



Exoplanet Direct Imaging: Coronagraph Probe Mission Study “EXO-C”

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For the EXO-C STDT and Design Team

Context for Study

- Flagship mission for spectroscopy of ExoEarths is a long-term priority for space astrophysics (Astro2010).
- Requires 10^{-10} contrast at $3 \lambda/D$ separation, (>10,000 times beyond HST performance) and large telescope > 4m aperture. Big step.
- Mission for spectroscopy of giant planets and imaging of disks requires 10^{-9} contrast at $3 \lambda/D$ (already demonstrated in lab) and ~ 1.5 m telescope. Should be much more affordable, good intermediate step.
- Various PIs have proposed many versions of the latter mission 17 times since 1999; no unified approach.

NASA HQ Astrophysics Implementation Plan

- New strategic mission expected to start in FY 17. It will be AFTA/WFIRST if budget allows. If not, need less expensive “probe” mission options as backups. Three to choose from: WFIRST, and 2 exoplanet.
- Probe mission terms:
 - cost ~ \$1B
 - technical readiness (TRL 5) by 2017
 - Launch in 2024
- EXO-C is an 18 month HQ-funded study of an internal coronagraph probe mission
 - Science & Technology Definition Team (STDT) selected May 2013. Previous competitors now working together.
 - Engineering Design Team in place at Jet Propulsion Laboratory, July 2013
 - Interim report for March 2014, Final report due January 2015

EXO-C Key People

Science and Technology Definition Team

Karl Stapelfeldt (Chair)
Rus Belikov (NASA/Ames)
Geoff Bryden (JPL/Caltech)
Kerri Cahoy (MIT)
Supriya Chakrabarti (UMass Lowell)
Mark Marley (NASA/Ames)
Michael McElwain (NASA/GSFC)
Vikki Meadows (U. Wash)
Gene Serabyn (JPL/Caltech)
John Trauger (JPL/Caltech)

JPL Engineering Design Team

Keith Warfield	Michael Brenner
Paul Brugarolas	John Krist
Frank Dekens	Jared Lang
Serge Dubovitsky	Joel Nissen
Bobby Effinger	Jeff Oseas
Brian Hirsch	Eric Sunada
Andy Kissil	

ExEP Office

Gary Blackwood	Wes Traub
Peter Lawson	Steve Unwin

Approach to the Study

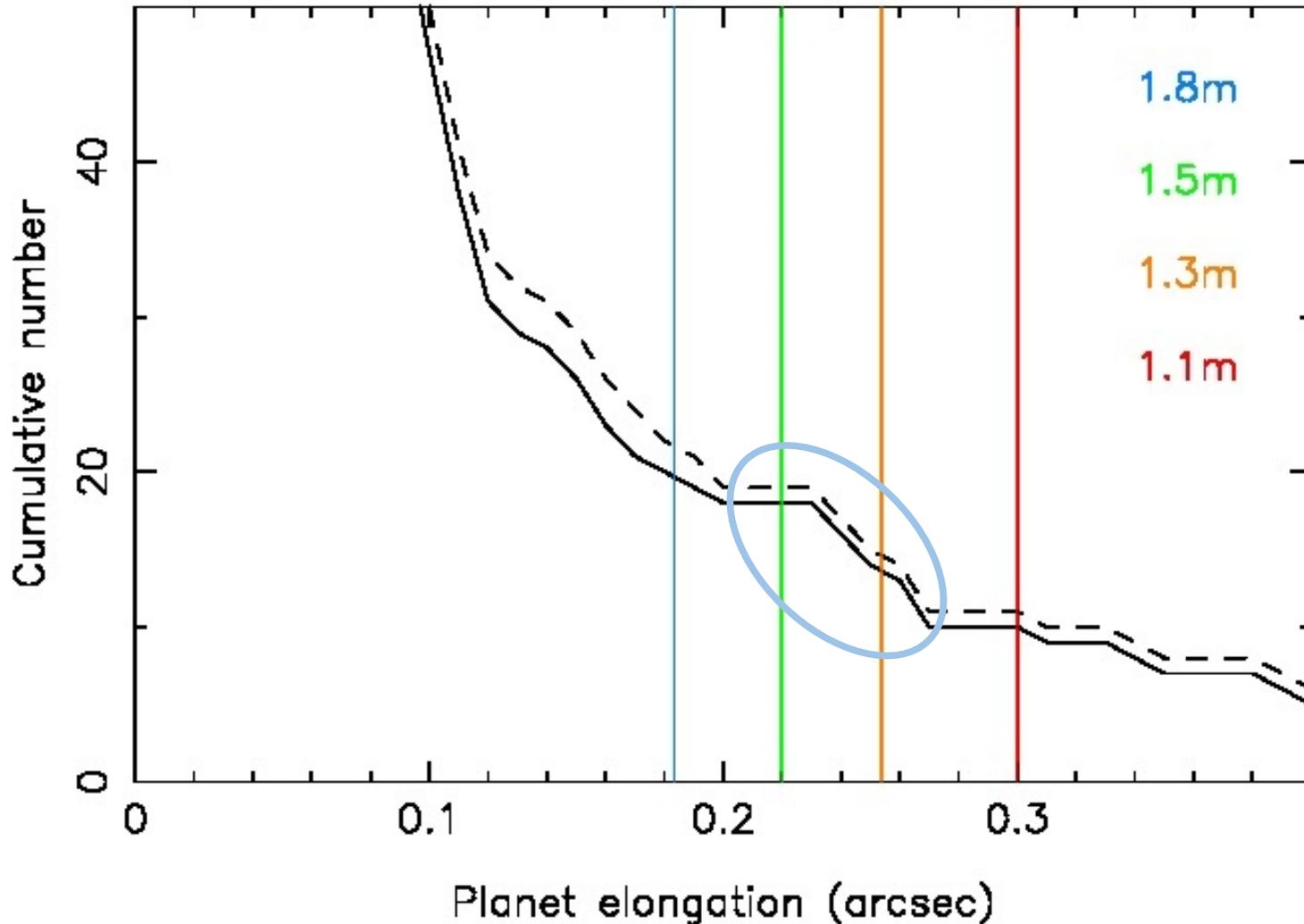
- Build on previous work (ACCESS, PECO, ...)
- Begin with science goals and trade studies of system-level issues: telescope design, orbit selection, pointing control, wavefront stability and control, cost
- Evaluate coronagraph options in the context of achievable system performance
- Engage Aerospace Corp. early in the study for cost feedback
- Innovate

