The THEIA Study

N. Jeremy Kasdin
Princeton University

HabEx Face-to-Face
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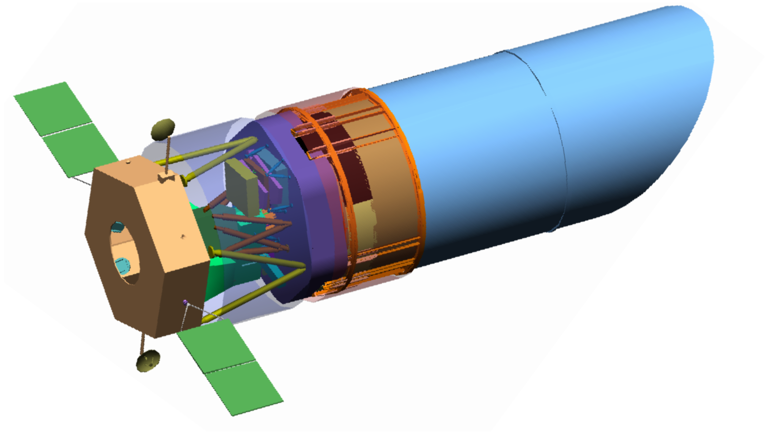
What we proposed:

A 4-m telescope with an internal coronagraph and external occulter hybrid that would reduce cost, increase efficiency, and maximize science, including spectra of earth-like planets from 250 to 1000 nm.

What they said about it:

Although XPC Should be able to achieve the desired 10^{10} starlight suppression without the need for an extremely large (> 4 m) telescope aperture with the proposed hybrid design (external + Internal coronagraph), the implementation carries with it all of the enormous challenges associated with an external, free-flying occulter. Deployment of the occulter on orbit will be risky and represents a single point failure. The difficulty of formation flying and repositioning/stationkeeping the occulter are underestimated. It may be a leap of faith to claim that the 4 meter light-weighted diffraction limited telescope system is at TRL 6, when the evidence provided is for a significantly smaller 2.4 meter mirror. Finally, the mission costs do not appear reasonable. It is not clear if the proposed hybrid approach yields cost savings as claimed.



THEIA: Telescope for Habitable Exoplanets and Intergalactic/Galactic Astronomy

Uses a 40 m external occulter operating at two distances for two wavelength bands for planet detection and characterization

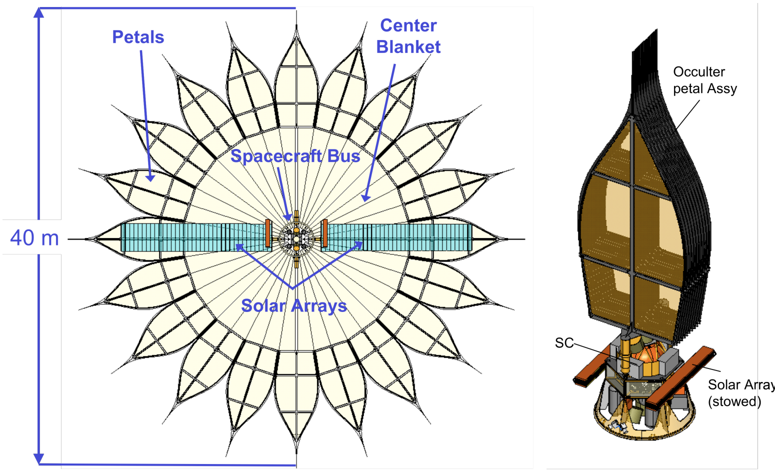
- 4 meter, on-axis telescope
- 5 year nominal mission length + 5 year extended
- Fit onto Atlas V launch Vehicle

(two launch vehicles for telescope and occulter)

- Existing spacecraft hardware

Science Instruments

- eXoPlanet Characterizer (XPC)
- Detect Earthlike Planets in Habitable Zone
- Characterize from 250-1000 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



- At $\eta_{\oplus}=1$, THEIA detects over 30 Earth-like planets
- THEIA characterizes almost 20 of them over the full spectral band, getting Ozone, Oxygen, CO2 and Water
- THEIA has enough repeat detections on five of them to characterize their orbits
- Because of the multiple distances, THEIA saves enough fuel to go an extra 5 years

Requirements Summary

Science Requirement	Performance Requirement	Design
Detect Earth twin at 10 parsec	Detect Earth twin at 10 parsec	40m occulter for starlight suppression over 0.4-1um band.
Detect ≥ 1 HZ planet with 95% confidence, if 30% of target stars have planets	Contrast ≥ 26 mags IWA ≤ 75 mas	
Detect Jupiter twin at 10 pc	OWA ≥ 500 mas	No restriction, not a design driver
Measure planet brightness within 10%	Contrast stability ≥ 28 mags	Main driver to occulter stability
		1 mm stability at tip, 100 um petal deformation
		100 mK PM stability
Detect atmospheric O_2, H_2O, O_3	Bandpass = 0.5 to 1.0 μm	2 broadband science channels feed 2 IFUs UV Ozone Camera - 4m aperture for throughput.
	Spectral resolution ≥ 70	
Survey formation & evolution of stars & galaxies with red-shifts up to 9	FOV = 15' x 19'	Star Formation Camera with 2 channels High efficiency detectors & large focal planes 6 Tbytes/day after x2 loss-less compression
	Pixel FOV = 18 mas	
	Diffraction limited to 10' off-axis	
Survey intergalactic web & investigate galactic interactions & effect on evolution	Bandpass = 100 to 300 nm Spectral resolution ≥ 30,000	UV Spectrograph with 2 channels on-axis entrance at Cassegrain-like focus LiF coated secondary mirror No extra reflections - UVS extends into bus

