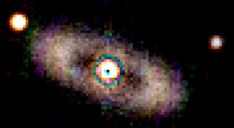
Exo-C Extended Study

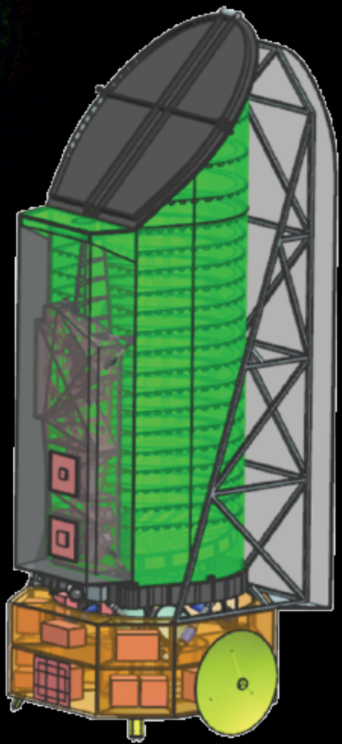
Final Report

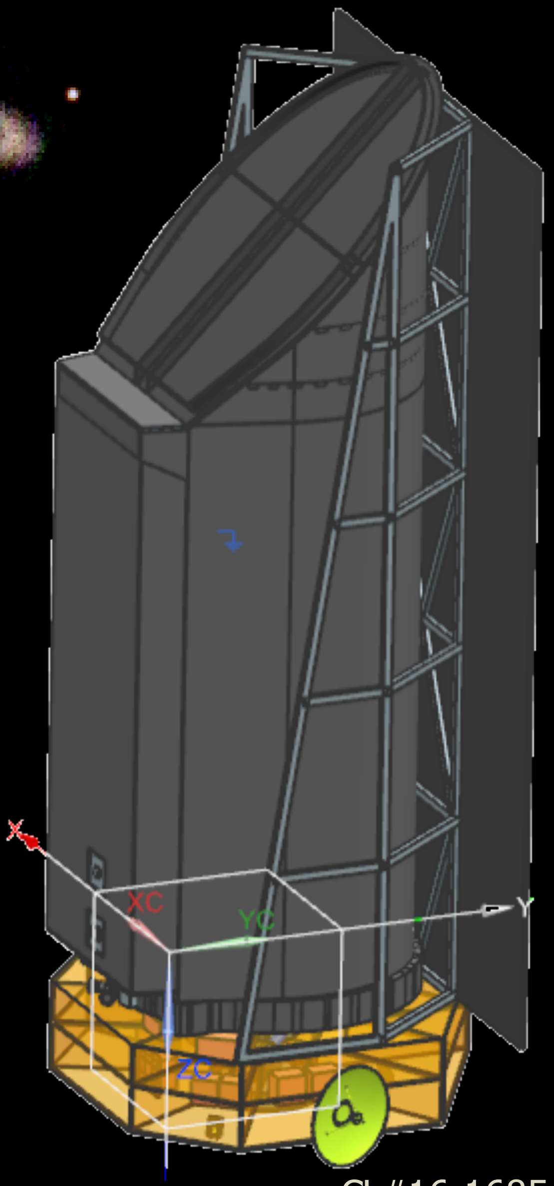
April 12, 2016
http://exep.jpl.nasa.gov/stdt/exoc/

Science & Technology Definition Team:
Kerri Cahoy (MIT/Chair), Ruslan Belikov & Mark Marley (NASA/Ames), Geoffrey Bryden, Eugene Serabyn, & John Trauger (JPL/Caltech), Supriya Chakrabarti (UMass Lowell), Karl Stapelfeldt & Michael McElwain (NASA/GSFC), Victoria Meadows (U of Washington)

JPL Engineering Design Team:
Keith Warfield (lead), Paul Brugarolas, Robert Effinger, Brian Hirsch, Andrew Kissil, John Krist, Joel Nissen, Jeffrey Oseas, Christopher Pong, Kevin Tan







Comparison of 1.4-m Exo-C with 2.4-m Exo-C ES

Drawings, K. Tan and K. Warfield for Exo-C (left) and Exo-C ES (right) [15]. Altair 12 hour composite V, R, I band simulation detecting a Jupiter and Saturn, K. Stapelfeldt for Exo-C, Exo-C ES

CL#16-1685

The Teams

Science & Technology Definition Team:

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

JPL Engineering Design Team:

Keith Warfield (lead), Paul Brugarolas, Bobby Effinger, Brian Hirsch, Andy Kissil, John Krist, Joel Nissen, Jeff Oseas, Chris Pong, Kevin Tan

NASA Exoplanet Program Office:

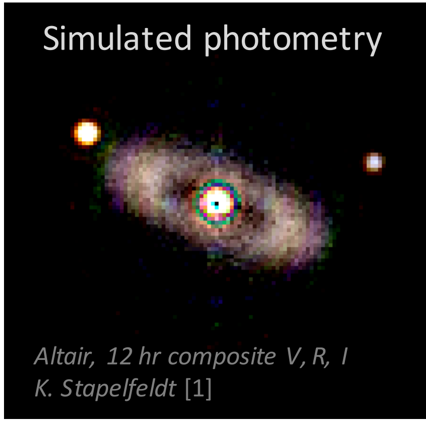
Keith Warfield, Gary Blackwood

Presentation Overview

1. Introduction – *K. Cahoy*
2. Science Goals and Requirements – *K. Cahoy*
3. Design Reference Mission – *K. Cahoy*
4. Baseline Mission Design – *K. Warfield*
5. Technology Development – *K. Warfield*
6. Cost Estimation – *K. Warfield*
1. Summary – *K. Cahoy*

Executive Summary

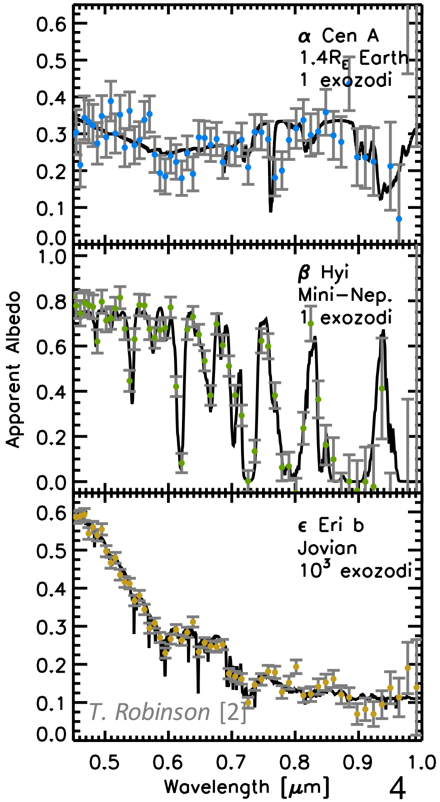
- Exo-C ES captures the science capability of a 2.4-m aperture space telescope designed specifically for exoplanet direct imaging. This report also:
- Summarizes significant technology developments in the past year,
  - Coronagraph contrast improvement, wavefront control and spectrograph technology maturation
- Highlights technology development needs,
  - 4k x 4k radiation-tolerant EMCCD detectors
  - 96 x 96 actuator deformable mirrors
  - Refinement and validation of contrast stability models to 10^{-11}
- And considers possible secondary payloads.
  - NIR coronagraph, Transit Spectrometer, NIRSpec "Lite"



Simulated photometry

Altair, 12 hr composite V, R, I
K. Stapelfeldt [1]

Simulated spectra



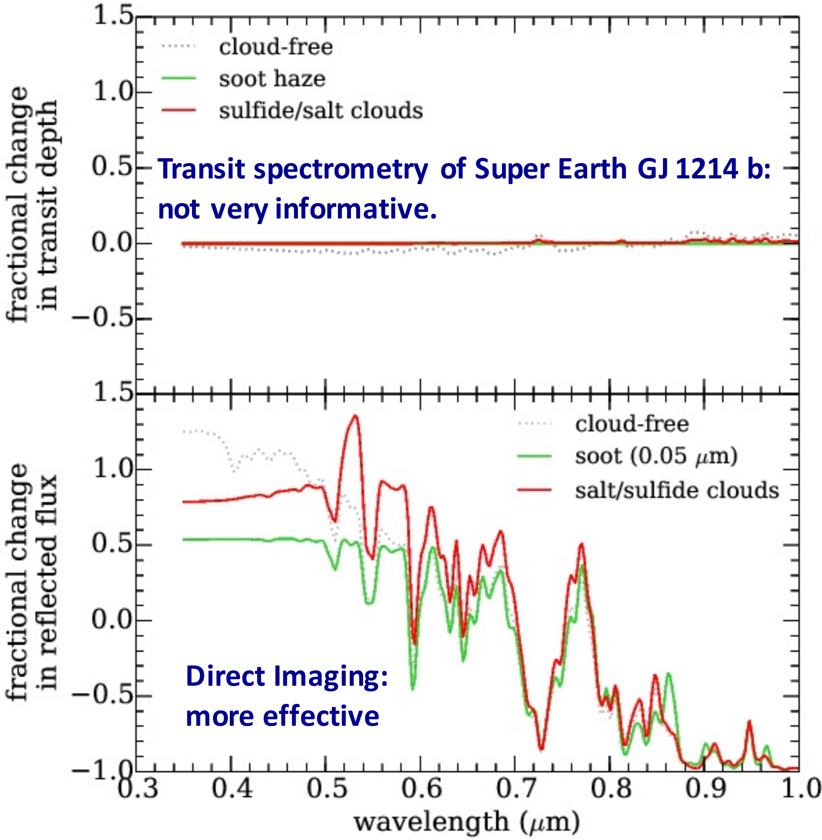
T. Robinson [2]

Study Charter

- Explore a 2.4 m telescope mission implementation based on the Exo-C design, utilizing an internal coronagraph, with a start between 2025 and 2030
- Describe science goals and performance requirements
- Describe mission concept, driving requirements
- Provide updated Design Reference Mission
- Update Probe-study assessment of technology development progress to date, and identify any new needs for this concept
- Estimate cost
- Deliver final briefing

Why a dedicated coronagraph mission?

- Radial velocity (RV) and transit surveys show exoplanets are <u>abundant</u>
- What are they like? Habitable?
  - Need spectral characterization
- Habitable zones (HZ) are further from star than transit observations currently reach
- Cooler Earth-like planets have small atmospheric scale heights
  - “Cold traps” affect vertical H2O distribution
  - Hard to probe with transit method
    - Transit spectra probe upper atmosphere
    - Need reflected photons from deeper in atmosphere



Transit spectrometry of Super Earth GJ 1214 b: not very informative.

Direct Imaging: more effective

GJ 1214b model spectra by C. Morley and M. Marley [3]

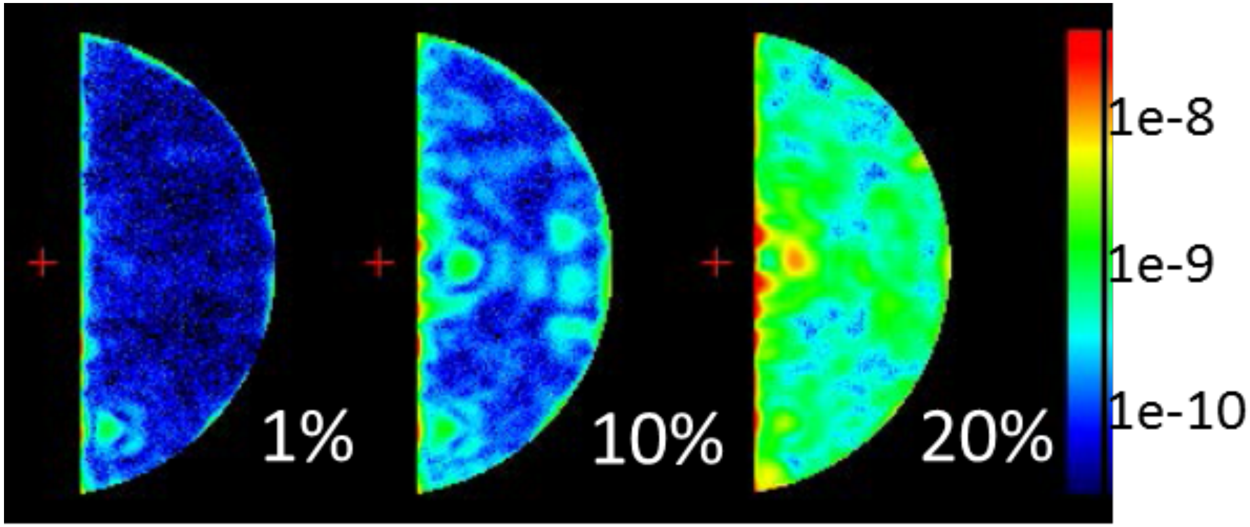
e.g., recent *Nature* and *the Atlantic* articles on challenges of transit observations with Hubble [19]

Direct imaging can capture Earth-like atmospheric properties
An ES science goal: measure H2O in the tropospheres of Super-Earths

Internal coronagraph technology maturity

- Development and laboratory contrast demonstrations on unobscured pupils have been ongoing for 10+ years, supported by TPF, SAT/TDEM
- Already demonstrated 10^{-9} visible contrast with 20% bandwidth at an inner working angle (IWA) of 3 /D [4, 5]
- Technology developments toward meeting mission requirements continue to show progress [17].