Science Goals

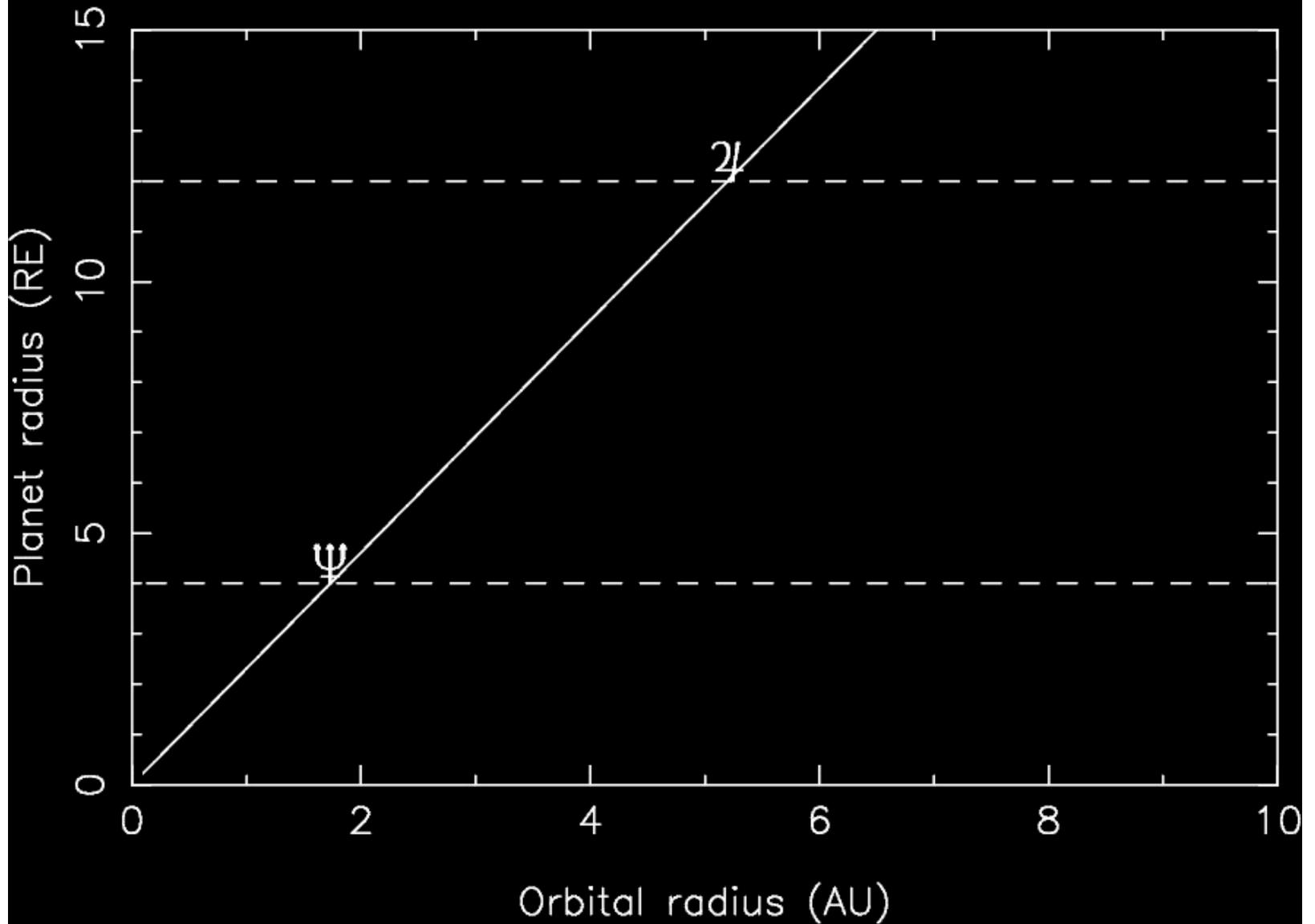
- Obtain optical spectra of the nearest RV planets: measure CH₄, H₂O, Rayleigh scat. Fix orbit inclination → planet mass.
- Search for planets beyond RV limits (Neptunes, super-Earths) in a TBD nearby star sample. Measure their orbits, carry out follow-on spectroscopy of the brightest ones
 - alpha Centauri system is a particularly important case
- Optical spectra of planets discovered by near-IR ground Adaptive Optics (AO)
- Image circumstellar disks beyond Hubble Space Telescope (HST), AO, and Atacama Large Millimeter/submillimeter Array (ALMA) limits:
 - Resolve disk structures: Size, extent, rings/gaps/asymmetries as evidence for planetary perturbations
 - Dust properties: diagnose via albedo, color, and phase function
 - Time evolution of the above from protoplanetary to debris disks
 - Assess dust content near HZ in maybe a dozen nearby sunlike stars