XPC Science Overview

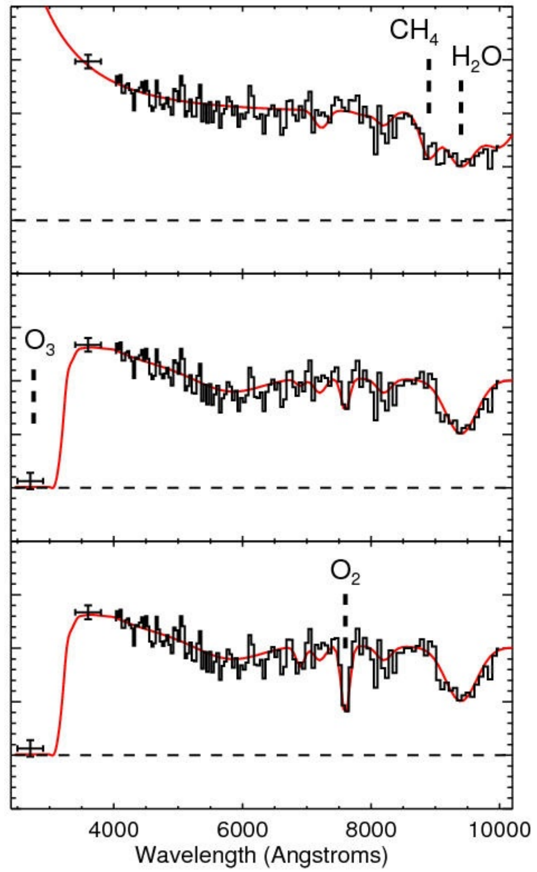
XPC's science case focuses on detecting Earth-size planets in the habitable zones of sun-like stars and then characterizing planet atmospheres by filter photometry and spectra. Major advantages over past concepts include: the extensive wavelength range from 250 to 1100 nm including a UV capability to detect the ozone cutoff and orbit determination.

XPC Detection

XPC will search about 80 target stars for planets in the habitable zone. The programmatic overview is that planets will be discovered at 400 to 700 nm with a ~20 m radius occulter at ~55,000 km from the telescope and further characterized in the red at 700 to 1100 nm after the occulter moves closer to the telescope (~35,000 km) to preserve the IWA. The plan of whether to follow up with a revisit or to characterize the planet's atmosphere immediately after discovery, and how best to measure the planet's orbit, is determined through automated DRM generation.

XPC Characterization

XPC will search for O_2 absorption; on Earth O_2 is produced in large quantities only by life. At UV wavelengths XPC can detect O_3 by the sharp cutoff. O_3 is a photolytic byproduct of O_2 and is useful because only small, undetectable amounts of O_2 are needed to generate a strong O_3 signature. All life on Earth requires liquid water. XPC will look for water vapor absorption that is suggestive of liquid water oceans. See Des Marais et al. (2002) for details of Earth's spectrum.



Simulation of Earth's normalized reflectance spectrum at different times (courtesy D. Lindler) The red curve is the low-resolution input spectrum, the black represents a spectrum with noise at the XPC level, the UV simulated data points are taken over five days each, for a planet at 10 pc.

Approaches to Planet Finding and Characterization

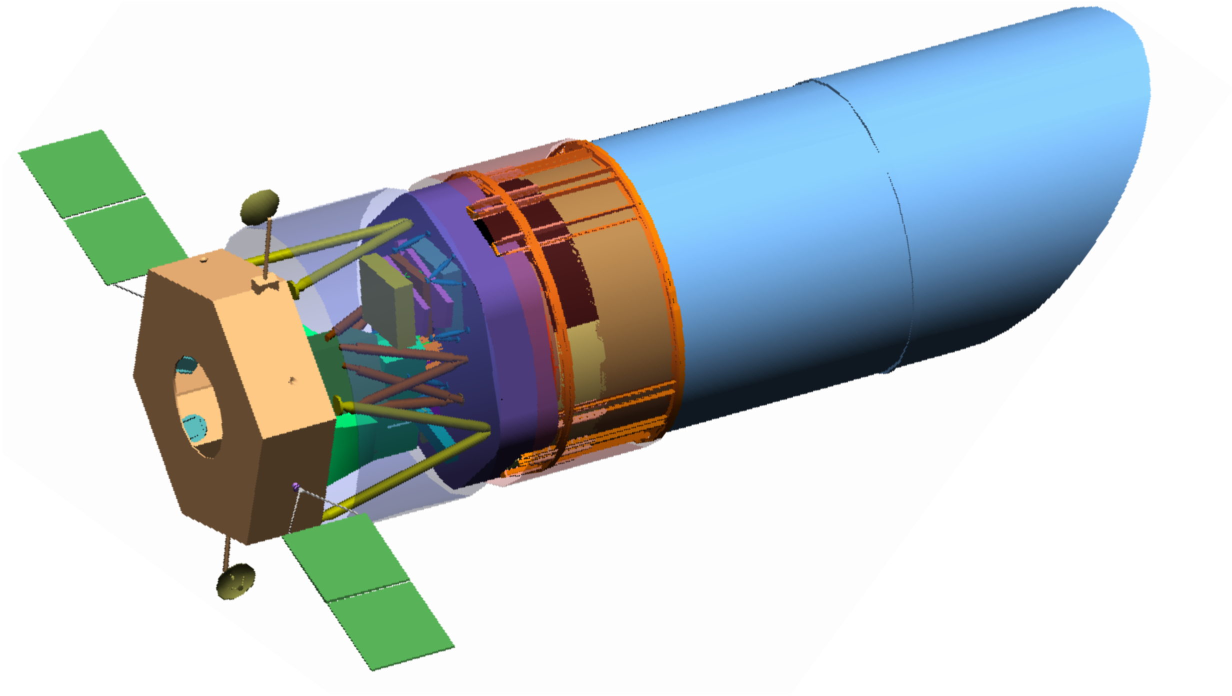
Requirements:

- Maximize unique planets found
- Characterize “at least one” from 250 - 1000 nm
  - Strong requirement to get Ozone cutoff as biomarker and reach water lines
- Revisit as many as possible (verification and orbits)

Design Constraints:

- 4 meter telescope
- 5 year nominal mission length + 5 year extended mission
- Fit onto Atlas IV launch Vehicle (possibly multiple launches)
- Existing spacecraft hardware (high TRL)

THEIA Telescope



On-axis, 4-meter three-mirror anastigmat

f1.5 ULE Primary

Diffraction limited at 300 nm

Al/MgF_2-coated primary

Al/LiF-coated secondary

Evolution, not Revolution

Internal Coronagraph vs. External Occulter

<u>Internal Coronagraph</u>

- Variable Inner Working Angle
- Fixed repointing
- Optics/Detector limited Bandwidth
- Low throughput
- Technology/Cost Drivers
    - Telescope Stability
    - Wavefront Control
    - Small IWA Coronagraph (2 λ/D)
    - Office-axis telescope

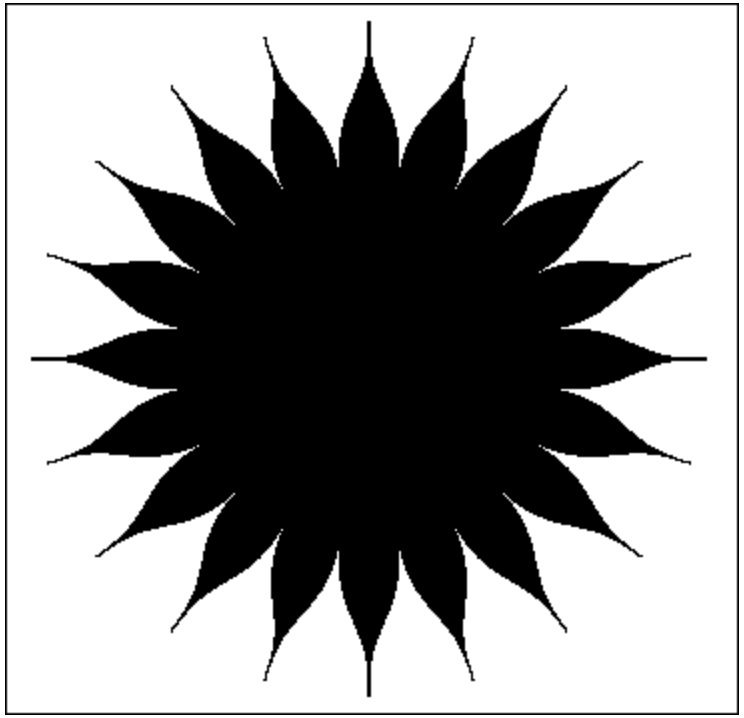
<u>External Occulter</u>

- Fixed Inner Working Angle
- Variable Slew Time
- 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
- Ozone deemed not possible by coronagraph
- Premium placed on small/nearby occulter => Two-Distance
  (lower mass, easier deployment, fits into fairing, smaller petals, lower fuel use, more rapid slews)

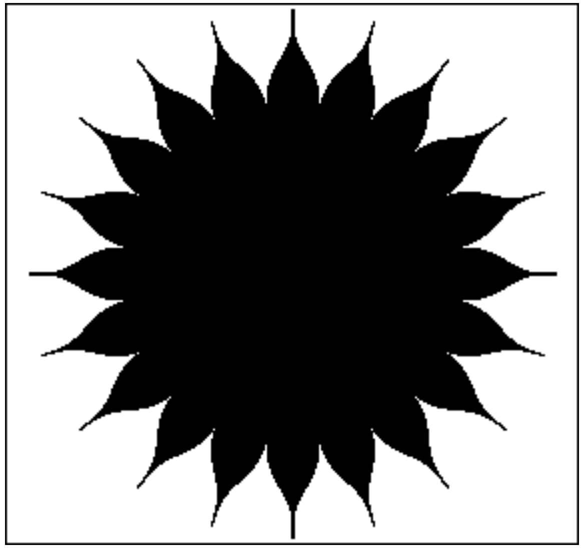
	1-dist. Occulter	2-dist. Occulter
Occulter distance (km)	70400	55000
Occulter IWA (mas)	75	75
Occulter spectral band (nm)	250-1000	250-700
Second occulter distance (km)	-	35000
Second occulter IWA (mas)	-	118
Second occulter spectral band (nm)	-	700-1000
Occulter radius (m)	25.6	20
Number of petals	20	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