<u>Unobscured</u> coronagraph technology needs ongoing support and testbed access



Hybrid Lyot coronagraph, lab measurements of contrast with bandwidth

Progress since this demo:
- 2 DMs used for full dark hole
- Mask rebuilt to exceed performance, **but HCIT time needed to demonstrate it**

J. Trauger et al. [4], [5]

Benefits of 2.4-m Exo-C ES

- Exo-C ES captures the capability between a 1.4 m Exo-C and larger > 4 m aperture mission
  - Design focus is to optimize exoplanet science
  - Agility of internal coronagraph mission allows a large number of targets to be observed at multiple times

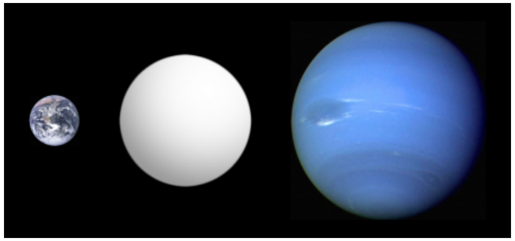


Illustration of Super-Earth COROT-7b (center) with Earth and Neptune [8]

- Benefits of a 2.4 m unobscured aperture dedicated mission:
  - Higher imager throughput (about 4 times better than obscured*)
  - Higher contrast at IWA and over wider bandwidths (improvement compared with ground or obscured aperture)
  - Longer integration times (compared with ground)
  - Simultaneously measure both polarizations
  - Dedicated mission time

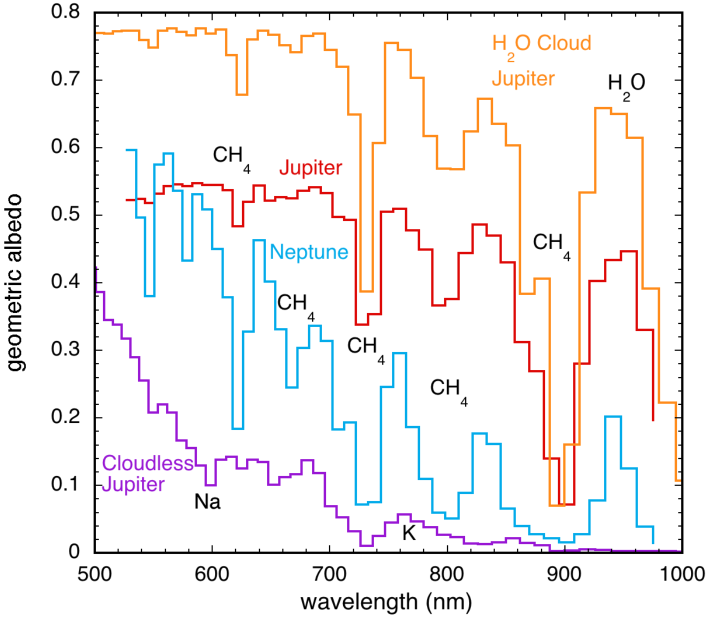
Benefits: Higher throughput, contrast, and bandwidth for many RV and new targets, multiple visits and revisits, dedicated integration time and mission time

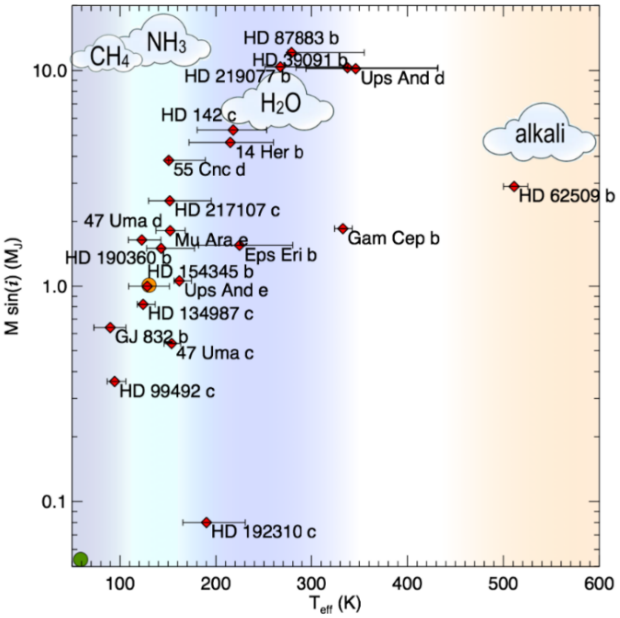
**See Appendix A for throughput details.*

2. Science Goals and Requirements

Science Goal: Study RV planets

- Optical spectra to detect gas absorbers like CH_4 and H_2O, Rayleigh scattering, constrain abundances, and constrain depth of cloud deck
- Measure photometric phase curves to constrain cloud heights and thus atmospheric abundances, identify haze, and search for ocean reflection signatures
- Astrometry to get orbit inclination and obtain planet mass without $\sin i$ ambiguity
- Image circumstellar disks, resolve structures, dust properties, look for rings, gaps, and asymmetries as evidence for planetary perturbations.





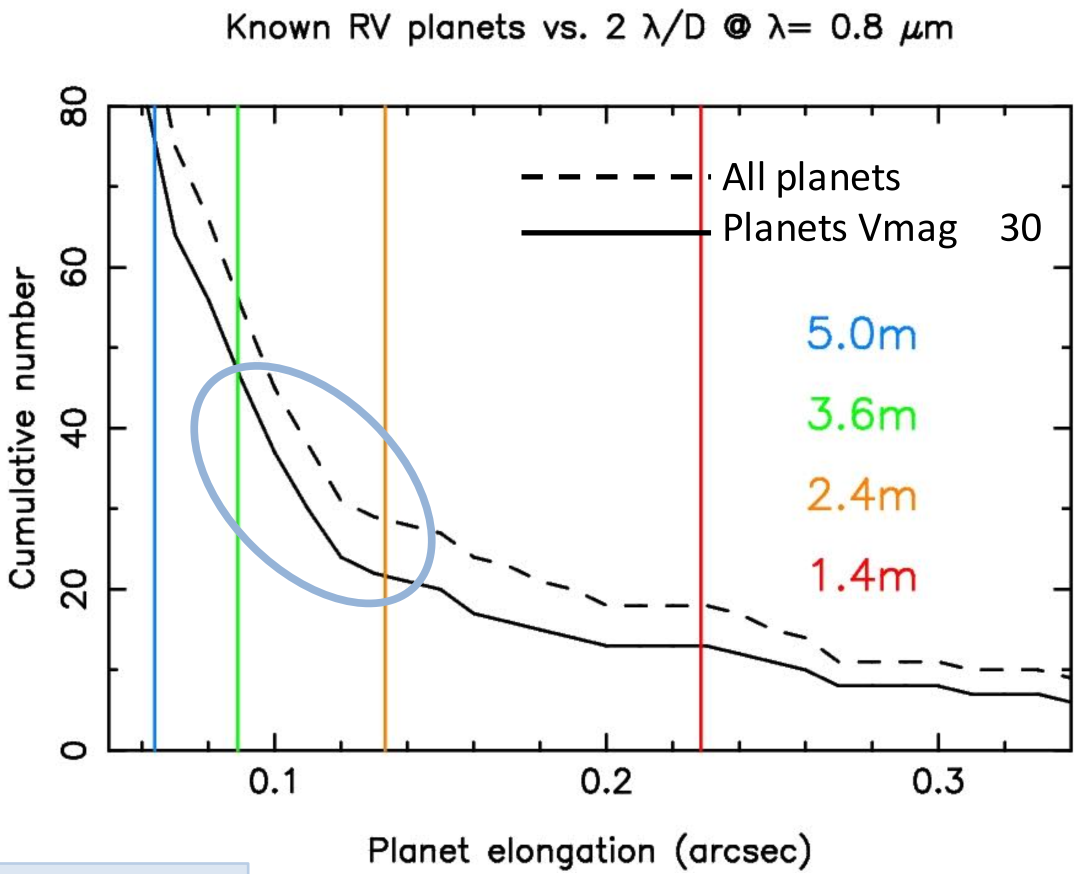
Left: simulated R=70 spectra showing clearly detectable absorption features for gas and ice giant planets.

Right: RV planets with possible cloud decks.

Both figures Marley et al. 2015 (ExEP study) [6]

Accessible RV Planets vs. Aperture Size

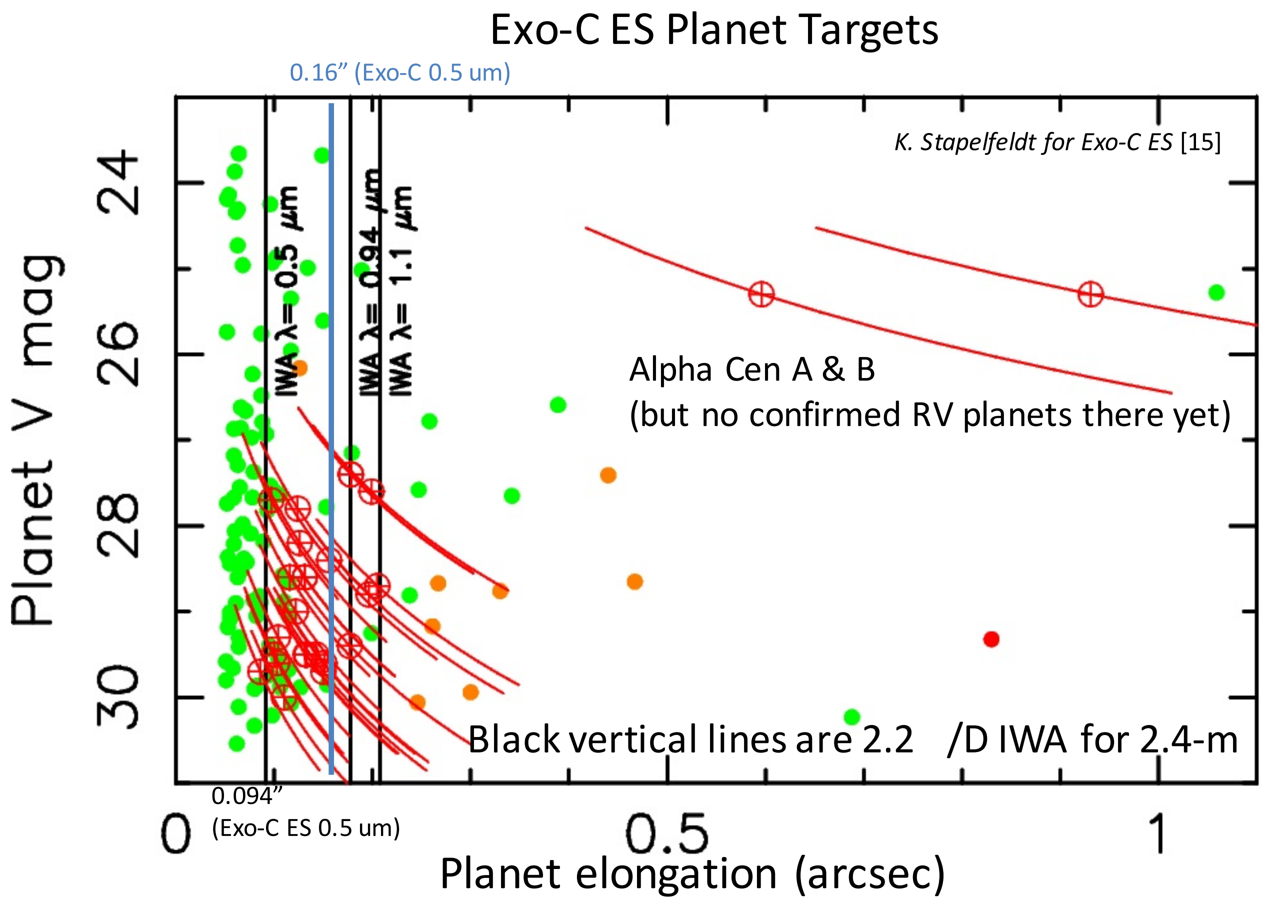
- Elongation is planet semi-major axis divided by distance from telescope to star
- Vertical lines show 2 /D Inner Working Angle (IWA) at 800 nm for different telescope aperture diameters



K. Stapelfeldt for Exo-C ES [7]

Science yield improves at a higher rate with aperture ≥ 2 m

Earths and RV planets with Exo-C ES



Alpha Cen A & B
(but no confirmed RV planets there yet)

Black vertical lines are 2.2 /D IWA for 2.4-m

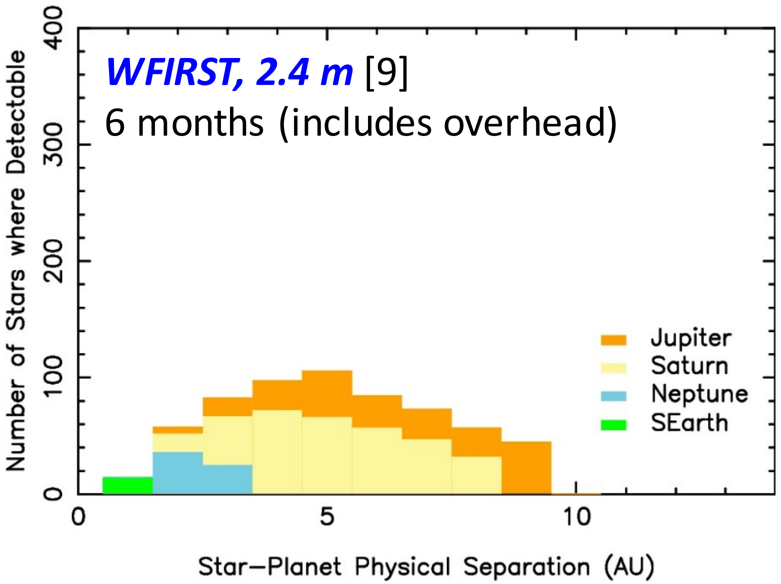
- RV planet with contrast 10^{-9}
- RV planet with contrast < 10^{-9}

Hypothetical Earth analog if found in nearby star HZ, curves show 0.7 AU to 1.7 AU around a G2 star

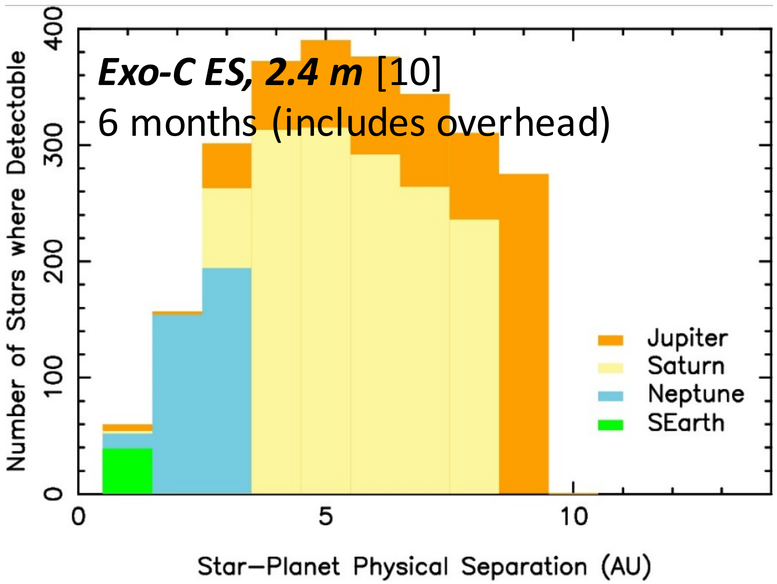
# HZs for Earths	Exo-C	Exo-C ES
0.50 m	7	**25**
0.94 m	2	**6**
1.10 m	2	**2**

At short wavelengths, Exo-C ES can search 3 times as many HZs for Earth analogs as Exo-C

