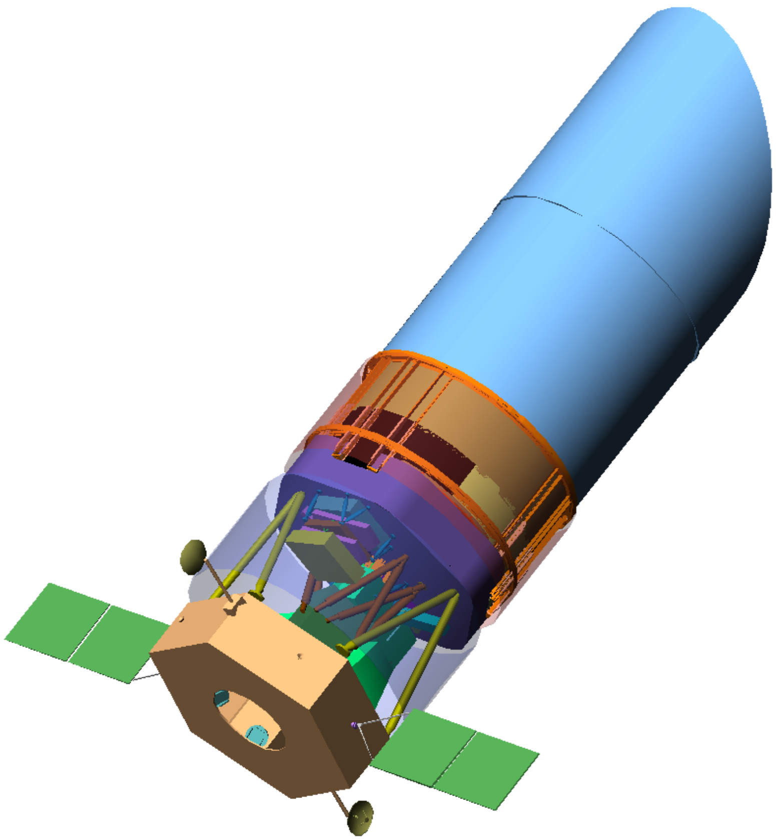
THEIA

Telescope for Habitable Exoplanets and Intergalactic/Galactic Astronomy



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Exoplanet Forum

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The THEIA Team

Industry Partners: Lockheed Martin, ITT Space Systems, LLC, Ball Aerospace

NASA Centers: JPL*, GSFC, Ames, Marshall

University Partners: Arizona State University, Caltech, Case Western Reserve University, University of Colorado, John Hopkins University, University of Massachusetts, University of Michigan, MIT, Penn State, Princeton University, Space Telescope Science Institute, University of California-Santa Barbara, University of California-Berkeley, University of Virginia, University of Wisconsin, Yale University

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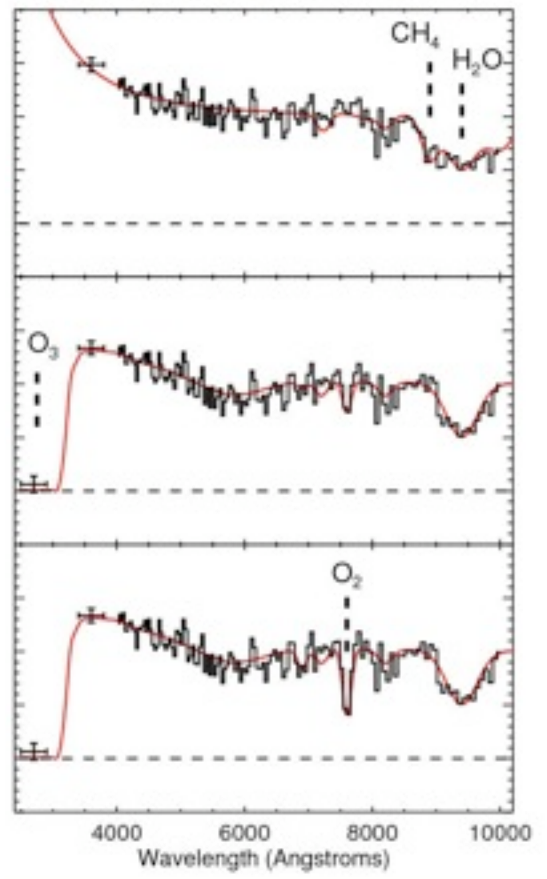
Outline

- The Science
- The Mission
- The Spacecraft
- The Hard Stuff
- The Cost

THEIA Science

- eXoPlanet Characterizer (XPC)
  - Detect Earthlike Planets in Habitable Zone
  - Characterize from 350-1000 nm
- Star Formation Camera (SFC)
  - Census of Star Forming Regions
  - Survey nearby galaxies from 190-1075 nm
  - Panchromatic survey of cosmological Targets
- UltraViolet Spectrograph (UVS)
  - Cosmic web spectroscopy
  - Galactic Interfaces
  - Star Formation
  - Planetary Transits



THEIA Mission

Approaches to Planet Finding and Characterization

Requirements:

- Maximize number of individual planets found
- Characterize planetary systems from 250 - 1000 nm
- Revisit as many as possible (seasonal variation and orbits)

Design Constraints:

- 4 meter, on-axis telescope
- 5 year nominal mission length + 5 year extended goal
- Fit onto Atlas V launch Vehicle with 5 m fairing
  (two launch vehicles for telescope and occulter)
- L2 Halo Orbit
- Existing spacecraft hardware

Two broad categories of missions:
Internal Coronagraphs and External Occulters

Internal Coronagraph vs. External Occulter

Internal Coronagraph
- Variable Inner Working Angle
- Fixed, rapid repointing
- Large viewing angles
- Optics/Detector limited Bandwidth
- Relatively Low throughput
- Technology/Cost Drivers
  - Off-axis, diffraction limited telescope
  - Telescope Stability
  - Wavefront Control
  - Small IWA Coronagraph (2 λ/D)

External Occulter
- Fixed Inner Working Angle
- Variable Slew Time
- Small field of regard
- Variable BW (depends on size)
- High throughput
- Technology/Cost Drivers
  - Size & Distance
  - Positioning Control & Slewing
  - Manufacturing & Deployment Accuracy
  - Stability

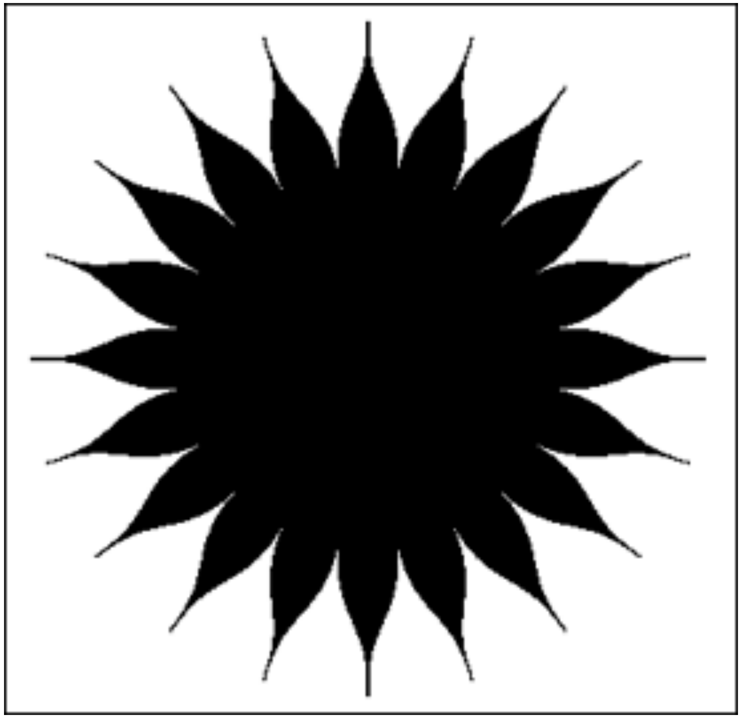
Notes:
- Hybrid design was not tenable
- Premium placed on small/nearby occulter (lower mass, easier deployment, fits into fairing, smaller petals, lower fuel use, more rapid slews, easier to test, looser tolerances)

Occulter Optimization

$$E_{\text{apod}}(\rho) \quad = \quad E_0 e^{ikz}\left(1 - \frac{2\pi}{i\lambda z}\int_0^R A(r) J_0\left(\frac{2\pi r\rho}{\lambda z}\right) e^{\frac{ik}{2z}\left(r^2+\rho^2\right)} r dr\right)$$

$$\begin{aligned}
\text{Minimize :} \quad & c \\
\text{subject to :} \quad & \quad Re(E_{\text{apod}}(\rho)) - c \leq 0 \\
& -Re(E_{\text{apod}}(\rho)) - c \leq 0 \\
& Im(E_{\text{apod}}(\rho)) - c \leq 0 \\
& -Im(E_{\text{apod}}(\rho)) - c \leq 0 \\
& \forall \quad \rho \leq \rho_{\max}, \quad \lambda \in [\lambda_{\min}, \lambda_{\max}] \\
& A(r) = 1 \quad \forall \quad 0 \leq r \leq a \\
& A'(r) \leq 0, \quad |A''(r)| \leq \sigma \quad \forall \quad 0 \leq r \leq R \\
& r A(r) \frac{2\pi}{N} \geq \sigma_1 \quad \forall \quad a < r \leq R \\
& r(1 - A(r)) \frac{2\pi}{N} \geq \sigma_2 \quad \forall \quad a < r \leq R
\end{aligned}$$

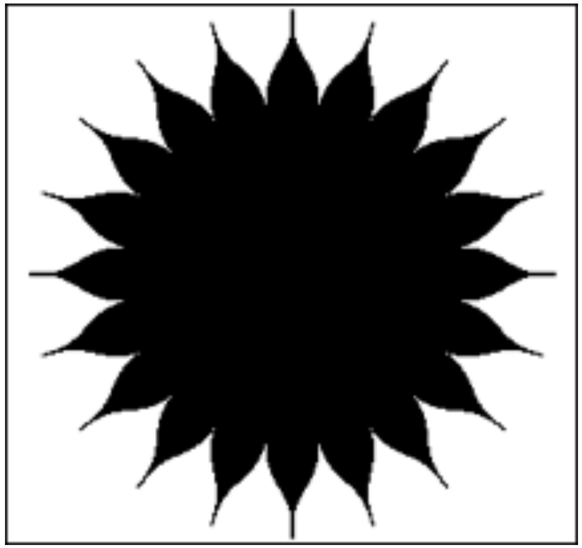
	1-dist. Occulter	2-dist. Occulter
Occulter distance (km)	70400	55000
Occulter IWA (mas)	75	75
Occulter spectral band (nm)	250-1000	250-700
Second occulter distance (km)	-	35000
Second occulter IWA (mas)	-	118
Second occulter spectral band (nm)	-	700-1000
Occulter radius (m)	25.6	20
Number of petals	20	20
Petal length (m)	19	10
Minimum gap between petals (mm)	0.12	1.0
Minimum width of petal tip (mm)	1.62	1.0



To scale:

Left: single distance occulter

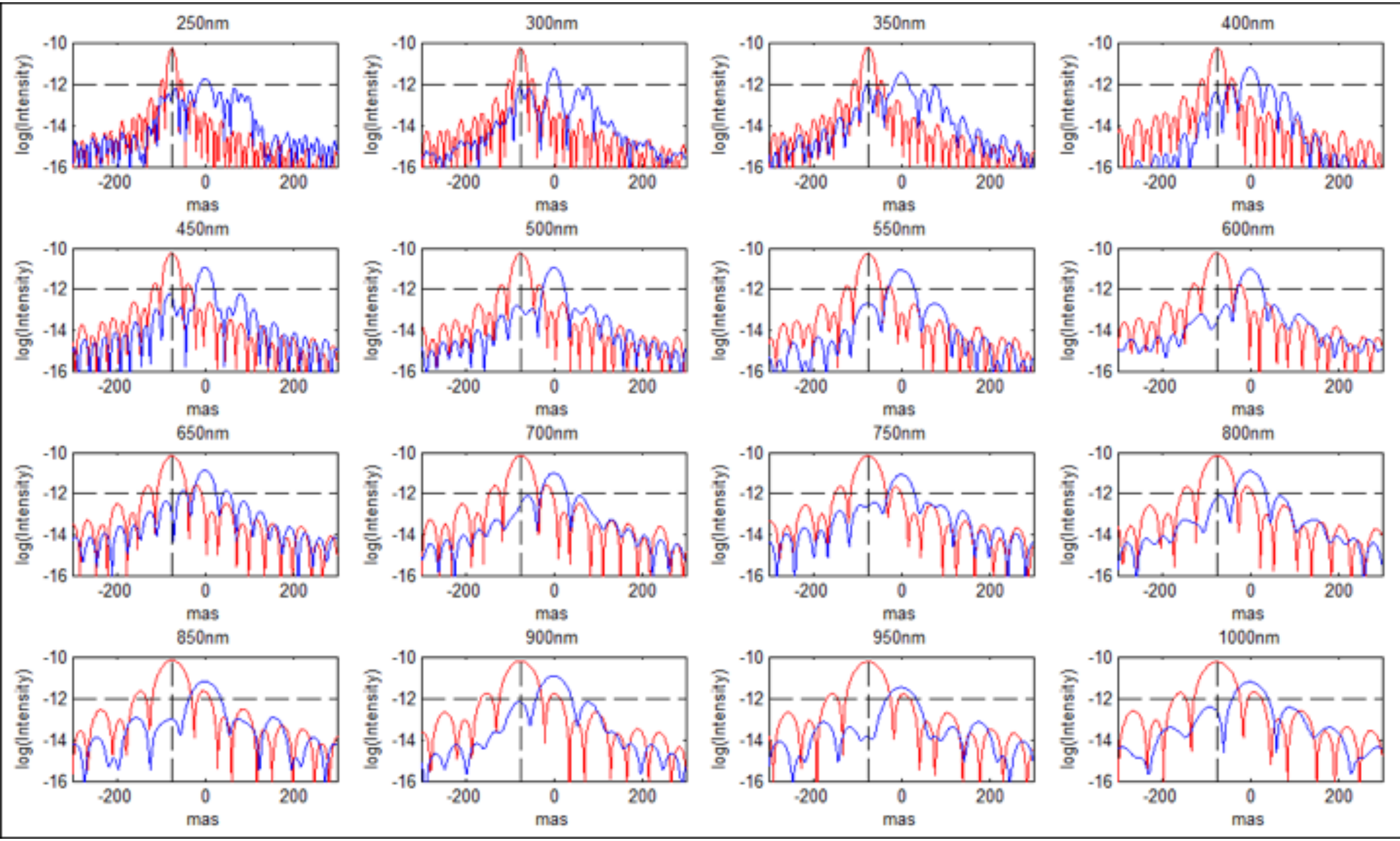
Right: two-distance occulter



Hybrid designs failed:

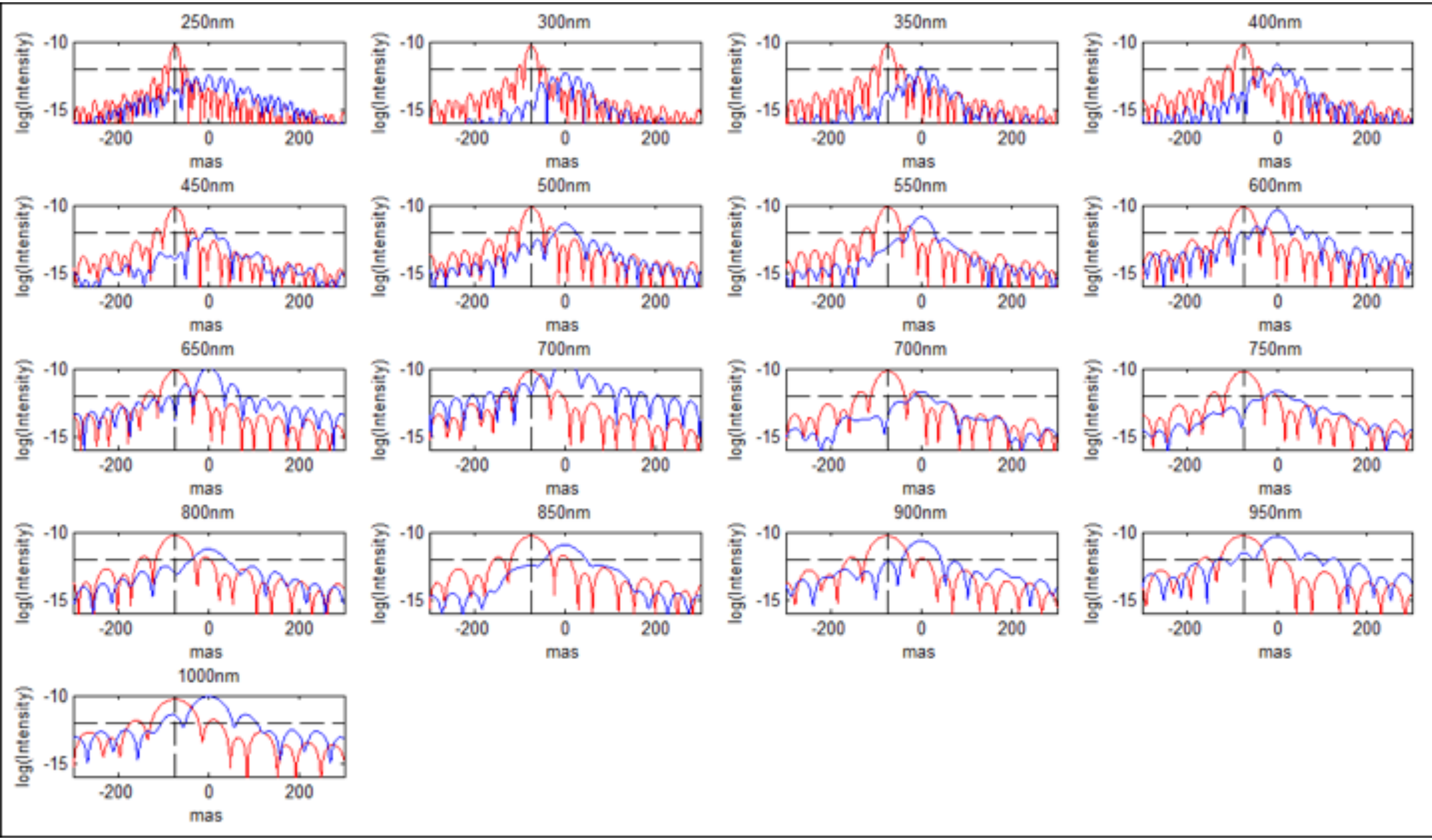
- don't work if too red
- can't be used in UV

Single-distance occulter



(Star in blue, planet in red.) 250-1000nm at 70400km.

Two-distance occulter



(Star in blue, planet in red.) 250-700nm at 55000km, 700-1000 at 35000km.

Design Reference Mission Builder

Common Elements

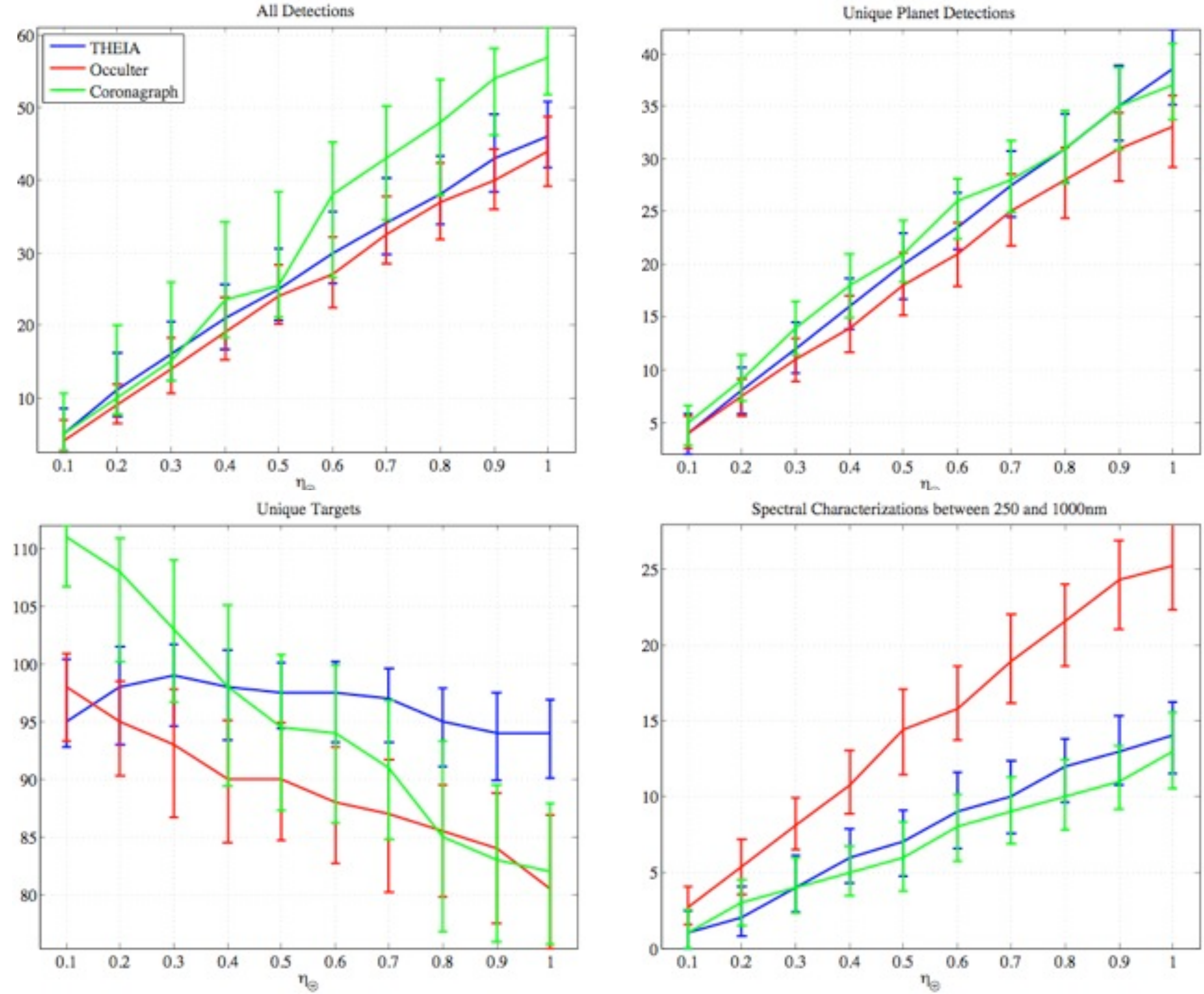
- 4m circular aperture telescope ($A=12.6m^2$)
- 5 year mission
- 6300kg launch vehicle capacity
- High QE (0.5-0.91), low read noise (3 e/pix) CCDs
- 1000s readouts
- 1.5 exozodi
- 510000km (azimuthal) Halo orbit
- 250-1000nm spectral capability

- 2 λ/D Coronagraph
- Single Distance Occulter
  - 25.6m radius (19m petals)
  - 4200kg dry mass
  - 70400km separation
  - 75mas geometric IWA
  - 59mas 50% throughput IWA
- THEIA
  - 20m radius (10m petals)
  - 3370kg dry mass
  - 250-700nm at 55000km separation (75mas IWA)
  - 700-1000nm at 35000km separation (118mas IWA)
  - 57.6mas 50% throughput IWA

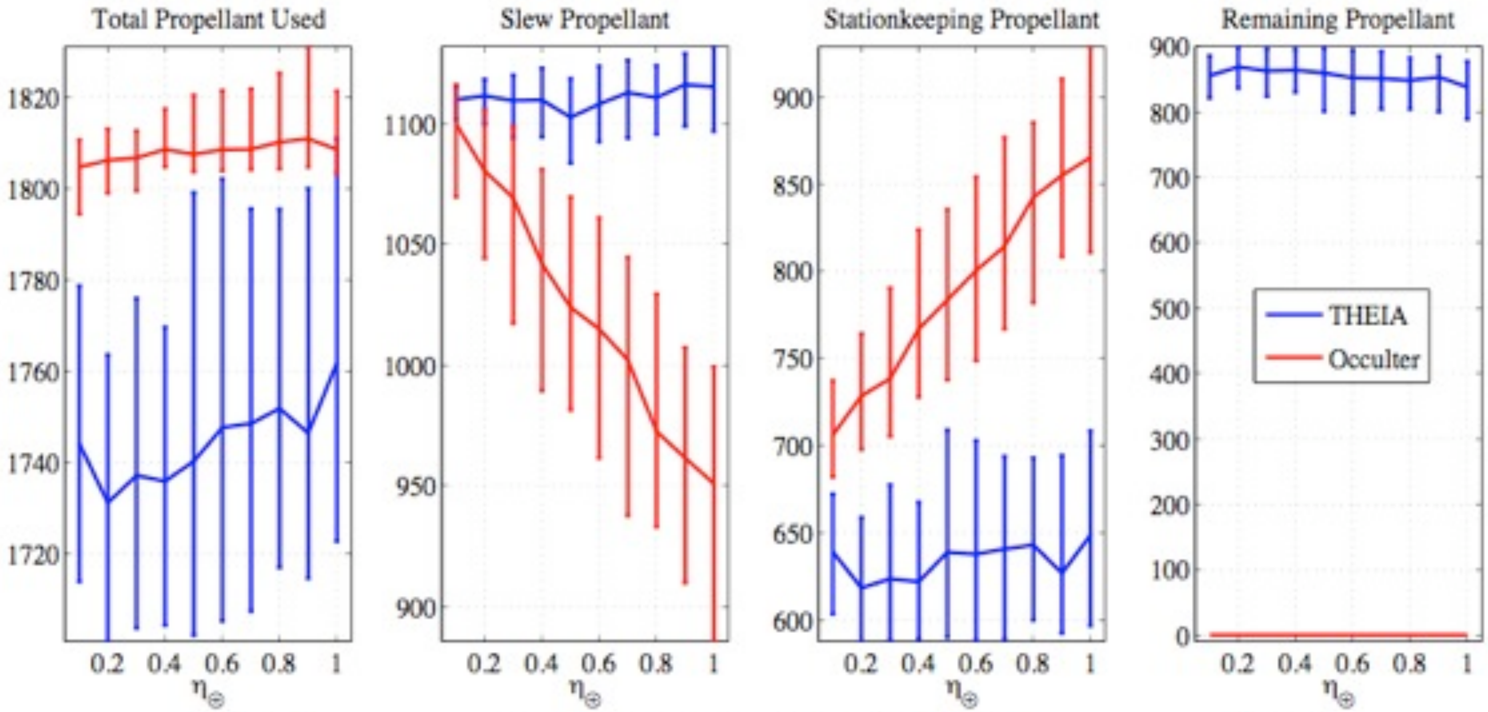
Planet Population and Mission Rules

- Earth twins (Earth mass and radius) on habitable zone orbits
  - a in $[0.7, 1.5]\sqrt{L}$
  - e in $[0, 0.35]$
  - $p = 0.26$
- η_{Earth} in $[0, 1]$
- 130 F, G, K stars, excluding binaries, with completeness > 0.1

