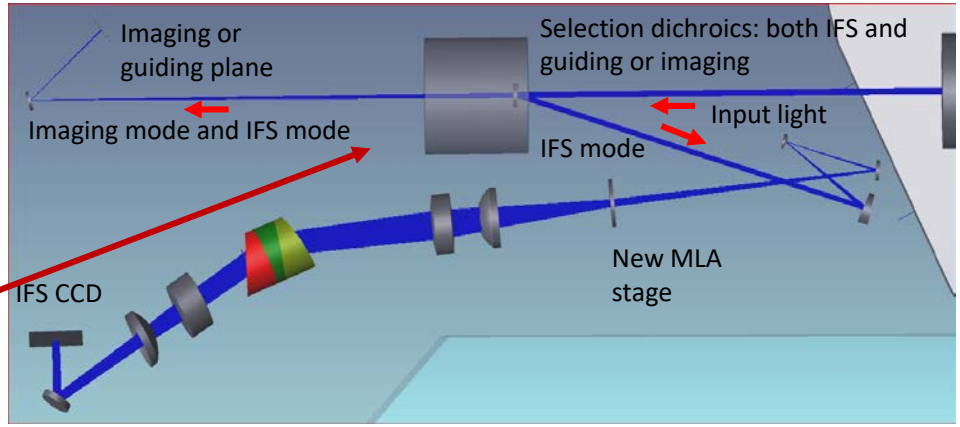
- Starshade makes 34% broad-band observations compared with coronagraph 18%.
  - Possible modifications to accommodate the same product of bandwidth × field of view on IFS, require larger camera (1.6k × 1.6k) or smaller spectral spacing.
- A rotation stage on the microlens array can reduce the intra-spectral spacing.
  - This system will create more cross-talk between spectra.
- IFS is modified (prism, lenses) to accommodate larger bandwidth.
- System conforms closely to the size of the existing Coronagraph IFS.

Coronagraph Selector Wheel

Coronagraph Only



Coronagraph and Starshade



Coronagraph/Starshade Selector can be Dark, mirror, imaging lens, pupil lens, open, focus diversity*3, plus additional dichroics

Filters, Masks and Science Wavelengths

Mask/filter sets for Coronagraph and Starshade CS

Mask/filter wheel	SPC (Imaging)	SPC (IFS)	HLS (Imaging)	Starshade (IFS and Imaging)	Baseline Filter Wheel Positions Req'd	Starshade-ready Filter Wheel Positions Req'd
Pupil Mask	1	3	open	open	5	5
Focal Plane Mask	2	9	2	open	14	14
Lyot Mask	1	1	1	open	4	4
Field Stop Mask	open	open	2	1	3	4
Color Filters	2	3	2	open	8	8
IFS/Guide select	Dark, mirror, imaging lens, pupil lens, open, focus diversity (x3)			4 to 6	8	Depends…

Starshade CS and ES require different sets of additional optics in the IFS/Guide select wheel. Exact optics count depends on number of imaging and IFS channels required for science

	Coronagraph	Coronagraph + Starshade CS	Coronagraph + Starshade ES
Coronagraph mode	Dk, M, IL, PL, O, FD1, FD2, FD3	Dk, PL, O, FD1, FD2, FD3	Dk, M, IL, PL, O, FD1, FD2, FD3
		B, C, D	
Starshade mode	N/A	A, B, C, D, E, F	A', B', C', D', E', F'
Total slots	**8**	**10 to 12**	**12 to 14**

Dichroic Filters in IFS Select wheel

	Coronagraph				Starshade-CS						Starshade-ES					
	HLC Imager	SPC IFS	SPC IFS	SPC IFS	IFS	IFS	IFS	Imager	Imager	Imager	IFS	IFS	IFS	Imager	Imager	Imager
Dichroic	D	B	C	C	A	B	C	D	E	F	A'	B'	C'	D'	E'	F'
λ Min	430	600	700	810	425	600	706	425	600	706	425	600	750	425	600	750
λ Center	515	660	770	890	515	725	855	515	725	855	495	700	875	495	700	875
λ Max	600	720	840	970	600	850	1000	600	850	1000	565	800	1000	565	800	1000
pixels per spectrum		25.2			48.2			N/A			40			N/A		
Instantaneous BW		18%			34%			34%			28%			28%		