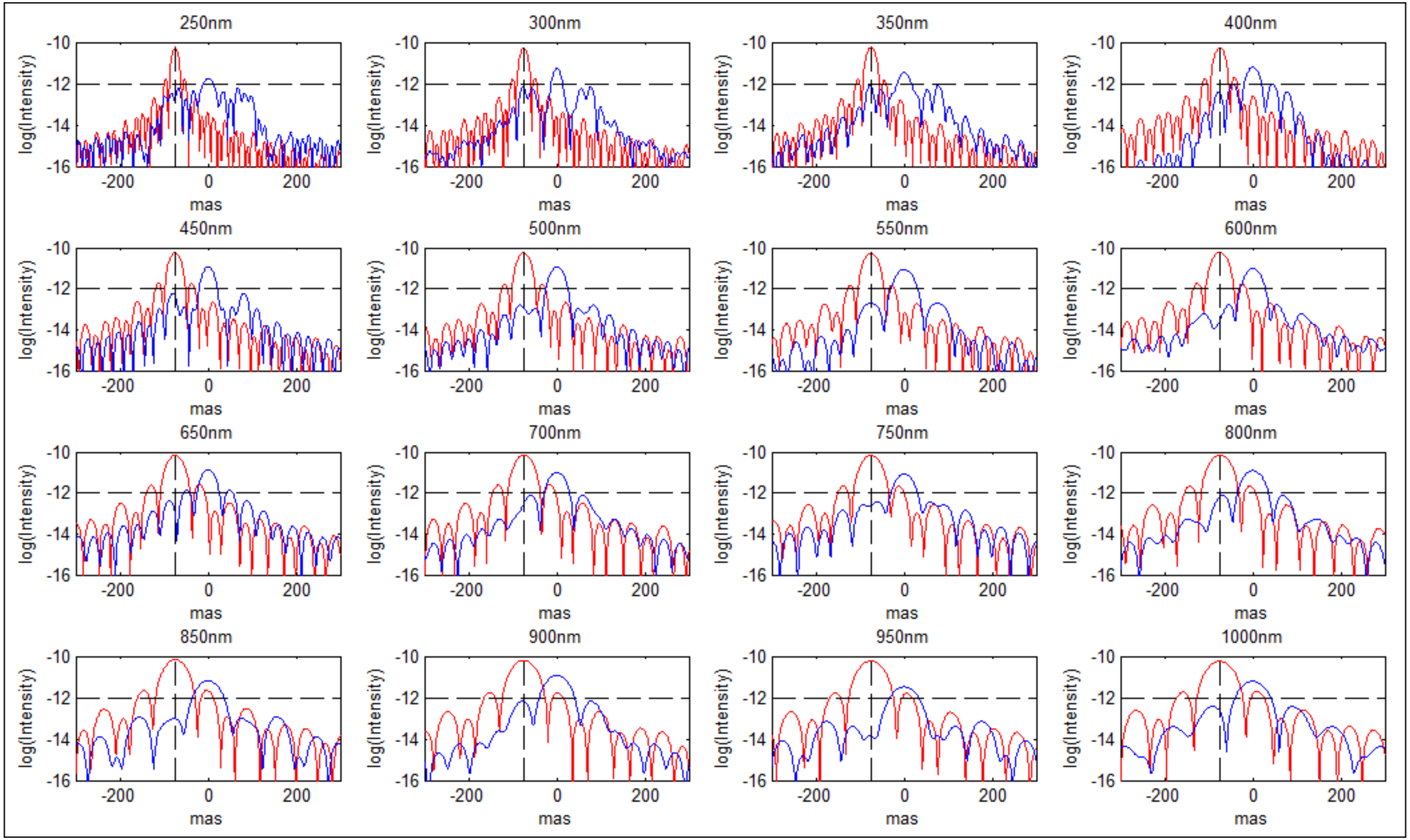
Right: two-distance occulter



Hybrid designs failed:

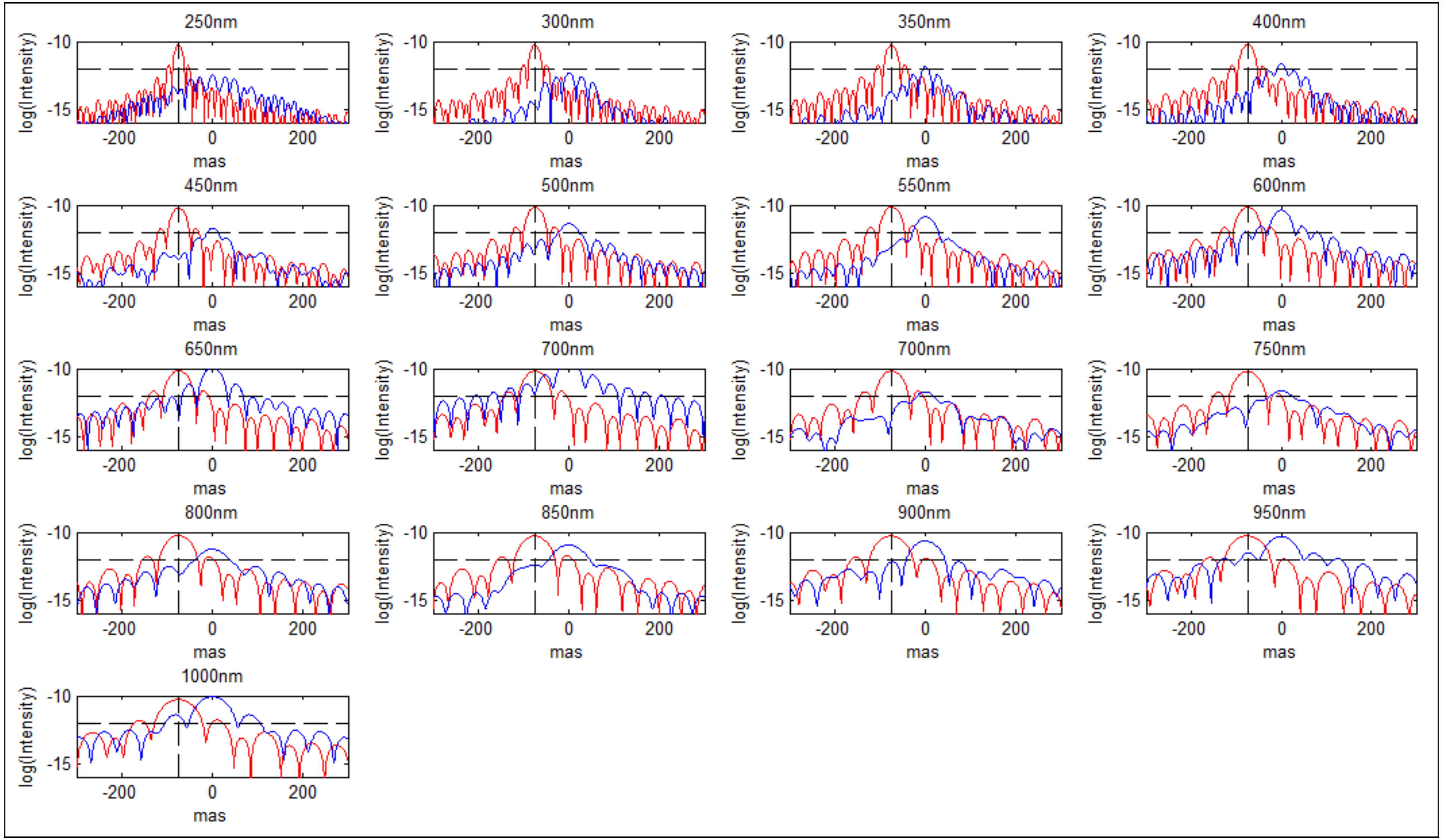
- don't work if too red
- can't be used in UV

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.

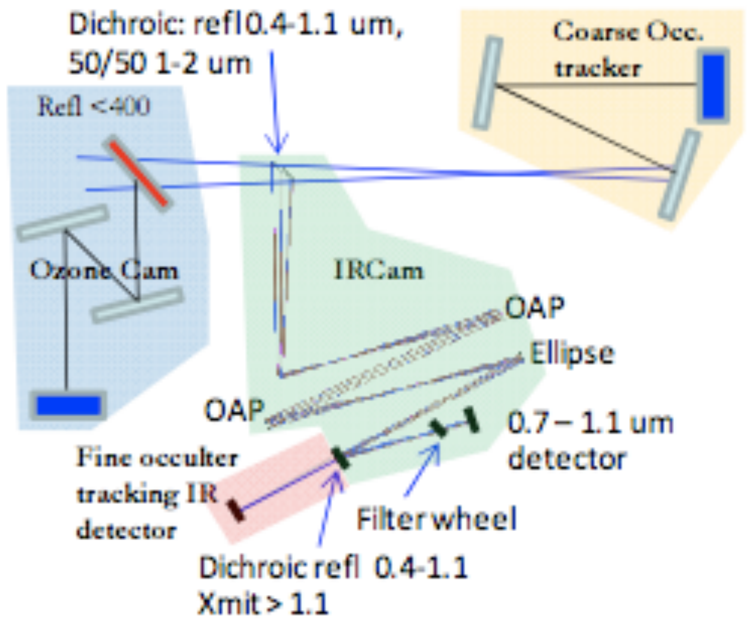
Occulter Requirements

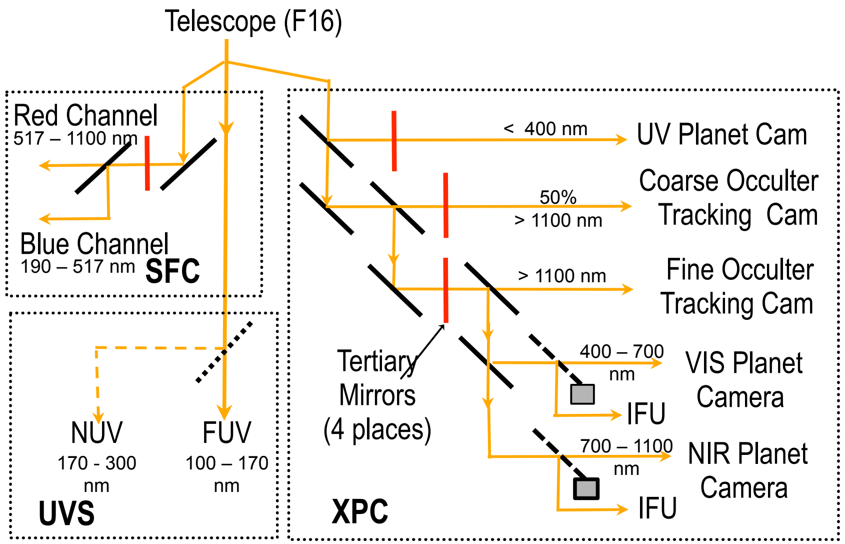
- Developed one of the first detailed error budgets for occulter
- We require 1e-12 contrast change at 75 (118) mas for individual contributions, for wavelengths < 900 nm
- We rely on calibration to achieve this level of contrast for wavelengths > 900 nm
  - The occulter shadow is not as deep at the long wavelength end, and aberration sensitivity is worse there.
- Smaller occulter due to two-distances is less sensitive to errors

