AFTA-WFIRST Coronagraph Instrument

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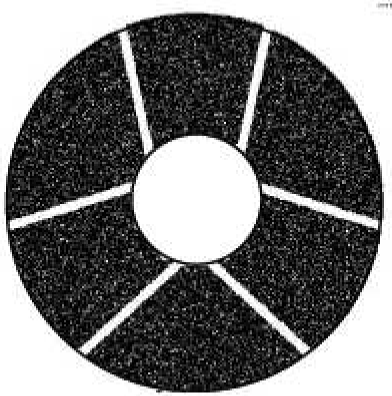
Overview

- Telescope
- Science Goals
- Coronagraph Performance Goals
- Mechanical Constraints
- Optical Layout
- Coronagraph Status
- Integral Field Spectrometer
- General Stability Requirements
- Integration Times
- Conclusions

AFTA Telescope

- 2.4 m
- Inclined geosynchronous orbit
- 5 year mission

- Pupil:



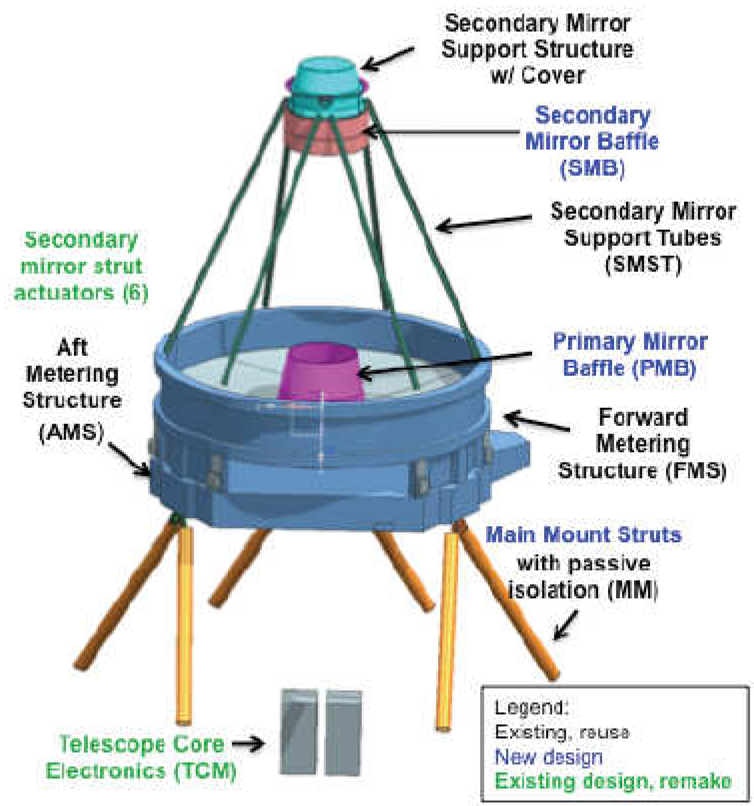


Figure 3-4: The telescope components without the outer barrel assembly.