Accessible RV planets

Known RV planets vs. $2 \lambda/D$ @ $\lambda = 0.8 \mu\text{m}$

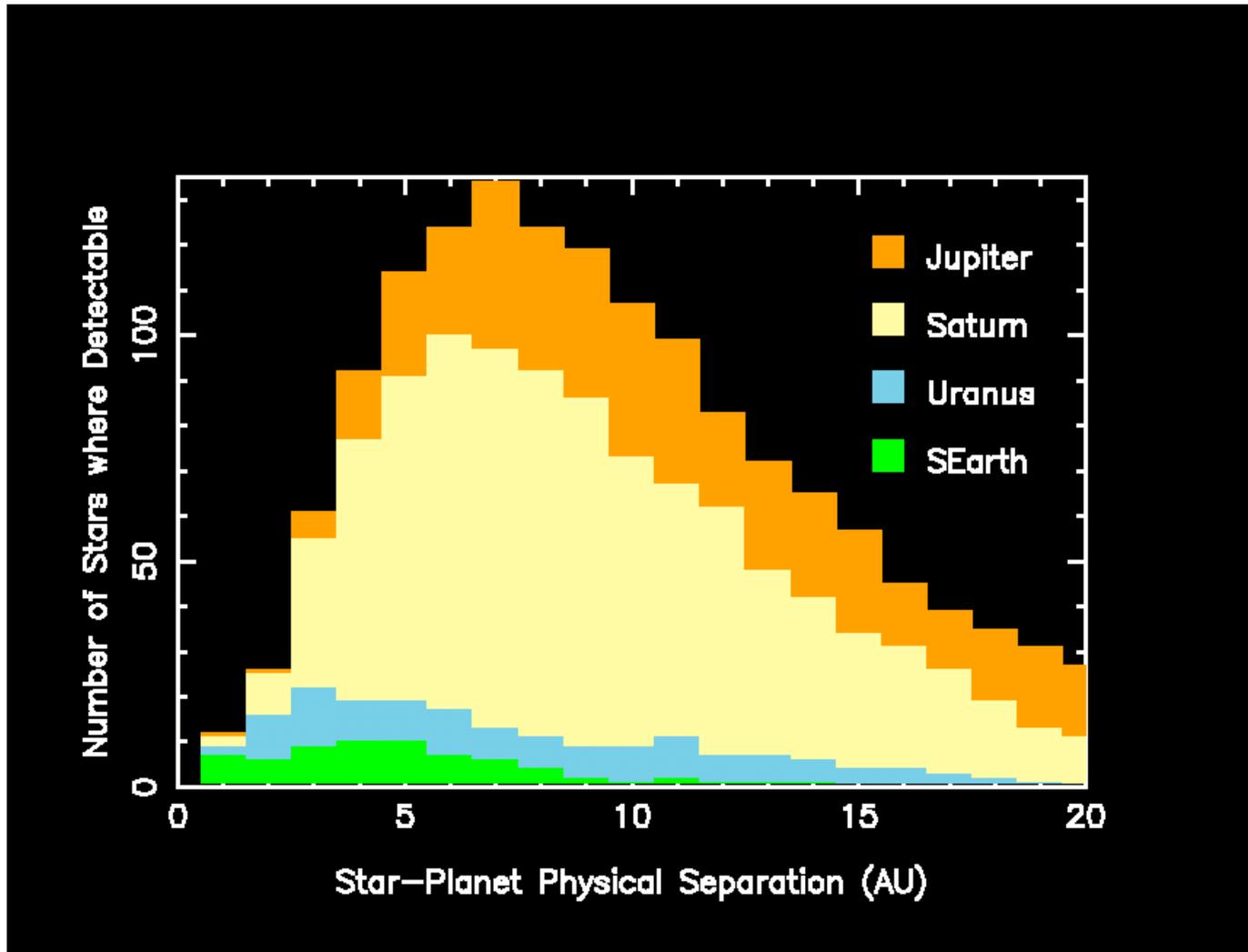


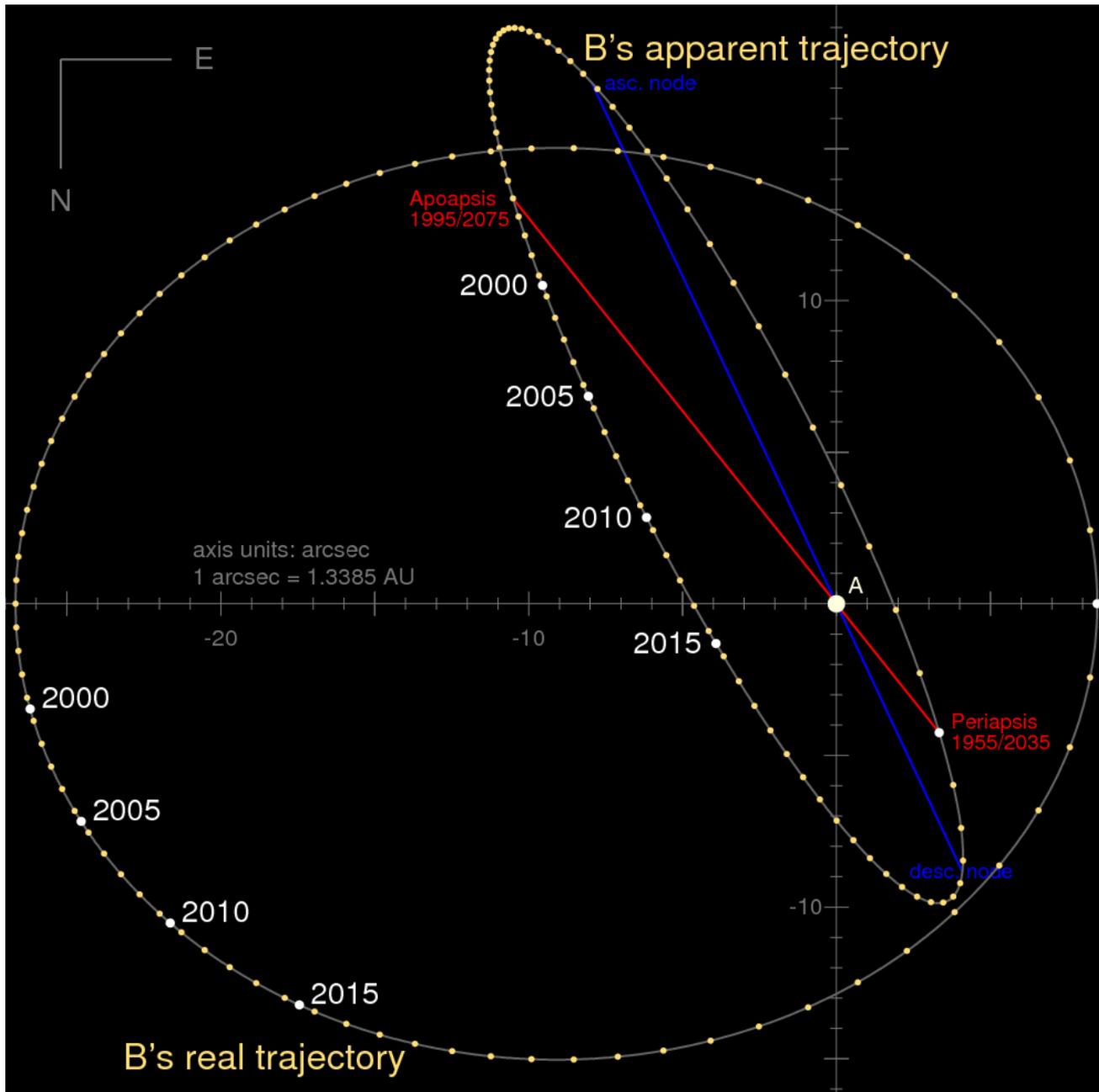
Planet size for $1e-09$ contrast at opposition



Planet detectability placeholder

from the Trauger et al. ACCESS study





alpha Cen orbit:

- 8.5" separation in 2025, growing to 10.5" a few years later
- Need coronagraph mask that covers both stars and can accommodate the variable separation