Sample Requirements for 1e-12 contrast changes

- Cross-track motion: < 70 cm
- Sinusoidal manufacturing error:
  - Long wave (meters): > 30 um
  - Short wave (10s of cm): 100 um
  - PSD evaluation underway
- Petal proportional width error: < 230 um max
- Petal length error < 1 cm
  - Note: this term was allocated 1e-13 in the error budget.
- Petal in-plane bending: < 10 cm at tip
- Petal out-of-plane bending: < 50 cm at tip (quadratic bend)
- Azimuthal rotation (along r=10 m circle): 0.003 deg (520um at tip).

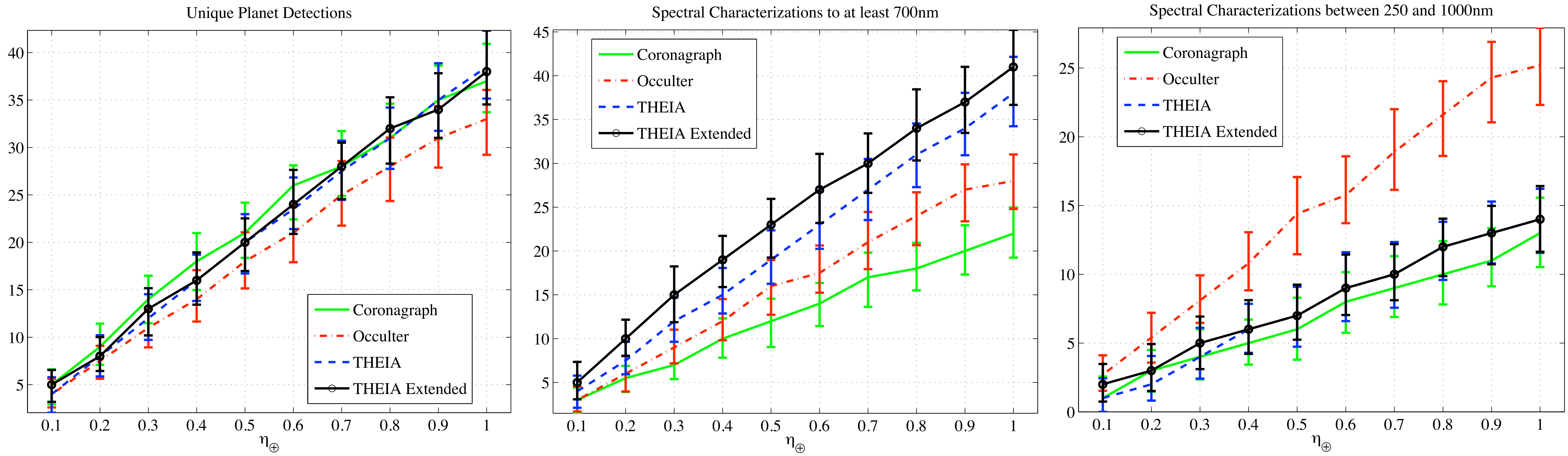
XPC Instrument





The XPC instrument suite consists of UV, Visible, and NIR science cameras, coarse and fine occulter tracking cameras (FOTC), and two Integral Field Unit Spectrometers. They are all fed by a 0.1 deg off-axis beam and picked off just before the Cassegrain focus. The optics operate at room temperature while the detectors are cooled to 150 K. A series of dichroic mirrors split the light. The Ozone Camera uses 2 aspheric optics to form an f/90 beam, corrected over a 10” field. The total number of reflections in this instrument, including the primary and secondary telescope mirrors, is five. The beam is Nyquist sampled on the detector at a wavelength of 250 nm. IR light up to 2 μm is passed to the f/6.5 COCT which has a 3’ field and 1” pointing precision to locate the occulter laser beacon and feedback position information for handoff to the FOTC (f/60, 20” field, 4 mas resolution). Visible and NIR light is split between two science channels (400-700 and 700-1000 nm), each with a filter wheel for spectrophotometry, a fine guiding mirror for beam stabilization, and a flip-in mirror to fit the IFUs. These science channels are identically designed to form an f/60 beam with a diffraction-limited 10” field and > 80% throughput on e2V Technologies L3CCDTM. The visible/IR cameras will be the exoplanet detection workhorses. They each have 8 reflections including the PM, SM, dichroic, two OAPs, 2 folds, and an ellipse, all easily fabricated. Based on the TPF-C CorSpec design, the IFSs have a 134 x 134 microlens array to obtain an R70 spectrum, again using L3 CCDs. We note that while all of our DRM studies were performed with conventional CCDs, the planet characterization science would greatly benefit from development of radiation hardened, zero read noise, high QE photon counting detectors in the NIR (700 to 1000 nm).