Exoplanet Detection vs. Contrast and Working Angle

Source: WFIRST-AFTA STDT Report, May, 2013

ExoPlanet Exploration Program

550 nm:
1 λ/D = 47 mas

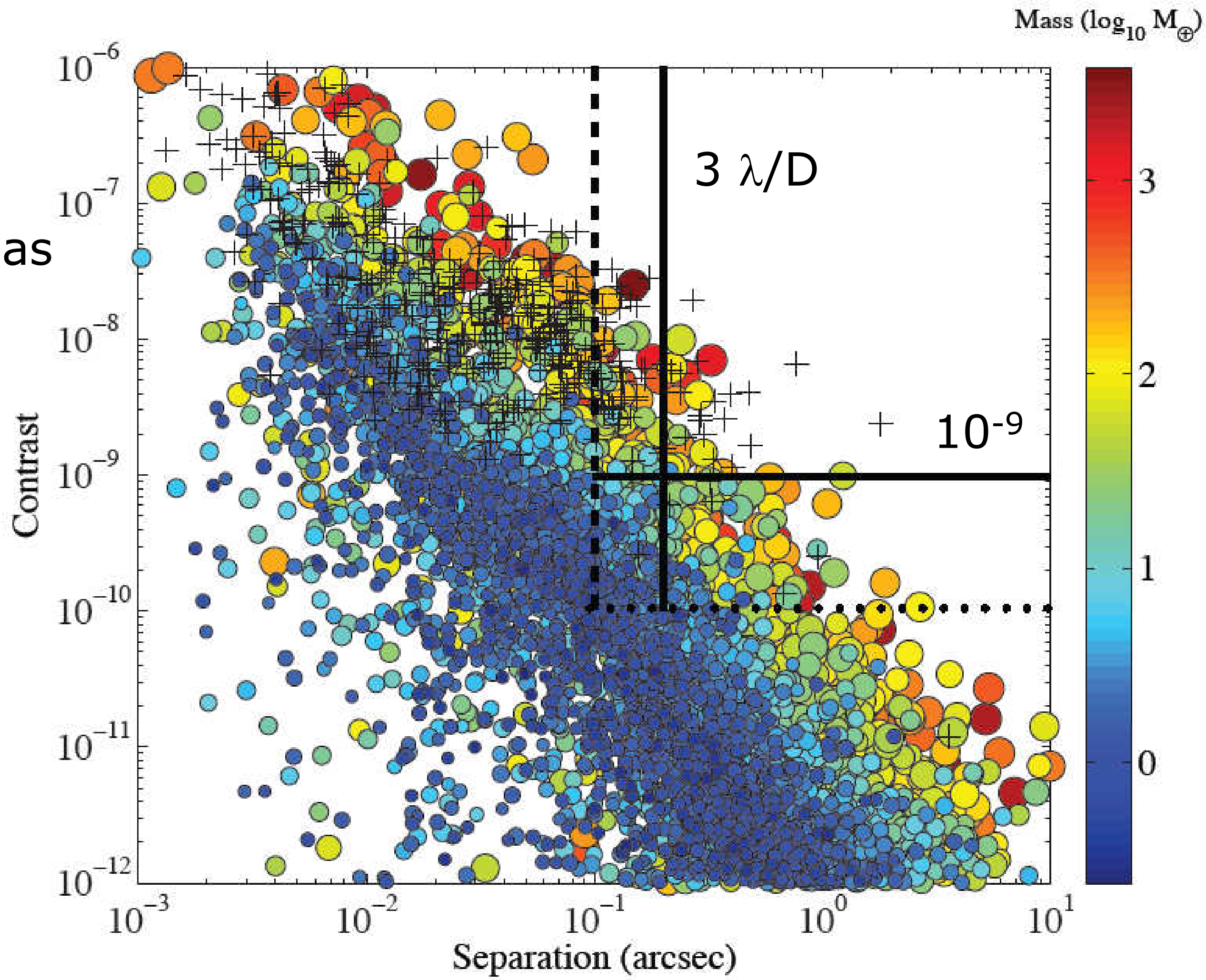


Figure 2-21: This figure is a snapshot in time of contrast and separation for model planets, ranging in size from Mars-like to several times the radius of Jupiter, for about 200 of the nearest stars within 30 pc. Color indicates planet mass while size indicates planet radius. Crosses represent known radial velocity planets. Solid black lines mark the baseline technical goal of 1 ppb contrast and 0.2 arcsec IWA, while the dotted lines show the more aggressive goals of 0.1 ppb and 0.1 arcsec IWA.