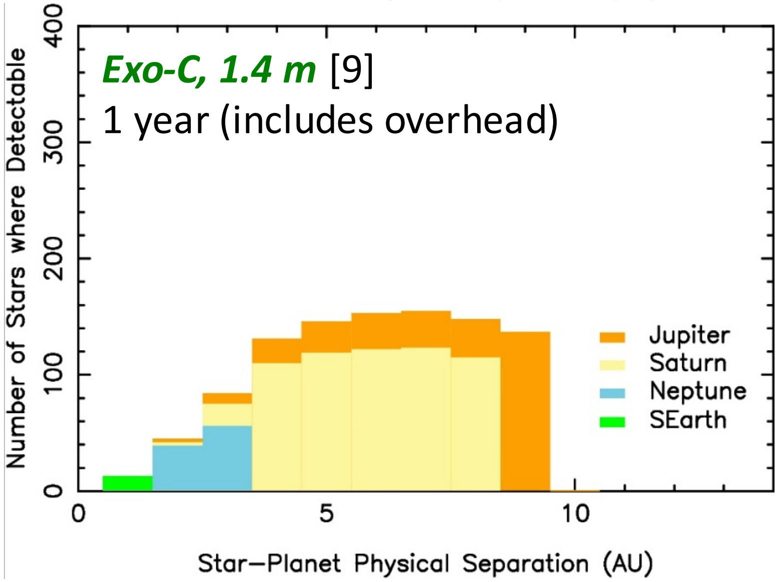
Exo-C ES increases search yield



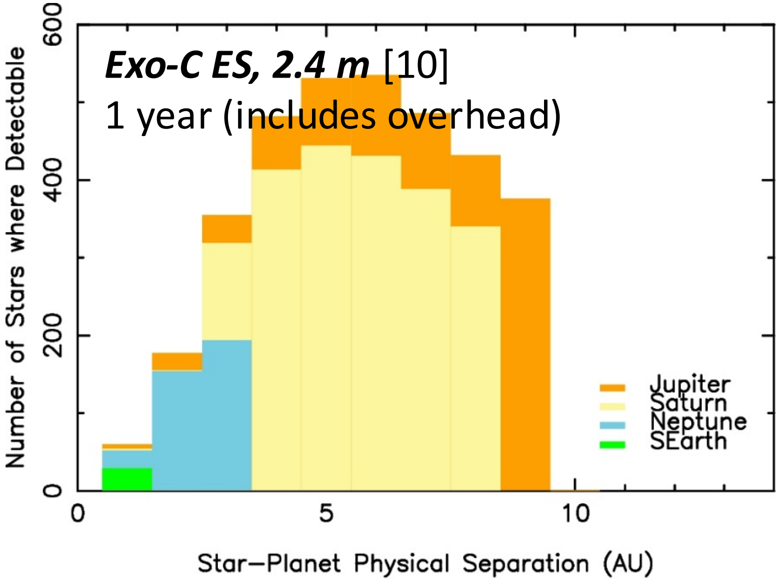
WFIRST, 2.4 m [9]
6 months (includes overhead)



Exo-C ES, 2.4 m [10]
6 months (includes overhead)



Exo-C, 1.4 m [9]
1 year (includes overhead)



Exo-C ES, 2.4 m [10]
1 year (includes overhead)

K. Stapelfeldt for Exo-C, ES [9,10]

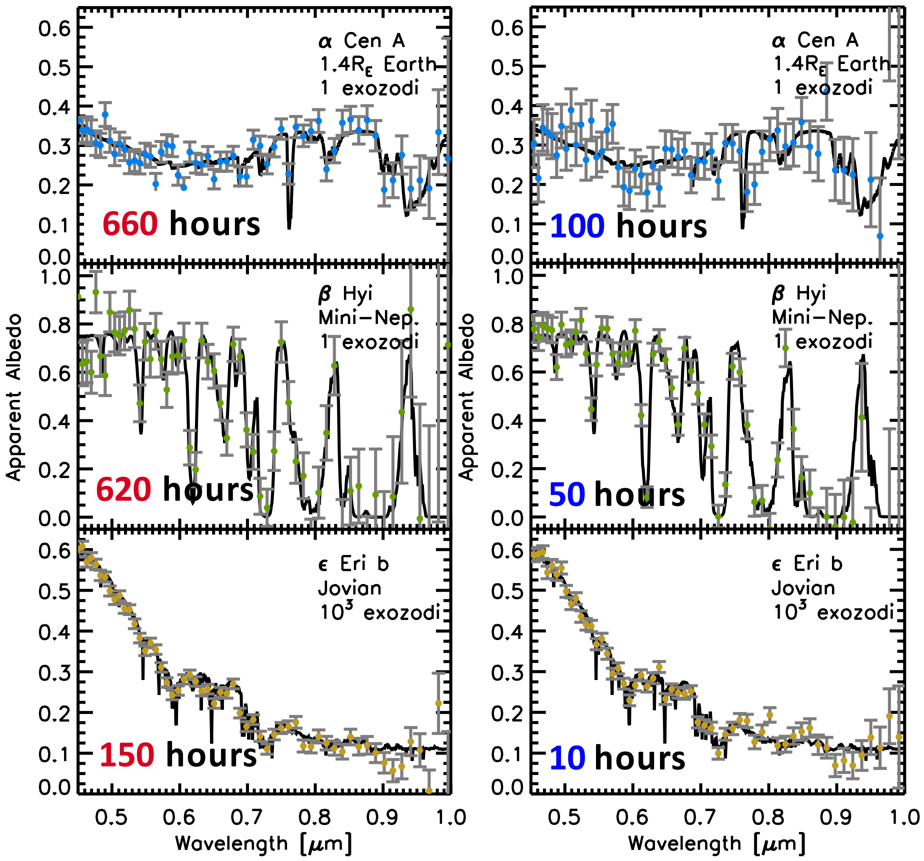
Exoplanet spectroscopy requirements

The benefit of the 2.4-m throughput is in yield and spectral quality, which can significantly reduce error bars and integration times

- WFIRST can spectrally characterize ~7 RV planets over mission [18]
- Exo-C ES can spectrally characterize 13-17 RV planets in 6 months (including overhead)
- Exo-C ES can spectrally characterize an additional **~45** planets in the discovery survey (of 370 stars in <1.5 years (including overhead), compared with an additional ~16 for WFIRST [18]

1.4 m Exo-C Spectra with long integration times

2.4 m Exo-C ES with much shorter integration times than Exo-C

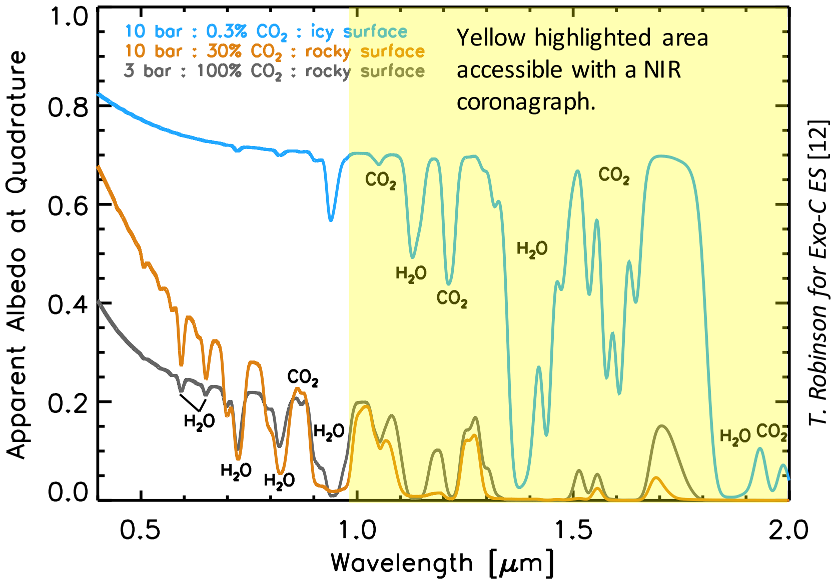


T. Robinson for Exo-C, Exo-C ES [13]

Exo-C ES Secondary Payload Options

1. Near-infrared (NIR) coronagraph

- Extends VIS spectra to include key spectral features of H2O and CO2, 1.0 μm to 2.0 μm
- Does not need cryogenic cooling
- Analysis needed:
  - How many targets good for both VIS + NIR?
  - How to manage differing integration times?
- Care needed so upstream dichroic does not affect wavefront quality (polarization, ghosts)



Yellow highlighted area accessible with a NIR coronagraph.

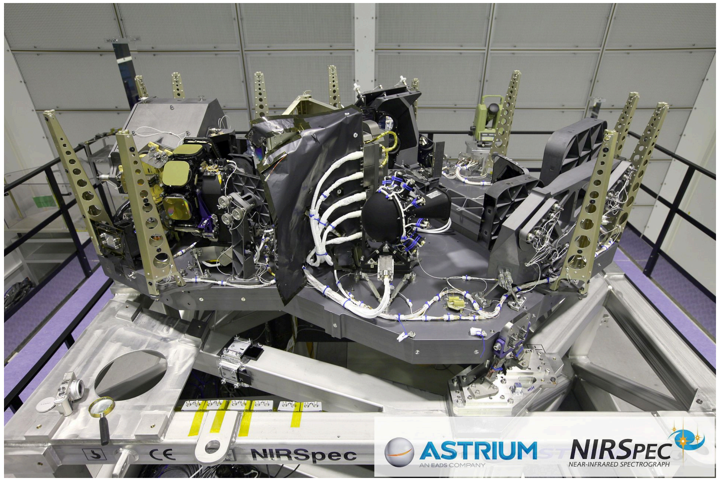
T. Robinson for Exo-C ES [12]

2. Transit Spectrometer

- Grisms could be added to the coronagraph
  - Use transmissive mask with some reflection to feed pointing sensor
  - Need optical configuration analysis

3. NIRspec (from JWST)

- Multi-object spectrograph, 0.6 μm to 2.0 μm
  - 2.0 μm instead of 5.0 μm avoids cooling complexity and still yields useful science observations



NIRSpec for JWST without radiators attached [14]

Exo-C ES Science Requirements

	Exo-C with D = 1.4 m	**Exo-C ES with D = 2.4 m**
Uncontrolled speckle contrast	10^{-9} at IWA	10^{-9} at IWA (smaller IWA than Exo-C)
Contrast stability	10^{-10}*	10^{-10}*
Spectral coverage	450–1000 nm	same
Spectral resolution > 500 nm	R = 70	same
Inner Working Angle 2 /D	0.16″ @ 500 nm, 0.24″ @ 800 nm	0.086” @ 500 nm, 0.14” @ 800 nm
Outer Working Angle > 20 /D**	2.4″ @ 800 nm	1.4” @ 800 nm
Spillover light from binary companion	3e-8 raw @ 8″ (100 λ/D away at 500 nm), TBD additional reduction from wavefront control	Alpha Cen b is ~1.7 times further away (13.7”) than for Exo-C due to change in D. Spillover light should be smaller, perhaps by a factor of 3, but depends on aberrations of the optics at these higher spatial frequencies which requires specific modeling.
Astrometric precision	< 30 milliarcsec (based on 0.3” orbit, and measuring semi-major axis to 10%)	Same (TBR: scientists anticipate only needing a factor of 2 error in mass; this needs to be mapped back to astrometric precision).
Imager field of view	At least 6” (twice the 3” OWA at 1000 nm)	At least 4” (twice the 2.06” OWA at 1000 nm), Would like larger for non-coronagraphic applications.
Mission lifetime	3 years	5 years

- Needs additional analysis. Observatory structural, optical and thermal models are not at high enough fidelity to support contrast stability requirements better than 10e-10. If post-processed contrast goals for Earth-like planets are 10e-10, need stability models to demonstrate stability to ~10e-11. Also need to carefully consider trade between improving contrast and how improving contrast can negatively impact throughput (shooting ourselves in the foot, e.g. [20]).

** Can only achieve N/2*lambda/D OWA with N x N actuator DM

3. Design Reference Mission

Observing with Exo-C ES

Exo-C ES has a 5 year mission lifetime allocated:
2 years on search + 2.5 years on characterization + 0.5 year on disks

Exo-C Working Filter Set	
V band 20%	Photometry & blocking
R band 20%	Photometry & blocking
I band 20%	Photometry & blocking
z band 20%	Photometry & blocking
B band 10%	Rayleigh scattering
650 nm 5%	Weak CH_4 band
793 nm 3%	Moderate CH_4 band
835 nm 6%	CH_4 continuum
885 nm 6%	Strong CH_4
940 nm 6%	$H_2 0$

Target Category	# Stars Exo-C | ES	Median Vmag Exo-C | ES
RV planet spectra	**11 | 17**	**5.7 | 5.1**
Search for HZ Earths Search for HZ SuperEarths	**7 | 25** **15 | 30**	**3.7 | 4.4**
Searches for larger planets	**135 | 370**	**3.8 | 4.6**
Survey for HZ dust	**150**	**3.7**
Debris disks in RV planet systems	**60**	**5.3**
Debris disks detected in far-IR	**150**	**5.3**
Protoplanetary disks	**40**	**11.4**