Current Working Science Requirements

Primary diameter	> 1.3	m
Uncontrolled speckle contrast	1e-09	raw
Stability over 48 hours	1e-10	
Bandwidth	450-1000	nm
IWA = $2 \lambda/D$	0.73	μrad (0.15 arcsec)
OWA = $24 \lambda/D$ @ 890 nm	14	μrad (2.8 arcsec)
Stray light from binary companion	1e-9	@ 8 arcsec separation
Spectral resolution $\lambda < 630$ nm	R > 25	
Spectral resolution $\lambda > 630$ nm	R > 50	
Astrometric precision	< 30	milli-arcsec
IFS FOV = $24 \lambda/D$ @ 890 nm	14	μrad (2.8 arcsec)
Mission Life	3	years

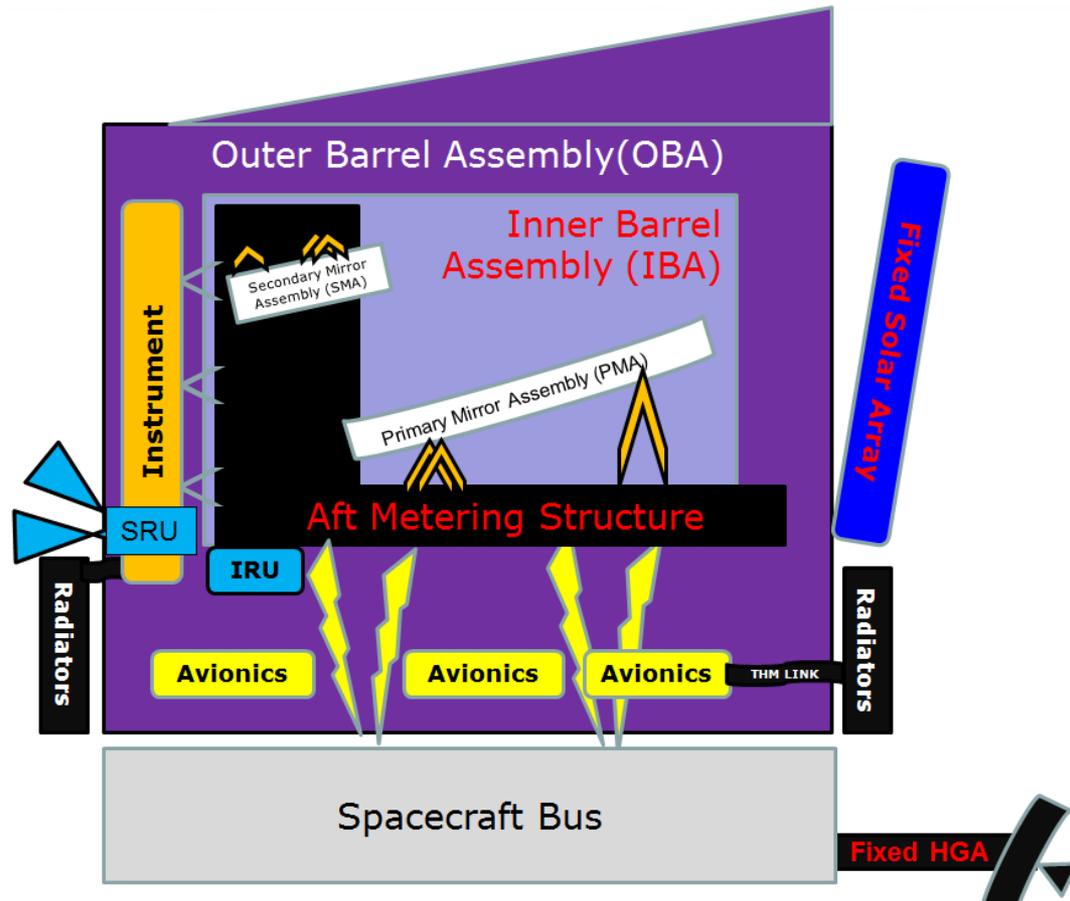
System Block Diagram

• Baseline Architecture:

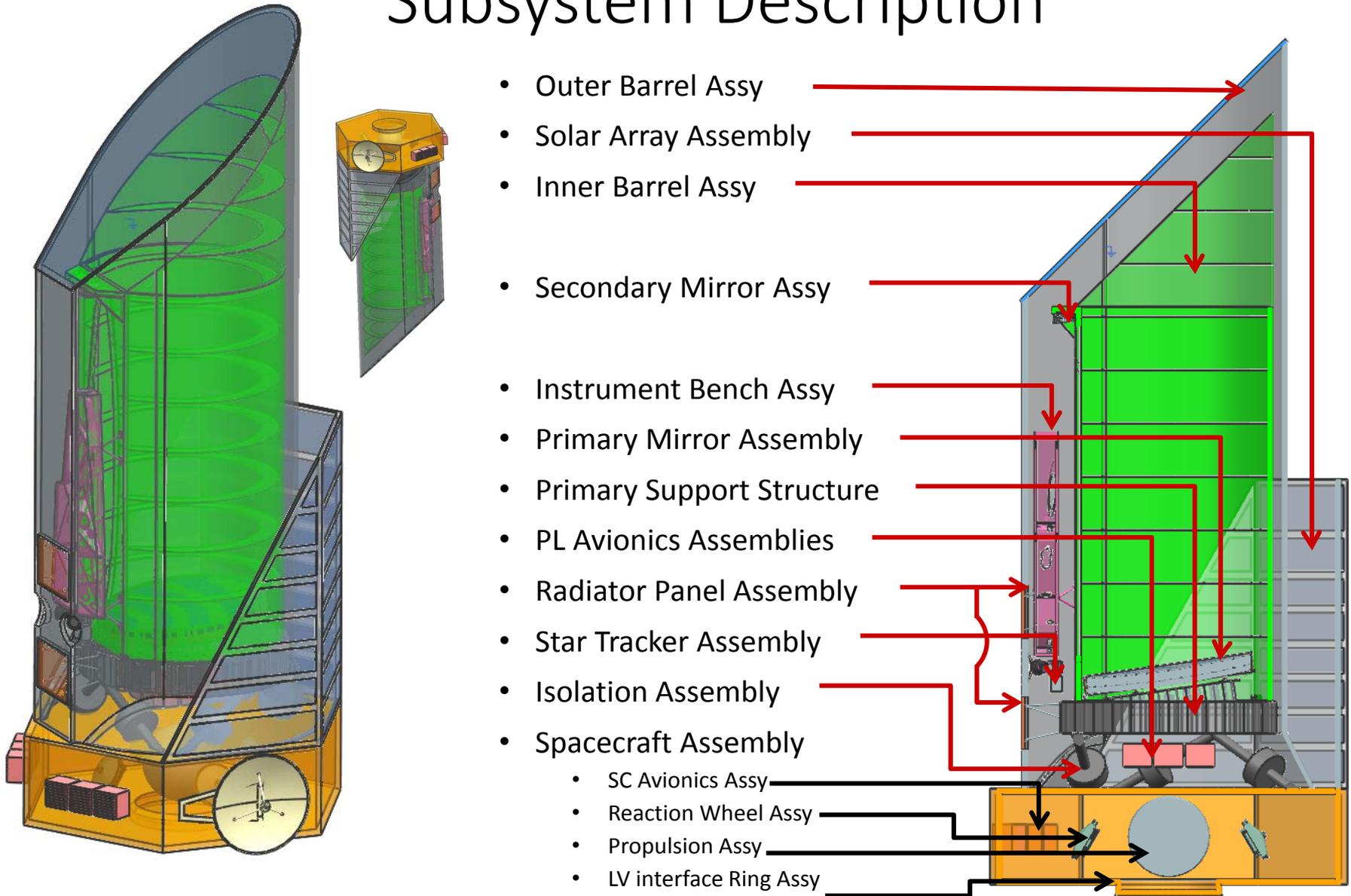
- **Trajectory: Drift away Earth Trailing Orbit**
- **Launch Vehicle: Falcon 9 or equivalent**
- **S/C Bus: Kepler Class**
- **Telescope: 1.5 m unobscured Cassegrain**
- **Instrument: Lateral Configuration**
 - Science: collects coronagraphic data
 - IFS: collects dispersed coronagraphic data
 - Fine guidance: tracks changes in centroid of star image (feeds-back to FSM mechanism)
 - Low-order wavefront: monitors changes in wavefront (feeds-back to DFMs)

• Key Parameters:

- **Launch date: 1/1/24 – 12/31/24**
- **Development Time: 60 Months**
- **Payload Mass:: 890 Kg**
- **ROM Cost: 925 M**