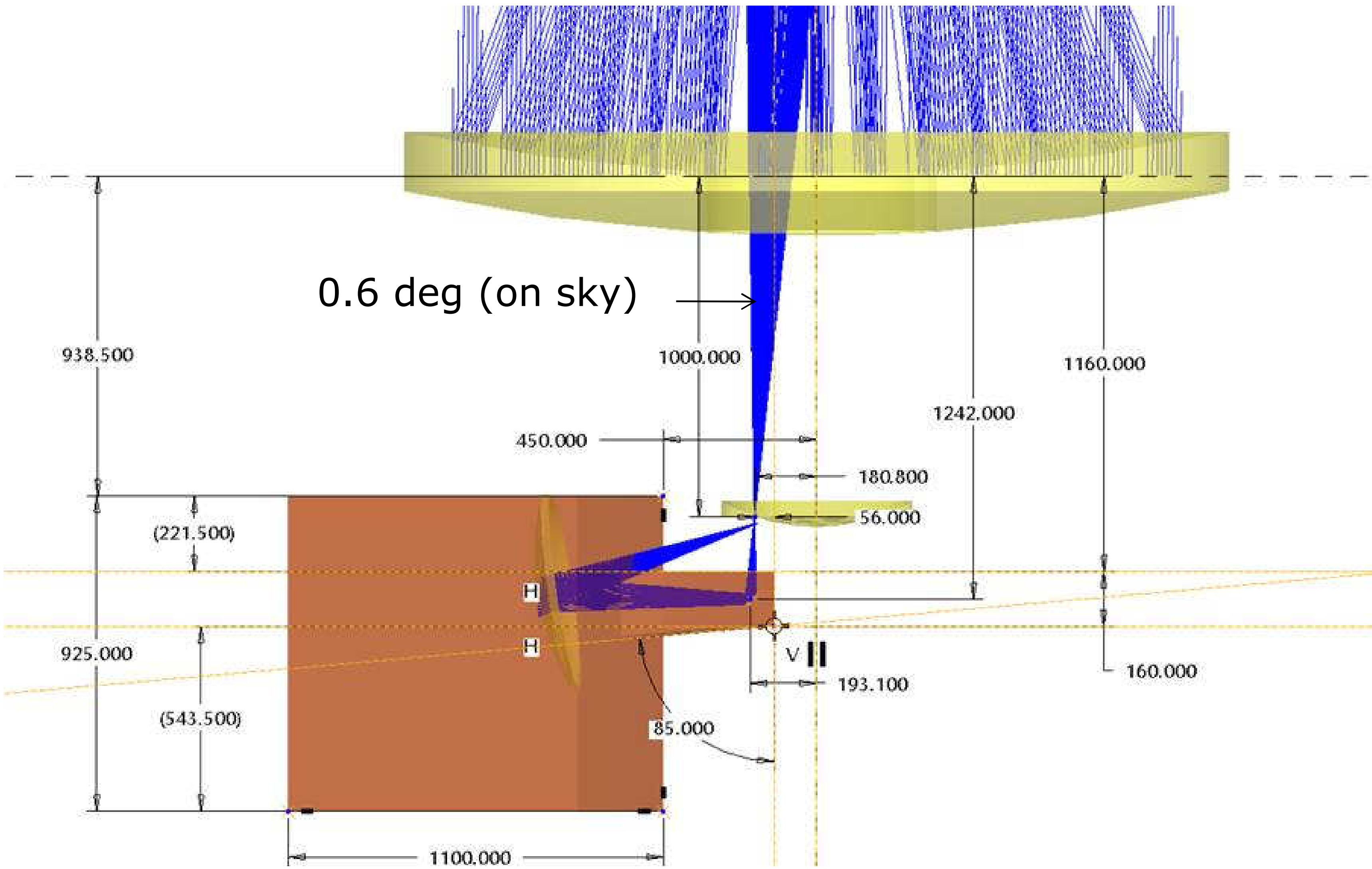
Coronagraph Performance Goals

Bandpass	400-1000 nm	Measured sequentially in five 18% bands
Inner Working Angle	100 mas	at 400 nm, 3 λ/D driven by challenging pupil
	250 mas	at 1 um
Outer Working Angle	1 arcsec	at 400 nm, limited by 64x64 DM
	2.5 arcsec	at 1 um
Detection Limit	Contrast =10^{-9}	Cold Jupiters, not exo-earths. Deeper contrast looks unlikely due to pupil shape and extrememe stability requirements.
Spectral Resolution	70	With IFS, ~70 across the spectrum.
IFS Spatial Sampling	17 mas	This is Nyquist for λ400 nm.