Credit for analysis to K. Stapelfeldt

Summary of mission observing time

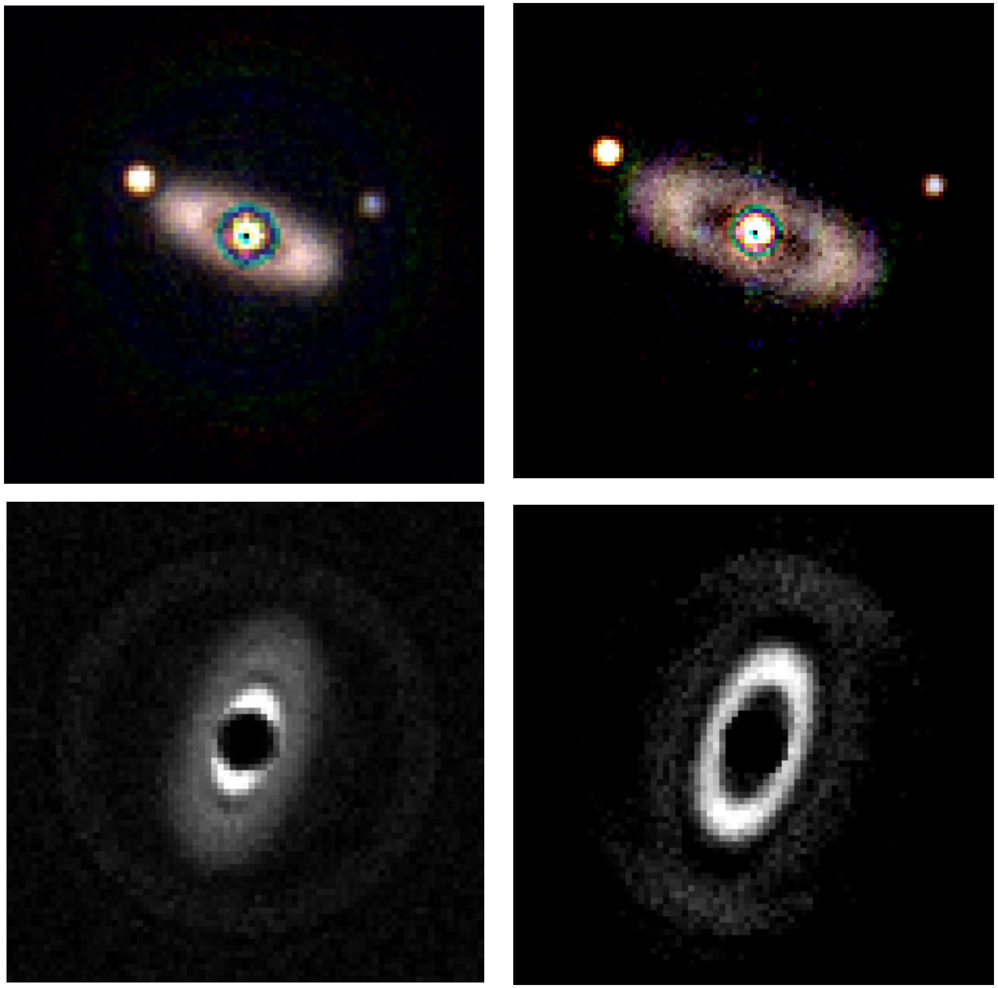
<table>
<tr><th># of Targets
ExoC | ES</th><th>Mission Time (days*)
ExoC | ES</th><th>Design Reference Mission</th></tr>
<tr><td>35 | 85</td><td>166 | 404</td><td>Exoplanet astrometry & multicolor photometry (known and mission-discovered planets)</td></tr>
<tr><td>20 | 60</td><td>215 | 520</td><td>Exoplanet spectra (known and mission-discovered planets)</td></tr>
<tr><td>15 | 30</td><td>113 | 188</td><td>Search Super Earths in nearest star Habitable Zones</td></tr>
<tr><td>150 | 370</td><td>359 | 461</td><td>Search for giant planets around nearby stars</td></tr>
<tr><td>75 | 75</td><td>34 | 34</td><td>Survey of Habitable Zone dust in A-K</td></tr>
<tr><td>60 | 60</td><td>30 | 30</td><td>Known disks within 40 pc</td></tr>
<tr><td>100 | 100</td><td>60 | 60</td><td>Young debris disks from WISE</td></tr>
<tr><td>40 | 40</td><td>24 | 24</td><td>Nearby protoplanetary disks</td></tr>
<tr><td><i>* Mission Time includes overhead</i>
<i>Credit for analysis to K. Stapelfeldt</i></td><td>3.0 yrs | 5.0 yrs</td><td>Total Science Observations
(0.2 years are reserved for in-orbit checkout)</td></tr>
</table>

Number of planet photometry and spectroscopy targets more than doubles for Exo-C ES (aperture and 2 yr increase in mission time)

Imaging simulations

Altair, 12 hrs integration time each in V, R, and I bands to form the composite image. Jupiter and Saturn analogs are detected.

50-zodi debris disk around the WISE excess star HIP 85790. 12 hours of integration time in V band



K. Stapelfeldt for Exo-C, ES [9,10]

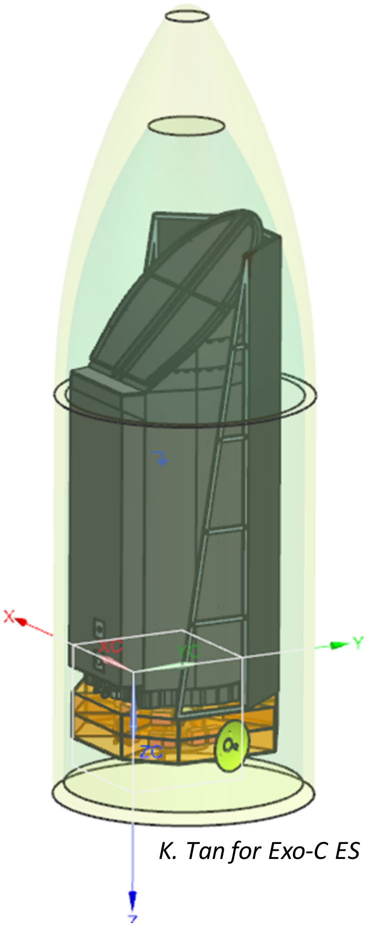
Exo-C ES / WFIRST CGI properties

Property	Exo-C ES (all HLC) [15]	WFIRST (HLC | Shaped Pupil) [18, 21]
Aperture diameter	2.4 m	2.4 m
IWA	2λ/D, 0.086" @500 nm, 0.14" @800 nm	~3λ/D, 0.15" @550 nm, 0.27" @1000 nm
OWA	20λ/D	10λ/D high contrast, 20λ/D lower contrast
Coronagraph FOV	> 4" (TBR)	2.9"
Effective contrast	10^{-9} at IWA (20% band)	3 x 10^{-9} at IWA (10% band)
Contrast stability	10^{-10}	10^{-9} or a few x 10^{-10} [estimated]
Imaging	5 bands, 400-1000 nm (1x10%, 4x20%)	430-980 nm (4 filters)
Spectroscopy	4 bands, 495-1000 nm (20%), R=70	3 bands (18%), 600-970 nm, R = 70
Pointing (tip/tilt 1000s)	0.5 mas	0.4 mas
Photometric throughput*	0.0786	0.0146* [estimated]
Spectroscopic throughput*	0.0524	0.0134* [estimated]
Ensquared energy	0.52	0.36
Bandwidth	20% HLC	10% HLC 18% SP
Allocated mission time	5 years	1 year
RV planet spectroscopy	13-17	7
HZ photometry	5	1

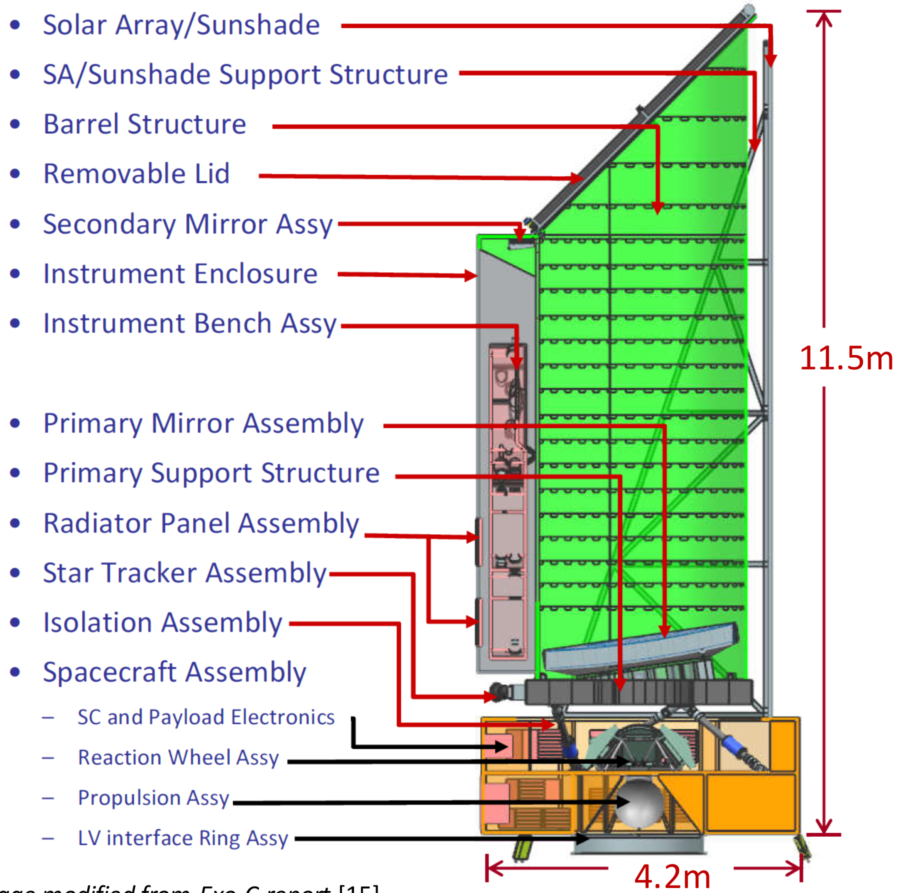
*See Appendix A, the number in this table includes an improvement factor of 1.25 times the throughput listed in Appendix A to account for expected improvements in WFIRST capability. We assume HLC for photometry for WFIRST and SP for spectroscopy.

4. Baseline Mission Design

Exo-C ES Mechanical Design Overview



K. Tan for Exo-C ES



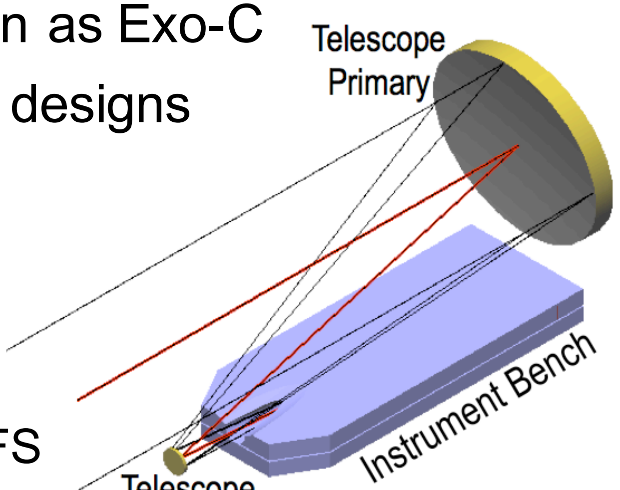
- Solar Array/Sunshade
- SA/Sunshade Support Structure
- Barrel Structure
- Removable Lid
- Secondary Mirror Assy
- Instrument Enclosure
- Instrument Bench Assy
- Primary Mirror Assembly
- Primary Support Structure
- Radiator Panel Assembly
- Star Tracker Assembly
- Isolation Assembly
- Spacecraft Assembly
  - SC and Payload Electronics
  - Reaction Wheel Assy
  - Propulsion Assy
  - LV interface Ring Assy

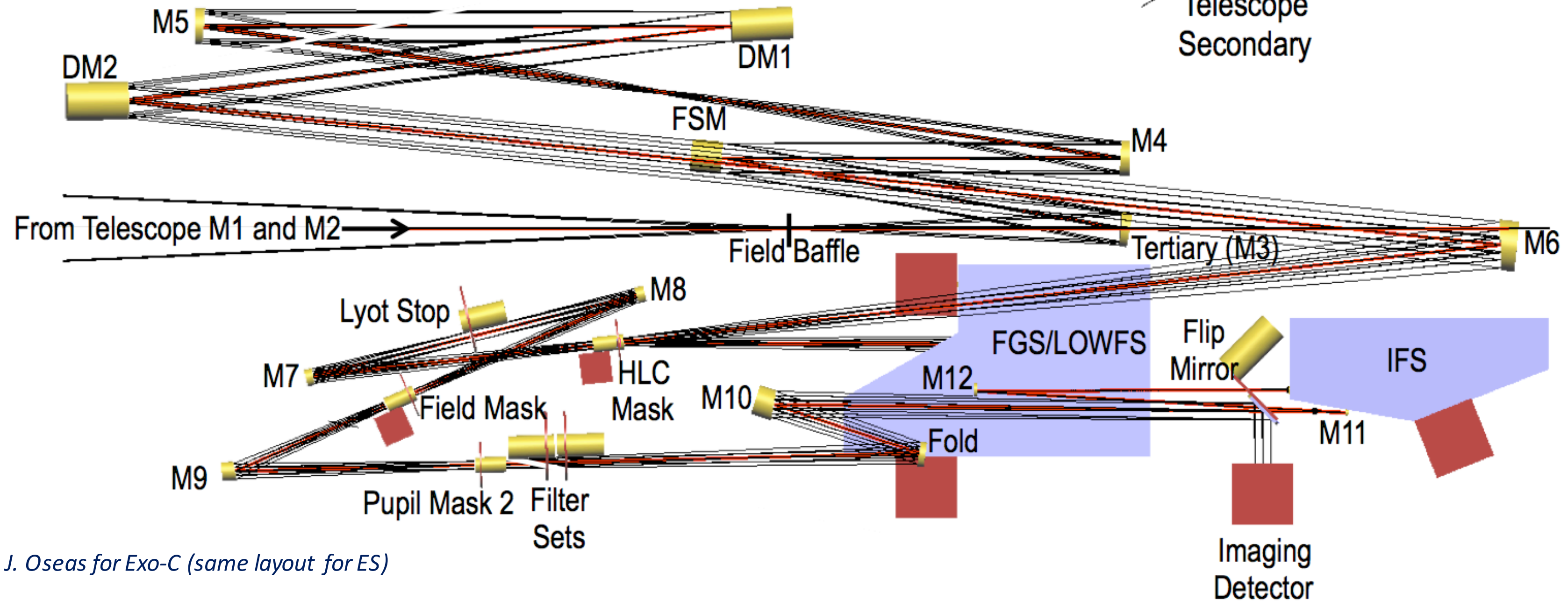
Image modified from Exo-C report [15].