IFS design

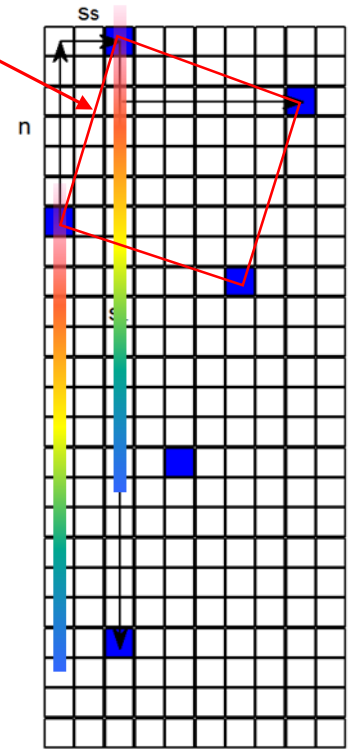
The main design driver between the coronagraph and starshade is the wider bandwidth.

1. Change the dispersing prism set
2. Redesign the lenses
3. Microlens array on rotation stage (or swap in a second one)

Using MLA rotation mandates a non-ideal distribution of light on the focal plane
Spectra fall across pairs of columns, affecting the SNR
Therefore, all else being equal, larger arrays are preferred

Area = M * (N + G)

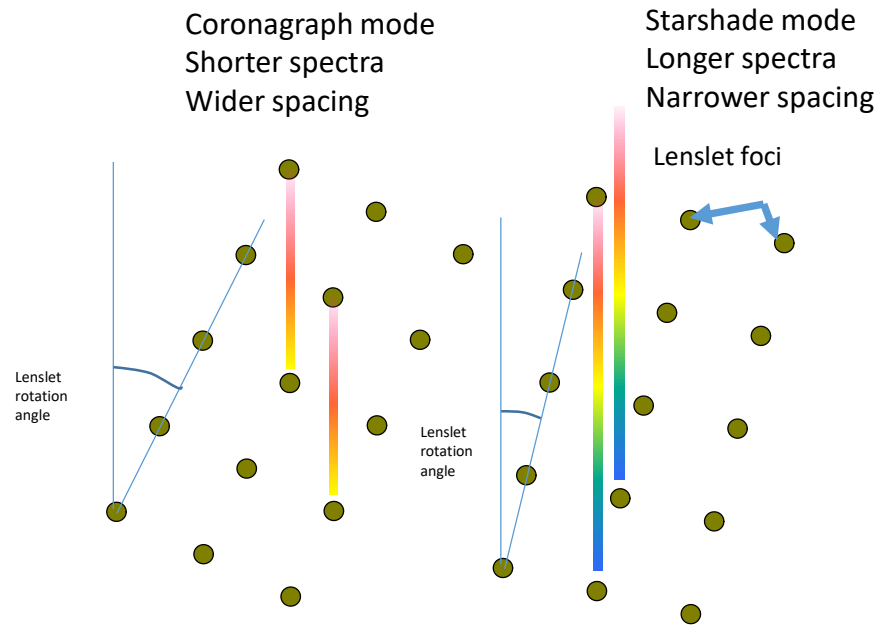
M = number of spectral gap columns + 1
N = number of pixels in spectrum
G = number of empty pixels at end of spectrum



CCD pixels

Lenslet swap options:

1/ Increase area and accept reduced FOV
2/ Maintain area and accept coarser pixel resolution of the FOV (maybe ~3/4)
3/ Use larger CCD