Key Characteristics

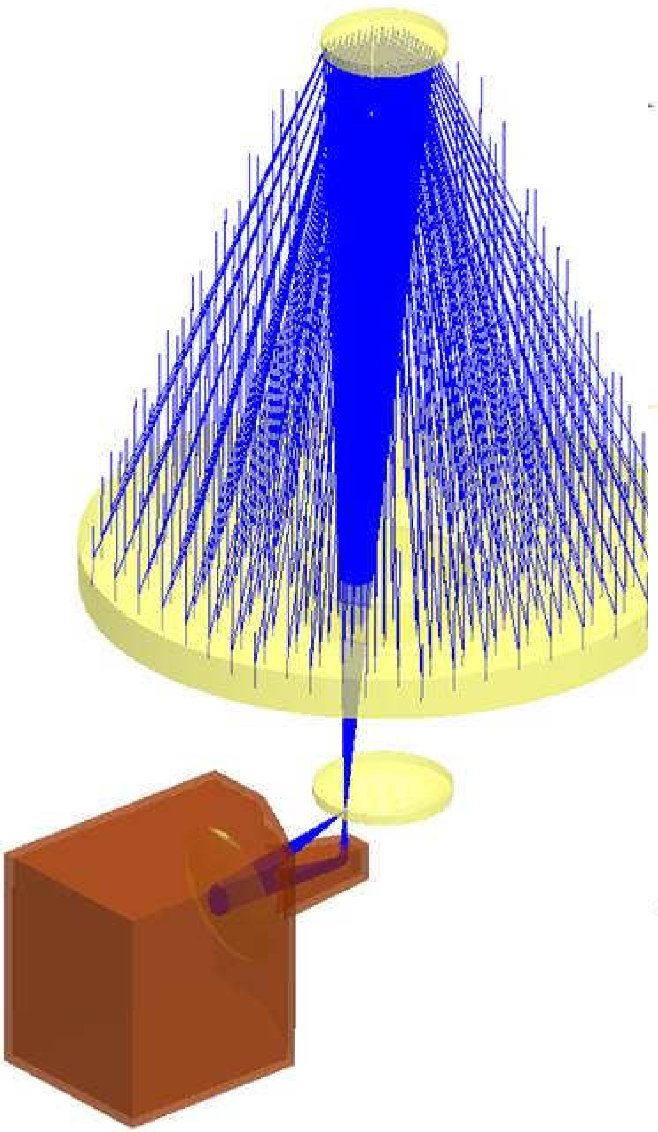
Coronagraph Type	Designed to support Lyot and shaped pupil coronagraphs.
Operating Temperature	Room Temperature, due to DM wavefront specifications.
Deformable Mirrors	Two 64x64 devices, sequentially placed for broadband dark hole control. Current design is for MEMS DM with 300 um pitch.
Detectors	Direct Imaging: 1K x 1K visible detector, 12 um (TBR) pixels Low Order Wavefront Sensor: E2V 39 (TBR), 24 um pixels IFS: 2K x 2K detector, ultra-low noise. 6.5 um pixels
IFS Bandpass	5 filters: 400-480 nm, 480-577 nm, 577-693 nm, 693-832 nm, 832-1000 nm