- Scaled-up version of the Exo-C design
  - Atlas V 541 launch fairing requires deployable sunshade for thermal stability
  - Larger diameter telescopes will require deployable scarf, smaller f/#, or a larger fairing

Exo-C ES Optical Design Overview

- Exo-C ES has the same lateral instrument design as Exo-C
- Lateral designs have advantages compared with designs behind the primary mirror:
  - Lower angles of incidence
  - Fewer folds needed (improves throughput)
  - Spacecraft height is reduced
  - Same 2 science detectors as Exo-C: Imaging and IFS



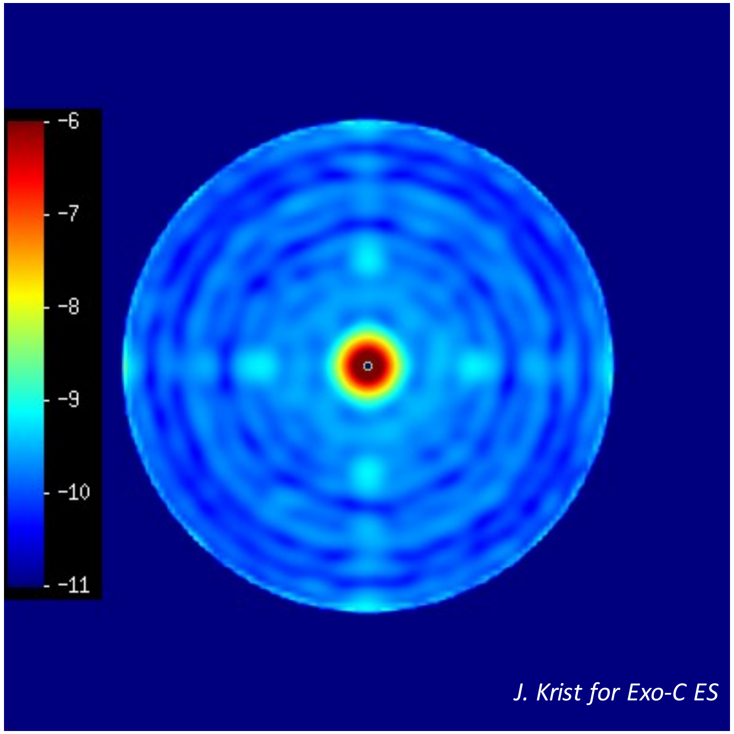


J. Oseas for Exo-C (same layout for ES)

Exo-C ES Science Imager

The Science Imager:

- Uses the 1k x 1k EMCCD under testing by WFIRST
  - Sufficient QE over 450 to 1000 nm band-pass
  - Sufficient FOV to acquire the star, 0.31 arcmin (control engineers estimate there is only an 8% chance the spacecraft will need to be slewed to aid in acquisition)
- Plate scale designed for planet detection at IWA
- 0.019” per pixel (2 pixels per λ/D at 450 nm)
- Smallest 2 λ/D IWA = 0.077” at 450 nm
- Largest possible OWA with 48 x 48 actuator DM = 0.928” at 450 nm, 2.06” at 1000 nm
- Compare with Exo-C
  - Smallest IWA = 0.133” at 450 nm
  - Largest DM-limited OWA = 3.5” at 1000 nm



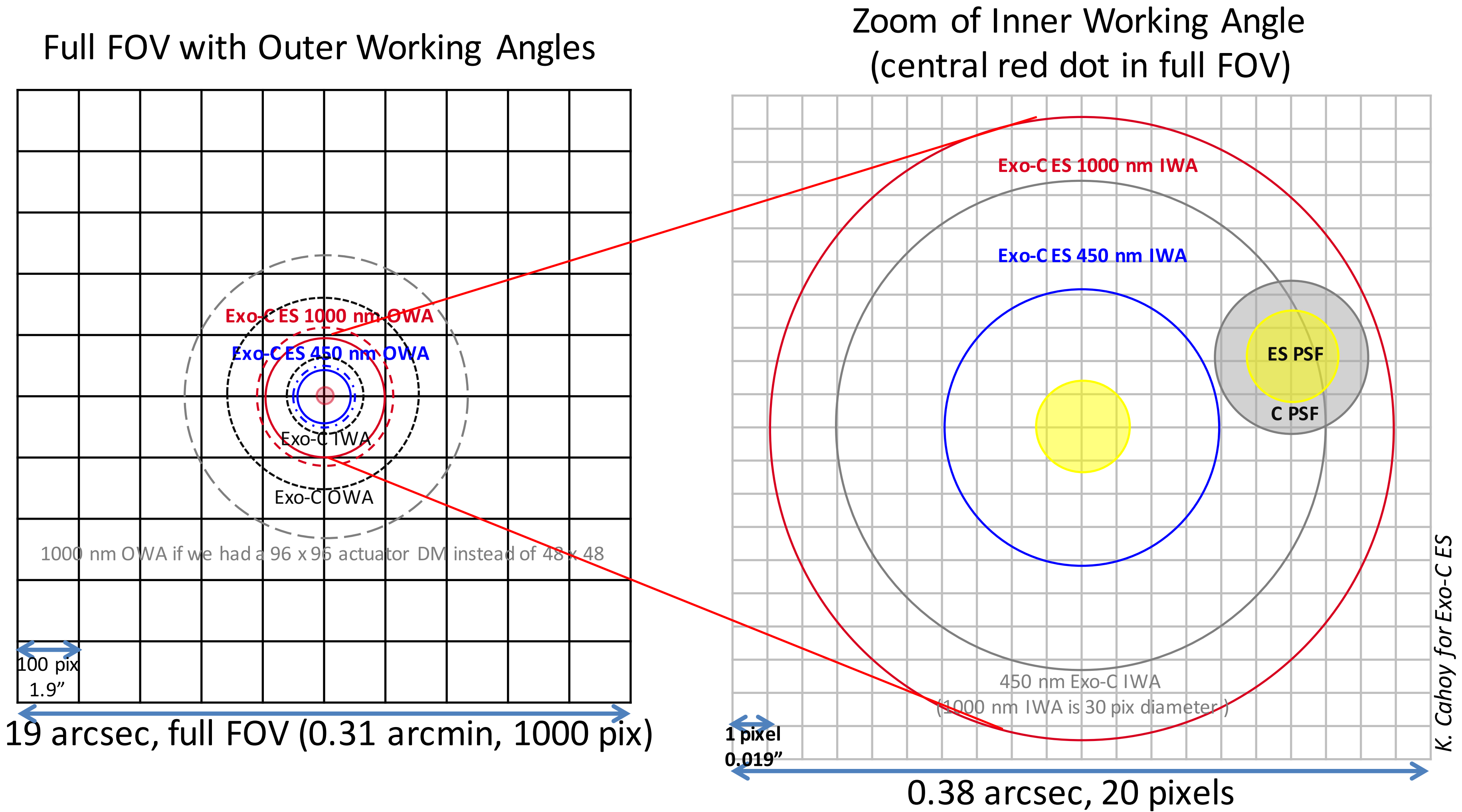
J. Krist for Exo-C ES

Sample High Contrast Image

Unsubtracted HLC dark hole, post EFC. Aberrations corrected below level of cross pattern from DM correction patterns by D. Moody.

Contrast scale is 10^(Value Shown).

Exo-C ES FOV, Working Angles, and PSF



K. Cahoy for Exo-C ES

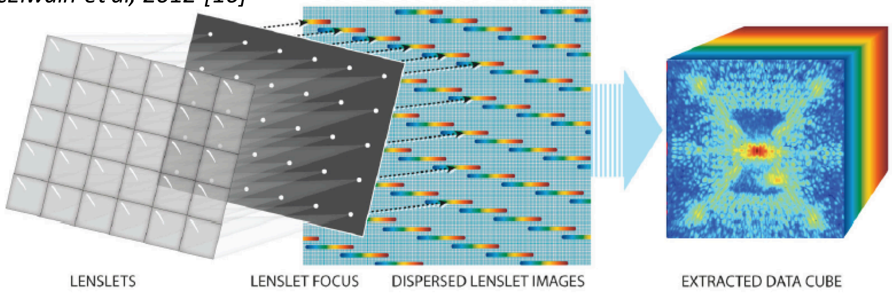
- Dashed lines are DM limit of N/2 λ/D with N = 48 actuators
- Solid lines are 20 λ/D

- 2 pixels per 450 nm 1 λ/D
- Exo-C and ES PSFs (1.22 λ/D) shown at 450 nm

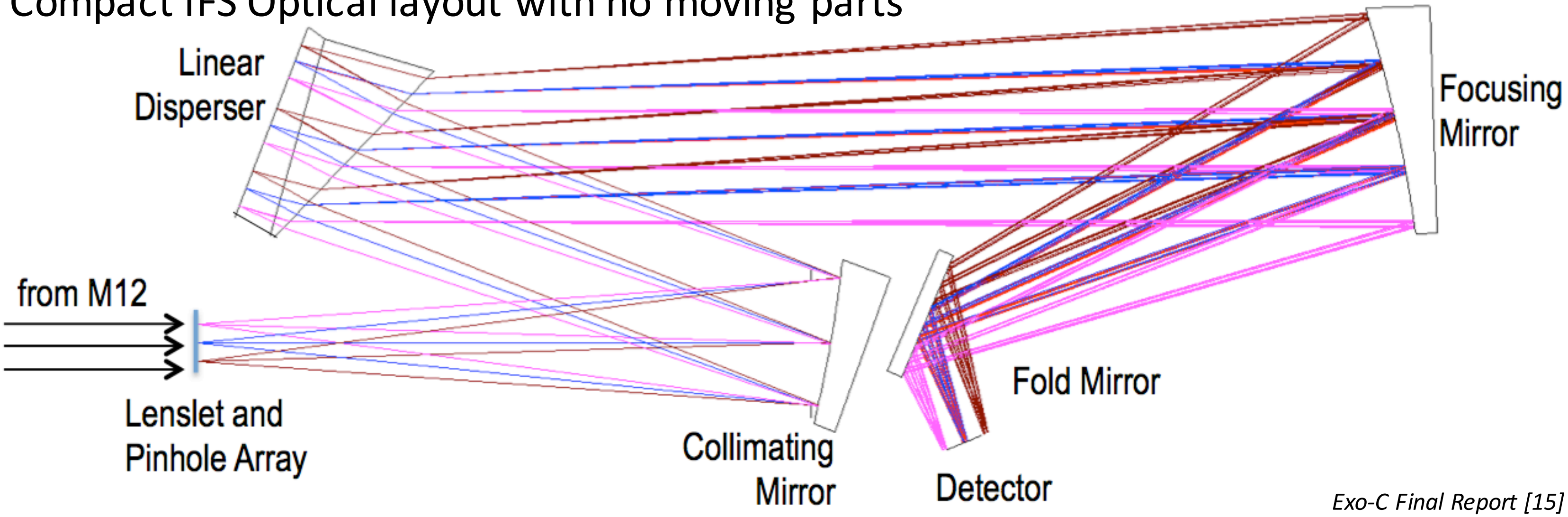
Integral Field Spectrograph (IFS)

- 1k x 1k EMCCD and 48 x 48 actuator DM
  - Exo-C: 71 x 71 lenslets with 2.3” x 2.3” FOV – does not cover OWA (3.5” x 2)
  - Exo-C ES: 71 x 71 lenslets with 1.4” x 1.4” FOV – does not cover OWA (2.06” x 2) (2 lenslets per λ/D at 450 nm)
- 2k x 2k EMCCD for Exo-C ES:
  - 143 x 143 lenslets, 2.7” x 2.7” FOV
- 4k x 4k EMCCD for Exo-C ES:
  - 286 x 286 lenslets, 5.4” x 5.4” FOV

McElwain et al, 2012 [16]



Compact IFS Optical layout with no moving parts



Exo-C Final Report [15]

Exo-C ES Pointing Performance

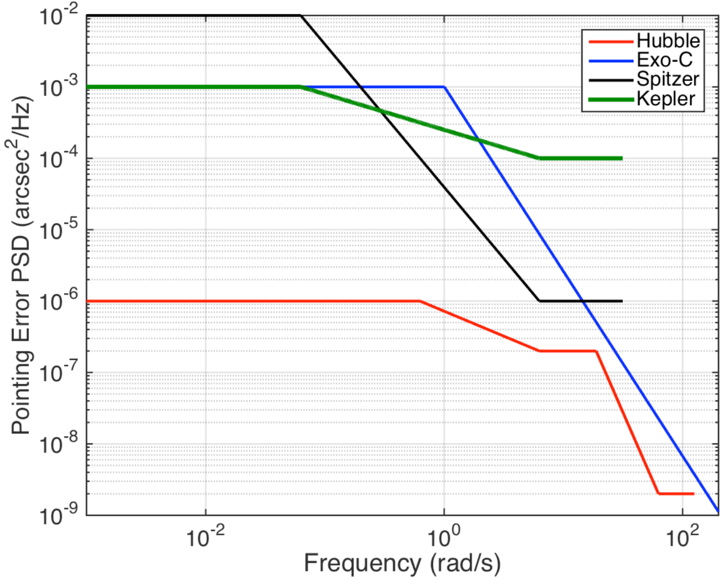
Exo-C ES meets its pointing performance by employing the following:

- **Fine Guidance Sensor (FGS) & Fast Steering Mirror (FSM)**: High-bandwidth control loop internal to the coronagraph. Rejects low- and intermediate-frequency disturbances.
- **Dual-stage vibration isolation**: Reaction wheel assembly (RWA) & payload isolators mitigate the effect of high-frequency reaction wheel disturbances.
- **Enhanced spacecraft attitude control**: FGS provides precise pointing knowledge to improve attitude control in the tip/tilt axes.