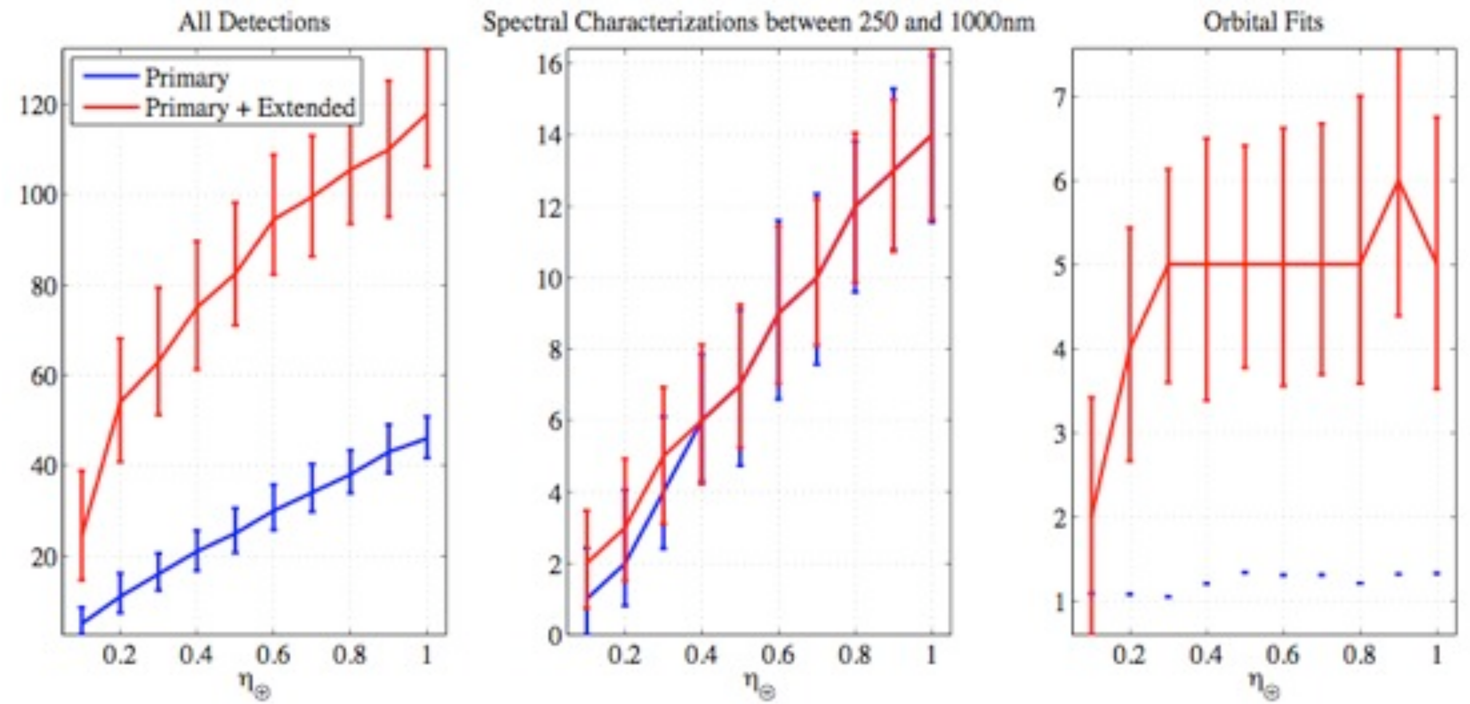
- 50 day integration cutoff
- Only one full spectrum is required for each detection
- For occulters:
  - Burn time must be >= 50% of any transit
  - For THEIA, spectra acquired in parts in two visits count as complete


All Detections
THEIA
Occulter
Coronagraph
Unique Planet Detections
Unique Targets
Spectral Characterizations between 250 and 1000nm
$\eta_{\oplus}$

Occulter propellant usage

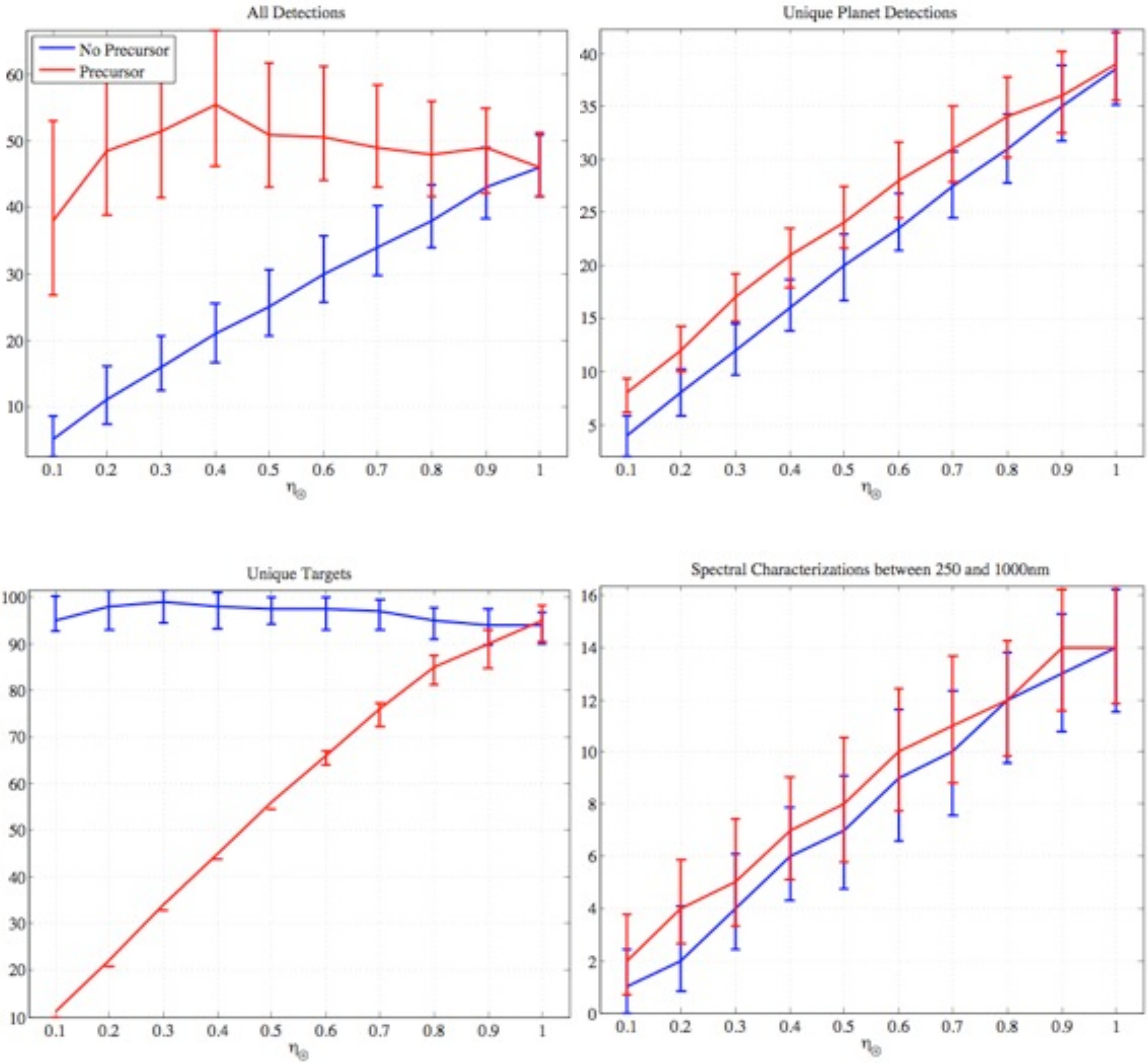


THEIA Primary and Extended Mission

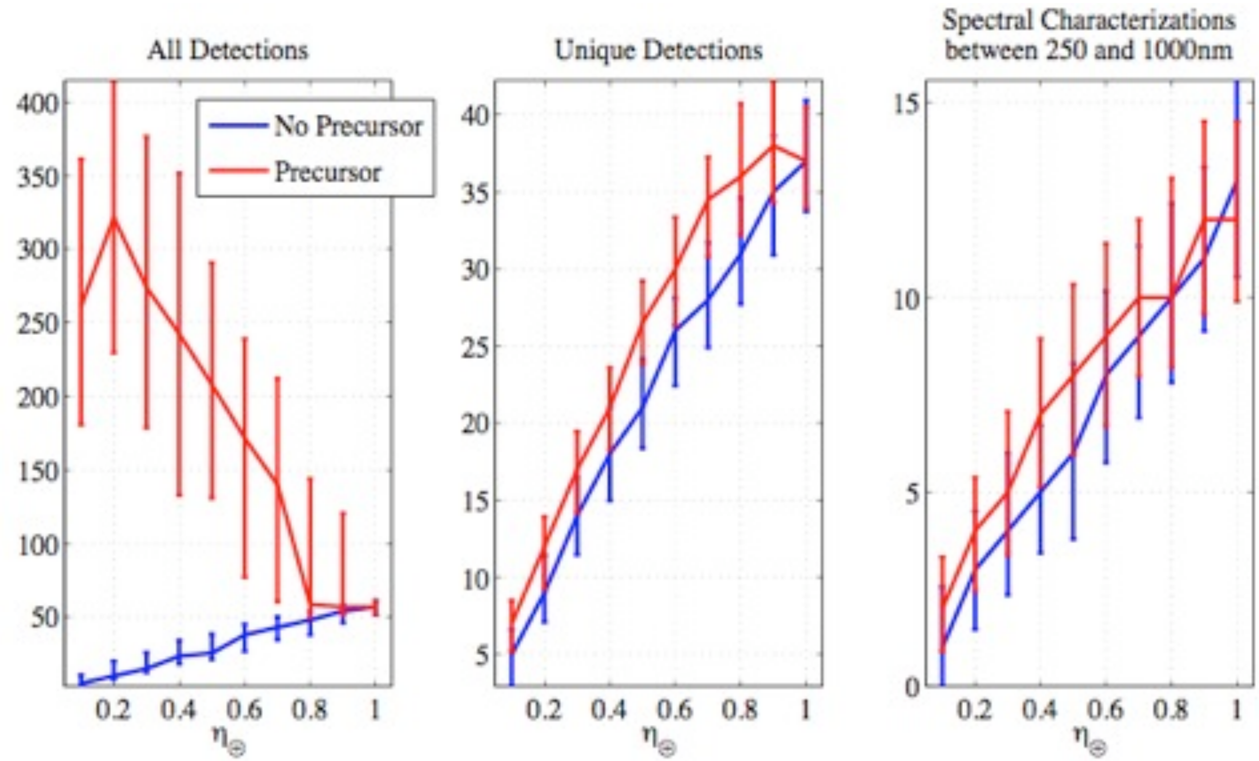


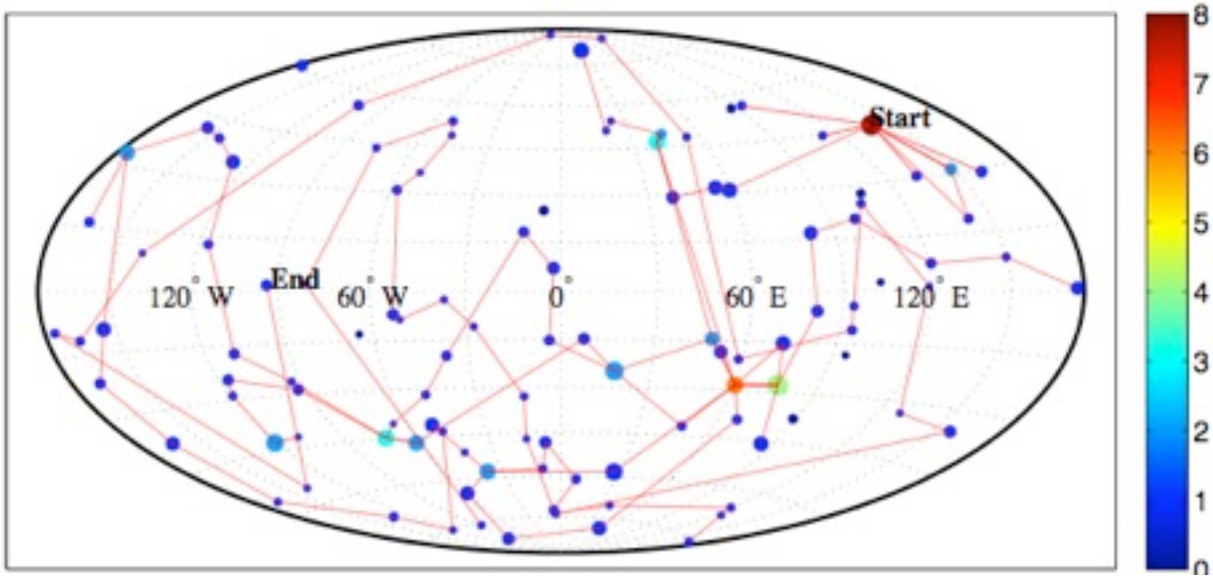
THEIA with and without precursor knowledge

Precursor is modeled as ideal classifier of which stars have planets, but not able to fit orbits



Coronagraph with and without precursor knowledge





Sample auto-scheduled mission timeline. Color scale indicates number of visits.