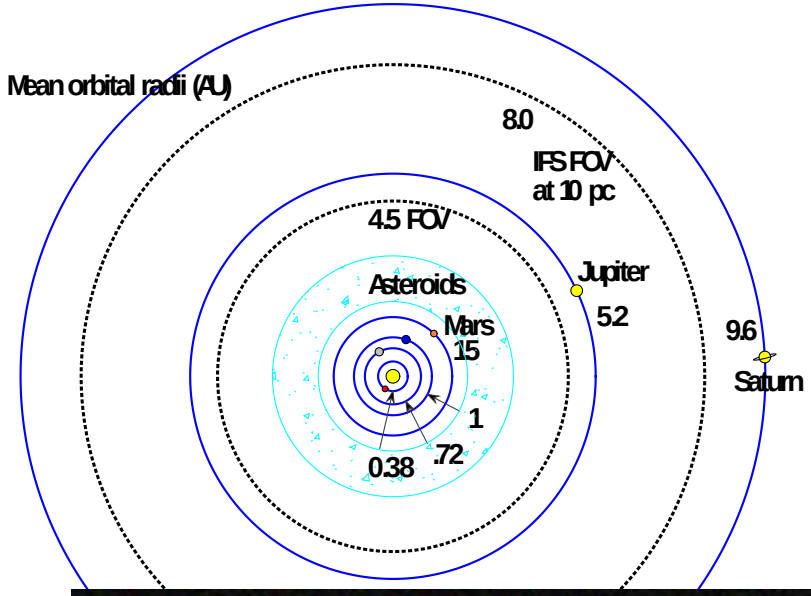
Effect of rotating the MLA is to increase cross-talk between spectra
Not a large effect, will measure at assembly time and deconvolve.
Cross talk is at the 2% to 5% level rather than 0% to 2% for coronagraph setup.
Probably okay for Starshade because of relatively limited scene contrast.

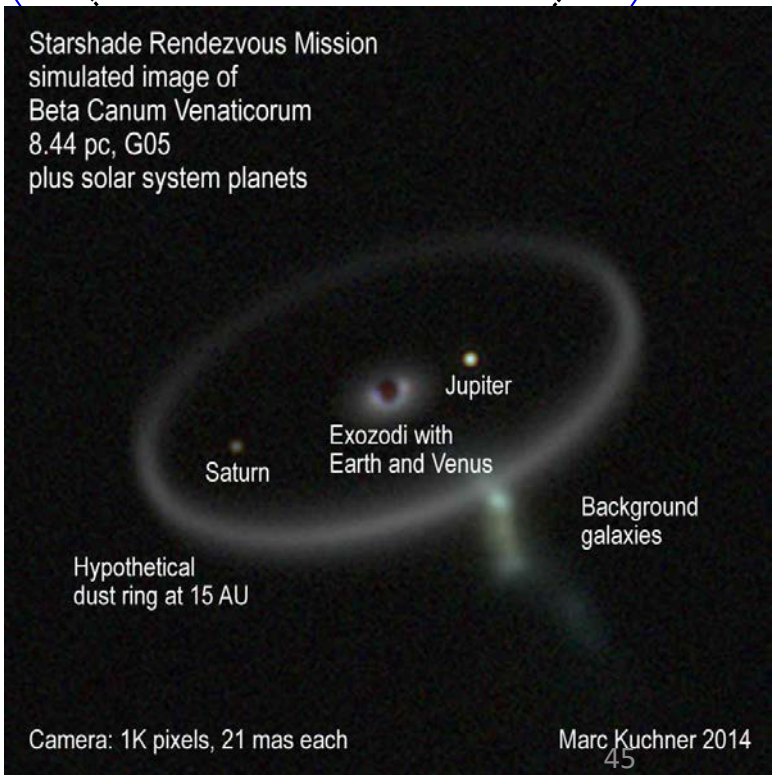
IFS Field of View

- Using the solar system as an analog:
  - At 10 parsec, the IFS's radial field of view is 8 AU.
  - Three planets visible- Earth, Mars, Jupiter, plus asteroids.
  - IFS CCD size is proportional to spectral bandwidth and (radial) field of view, so that increasing the BW to 34% from 18% almost halves the field of view to 4.5 AU.
  - Then, only two planets visible- Earth, Mars, plus asteroids.
  - Saturn is beyond either FOV unless the system is inclined

- A larger FOV aids dust studies and discrimination of background objects

- The full benefits of a wider FOV needs study.