Pointing Requirements		Predicted Performance	Units
Telescope Pointing (Angle in the sky, RMS per axis)			
Accuracy	2	1	milli-arcsec tip/tilt
	10	1	arcsec roll
Stability (1000 s)	16	4	milli-arcsec tip/tilt
	10	1	arcsec roll
Coronagraph Pointing (Angle in the sky, RMS per axis):			
Accuracy	0.2	0.1	milliarcsec tip/tilt
Stability (1000 s)	**0.5***	**0.1***	milliarcsec tip/tilt

**For Exo-C, was 0.8 required and 0.3 predicted, mas tip/tilt*

Required body pointing PSD compared to other missions



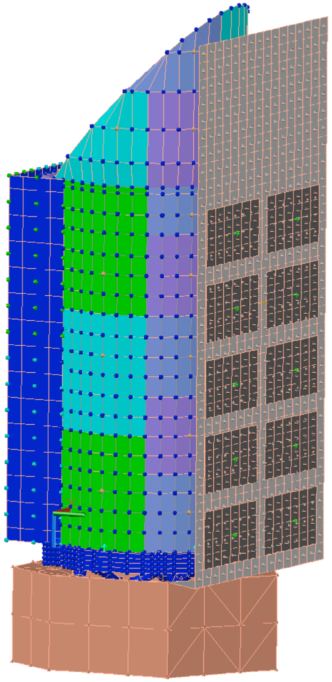
C. Pong for Exo-C ES

Exo-C ES Contrast Stability

Exo-C ES meets its Contrast Stability with:

- Thermal control of the primary mirror, barrel assembly and instrument (active heating)
- Thermal isolation from the spacecraft bus
- Operation with symmetric thermal distribution of heat from solar-angle pointing
- Exo-C models currently support contrast stability of 10^{-10}, additional analyses are needed for Exo-C ES as well as higher fidelity models
- Ideally would like 10^{-11} stability to enable post-processing toward retrieving Earth-like planets
- Also note that jitter instability may be an issue (WFIRST-AFTA finding, ~10^{-10})
- Need validated models with lab experiments, based on 0.4-0.8 mas jitter sensitivity; need both jitter and thermal models

Flat panel supports thermal stability.
Symmetric thermal design about +/- 15 degrees roll w.r.t. the Sun



R. Effinger for Exo-C ES

Exo-C ES Telescope Power vs. Thermal Set-point

	Thermal Set-point Scheme			
	Barrel, Scarf 200 to 150K PM, SM 240K	Barrel, Scarf 200 to 150K PM, SM 295K	Everything 295 K	Barrel 250K Scarf 220K PM,SM 295K
Barrel	187	178	1268	747
PM	41	113	58	83
PSS	85	80	682	802
Scarf	323	321	3544	836
PM Bipods	10	10	10	10
SM	2	2	2	2
Isolators	60	60	60	60
Total	**708**	**764**	**5624**	**2540**
Wrap-up Factor (from simple to detailed model)	31%	31%	31%	31%
Extrapolated Total	**929**	**1002**	**7378**	**3332**

All units are in Watts

R. Effinger

Summary of Exo-C ES Mass and Power

	Total CBE Mass (kg)	Cont. (%)	Total Mass w/ Cont. (kg)	Total CBE Power (W)	Cont. (%)	Total Power w/ Cont. (W)
1.4m Exo-C Wet Mass and Power	**1138.4**	***42%***	**1619.3**	**1392.0**	***43%***	**1990.6**
Total Observatory Wet Mass	**3977.9**	***37%***	**5430.4**	**1857.5**	***43%***	**2656.3**
Hydrazine	600.0	*0%*	600.0			
Total Observatory Dry Mass (PBE)	**3377.9**	***43%***	**4830.4**	**1857.5**	***43%***	**2656.3**
Additional Contingency	689.8	*20%*		241.5	*13%*	
Observatory Dry Mass (CBE) + Contingency	3377.9	*23%*	4140.6	1857.5	*30%*	2414.8
Payload (Telescope and Coronagraph)	**1642.9**	***30%***	**2135.7**	**1370.6**	***30%***	**1781.8**
Telescope Assembly	1344.2	*30%*	1747.5	1093.0	*30%*	1420.9
IR Coronagraph	200.0	*30%*	260.0	150.0	*30%*	195.0
Vis Coronograph Instrument	98.6	*30%*	128.2	127.6	*30%*	165.9
Total Spacecraft Dry Mass	**1735.1**	***16%***	**2004.9**	**486.9**	***30%***	**633.0**

- Spacecraft and telescope mass estimates scaled up from the Exo-C estimate on a part-by-part evaluation
- Propellant scaled down from WFIRST based on observatory dry mass ratio
- Vis Coronagraph mass and power taken from Exo-C unchanged
- IR Coronagraph mass and power taken from a Team X analogy evaluation session
- Telescope power estimate developed from a thermal model set point analysis
- Exo-C-ES fits on the Atlas V 541 launch vehicle

5. Technology Development

Exo-C ES Technology Development

- Detectors
  - For improved spectral resolution over more of the FOV, develop low-noise, radiation-tolerant EMCCDs (currently 1k x 1k, up to 4k x 4k)
  - Identify and assess candidate CCDs for a NIR CGI secondary payload
- Deformable mirrors
  - To increase the size of the OWA, which is important considering that OWA inversely depends on D and will decrease with larger D, need DMs with more actuators (currently 48 x 48, up to 96 x 96 or more)
- Contrast stability
  - Cannot set a science requirement for Earth-detecting contrast of 10^-10 raw without demonstrating 10^-11 contrast stability is possible
    - Requires refined structural, thermal, optical performance (STOP) modeling and importantly, model validation, to make this case for larger D missions
- IFS
  - Detailed modeling of sensitivity and sampling and expected performance synthesizing spectra from 4+ bands of measurements

7. Summary

Exo-C ES Study Accomplishments

1. Quantified performance improvement expected for a dedicated 2.4-m aperture direct imaging mission
   - E.g., look for H2O in the tropospheres of Super-Earths
   - Significant increase in number of gas and ice giants (hundreds)
   - Triples the number of HZ Earths reachable with photometry
2. Considered 5+ years of scientific and technical progress contributing to the case for flying this type of mission
3. Identified several coronagraph instrument design challenges relevant to ES and larger aperture missions
4. Developed a flat sunshade/array and heated thermal approach to achieving very high telescope/wavefront stability needed for imaging exoplanets in reflected light
5. Identified stability work remaining to meet requirements for imaging and characterizing Earth-like exoplanets

References

[1] Simulated image of Altair system by Karl Stapelfeldt for Exo-C.
[2] Simulated RV planet spectra by Ty Robinson for Exo-C. Known RV planet around epsilon Eridani (bottom panel) and two hypothetical planets around the nearby stars Cen A and Hyi. The integration times (per bandpass) assumed for each planet are 660, 620, and 150 hours, respectively. Note how the S/N degrades beyond 0.8 µm due to the declining quantum efficiency of the detector.
[3] C. Morley and M. Marley ; GJ 1214b model spectra for Exo-C. Models of GJ1214b with cloud/haze opacity necessary to match the available transit data. The matching can be done with either thick clouds or a sooty haze. The point is that these can obscure the near-IR water bands and even the optical bands in transmission, but not in reflection
[4] Data from this figure of a Hybrid Lyot Coronagraph are from John Trauger, Dwight Moody, Brian Gordon, John Krist, and Dimitri Mawet, "Complex apodization Lyot coronagraphy for the direct imaging of exoplanet systems: design, fabrication, and laboratory demonstration," Proc. SPIE 8442, Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave, 84424Q (August 22, 2012); doi:10.1117/12.926663.
[5] Image taken from Stapelfeldt et al. 2015, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150007911.pdf, "Exo-C: A probe-scale space mission to directly image and spectroscopically characterize exoplanetary systems using an internal coronagraph."
[6] M. Marley for Exo-C Exoplanet Program study, 2015.
[7] K. Stapelfeldt for Exo-C Extended study, 2016.
[8] https://en.wikipedia.org/wiki/Super-Earth#/media/File:Exoplanet_Comparison_CoRoT-7_b.png accessed 2/18/2016
[9] K. Stapelfeldt for Exo-C study, 2015
[10] K. Stapelfeldt for Exo-C ES study, 2016
[11] M. Marley and R. Lupu for Exo-C and ExEP, 2015
[12] T. Robinson for Exo-C ES, 2016
[13] T. Robinson, for Exo-C and Exo-C ES. Note that contrast for alpha Cen is degraded by x10 to simulate companion leakage. Note that the 2.4 m alpha Cen is at 45 deg phase and not quadrature as quadrature is outside of OWA
[14] NIRSpec on JWST, https://en.wikipedia.org/wiki/NIRSpec_(Near-Infrared_Spectrograph)#/media/File:NIRSpec_Astrium.jpg accessed March 4, 2016
[15] Exo-C Final Report, https://exep.jpl.nasa.gov/stdt/Exo-C_Final_Report_for_Unlimited_Release_150323.pdf accessed March 11, 2016
[16] M. McElwain et al., Scientific design of a high contrast integral field spectrograph for the Subaru Telescope, Proc. SPIE 8446, Ground-based and Airborne Instrumentation for Astronomy IV, 84469C (September 24, 2012); doi:10.1117/12.927108
[17] F. Shi, et al. WFIRST Coronagraph Milestone 6 Final Report: Low Order Wavefront Sensing and Control, http://wfirst.gsfc.nasa.gov/science/sdt_public/wps/references/WFIRST_CGI_Milestone6_Final_Report.pdf accessed March 30, 2016
[18] Spergel and Gehrels, et al., WFIRST AFTA SDT Report, http://wfirst.gsfc.nasa.gov/science/sdt_public/WFIRST-AFTA_SDT_Report_150310_Final.pdf accessed March 30, 2016
[19] L. Kreidberg, et al., "Clouds in the atmosphere of the super-Earth exoplanet GJ 1214b", Nature, doi:10.1038/nature12888, and http://www.theatlantic.com/science/archive/2016/03/cloudy-with-a-chance-of-planet-spotting/474222/
[20] D. Mawet, et al., "Fundamental limitations of high contrast imaging set by small sample statistics", ApJ, 792, 2 (2014) doi:10.1088/0004-637X/792/2/97
[21] WFIRST MCR presentation, December 2015, Coronagraph Instrument (CGI) and Tertiary Collimator Assembly (TCA), filename 10_CGI_TCA_MCR_Demers.pdf

End

Backup: Additional Findings

Backup: “Cut” Slides

Backup: Appendix A

Additional Findings: 1

- Radiation damage likely to detectors, probable need for shutters for protection from radiation damage
- Make sure that scheduled mission time for internal coronagraph observations is *not contiguous* (including WFIRST). Would be best to allow planet orbit positions to change, *e.g.*, schedule 6 months at beginning of WFIRST mission and 6 months at end.
- Analysis needed on how to schedule observations to optimally sample within a HZ for new systems
- Need to carefully consider trade between improving contrast and how improving contrast can negatively impact throughput (shooting ourselves in the foot).

Additional Findings: 2

- Need new spillover light from binary companion assessment for larger angular separation due to larger D and to consider optical aberrations at higher spatial frequencies
- Need new analysis of the astrometric precision requirement based on science “instinct” that mass is only needed to within a factor of 2; also need to verify that science instinct is correct via modeling
- Need assessment of reach and impact of a NIR internal coronagraph
- When comparing performance between missions and instruments with a goal of assessing key technologies, helpful to have a defined set of filters and bandwidths. It is hard to assess how different instruments perform when filter selection and bandwidth could significantly contribute.

Additional Findings: 3

- Need to assess the contribution of star brightness to contrast stability. If the LOWFS loop can be run faster on a brighter star, that may improve the contrast stability
- Need thicker silicon substrate EMCCDs to get a better QE out to 1.0 um, because dark current is worse for red-sensitive detectors. The improved QE on such devices is not worth the dark current.
- Need to assess current state of development for NIR detectors and perform analyses on how the state of the art readnoise and dark current can get and how that will affect measurements; what development is needed to enable science without requiring cryocooling
- Need a common approach for what qualifies as a complete spectral measurement across multiple studies/programs

Additional Findings: 4

- Would be helpful to approach integrated modeling as creating a “digital twin” of the hardware, that is constantly being updated and refined to reflect as-built performance
- Need to consider trade between reducing the IWA and expected science return; need a study to consider how contrast at IWA might improve with relaxed contrast requirements out to OWA for an unobscured pupil
- Need to assess methods for achieving astrometric precision, printed masks, use of the DM – factors such as stability with time and aging as well as thermal and dynamic stability
- Need to assess whether or not the control sampling rate can be increased (and to what value is best) due to larger aperture and more photons
- Assess the quantization required for the fine steering mirror

Additional Findings: 5

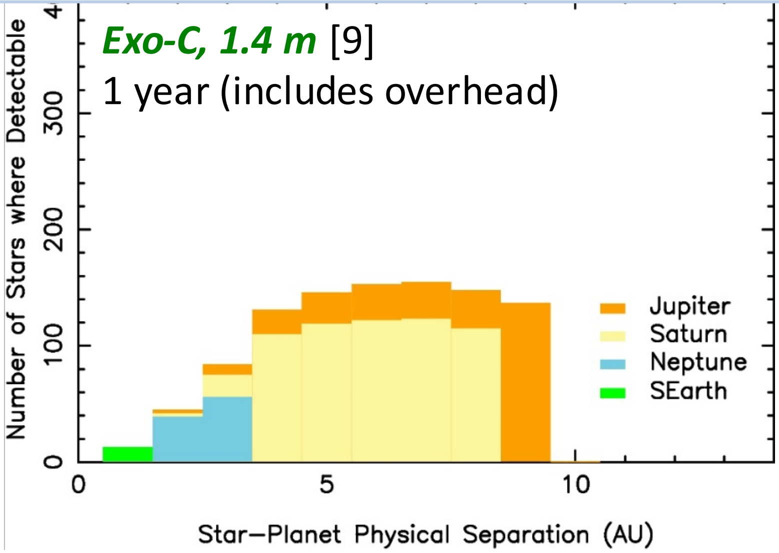
- Assess the impact of having a non-point-source (finite radius star) on pointing uncertainty for target stars

Backup: Search: Planets in reach of Exo-C ES

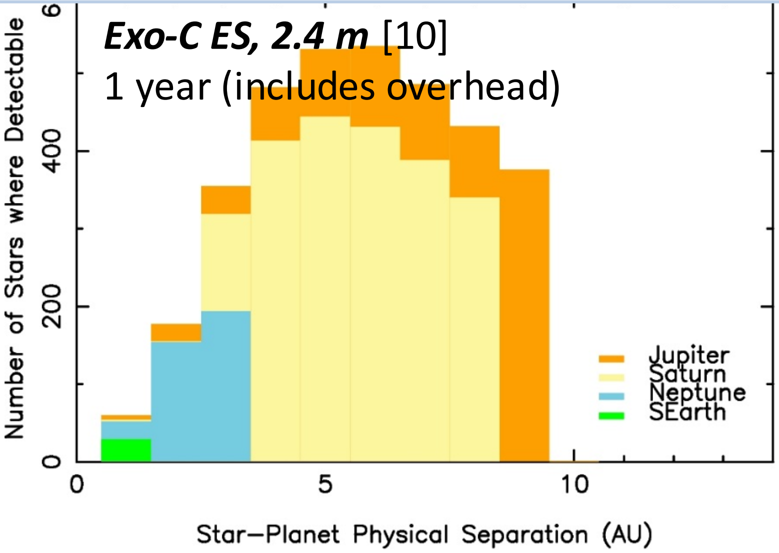
Exo-C ES significantly increases (by hundreds) the yield of Jupiters and ice giants compared with Exo-C

Exo-C ES can search 25 HZs for Earths at short wavelengths, Exo-C can search 7 HZs for Earths

Exo-C ES can reach 39 Super-Earths at short wavelengths, Exo-C can reach 15 Super-Earths [15]



Exo-C, 1.4 m [9]
1 year (includes overhead)



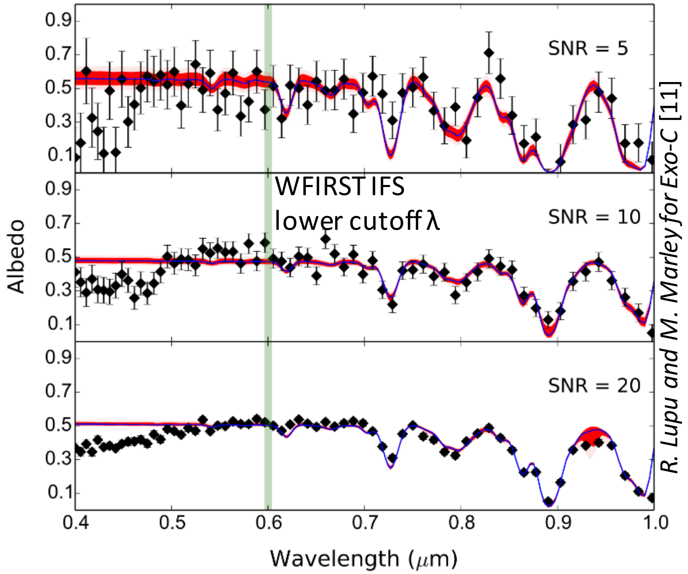
Exo-C ES, 2.4 m [10]
1 year (includes overhead)