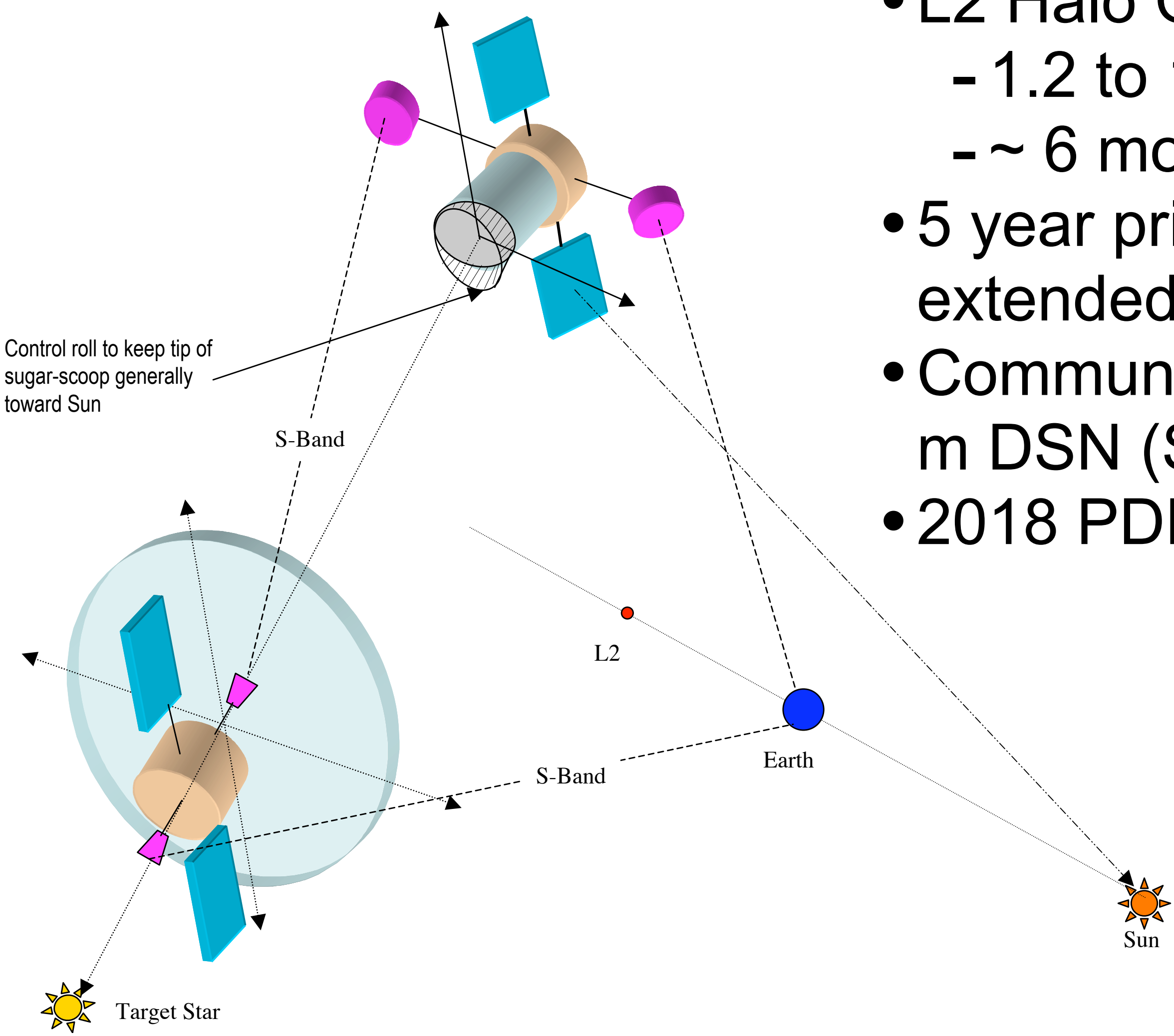
Some Conclusions

- Coronagraph, Occulter, and Theia get close to the same science (assuming 2 lambda/D iwa for coronagraph); driven by characterization.
- Increasing coronagraph to 6 m would get all characterization
- Choice of design mostly based on architecture, technology readiness and cost

Is cost of occulter less than delta-cost for making an internal coronagraph meet requirements? Is one fundamentally harder?

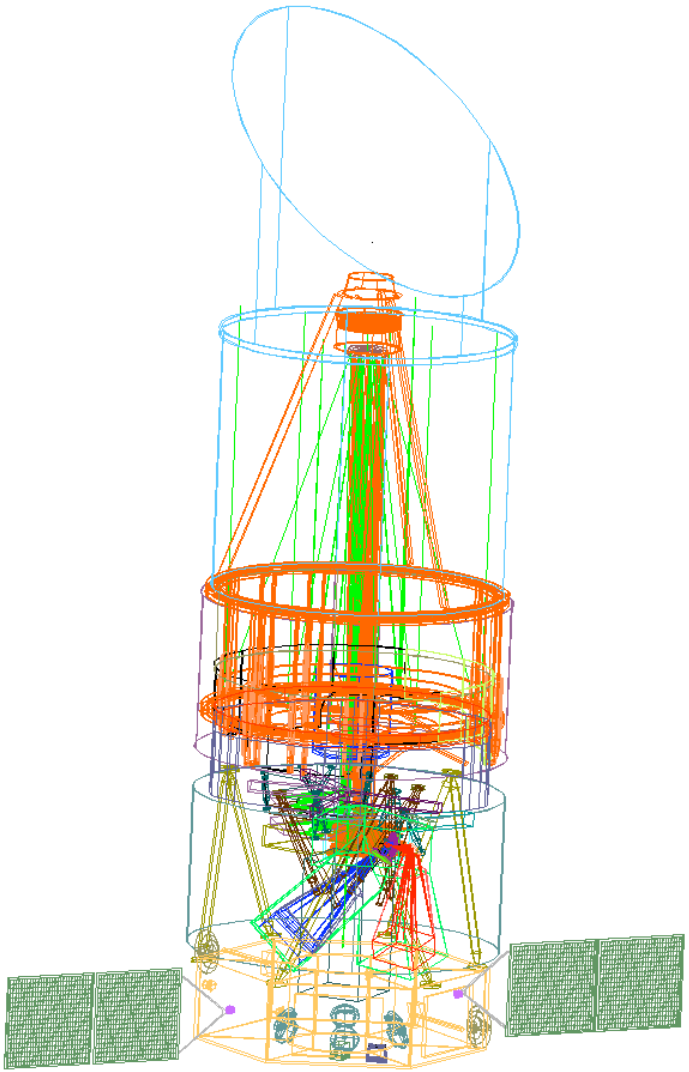
For this study we concluded yes and present a demonstration proof of an occulter based mission. Nevertheless, many open questions still to be studied.

THEIA Mission



- Separate Atlas-V 551 launches
- L2 Halo Orbit
  - 1.2 to 1.8 Mkm Earth range
  - ~ 6 month orbit period
- 5 year primary mission (5 yr extended)
- Communication & Tracking via 34 m DSN (S-band and Ka-band)
- 2018 PDR

Observatory

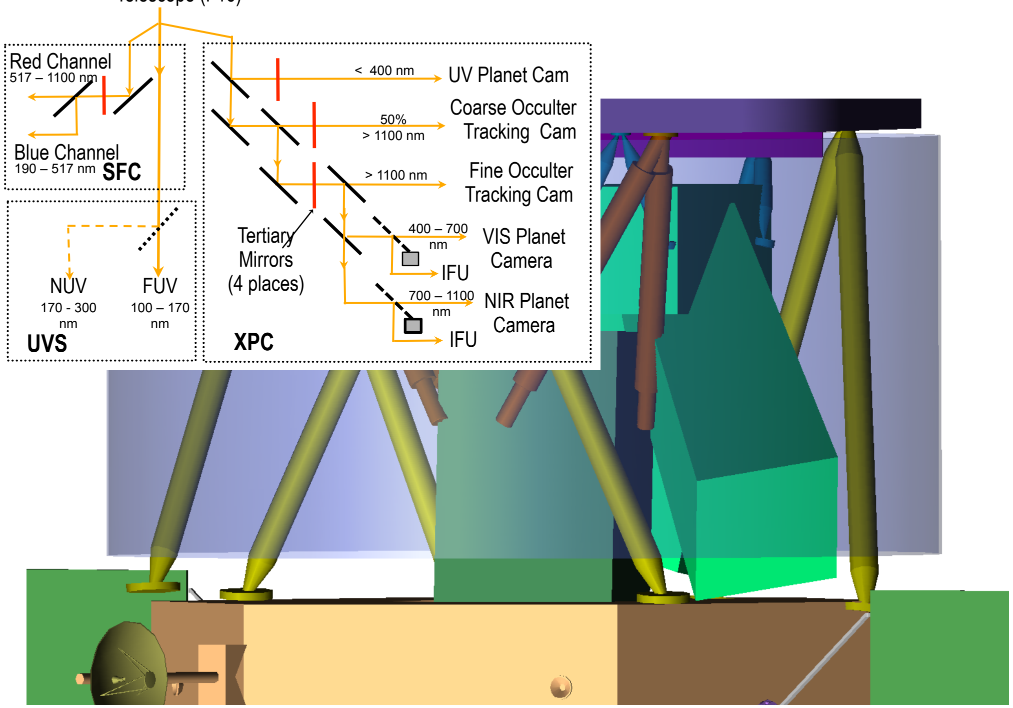


- 4m, On-axis, F16 TMA Telescope
  - 300 nm diffraction limited
  - F1.5 primary
  - MgF coated primary
  - LiF coated secondary
- 45 degree Sugar-Scoop Sunshade
- Active Isolation Struts to 30 marcsec
- 3-axis Pointing to ± 3 arcsec
- HR-16 Reaction wheels
- 5 kw Solar Array
- S-Band occulter and Earth link
- Ka-Band High-rate Downlink
- 2 Gimbaled High Gain Antennas

Payload Layout

XPC Instruments

- 3 Science Cameras (250-400, 400-700, 700-1000)
- 2 Integral Field Units
- Coarse and Fine IR Occuler Tracking Camera
  - Fine 20 arcsec field with 2k x 2k detectors
  - Coarse with 200 arcsec field



SFC Instruments

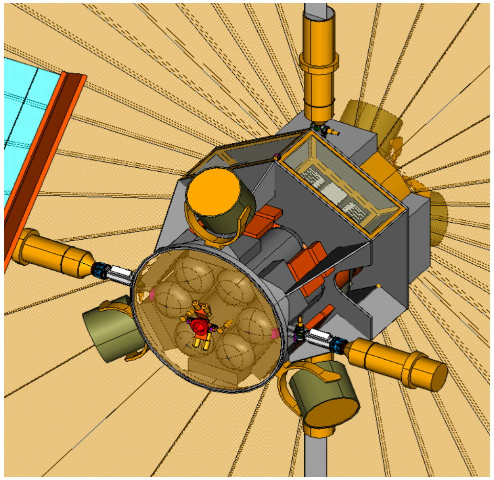
- Dual-Channel, Widefield Imager
- 19' x 15' FOV
- 3.3 Gpixel FPAs, 66 x 55 cm
- 517 nm Dichroic split
- 4 mas pointing with FSM

UVS Instruments

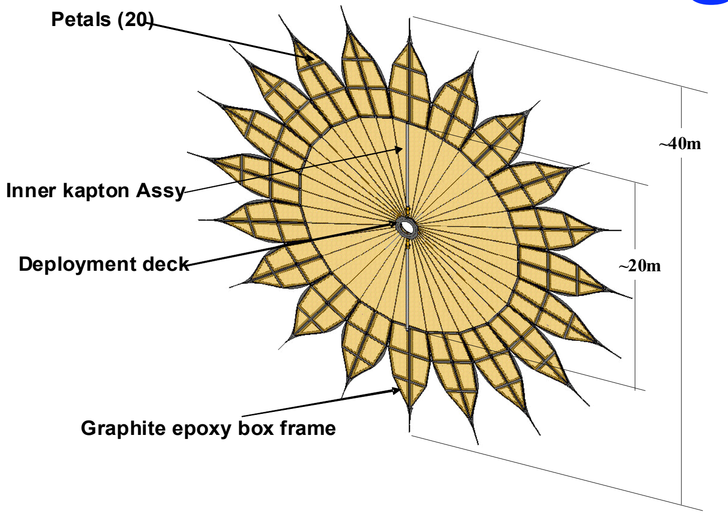
- Multi-Purpose Ultraviolet Spectrograph (100-300 nm)
- 30,000 - 100,000 Spectral Resolution
- Fed direct from secondary
- Photon-counting, 50k x 1k microchannel array (100-170 nm)
- Photon counting 8k x 8k CCD (170-300 nm)

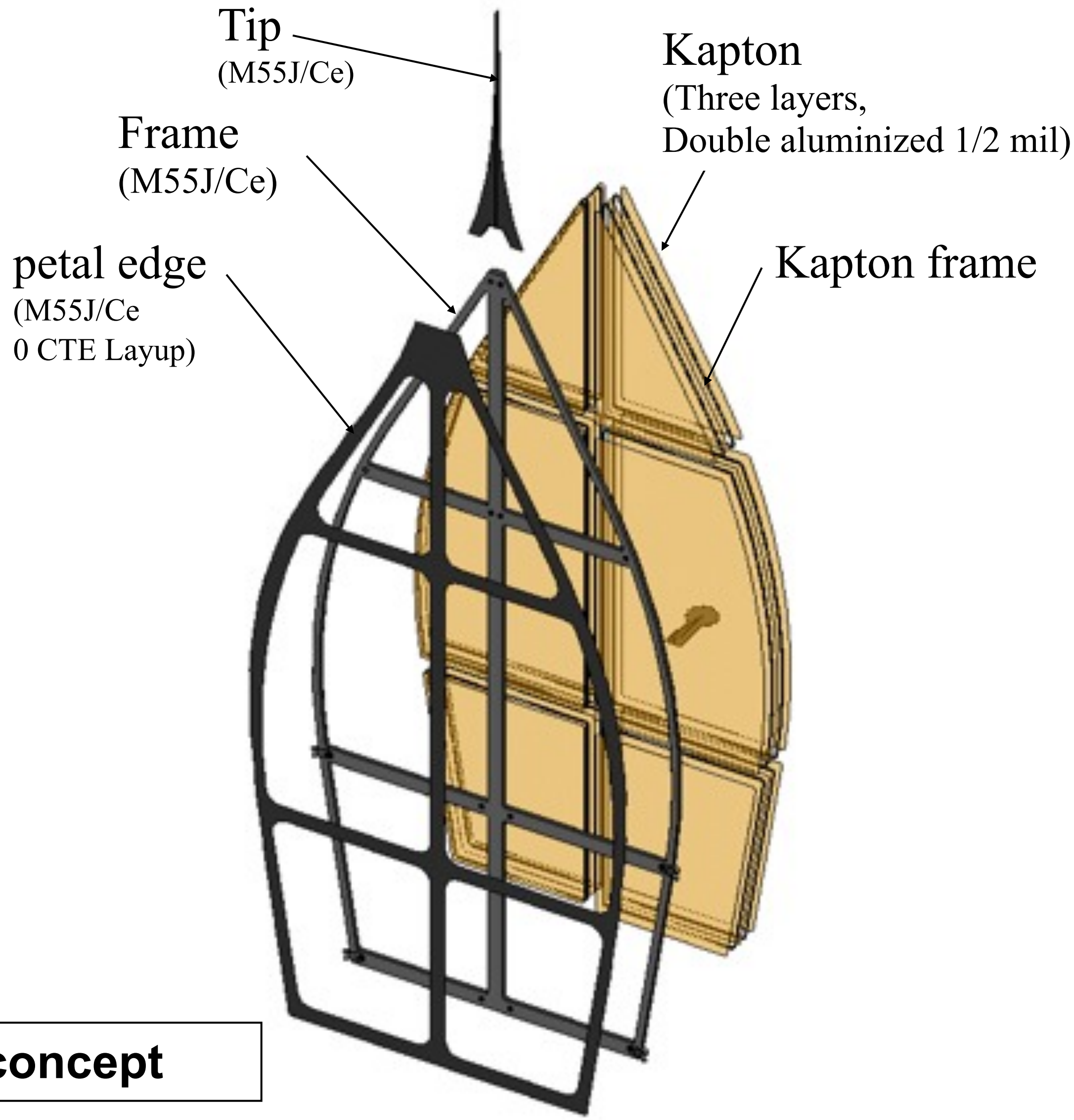
Occulter

- Starshield and associated support hardware is considered the payload
  - Includes launch support structure (cages the petals) that gets jettisoned after launch
- Ion propulsion for retargeting maneuvers
  - 2 NEXT-Ion thrusters firing together gives 450 mN of thrust
  - 6 total thrusters: 3 for 2 redundancy on front side and 3 for 2 redundancy on back side
- 15 kW solar array: 2 wings, single axis gimbals (stay behind and parallel to starshield)
- Hydrazine propulsion for lateral station keeping
- S-Band communications: Universal Space Transponder, small SSPA, 2 helical LGAs
  - UST integrates interspacecraft com with deep space transponder, supports 2-way Doppler and Ranging to Earth and proximity spacecraft
- Ka-Band beacon (carrier only) for formation acquisition: single board radio, 2 horns
- IR Laser beacon for formation acquisition