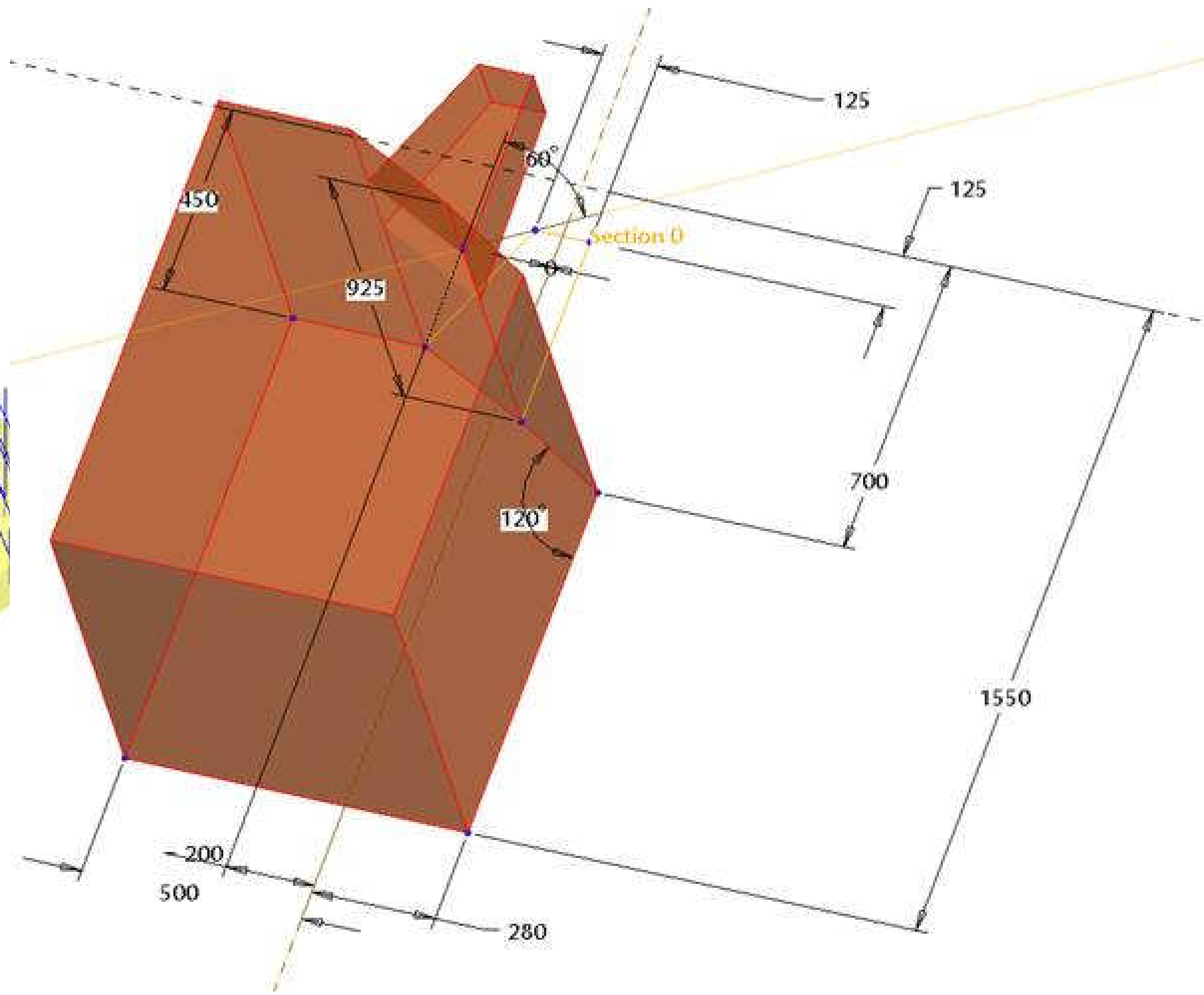
Volume Constraint (July 2013)