K. Stapelfeldt for Exo-C, ES [9,10]

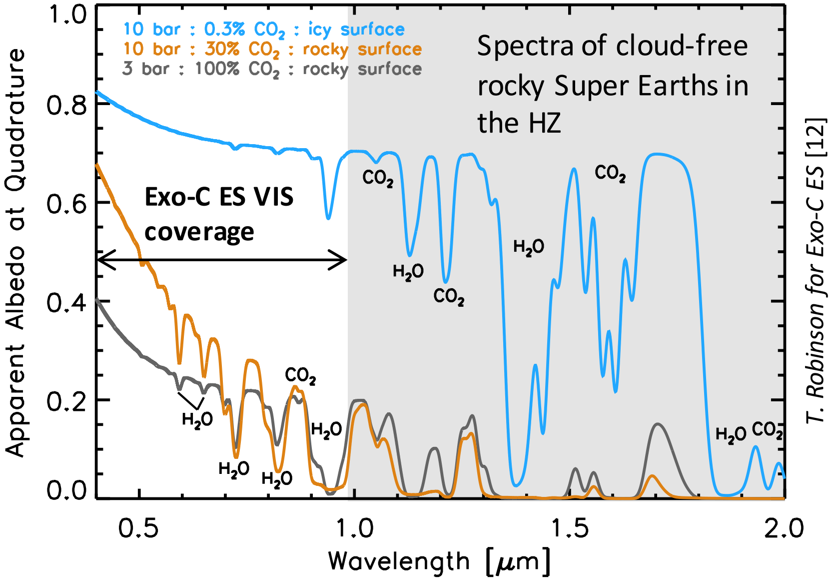
Backup: Exoplanet spectroscopy requirements

- Spectral resolution of *R* = 70 required
  - Measure strong and weak CH_4 bands
  - Measure O_2 0.76 μm feature in Earth-like atmospheres (not shown here)
  - Provide clean inter-band continuum
- Wavelength coverage spans visible
  - 0.45 μm short wavelength cutoff provides access to Rayleigh scattering continuum
  - 1.0 μm long wavelength cutoff covers 0.94 μm H_2O line & continuum
  - Strong lines out to 2.0 μm motivates NIR coronagraph secondary payload
- S/N = 5 supports use of the the stronger spectral features
- S/N = 10 allows use of the weaker spectral features

How SNR affects ability to retrieve CH4 abundance



R. Lupu and M. Marley for Exo-C [11]

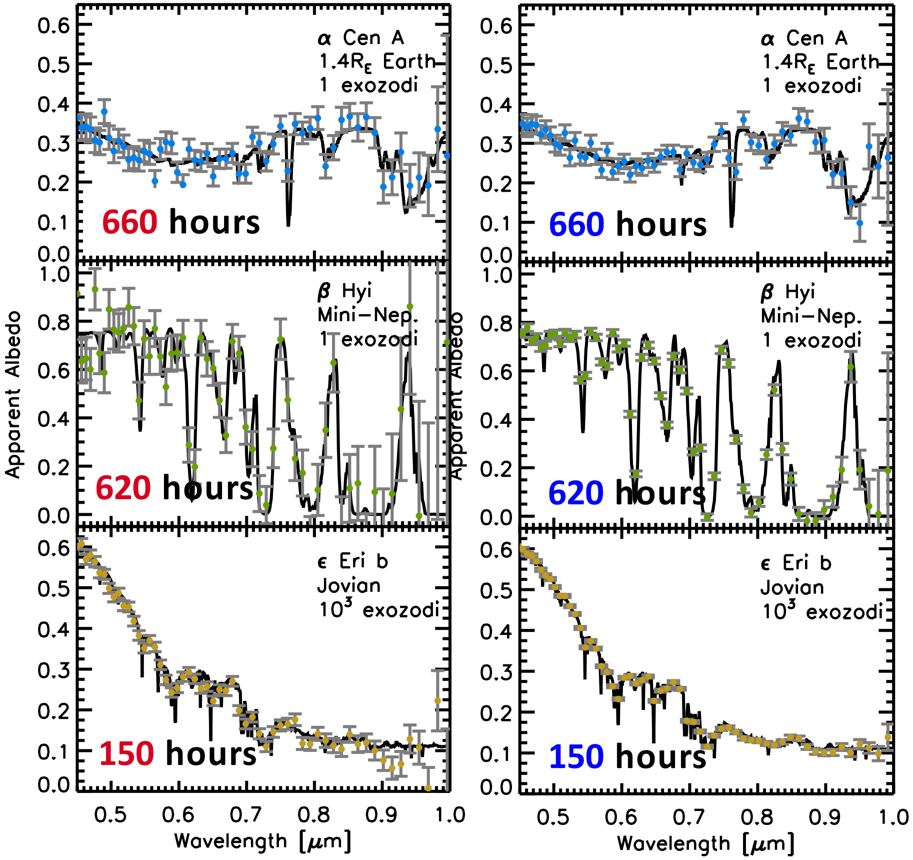


Spectra of cloud-free rocky Super Earths in the HZ

T. Robinson for Exo-C ES [12]

Backup: Exoplanet spectroscopy requirements

This backup slide is to demonstrate the improvement in quality (SNR) (blue) with Exo-C ES when using the same integration time as Exo-C (red).



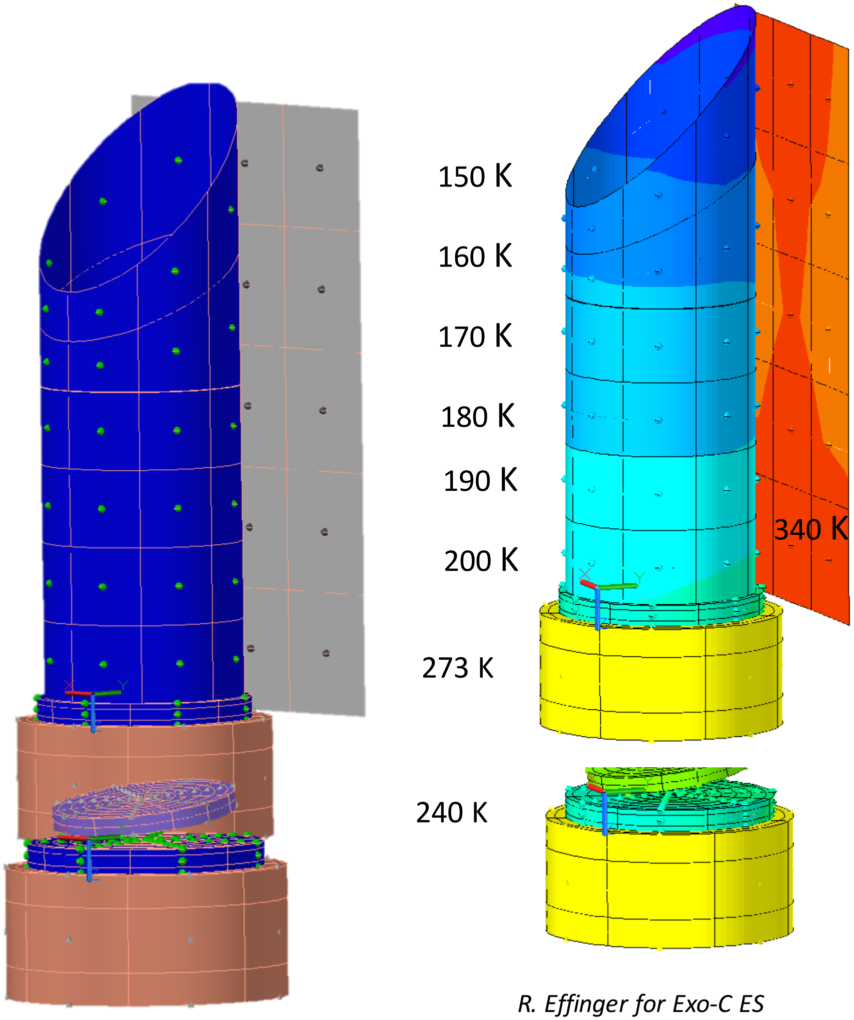
1.4 m Exo-C Spectra with long integration times

2.4 m Exo-C ES with better SNR, same integration times as Exo-C

T. Robinson for Exo-C, Exo-C ES [13]

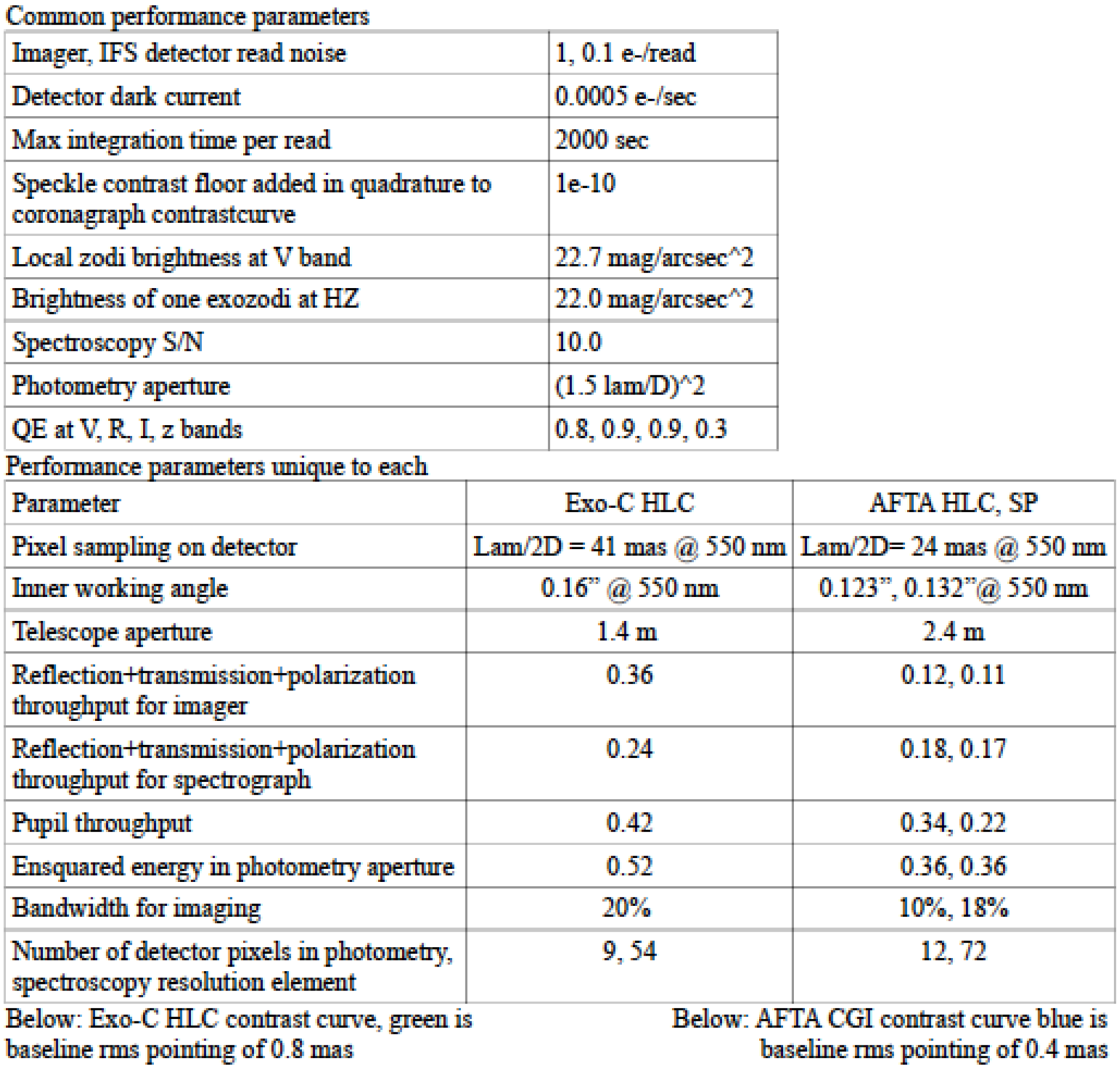
Backup: Exo-C ES Low-resolution Thermal Model

- Simplified model with the same geometry as Exo-C
  - Same optical and thermal properties
  - Same MLI insulation
  - Detailed conduction paths are not modeled (no bipods or fittings)
  - No instrument and enclosure
- Thermal set-point scheme similar to Exo-C, but simplified
  - 6 circumferential heater zones along barrel
  - Linearly decreasing, 200 to 150 K
  - 1 heater zone on PSS, 200 K
  - Spacecraft interface temperature constant boundary condition, 273K



R. Effinger for Exo-C ES

Appendix A: CGI comparison models used



Common performance parameters

Imager, IFS detector read noise	1, 0.1 e-/read
Detector dark current	0.0005 e-/sec
Max integration time per read	2000 sec
Speckle contrast floor added in quadrature to coronagraph contrastcurve	1e-10
Local zodi brightness at V band	22.7 mag/arcsec^2
Brightness of one exozodi at HZ	22.0 mag/arcsec^2
Spectroscopy S/N	10.0
Photometry aperture	(1.5 lam/D)^2
QE at V, R, I, z bands	0.8, 0.9, 0.9, 0.3

Performance parameters unique to each

Parameter	Exo-C HLC	AFTA HLC, SP
Pixel sampling on detector	Lam/2D = 41 mas @ 550 nm	Lam/2D= 24 mas @ 550 nm
Inner working angle	0.16" @ 550 nm	0.123", 0.132"@ 550 nm
Telescope aperture	1.4 m	2.4 m
Reflection+transmission+polarization throughput for imager	0.36	0.12, 0.11
Reflection+transmission+polarization throughput for spectrograph	0.24	0.18, 0.17
Pupil throughput	0.42	0.34, 0.22
Ensquared energy in photometry aperture	0.52	0.36, 0.36
Bandwidth for imaging	20%	10%, 18%
Number of detector pixels in photometry, spectroscopy resolution element	9, 54	12, 72

Below: Exo-C HLC contrast curve, green is baseline rms pointing of 0.8 mas

Below: AFTA CGI contrast curve blue is baseline rms pointing of 0.4 mas

Content from K. Stapelfeldt for Exo-C ES.