Starshade



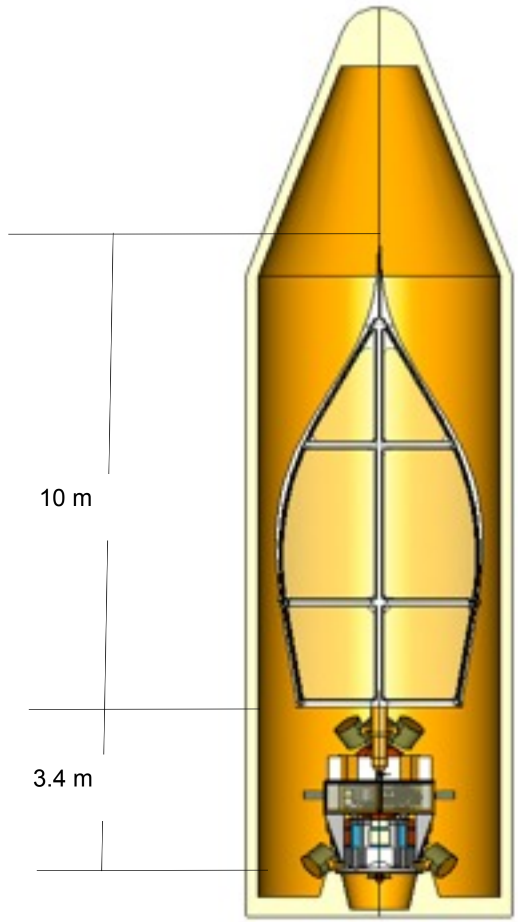


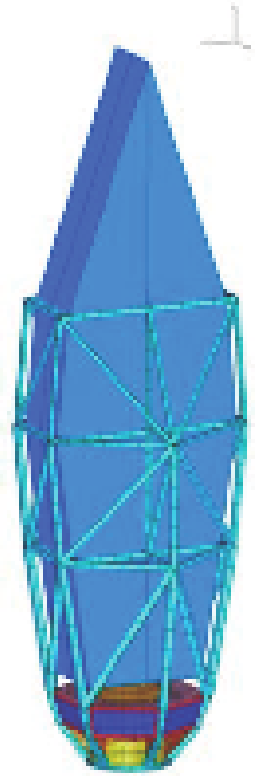
- A light-weight frame provides attach points for hinges and stowage
- Multiple layers of very thin kapton provide for meteorite protection throughout the occulter area

Simple, modular, assembly concept

Stowed Configuration: 45m

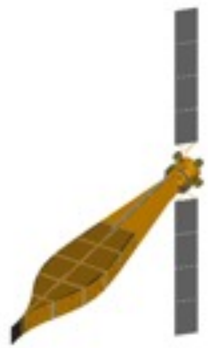
- Adequate clearances exist inside the Atlas V 5 m long fairing
- Launch support is provided by truss structure which is jettisoned after launch





Petal launch support shown for 45 m design

Deployment Description

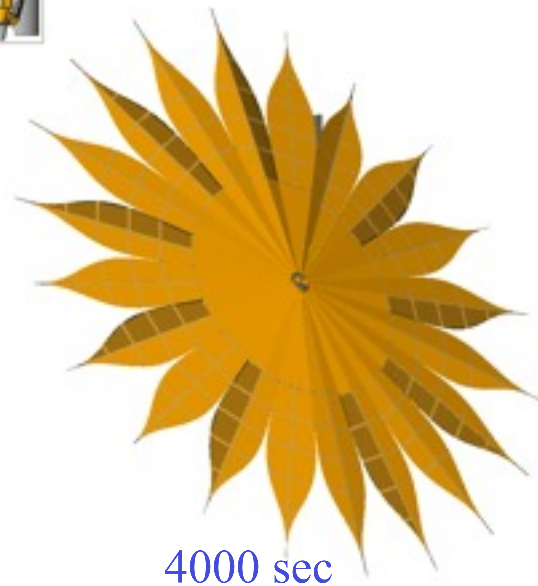


0 sec

Solar array deploys
Occulter mast deploys linearly

1000 sec

Mast rotational joints
control sequence and
lockup velocities



4000 sec

38 passively damped,
spring-actuated, hinge
lines deploy sequentially

The Hard Stuff

- 4-m, Diffraction Limited Telescope at 300 nm (4/5)
- Photon Counting Detectors out to 1000 nm (4)
- Large Focal Plane Arrays (3)
- Precision Occulter Manufacturing, Deployment & Stability (3)
- Occulter Test Program (3)
- Tight Formation Flying (4)

Plus . . .

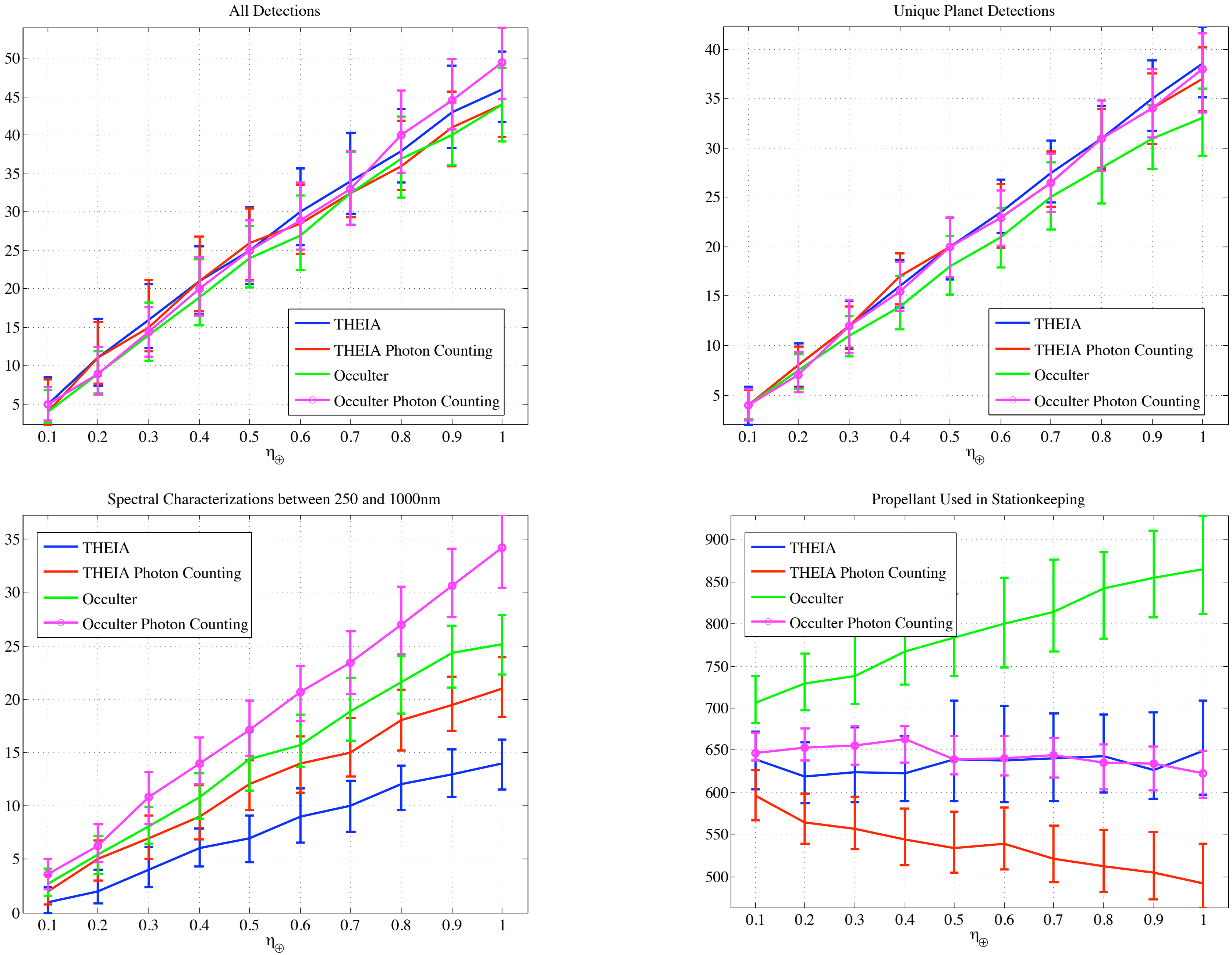
- Ion Electric Propulsion (4/5)
- High Rate Data Downlink (>6)
- High Volume Data Storage

The Telescope

Recent progress in large mirror manufacturing has significantly reduced technology development risk.

- Abrasive Water Jet (AWJ) cutting to aggressively lightweight a mirrors' core.
- The invention of Low Temperature Fused (LTF) Corning ULE\Rtrademark mirror blanks.
- Segmented core fabrication that reduces manufacturing time and risk of breaking a full-sized fragile core.
- Pocket milled face-sheets that significantly reduces overall mirror weight.
- Computer controlled active laps polishing of highly aspheric optics.
- The combination of pocket-milling and deep segmented AWJ cores.
- Technology advancement in optic and telescope metrology.

Photon Counting Detectors



Starshade Manufacture, Deployment, and Test

	Manufacture, Deployment, or	amplitude	Notes
1	Petal r.m.s. shape vs design, 1/f^2 power law	100 um	Dominated by low spatial frequencies, p = 10 m
2	Petal proportional shape error	80 um	at maximum width, decreasing with petal width
3	Petal length (clipping at tip)	1 cm	
4	Petal azimuthal position	0.003 deg	1 mm at petal tip
5	Petal radial position	1 mm	
6	In-plane rotation about base	0.06 deg	1 cm at petal tip
7	Petal bend with r^2 deviation	5 cm	
8	Out of plane petal bending, r^2 deviation	>50 cm	
9	The cross-track (telescope/occulter alignment)	75 cm	

Contrast change below 10^{-12} at 0.6 micron

To meet requirements, instrument must be stable or calibrated to a contrast of 6 x 10^{-12}

	Requirement	Budget
Instrument Contrast (Static, coherent)	1.00E-11	1.02E-11
Dynamic Contrast	6.00E-12	5.57E-12

Coherent Static Contrast			**1.02E-11**
Ideal Design			1.00E-12
Petal Shape			
	Proportional Width Error		
		Single Petal	1.00E-12
		Common	
	Constant Width Error		
		Single Petal	1.00E-12
		Common	
	Sinusoidal Error		
		Single Petal	2.00E-12
		Common	
	Petal Length (clipping)		
		Single Petal	1.00E-13
		Common	
Micrometeorites			
		Total xmit	1.00E-12
Deployment			
	Petal Position		
		Single Petal Radial	1.00E-12
		Common Radial	
		Single Petal Azimuthal	1.00E-12
		Common Azimuthal	
		Single Petal out-of-plane	1.00E-13
		Common out-of-plane	
Pointing			
	Cross-track error (offset)		2.00E-12

Coherent Dynamic (slow-time scale varations)		**1.42E-12**
Petal Position		
	Single Petal Radial	2.00E-13
	Common Radial	
	Single Petal Azimuthal	2.00E-13
	Common Azimuthal	
Petal Shape		
	Sinusoidal Thermal single petal	1.00E-14
	Sinusoidal Thermal common	
	Gross change thermal single petal	1.00E-14
	Gross change thermal common	
Pointing		
	Cross-track error (dynamic)	1.00E-12

Incoherent Scatter (contributes like zodi)

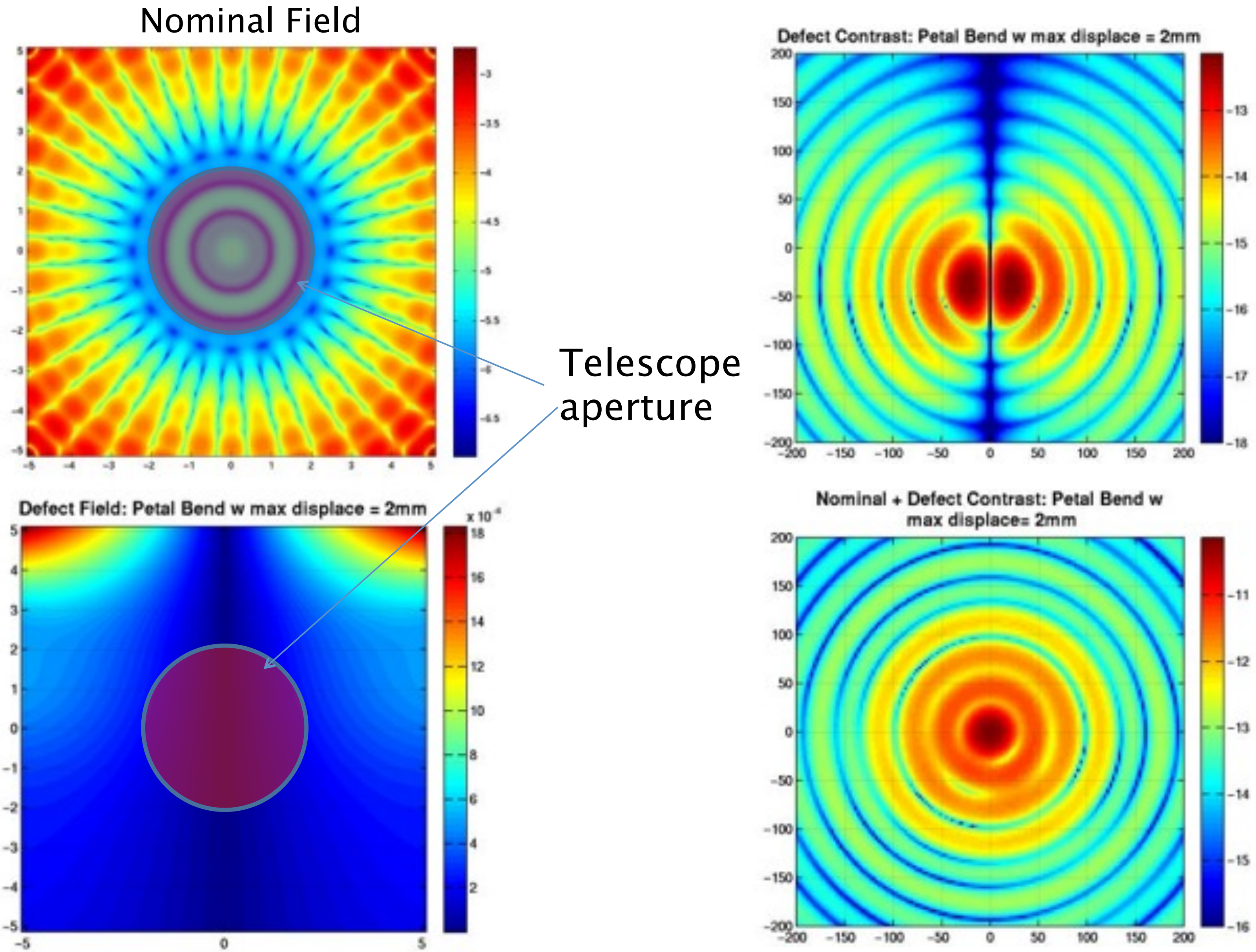
Jitter (incoherent scatter, motions short compared to integ. Time)	1.00E-11

Edge Scatter (solar)	1.00E-11

Where did the requirements come from?