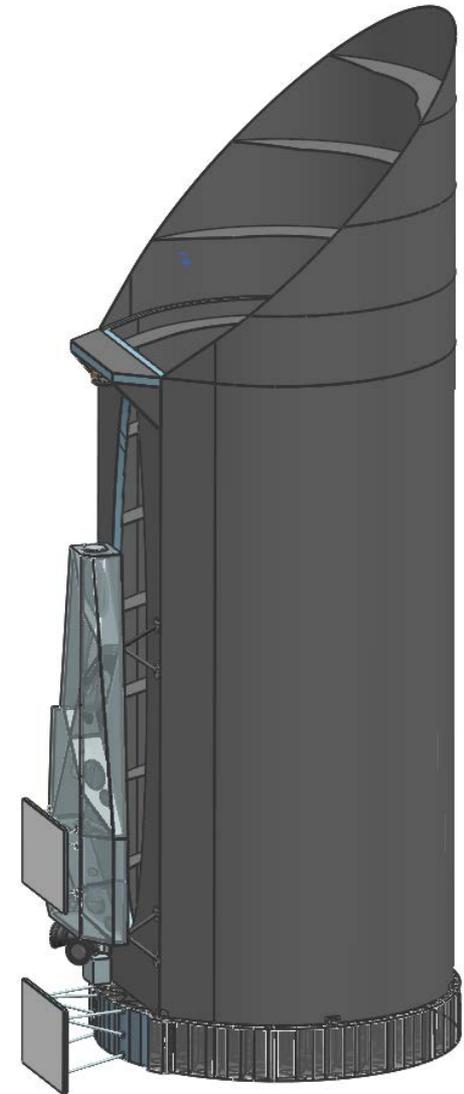
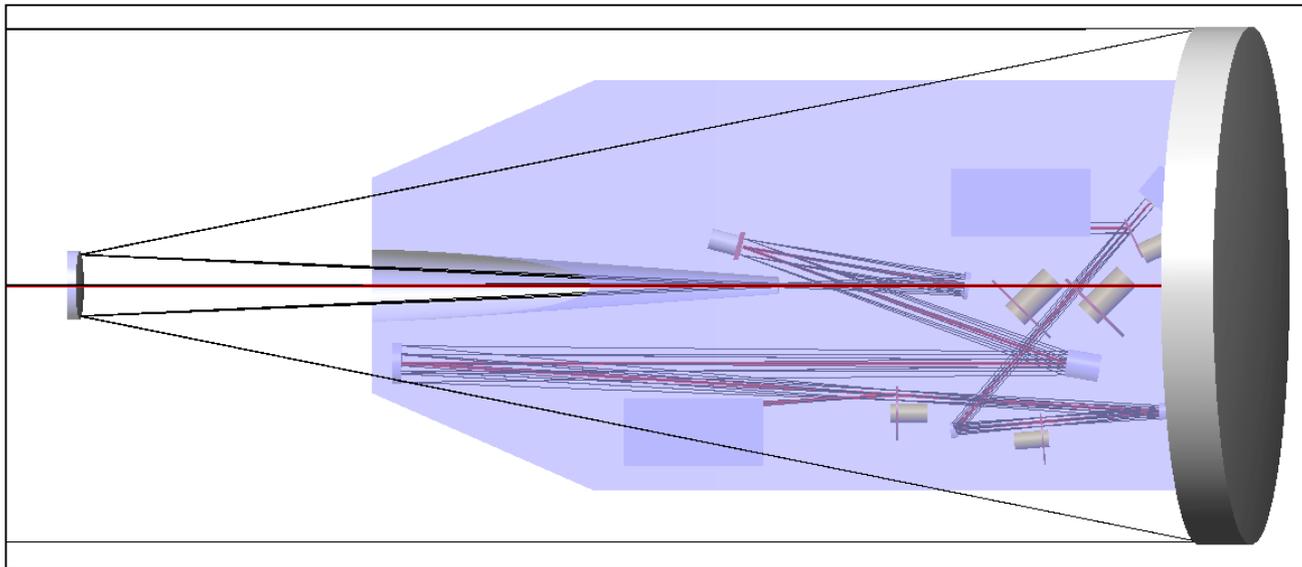


Subsystem Description



Instrument Layout

- Unobscured telescope form is baselined
- Cassegrain form baselined: Short Primary-Secondary spacing -> less mass
- Deformable Mirror (DM) is 48 mm
- Lateral Instrument Configuration along side Inner Barrel Assembly



Engineering Trades

- Unanimous decision for unobscured telescope
 - Better throughput, resolution, stiffness, coronagraph TRL. Slightly higher cost
- Telescope aperture of 1.3-1.5m appears to be affordable
- Decided on Earth-trailing orbit
 - Better thermal stability & sky visibility than EO. No propulsion needed. Acceptable data rates.
- Integral Field Spectrograph in addition to filter imaging
 - Simultaneous measurements over \sim 20% bandpass
 - Supports speckle rejection as well as planet spectra