Starshade-Coronagraph Option Space

	Option 0	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Modifications to Coronagraph	None	Dichroics added to filter wheel	Rotatable MLA Modify IFS CCD 201	Modify IFS Larger EMCCD CCD 207	Modify IFS Largest EMCCD ¼ CCD 282	Dedicated Starshade instrument	Use Wide Field Instrument IFU
Features	No changes	Guiding on imager	Wider bandwidth	Wider bandwidth Wider FOV	Wider bandwidth Widest FOV	Widest bandwidth Widest FOV	150 mas fields R = 100
Details	No light to guide channel	3(+) dichroics MLA fixed	MLA rotates or switches	MLA fixed	MLA fixed	Pickoff mirror Add IR guider Add new design IFS	No guide channel
Notes		Restricted starshade BW 13 um pixels	More spectral crosstalk in SS mode	16 um pixels Coronagraph can also use wider FOV	13 um pixels New design IFS Coronagraph uses part of FOV	Room exists between support structures 4/3 x larger pixel FOV	Could a guide channel be added?
EMCCD		1k x 1k	1k x 1k	1.6k x 1.6k	2k x 2k	2k x 2k	(H2RG)
Throughput		~20%	~20%	~20%	~20%	~36%	36%?
Radial FOV (arcsec)		0.8	0.8	1.2	1.5	2	~1.5
λ Min (nm)		600	425	425	425	425	600?
λ Max (nm)		970	1000	1000	1000	1000	1400?
Bandwidth		18%	34%	34%	34%	50%	50%
Figure of Merit BW*√TP*FOV	0	6	12	18	23	60	45?
*(√TP ~ SNR)			CCD exists- will be qualified	CCD exists Need to qualify	Full CCD in testing. Need to qualify ¼ CCD. Can also use 2x2 EMCCD 201	Add IR guide channel and EMCCD. High throughput possible	Add IR guide channel somehow Yields additional spectral lines of CO_2, O_2 and CH_4 lines below 1300 nm

Baseline (Opt. 2) and Variants

Backup charts

Other options

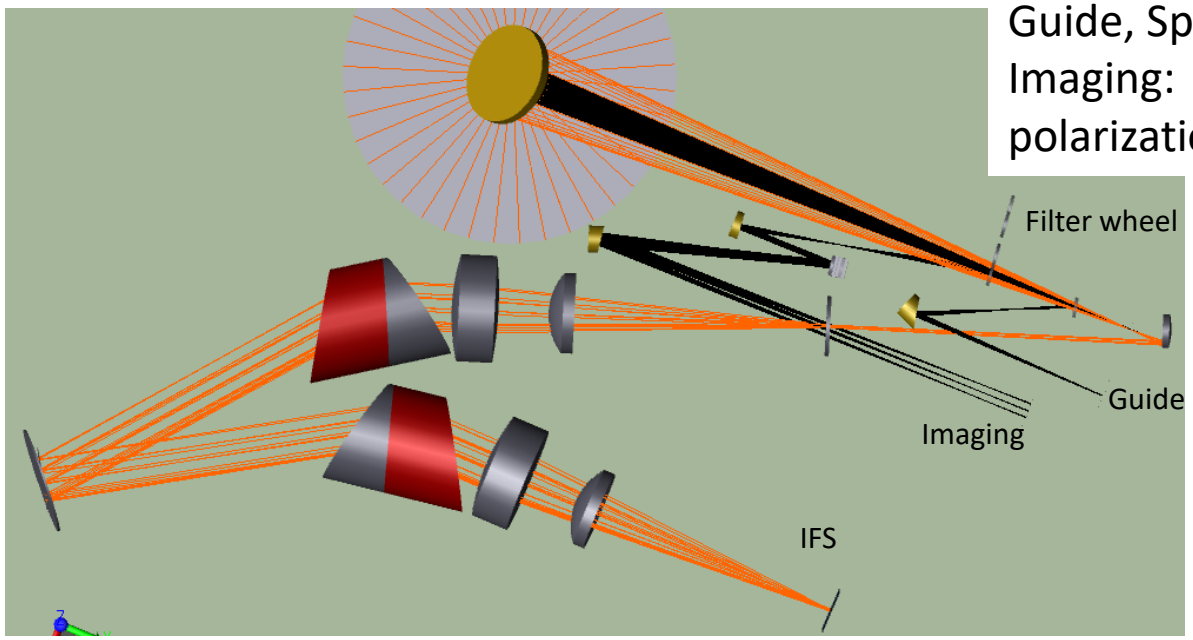
- What about using the Wide Field IFU?
  - Larger spectral range (with larger IWA)
  - Coarser spatial resolution
  - No guide channel- there may be room to install one
  - Noisy detector (est. 0.45 e-/px/s and 5e- read noise)
  - Programmatically difficult?
- What about a dedicated instrument?
  - Faster integration- more science, less impact on Wide Field
  - More mass, total power about equal
  - More work to I&T