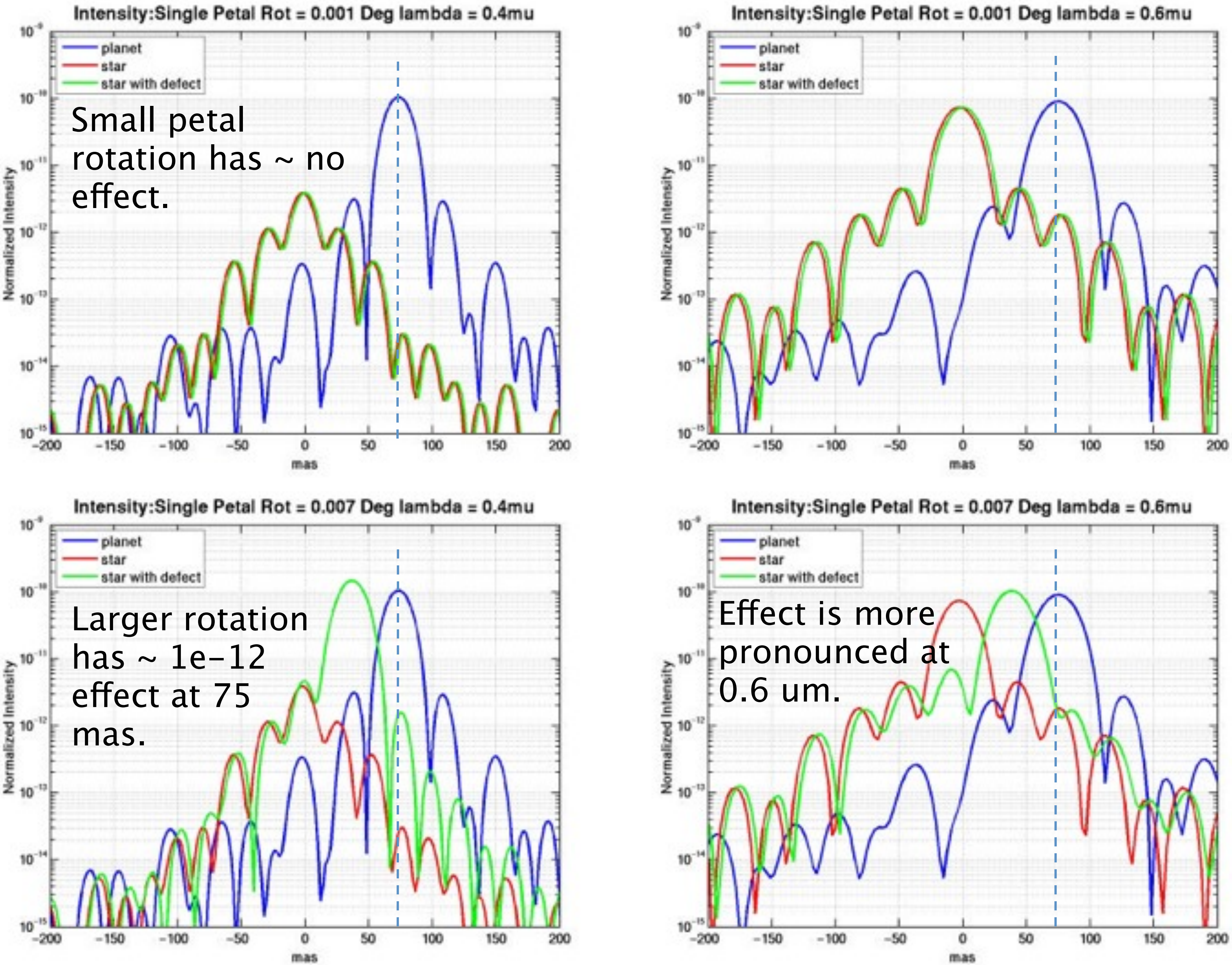
- The nominal field of the ideal occulter is evaluated at the telescope entrance pupil using an analytic solution from Vanderbei, et al.
- Defects along the occulter petals are modeled as a set of small slits whose fields are combined with the nominal occulter field using Babinet's Principle.
- The image plane field is simply the FT of the combined field at the telescope pupil.

Field at Pupil, Image Plane Intensity for a 2 mm (at tip) Petal Bend



Critical Wavelength for Tolerancing: 0.6 um

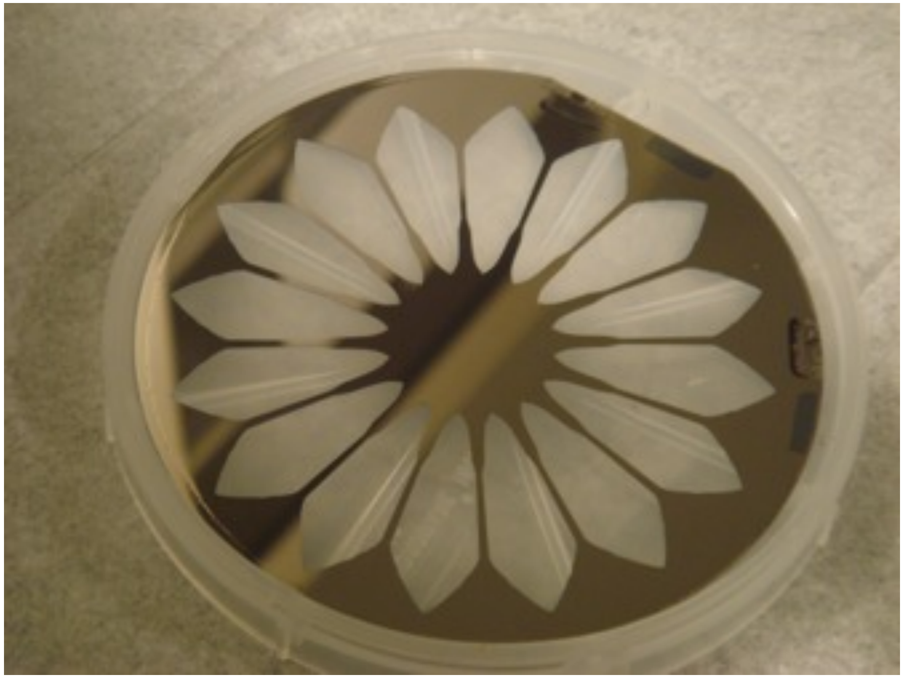
- The THEIA occulter is designed to have better than 1e-12 contrast at 75 mas over the bandpass 0.3 – 0.6 microns, at a distance of 55,000 km.
- It is moved to 35,000 km to obtain 1e-12 contrast at 118 mas over 0.7 – 1.0 um.
- For the shorter band, the nominal performance is at the 1e-12 limit at 0.6 um.
- This is also the wavelength that generally has the highest sensitivity to perturbations. **Tolerancing was performed at 0.6 um, representing the worst case in the visible band.**
- See next page for a comparison of 0.4 um and 0.6 um for a 1.2 mm (at tip) single petal rotation.
- NOTE: the occulter is more sensitive to aberrations in the 0.7-1 um band than at 0.6 um. THEIA will rely on modeling based on the chromaticity of speckles to calibrate the scatter at 1 um.


Intensity:Single Petal Rot = 0.001 Deg lambda = 0.4mu
planet
star
star with defect
Small petal rotation has ~ no effect.
Normalized Intensity
mas
Intensity:Single Petal Rot = 0.001 Deg lambda = 0.6mu
planet
star
star with defect
Normalized Intensity
mas
Intensity:Single Petal Rot = 0.007 Deg lambda = 0.4mu
planet
star
star with defect
Larger rotation has ~ 1e-12 effect at 75 mas.
Normalized Intensity
mas
Intensity:Single Petal Rot = 0.007 Deg lambda = 0.6mu
planet
star
star with defect
Effect is more pronounced at 0.6 um.
Normalized Intensity
mas

How do we know its possible?

- ✓ Subscale laboratory experiments to verify optics
- Manufacturing and alignment plan
- Subscale test program for deployment
- ✓ Detailed thermal/mechanical modeling combined with optical propagation

Laboratory verification



2-year verification study to examine occulter and hybrid occulter performance at 10^8 to 10^{10} level

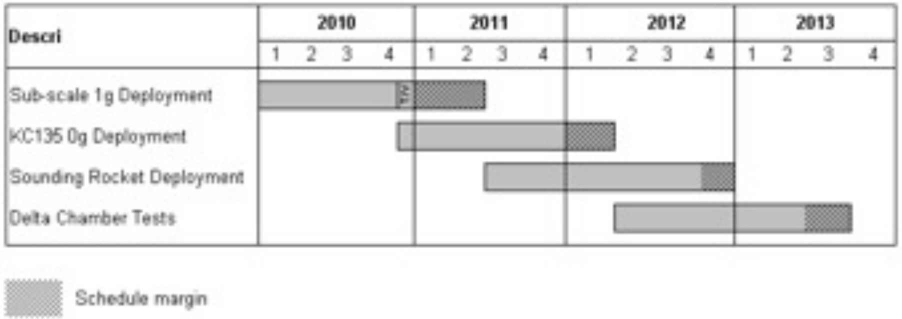
- Uses a diverging beam from a spatial filter to minimize aberrations from optics
- Scaling relations relate the shadow to an on-sky system
- Uses an optimized outer structure on a free-standing mask
- Will be used with both monochromatic and wideband sources.

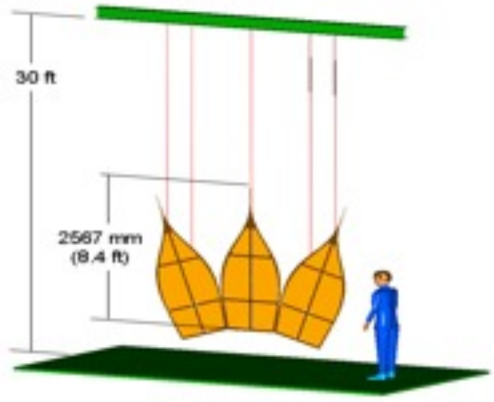
Currently under construction, first results expected this summer

Manufacturing and Alignment

A detailed plan has been formulated for manufacturing processes at various assembly levels including precision metrology.