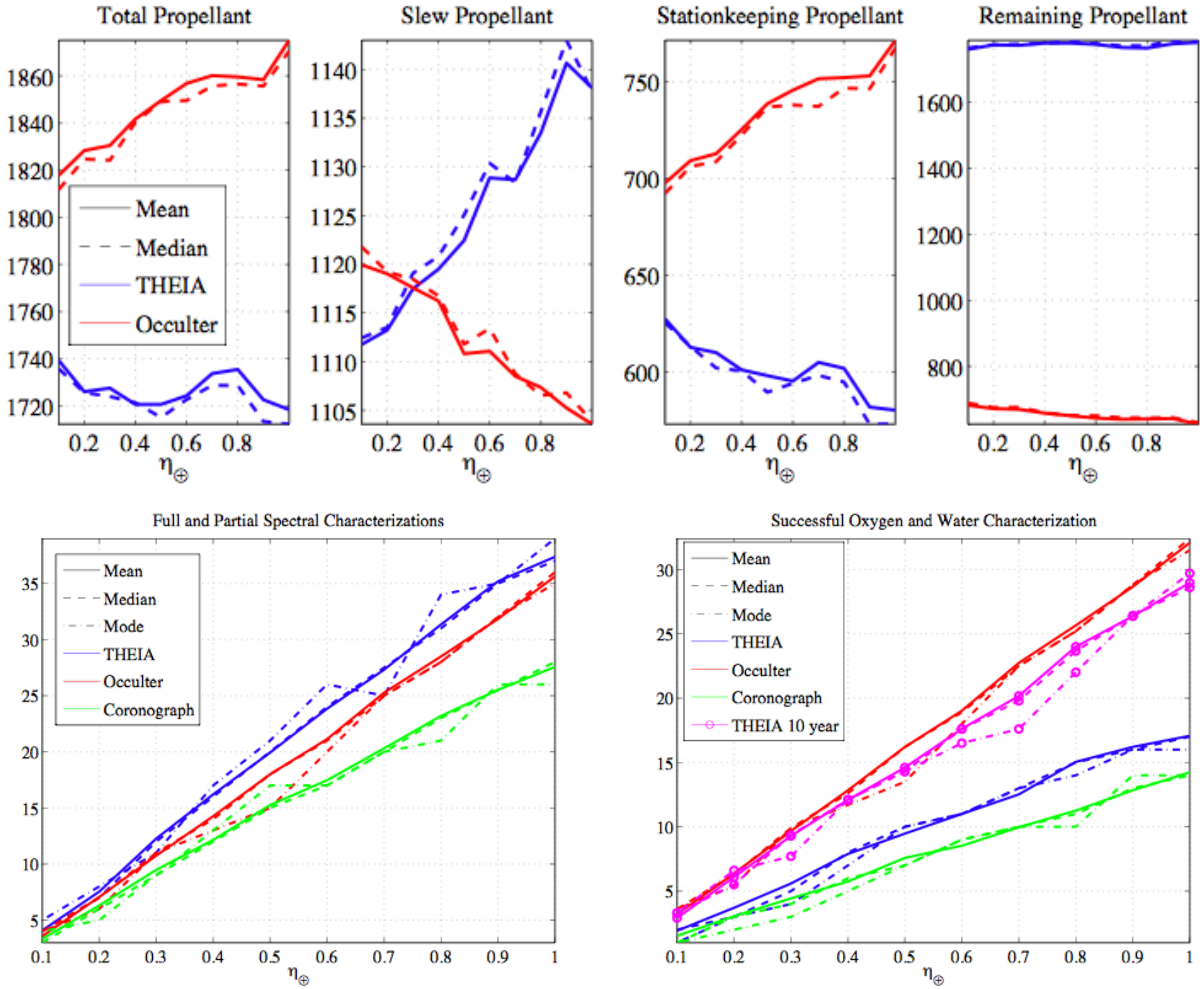
Design Reference Mission



(1) 2 λ/D coronagraph; (2) a single distance 52 m occulter; (3) baseline THEIA design and (4) an extended mission.

Limitations of Single-Distance Occulter:

- Fuel exhausted after 5 years (no extended mission and limited revisits for orbit determination)
- Longer petals (complicates packaging)
- Tighter tolerances


Total Propellant
Slew Propellant
Stationkeeping Propellant
Remaining Propellant
Mean
Median
THEIA
Occulter
η⊕
Full and Partial Spectral Characterizations
Successful Oxygen and Water Characterization
Mode
Coronograph
THEIA 10 year

3 Technology Tall Poles

- (1) building and deploying the occulter to demanding tolerances;
- (2) building a 4-meter telescope diffraction-limited at 300 nm
- (3) building large focal plane arrays (SFC).