A Dedicated Starshade Instrument?

Dedicated Starshade Instrument

Components of a dedicated instrument

Functions
Guide, Spectroscopy,
Imaging:
polarization imaging, 3 color imaging

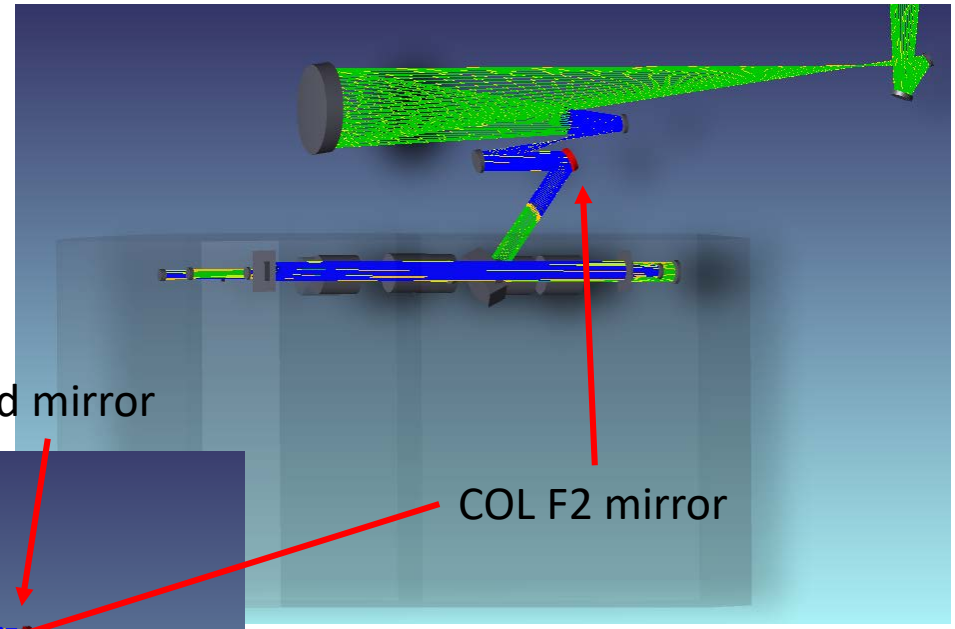


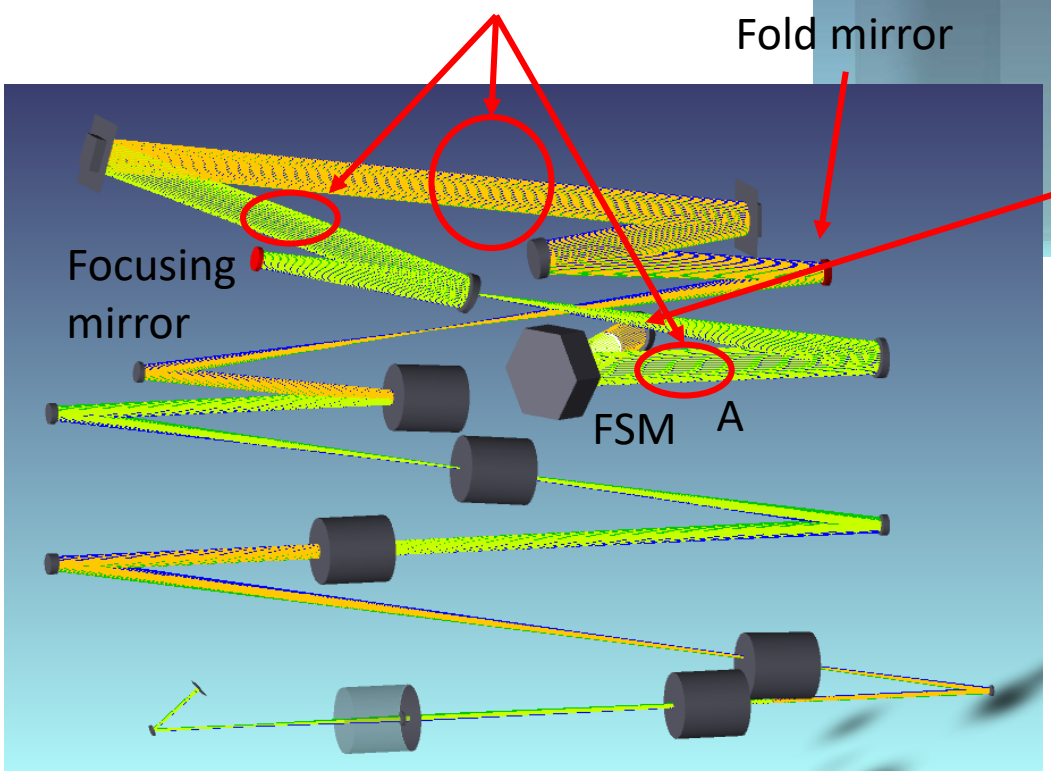
Overall dimensions similar to existing IFS and imaging channels, so not a very large extension to the optical system.
Adding some mass (10 to 20 kg including 50% margin) and power, but the total power should be similar since coronagraph focal planes will not operate simultaneously with starshade.
Increases complexity of the overall system, but existence as a standalone system somewhat mitigates extra I&T.

Benefits are:
Much reduced integration time (~3x quicker) yielding more science in a given time, or the same science in less time- less impact on Wide Field observations.

Extracting a beam

Standalone Starshade instrument residing between the support structure inside the coronagraph box
Extract beam at
Location A: 6 reflections 83% TP
Needs an actuated mirror
Other locations are less desirable





Plane mirrors high in the beamtrain
- Col F2- outside coronagraph enclosure
  - 7 reflections 86% TP
- Focusing mirror – moves
  - 10 reflections 74% TP
- Fold mirror after DM2/R1 OAP1
  - 16 reflections 61% TP

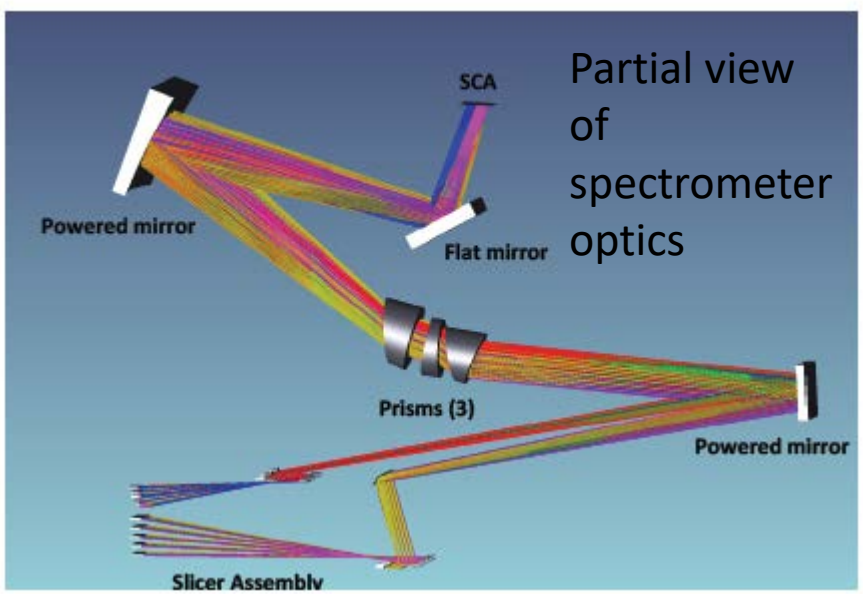
Throughput to field camera (excludes other losses)
23 reflections 50% TP

Using the Wide Field Instrument IFU?