Deployment Test Program





- Subscale 1-g deployment tests, thermal and dynamical response tests, and material testing (ambient and thermal vacuum)
- 1/20th scale KC-135 deployment tests
- 1/5th scale sounding rocket test and vaccum chamber deployment
- full scale qualification unit

Formation Flying

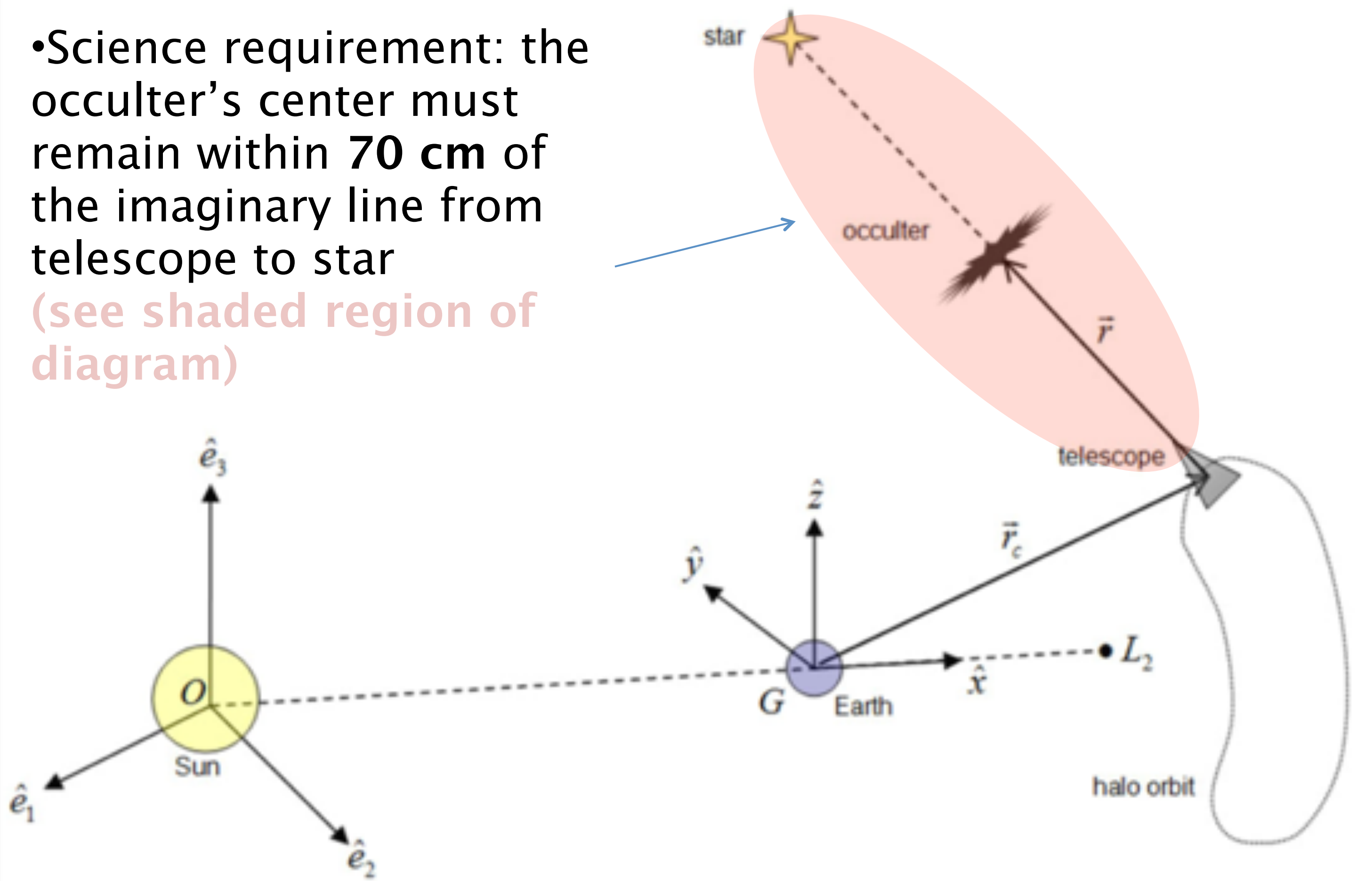
Four Stage Retargeting:

- Conventional RF Ground tracking (< 100 km)
- Observatory angle sensing of a Ka-Band beacon from the occulter spacecraft (± 16 km)
- XPC IR imaging of a laser beacon (± 70 m)
- <u>XPC IR imaging of light leaking around the occulter (± 35 cm)</u>

All are low to medium TRL and need technology development and verification.

Occulter Stationkeeping

- Science requirement: the occulter's center must remain within **70 cm** of the imaginary line from telescope to star **(see shaded region of diagram)**

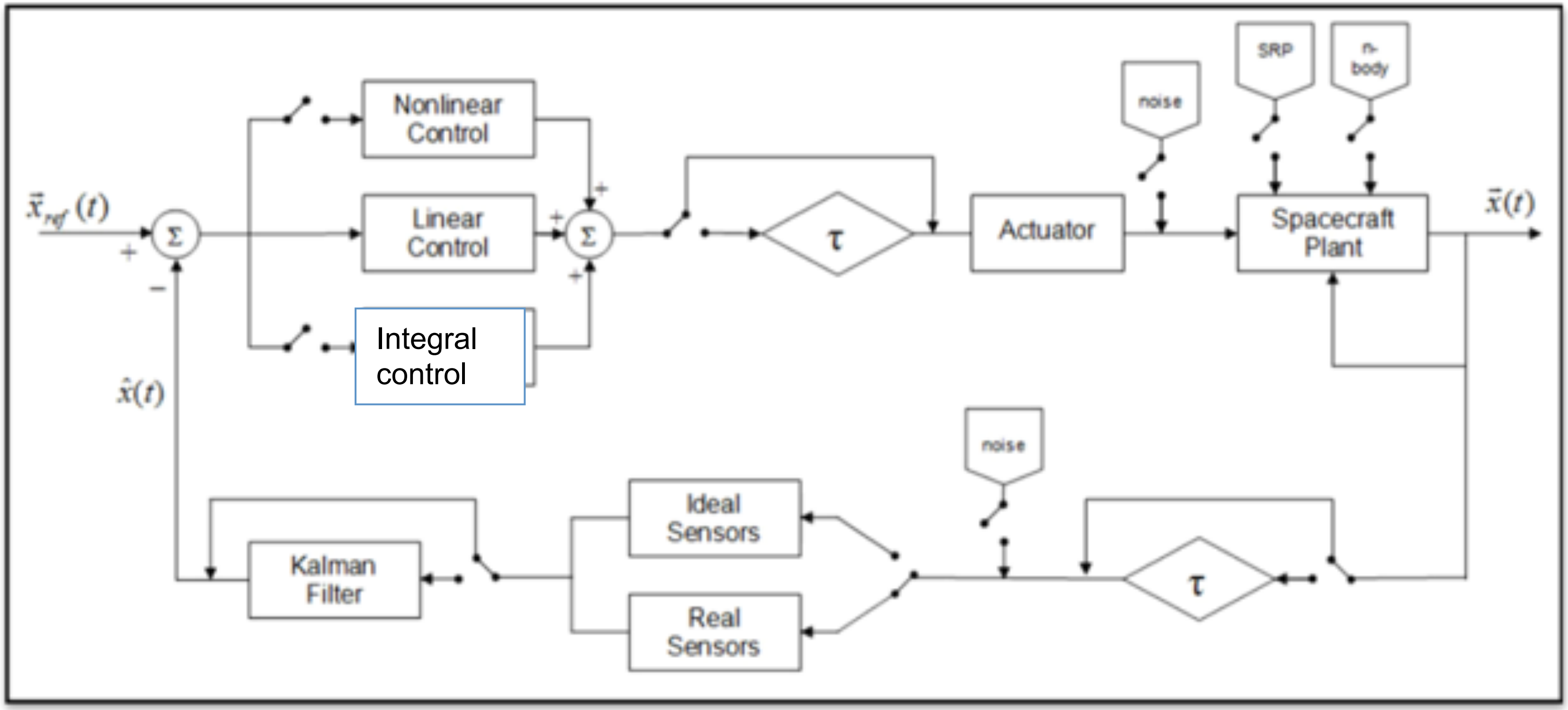


Control System Challenges

- ✓ Nonlinear dynamic system
- ✓ Limited information (relative position only)
- ✓ Complex sensor with photon noise
- ✓ Sensor latency
- ✓ Solar radiation
- Third body perturbations
- ✓ Navigation errors
- Time delays
- ✓ Discrete updates
- ✓ Orbital motion
- Aberration of starlight
- On/off hydrazine thrusters
- Thruster noise and min/max thrust

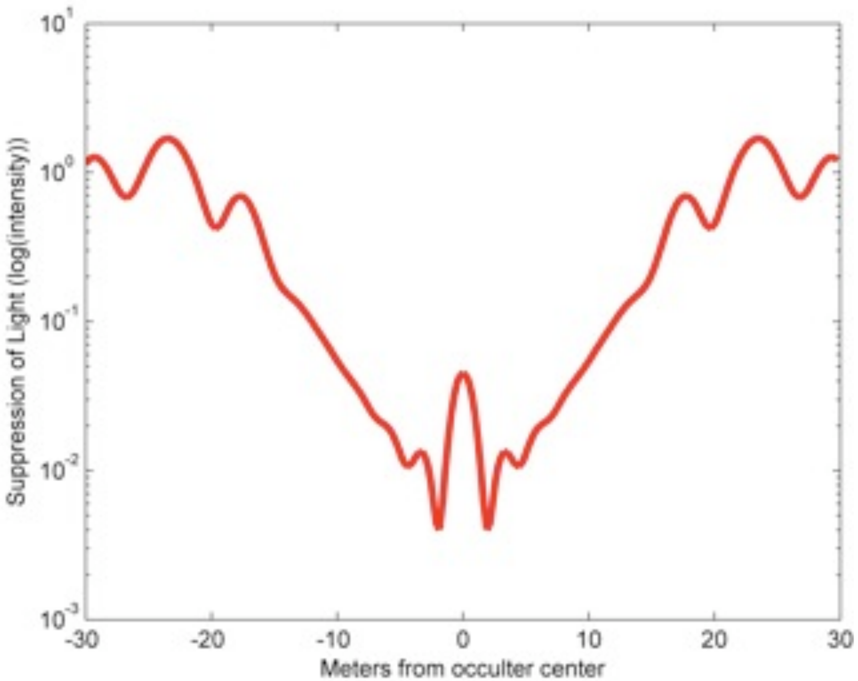
Control System Schematic

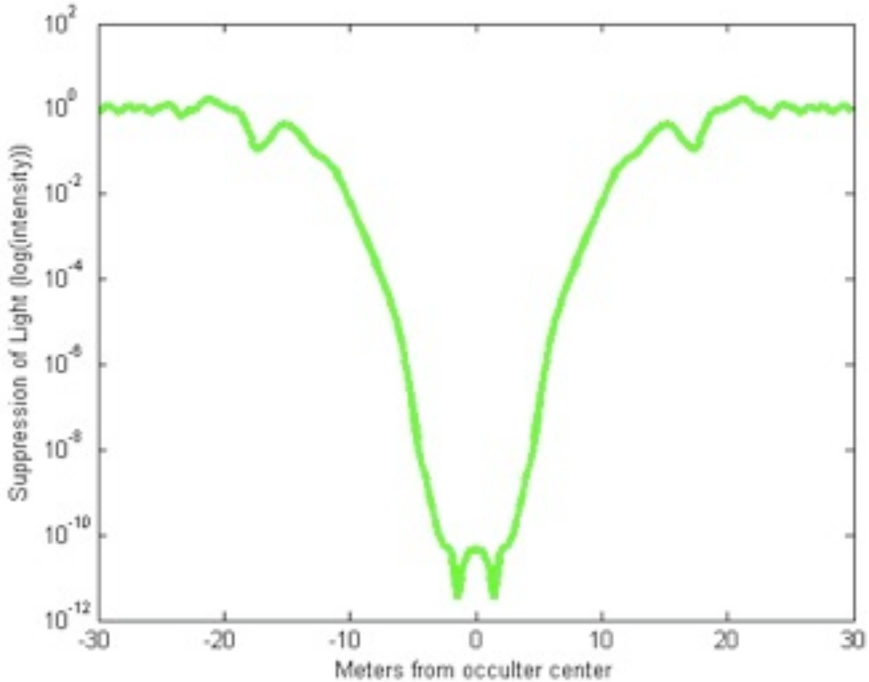
- "Toggles" are switched on to improve realism of simulation



Wednesday, April 22, 2009

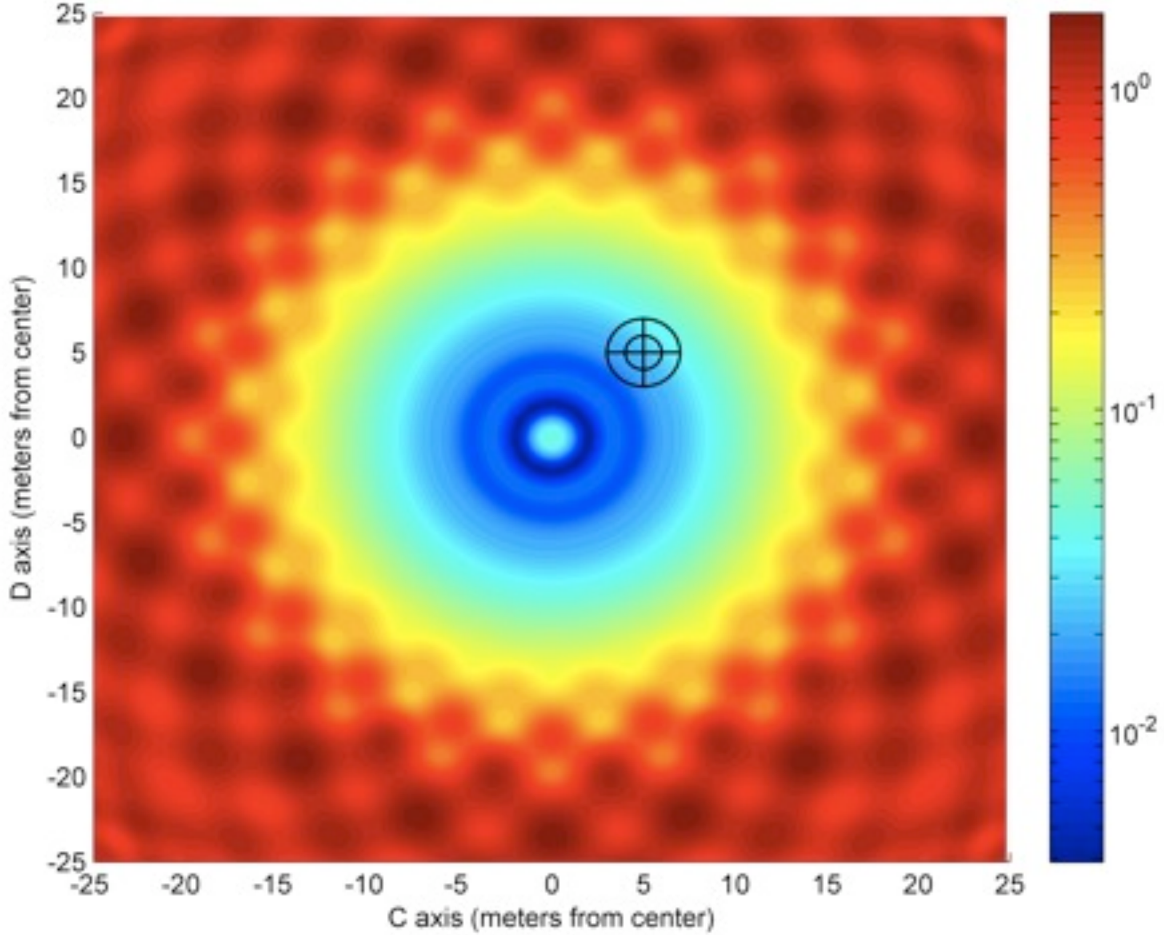
NIR Suppression vs. Visible Suppression (1.55 µm and 0.50 µm)