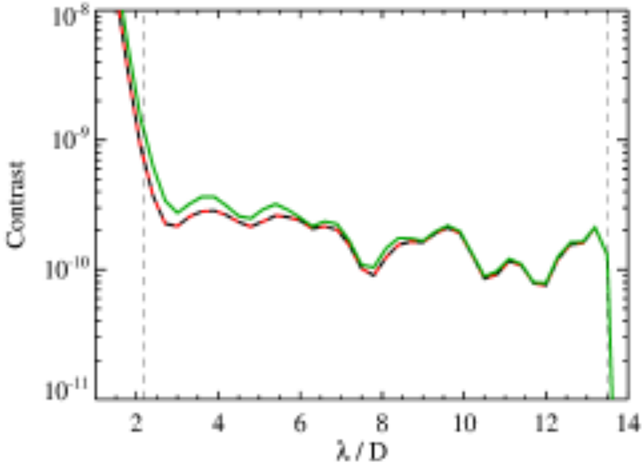
From a file originally named: ExoC_AFTA_compare_revised.pdf

Appendix A: CGI comparison models used

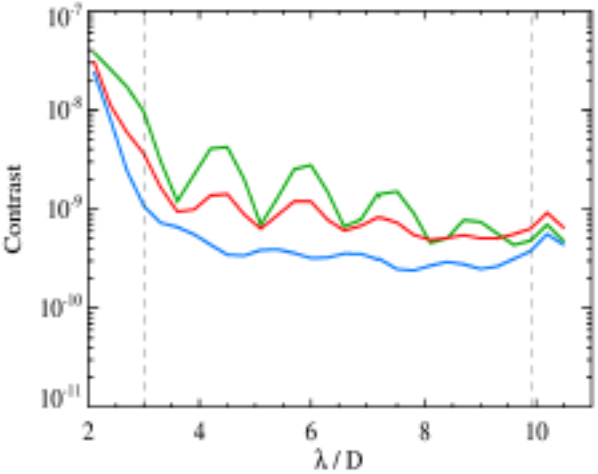
Content from K. Stapelfeldt for Exo-C ES.

From a file originally named:
ExoC_AFTA_compare_revised.pdf

Below: Exo-C HLC contrast curve, green is baseline rms pointing of 0.8 mas



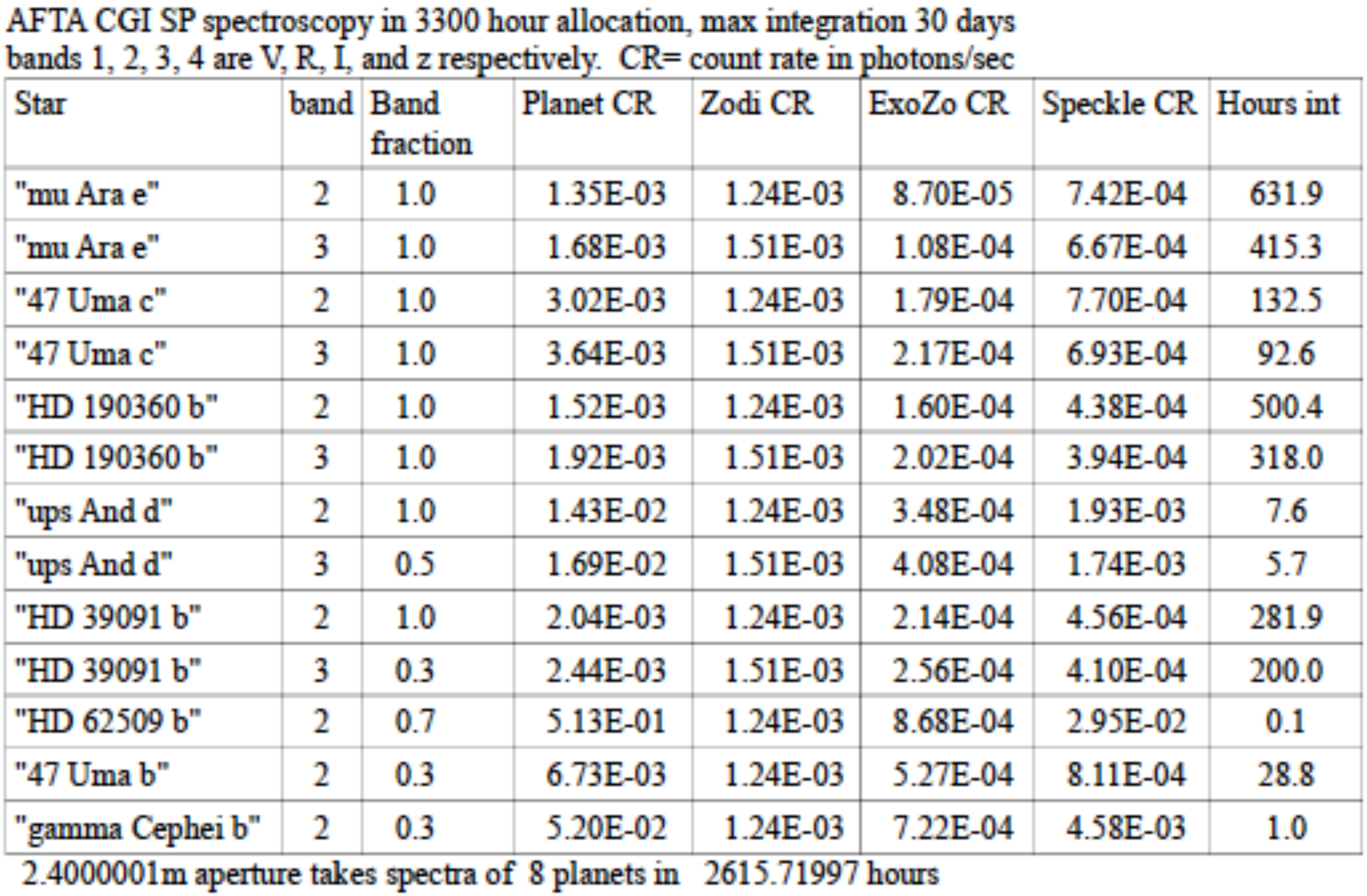
Below: AFTA CGI contrast curve blue is baseline rms pointing of 0.4 mas



Appendix A: CGI comparison models used

Content from K. Stapelfeldt for Exo-C ES.

From a file originally named:
ExoC_AFTA_compare_revised.pdf



AFTA CGI SP spectroscopy in 3300 hour allocation, max integration 30 days
bands 1, 2, 3, 4 are V, R, I, and z respectively. CR= count rate in photons/sec

Star	band	Band fraction	Planet CR	Zodi CR	ExoZo CR	Speckle CR	Hours int
"mu Ara e"	2	1.0	1.35E-03	1.24E-03	8.70E-05	7.42E-04	631.9
"mu Ara e"	3	1.0	1.68E-03	1.51E-03	1.08E-04	6.67E-04	415.3
"47 Uma c"	2	1.0	3.02E-03	1.24E-03	1.79E-04	7.70E-04	132.5
"47 Uma c"	3	1.0	3.64E-03	1.51E-03	2.17E-04	6.93E-04	92.6
"HD 190360 b"	2	1.0	1.52E-03	1.24E-03	1.60E-04	4.38E-04	500.4
"HD 190360 b"	3	1.0	1.92E-03	1.51E-03	2.02E-04	3.94E-04	318.0
"ups And d"	2	1.0	1.43E-02	1.24E-03	3.48E-04	1.93E-03	7.6
"ups And d"	3	0.5	1.69E-02	1.51E-03	4.08E-04	1.74E-03	5.7
"HD 39091 b"	2	1.0	2.04E-03	1.24E-03	2.14E-04	4.56E-04	281.9
"HD 39091 b"	3	0.3	2.44E-03	1.51E-03	2.56E-04	4.10E-04	200.0
"HD 62509 b"	2	0.7	5.13E-01	1.24E-03	8.68E-04	2.95E-02	0.1
"47 Uma b"	2	0.3	6.73E-03	1.24E-03	5.27E-04	8.11E-04	28.8
"gamma Cephei b"	2	0.3	5.20E-02	1.24E-03	7.22E-04	4.58E-03	1.0

2.4000001m aperture takes spectra of 8 planets in 2615.71997 hours

Appendix A: Exo-C and Exo-C ES Spectroscopy

From Karl Stapelfeldt:
Here are some output rows comparing Exo-C (regular type) and Exo-C ES (bold type) spectroscopy integration times for the same targets. Something isn't right with the ES values for eps Eri, I believe the Exo-C model PSF is truncated by a field stop and thus can't be rescaled to show the Exo-C ES PSF at the large 1.1" distance where this planet is located.

All are for spectroscopy S/N of 10.

		PCR	ZODI CR	ExoZ CR	Speck CR		
"beta Pic b"	, 1,	1.0,	1.53E-03,	2.39E-03,	6.30E-05,	1.11E-03,	383.8
"beta Pic b"	, 2,	1.0,	1.57E-03,	3.45E-03,	6.47E-05,	1.14E-03,	376.0
"beta Pic b"	, 3,	1.0,	1.49E-03,	4.20E-03,	6.15E-05,	1.09E-03,	423.4
"beta Pic b"	**, 1,**	**1.0,**	**2.19E-03,**	**1.20E-03,**	**3.16E-05,**	**1.36E-03,**	**184.8**
"beta Pic b"	**, 2,**	**1.0,**	**2.25E-03,**	**1.73E-03,**	**3.25E-05,**	**1.39E-03,**	**178.5**
"beta Pic b"	**, 3,**	**1.0,**	**2.14E-03,**	**2.11E-03,**	**3.08E-05,**	**1.32E-03,**	**198.6**
"mu Ara e"	, 2,	1.0,	1.89E-03,	3.45E-03,	2.42E-04,	5.83E-04,	259.9
"mu Ara e"	, 3,	1.0,	2.34E-03,	4.20E-03,	3.00E-04,	7.23E-04,	175.7
"mu Ara e"	**, 2,**	**1.0,**	**2.53E-03,**	**1.73E-03,**	**1.21E-04,**	**6.15E-04,**	**139.3**
"mu Ara e"	**, 3,**	**1.0,**	**3.14E-03,**	**2.11E-03,**	**1.50E-04,**	**7.64E-04,**	**93.6**
"47 Uma c"	, 1,	1.0,	2.21E-03,	2.39E-03,	3.51E-04,	3.79E-04,	181.9
"47 Uma c"	, 2,	1.0,	3.13E-03,	3.45E-03,	4.98E-04,	5.37E-04,	96.2
"47 Uma c"	, 3,	0.6,	3.78E-03,	4.20E-03,	6.01E-04,	6.49E-04,	68.7
"47 Uma c"	**, 1,**	**1.0,**	**4.01E-03,**	**1.20E-03,**	**1.76E-04,**	**8.99E-04,**	**57.9**
"47 Uma c"	**, 2,**	**1.0,**	**5.68E-03,**	**1.73E-03,**	**2.50E-04,**	**1.27E-03,**	**31.1**
"47 Uma c"	**, 3,**	**1.0,**	**6.86E-03,**	**2.11E-03,**	**3.02E-04,**	**1.54E-03,**	**22.4**
"HD 190360 b"	, 2,	1.0,	1.58E-03,	3.45E-03,	4.44E-04,	3.24E-04,	356.1
"HD 190360 b"	, 3,	0.4,	2.00E-03,	4.20E-03,	5.61E-04,	4.09E-04,	230.8
"HD 190360 b"	**, 2,**	**1.0,**	**2.95E-03,**	**1.73E-03,**	**2.23E-04,**	**8.17E-04,**	**105.1**
"HD 190360 b"	**, 3,**	**1.0,**	**3.73E-03,**	**2.11E-03,**	**2.81E-04,**	**1.03E-03,**	**68.6**
"ups And d"	, 1,	0.8,	5.44E-03,	2.39E-03,	7.00E-04,	5.88E-03,	37.3
"ups And d"	**, 1,**	**1.0,**	**2.09E-02,**	**1.20E-03,**	**3.51E-04,**	**2.98E-03,**	**3.3**
"HD 62509 b"	, 1,	0.1,	6.23E-02,	2.39E-03,	1.59E-03,	1.41E-01,	1.7
"HD 62509 b"	**, 1,**	**1.0,**	**6.08E-01,**	**1.20E-03,**	**8.00E-04,**	**5.22E-02,**	**0.1**
"eps Eridani b"	, 1,	1.0,	7.78E-03,	2.39E-03,	3.96E-04,	4.92E-04,	17.1
"eps Eridani b"	, 2,	1.0,	1.30E-02,	3.45E-03,	6.63E-04,	8.23E-04,	7.2
"eps Eridani b"	, 3,	1.0,	1.77E-02,	4.20E-03,	9.02E-04,	1.12E-03,	4.4
"eps Eridani b"	, 4,	1.0,	5.29E-03,	1.26E-03,	2.69E-04,	3.35E-04,	33.6
"eps Eridani b"	***, 1,***	***1.0,***	***1.59E-02,***	***1.20E-03,***	***1.99E-04,***	***0.00E+00,***	***4.9***
"eps Eridani b"	***, 2,***	***1.0,***	***2.66E-02,***	***1.73E-03,***	***3.32E-04,***	***0.00E+00,***	***2.2***
"eps Eridani b"	***, 3,***	***1.0,***	***3.62E-02,***	***2.11E-03,***	***4.53E-04,***	***0.00E+00,***	***1.4***
"eps Eridani b"	***, 4,***	***1.0,***	***1.08E-02,***	***6.30E-04,***	***1.35E-04,***	***0.00E+00,***	***9.2***

Reference: WFIRST coronagraph milestones

MS #	Milestone	Date
1 ✓	First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than 10^{-4} and 20 μm pixel size.	7/21/14
2 ✓	Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	9/30/14
3	First-generation PIAACMC focal plane phase mask with at least 12 concentric rings has been fabricated and characterized; results are consistent with model predictions of 10^{-8} raw contrast with 10% broadband light centered at 550 nm.	12/15/14
4	Hybrid Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	2/28/15
5 ✓	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a static environment.	9/15/15
6	Low Order Wavefront Sensing and Control subsystem provides pointing jitter sensing better than 0.4 mas and meets pointing and low order wavefront drift control requirements.	9/30/15
7	Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.	8/25/16
8	PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized.	9/30/16
9	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.	9/30/16

https://conference.ipac.caltech.edu/wfirs2014/talks/WFIRS2014_Poberezhskiy.pdf