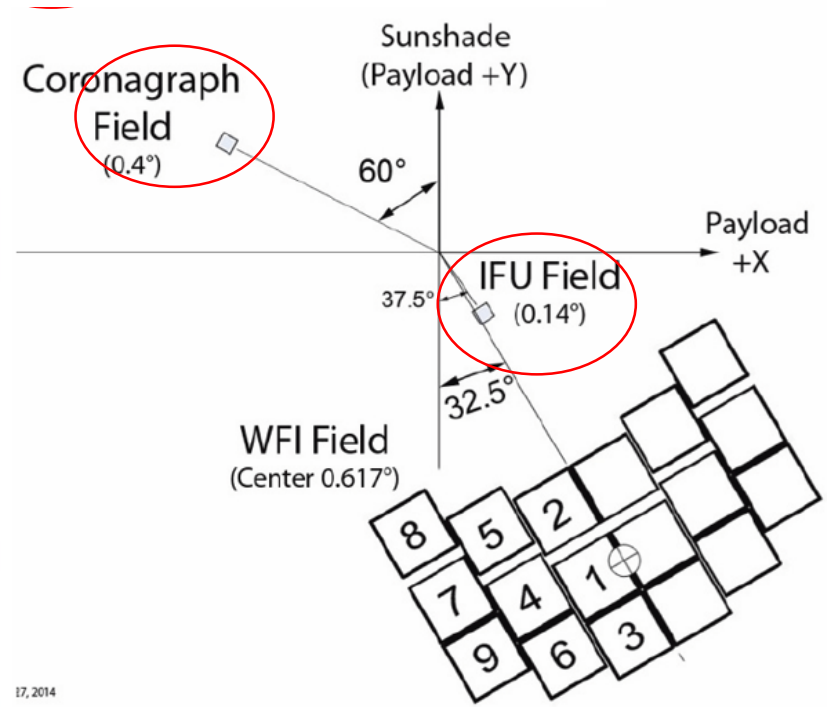
Wide field Instrument

Mode	Wavelength Range (μm)	Sky Coverage (active area)	Pixel Scale (arcsec/pix)	Dispersion	FPA Temperature (K)
Imaging	0.76 – 2.0	0.281 deg^2	0.11	N/A	≤100
GRS Spect.	1.35 – 1.89	0.281 deg^2	0.11	R=461λ (2-pixel, grism in element wheel)	≤100
SN Ia Spect. / Photo-z Calib.	0.6 – 2.0	3.00 x 3.15 arcsec 6.00 x 6.30 arcsec	0.075	R~100 (2-pixel; IFU spectrograph, 1 slice maps to 2 pixels)	≤100
Fine Guiding	0.76 – 2.0	0.281 deg^2	0.11	Guide off wide-field focal plane using windowing function of H4RG	≤100