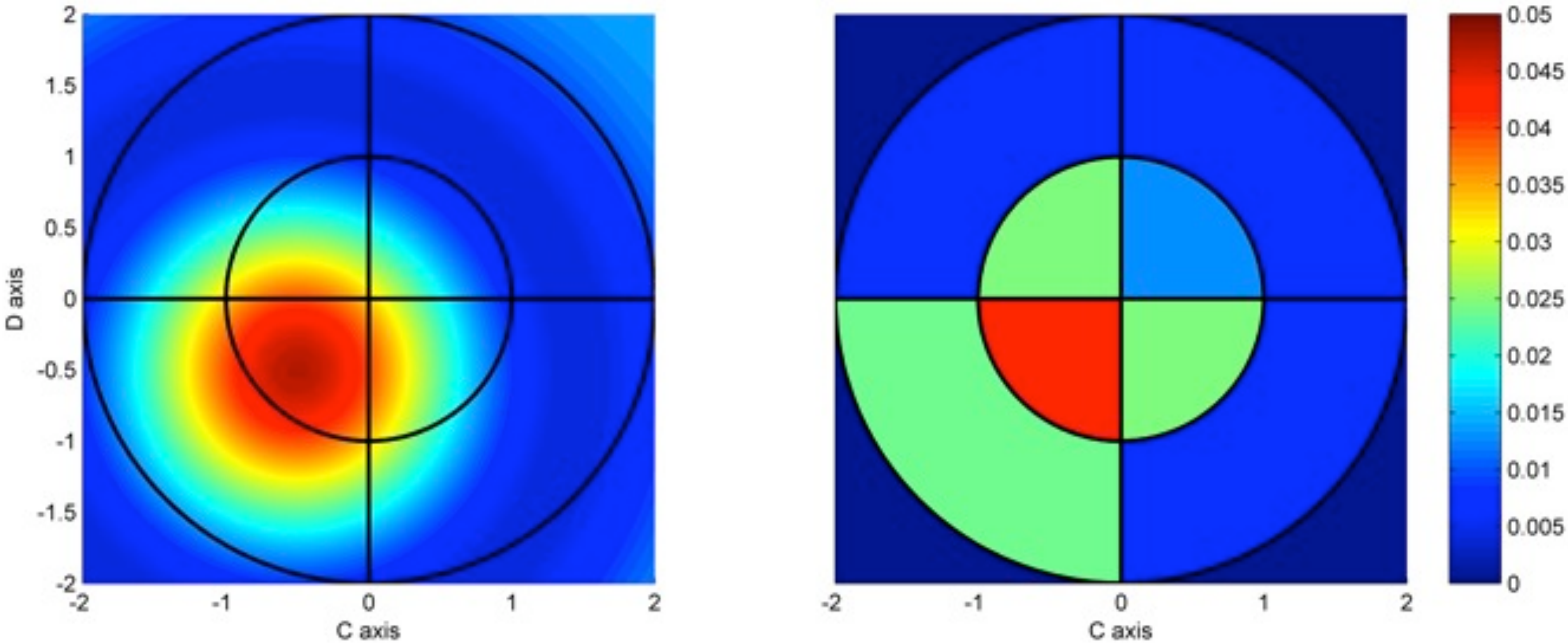
NIR (left) and Visible (right): Suppression is highly dependent upon wavelength. There exists a tradeoff in the magnitude of the suppression and the number of photons available for collection; we wish to suppress the light enough for observation (10^-10) but retain rapid enough photon collection to allow for less noisy, more frequent measurement outputs.

Pupil size compared to suppression profile



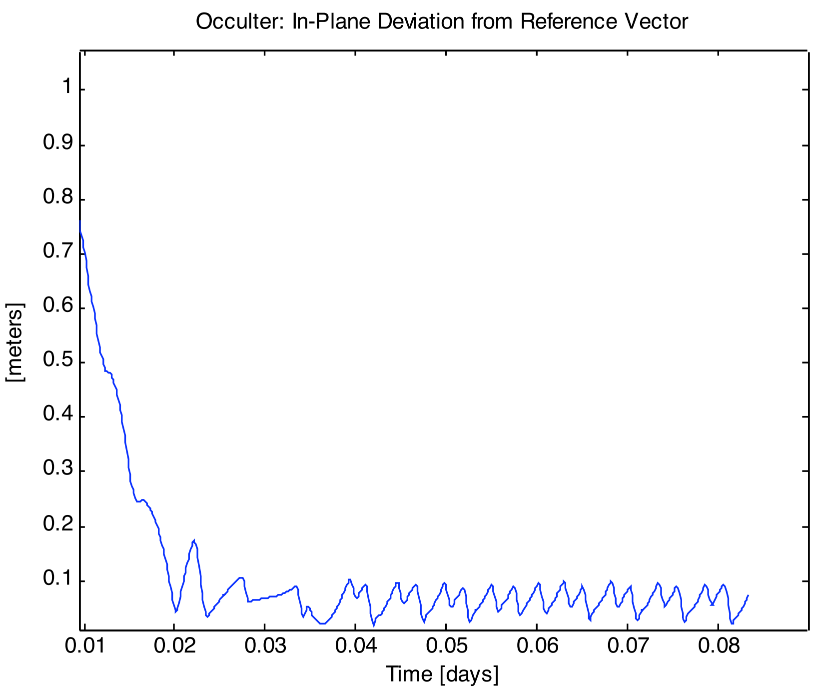
The pupil only captures a small area of the suppression profile. Thus it is prone to ambiguities and must collect enough photons to accurately determine its offset from the ideal alignment.

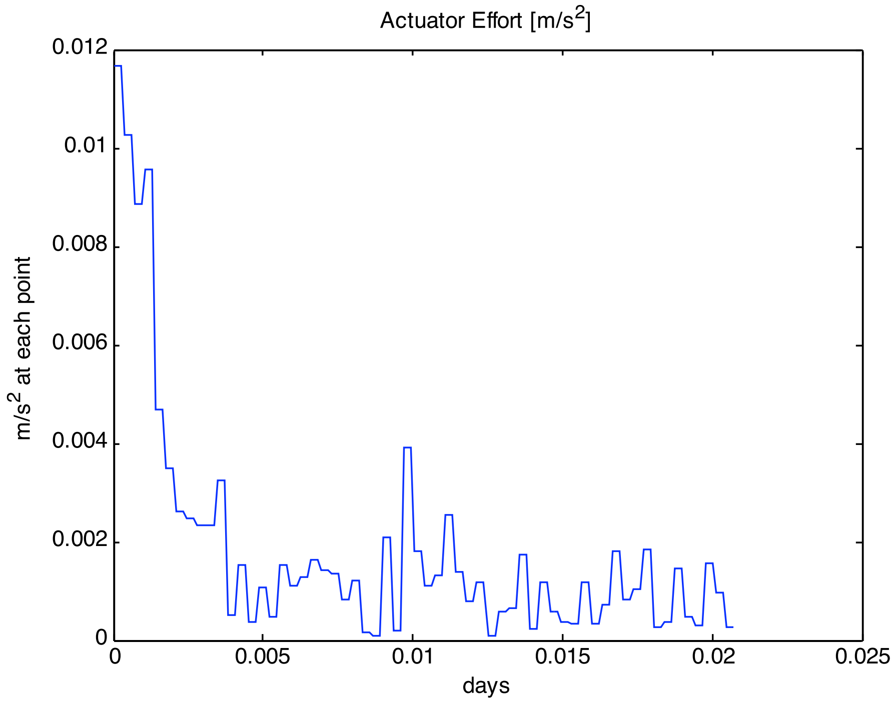
Sensors: Segmented Pupil Intensity Averaging



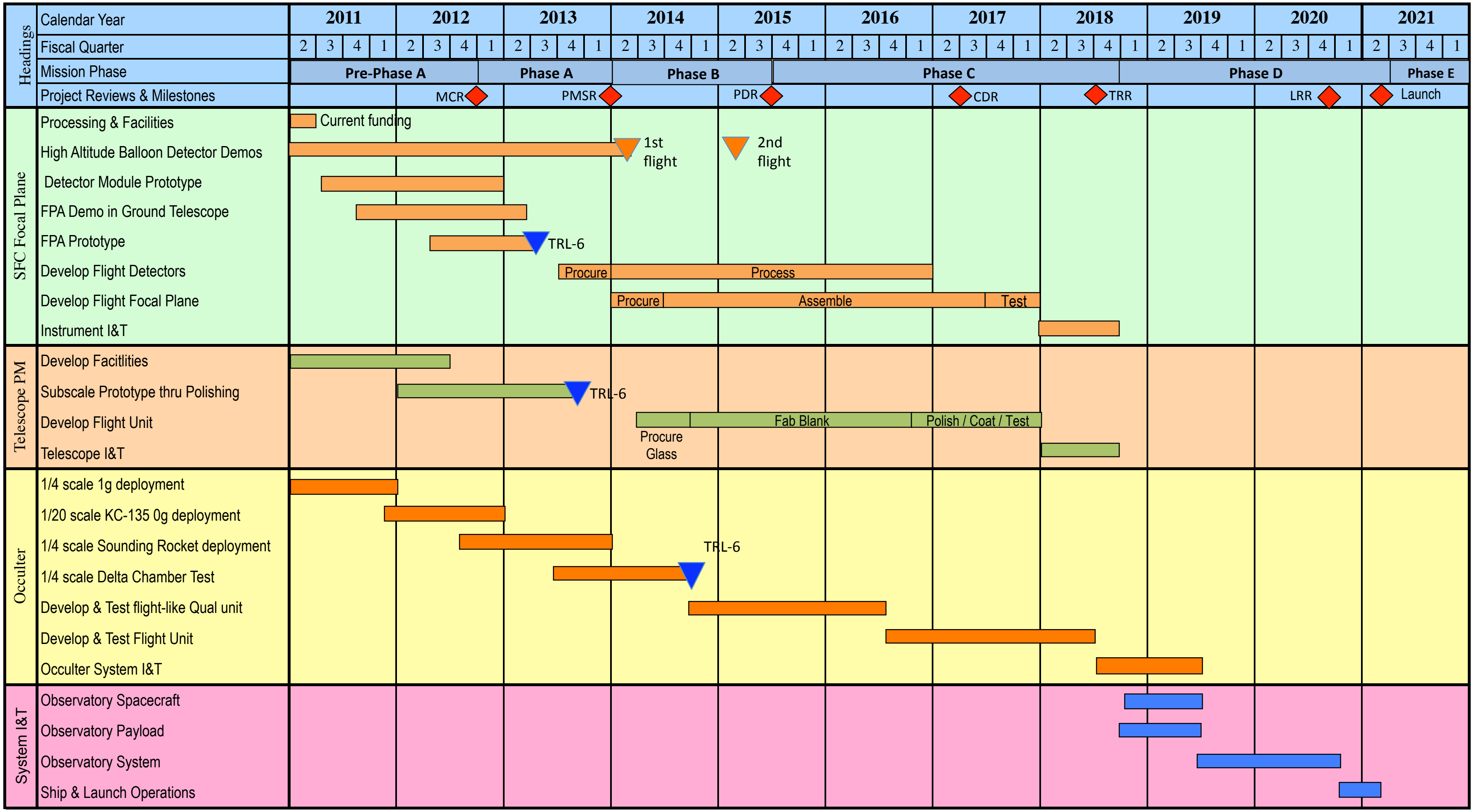
Because the segments are larger than the details of the suppression profile, this leads to ambiguities in position calculations. An eight-segment pupil is necessary to prevent trapping the pupil in local minima and maxima.

Results


Occulter: In-Plane Deviation from Reference Vector
[meters]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Time [days]


Actuator Effort [m/s2]
m/s2 at each point
0.012
0.01
0.008
0.006
0.004
0.002
0
0
0.005
0.01
0.015
0.02
0.025
days

Schedule


Headings
Calendar Year
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
Fiscal Quarter
Mission Phase
Pre-Phase A
Phase A
Phase B
Phase C
Phase D
Phase E
Project Reviews & Milestones
MCR
PMSR
PDR
CDR
TRR
LRR
Launch
SFC Focal Plane
Processing & Facilities
Current funding
High Altitude Balloon Detector Demos
1st flight
2nd flight
Detector Module Prototype
FPA Demo in Ground Telescope
FPA Prototype
TRL-6
Develop Flight Detectors
Procure
Process
Develop Flight Focal Plane
Procure
Assemble
Test
Instrument I&T
Telescope PM
Develop Factilities
Subscale Prototype thru Polishing
TRL-6
Develop Flight Unit
Fab Blank
Polish / Coat / Test
Procure Glass
Telescope I&T
Occulter
1/4 scale 1g deployment
1/20 scale KC-135 0g deployment
1/4 scale Sounding Rocket deployment
TRL-6
1/4 scale Delta Chamber Test
Develop & Test flight-like Qual unit
Develop & Test Flight Unit
Occulter System I&T
System I&T
Observatory Spacecraft
Observatory Payload
Observatory System
Ship & Launch Operations

Cost

Cost Element	Team-X	THEIA Team	Cor
Pre-Phase A Mission Concept	15	15	THEIA team estimate
Total Technology Development	150	150	THEIA team estimate
Occulter Starshield	40	40	
Primary Mirror	50	50	
SFC Focal Plane	40	40	
NEXT Ion thruster testing	20	20	
Management, Sys Engr., Mission Design and Mission Assurance	160	140	Derived from other ch
Science and Science Data Center	250	250	
Payload System	3000	2200	
Exoplanet Characterizer	150	150	
Star Formation Camera	400	400	
UV Spectrometer	200	200	Goddard IDC estimat
Fine Guidance Sensors	80	80	
Occulter Starshield	100	100	
Other	25	20	Derived from other changes
Telescope	2000	1200	See Text
Flight Systems (Observatory & Occulter)	560	500	THEIA est. uses screened MIL 883B parts versus Class S (do not need extra rad hardness)
System Level I&T (ATLO)	40	100	THEIA est. adds I&T of instruments with telescope & a complex shipping container
Mission Operations & Ground Data Systems	190	130	THEIA est. removes DSN cost, per assumption that THEIA will be an assigned mission
Education and Public Outreach	40	35	Derived from other changes
Reserves	1200	1000	Derived from other changes
Launch Services	440	440	2 Atlas V 551s
Total Mission	**6000**	**5000**