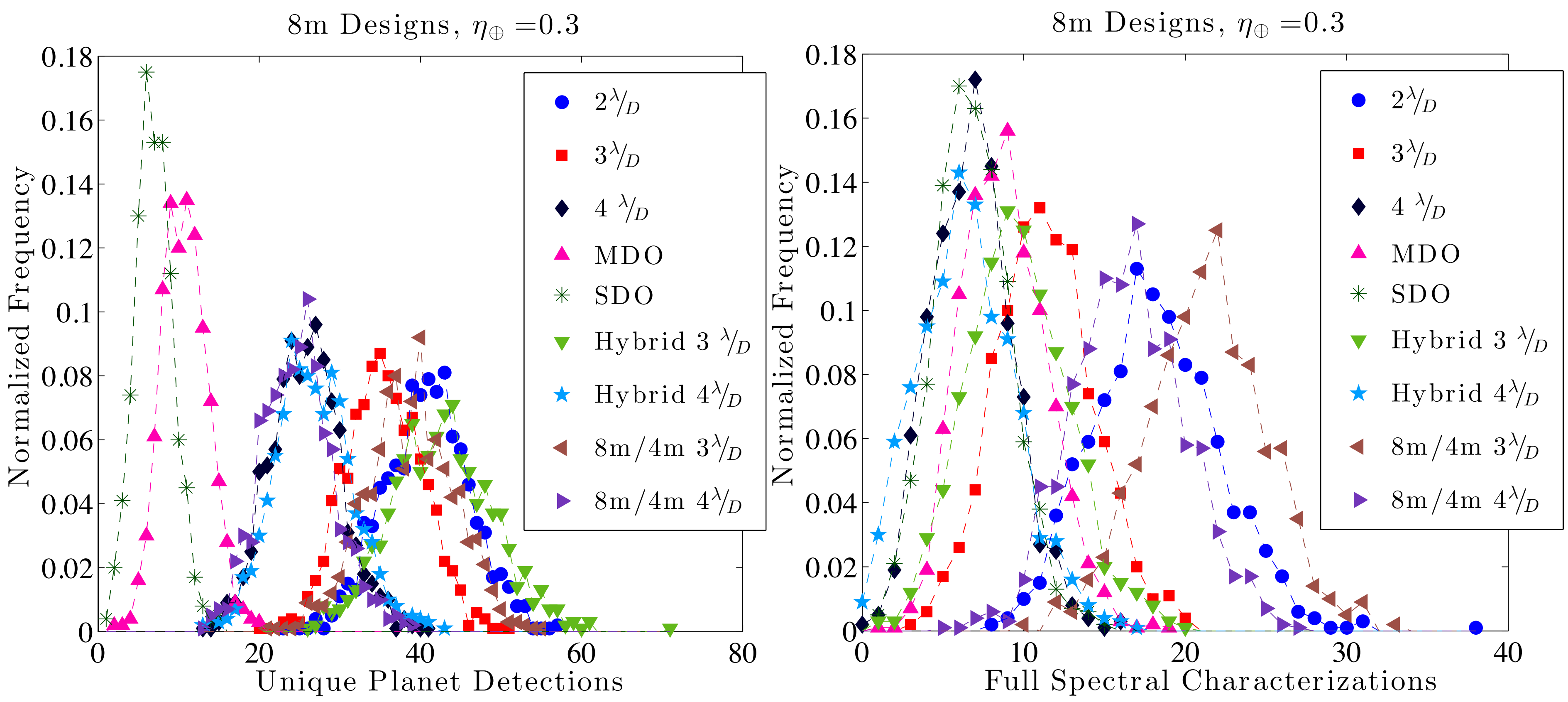
Some Conclusions

- 2 λ/D Coronagraph, Occulter, and THEIA get essentially the same science
- Increasing coronagraph telescope diameter to 6 m would get all characterization
- Choice of design almost entirely based on technology readiness and cost

The occulter/spacecraft adds roughly $750 M to cost of THEIA. Is that less than delta-cost for making an internal coronagraph meet requirements?

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

A Hybrid Design that Does Work (from my 2012 talk to the ExoPAG):



Plots courtesy of Dmitry Savransky

These sorts of full mission simulations are still in their infancy, but there is a growing number of approaches (Savransky 2010, Stark 2014, Stark 2015, Turnbull 2012).

Further work is critical for successful future mission design and technology decisions.

The THEIA Team

Paul Atcheson, Matt Beasley, Rus Belikov, Morley Blouke, Eric Cady, Daniela Calzetti, Craig Copi, Steve Desch, Phil Dumont, Dennis Ebbets, Rob Egerman, Alex Fullerton, Jay Gallagher, Jim Green, Olivier Guyon, Sally Heap, Rolf Jansen, Ed Jenkins, Jim Kasting, Ritva Keski-Kuha, Marc Kuchner, Roger Lee, Don J. Lindler, Roger Linfield, Doug Lisman, Rick Lyon, John MacKenty, Sangeeta Malhotra, Mark McCaughrean, Gary Mathews, Matt Mountain, Shouleh Nikzad, Bob O'Connell,William Oegerle, Sally Oey, Debbie Padgett, Behzad A Parvin, Xavier Prochaska, James Rhoads, Aki Roberge, Babak Saif, Dmitry Savransky, Paul Scowen, Sara Seager, Bernie Seery, Kenneth Sembach, Stuart Shaklan, Mike Shull, Oswald Siegmund, Nathan Smith, Remi Soummer, David Spergel (PI), Phil Stahl, Glenn Starkman, Daniel K Stern, Domenick Tenerelli, Wesley A. Traub, John Trauger, Jason Tumlinson, Ed Turner, Bob Vanderbei, Roger Windhorst, Bruce Woodgate, Bob Woodruff

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

NASA Partners: Jet Propulsion Laboratory/Caltech, Goddard Space Flight Center, Ames Research Center, Marshall Space Flight Center

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