Compare with ~ 20 mas for coronagraph



Partial view of spectrometer optics



WFIRST Wide field instrument

Images: Pasquale et al. SPIE-OSA/ Vol. 9293 929305-1

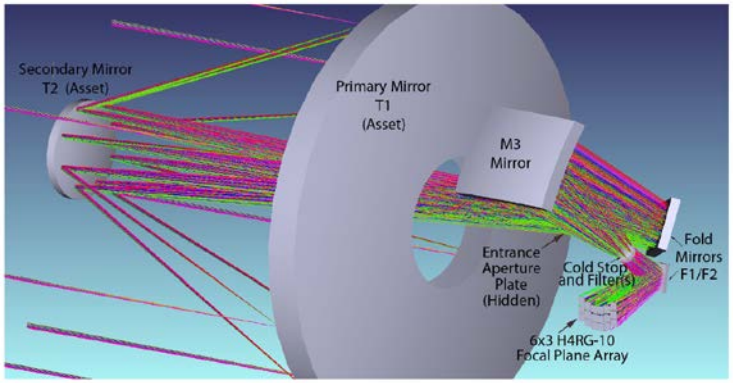
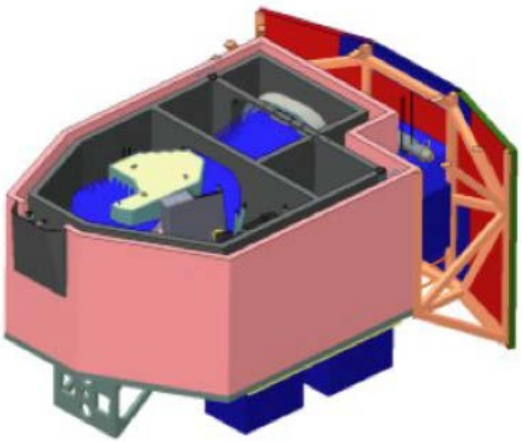
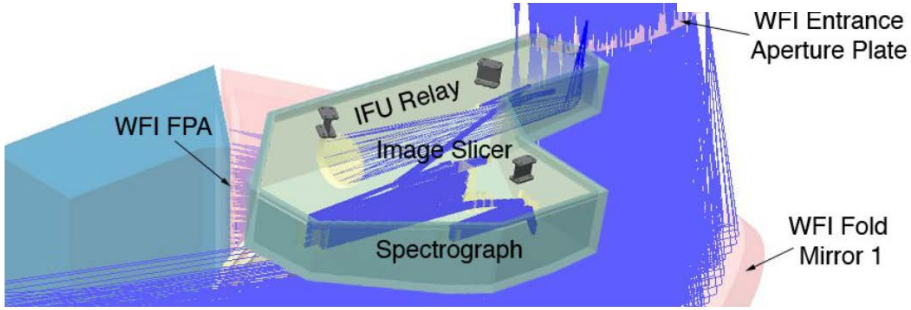


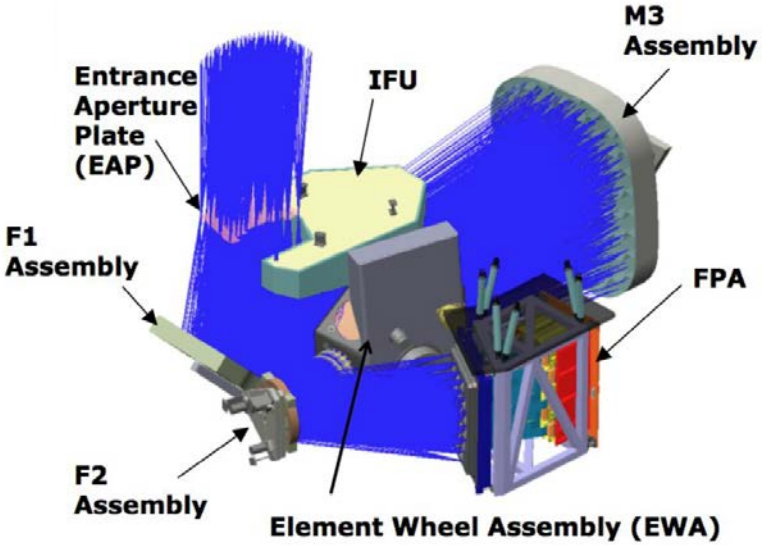
Figure 1. Optical Layout of WFIRST AFTA Wide-Field Instrument (Design Cycle 4)

Guide channel would work from 1400 nm upwards.
Benefit: instrument opens up additional spectrum.
Downside: Loss of some spatial resolution



To add a guide channel
No headroom, but there appears to be space around the IFU
Any space underneath?





Detector Trades?

EMCCDs

	N pixels	Pixel size	Qualified?	Notes
CCD-201	1024x1024	13	Yes	Baseline
4 * CCD-201	2048x2048	13	Yes	Pyramid optics
CCD-207	1632x1608	16	Working	Preferred
CCD-282	4096x4096	13?	Development	Too large?
¼ CCD-282	2048x2048	13?	Development	Better