Choosing a coronagraph

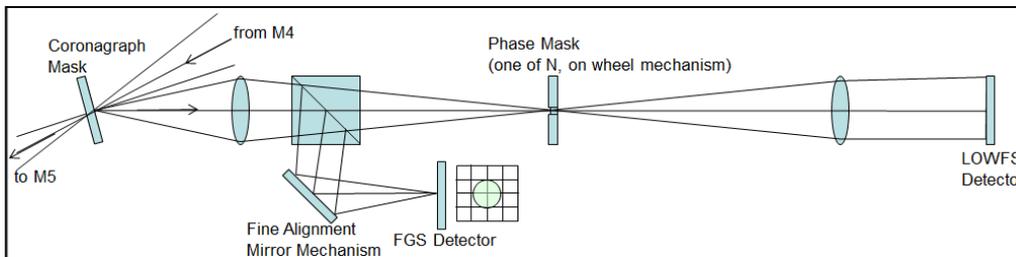
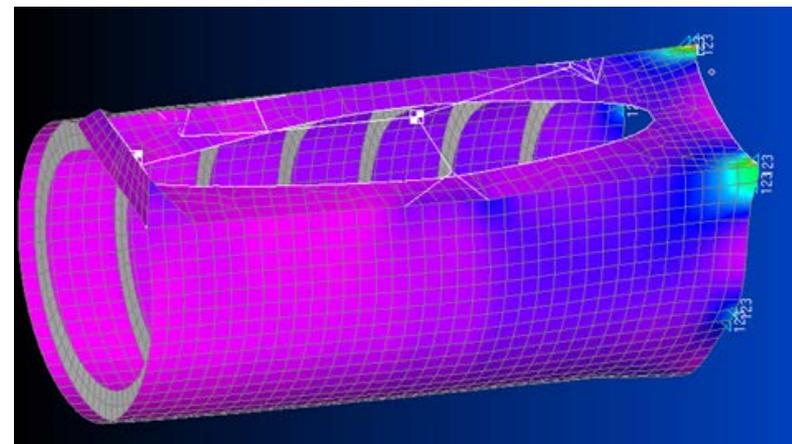
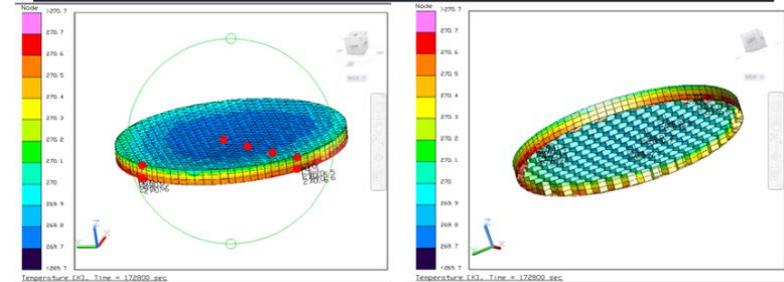
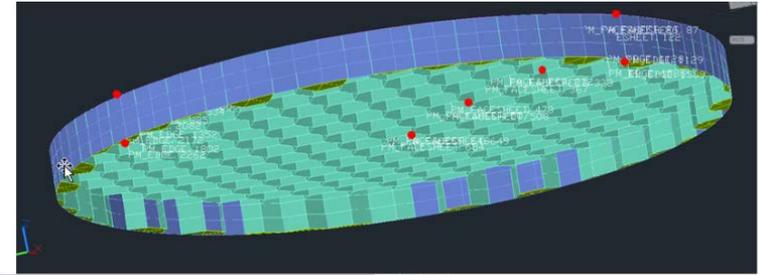
- Pre-requisite is having some understanding of likely pointing performance, thermal stability, and control authority over time-variable low order aberrations.
- Six concepts to be evaluated: hybrid Lyot, PIAA, shaped pupils, vector vortex, two visible nuller variants.
- Optical simulations flow to science yield estimates. Demonstrated lab performance will be highly weighted. Telescope pointing stability strongly affects science yield.
- EXO-C decision will be totally independent of AFTA choice

Thoughts on 3 year Design Reference Mission

Science Type 	Visits		Science Observation times		Non-observing time between observations		Total Mission Time	Calculated Observation efficiency of each Science Type
	number of targets	Ave number of visits	Average Integration time per visit	Total Observe time per Science Type	Total non-observe time per visit	Total non-observe time per Science Type		
	N_target	N_visit	t_I (hrs)	T_Obs (days)	T_NO= T_SC+T_T +T_IO hrs	(days)	(days)	
Spectroscopy of Known Cxoplanets (known from RV and exo-C survey)	30	1	100	125	8	10.0	135	93%
Planet discovery surveys								
Survey nearby stars for super-Earths within the habitable zone	20	6	20	100	8	40	140	71%
Search for giant planets around nearby stars	150	3	20	375	8	150	525	71%
Disk Imaging Surveys								
Detection survey in RV planet systems	200	1	12	100	3	25.0	125	80%
Known debris disks within 40 pc	80	1	6	20	3	10.0	30	67%
Young debris disks from WISE	120	1	6	30	3	15.0	45	67%
Nearby protoplanetary disks	80	1	6	20	3	10.0	30	67%
Total on-orbit ops time				770		260	1030	
Initial On-Orbit Checkout (days)							60	
Total (days)							1090	71%
Total (years)							3.0	

Current Work

- Coronagraph Trade in process
- Initial Thermal Performance Modeling
- Initial Structural Modeling for configuration and loads
- Pointing Requirements Generation
- Back end Instrument detailed optics layout for IFS, LOWS, FGS, and Science



General Astrophysics Capability

- High contrast science on post-main sequence stars, AGN/quasars, ...
- Imaging camera will have 1 arcmin FOV with small filter set; IFS will have $\sim 2.8''$ FOV.
- Camera and IFS can be used without coronagraphic spots
- Pointing performance for targets other than bright stars is still TBD. Support for moving targets doable but not in baseline cost.
- Not currently planning for UV capability (cost)
- A second instrument could be accommodated in terms of payload mass/volume, but not in terms of cost.

Conclusions

- EXO-C Study is well underway. We will show what an affordable, optimal, high TRL exoplanet imaging mission can do.
- We are eager to get our first Structural-Thermal-Optical models to assess telescope stability
- Capability to search alpha Cen system may be key to selling the mission
- Please see me here, or send me your suggestions for things we should look into or how you'd like to help: karl.r.stapelfeldt@nasa.gov.