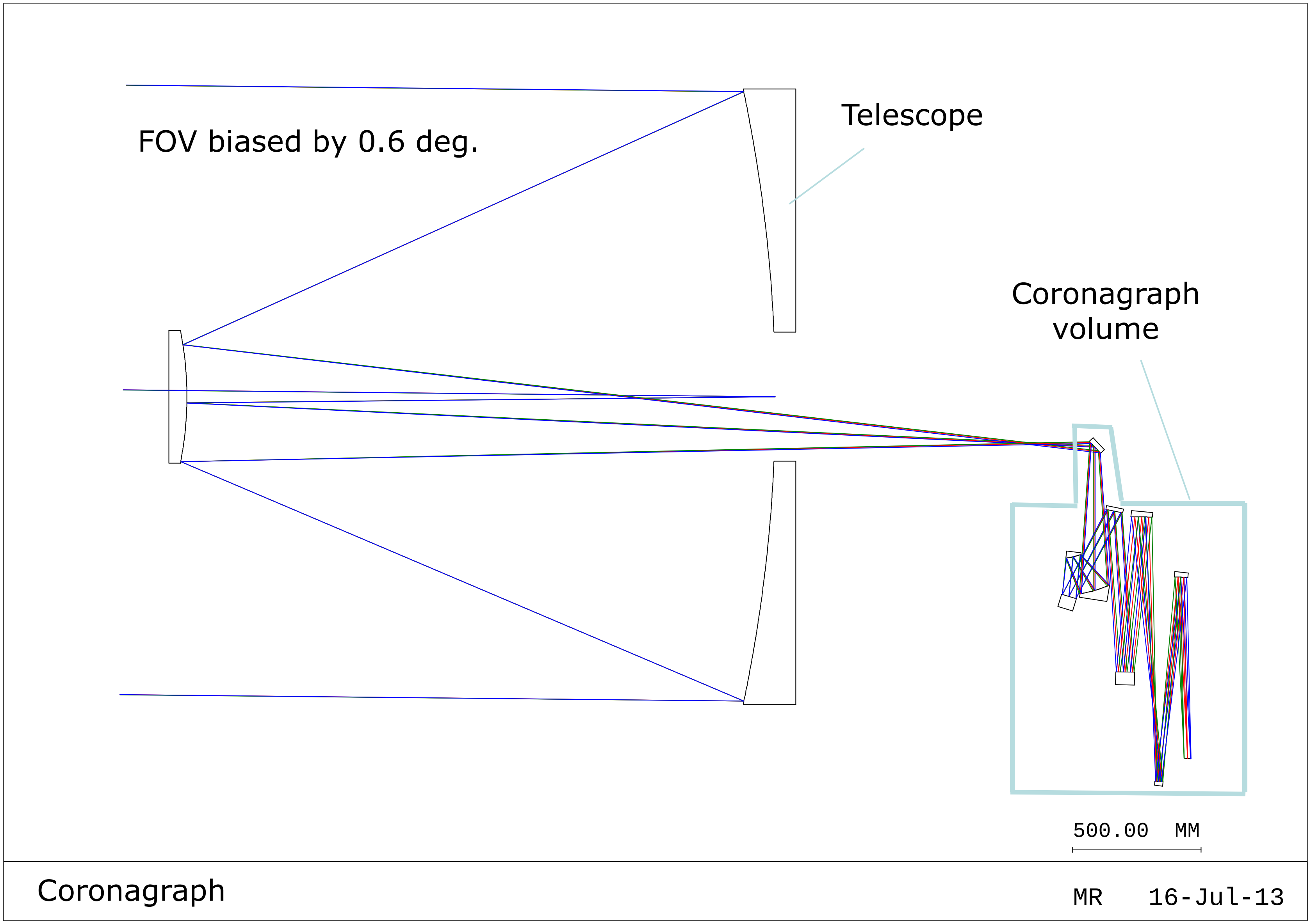
Coronagraph is designed to be serviceable on orbit. Box is installed on rails inside of an instrument carrier.

Cycle 4 Configuration (July 2013)

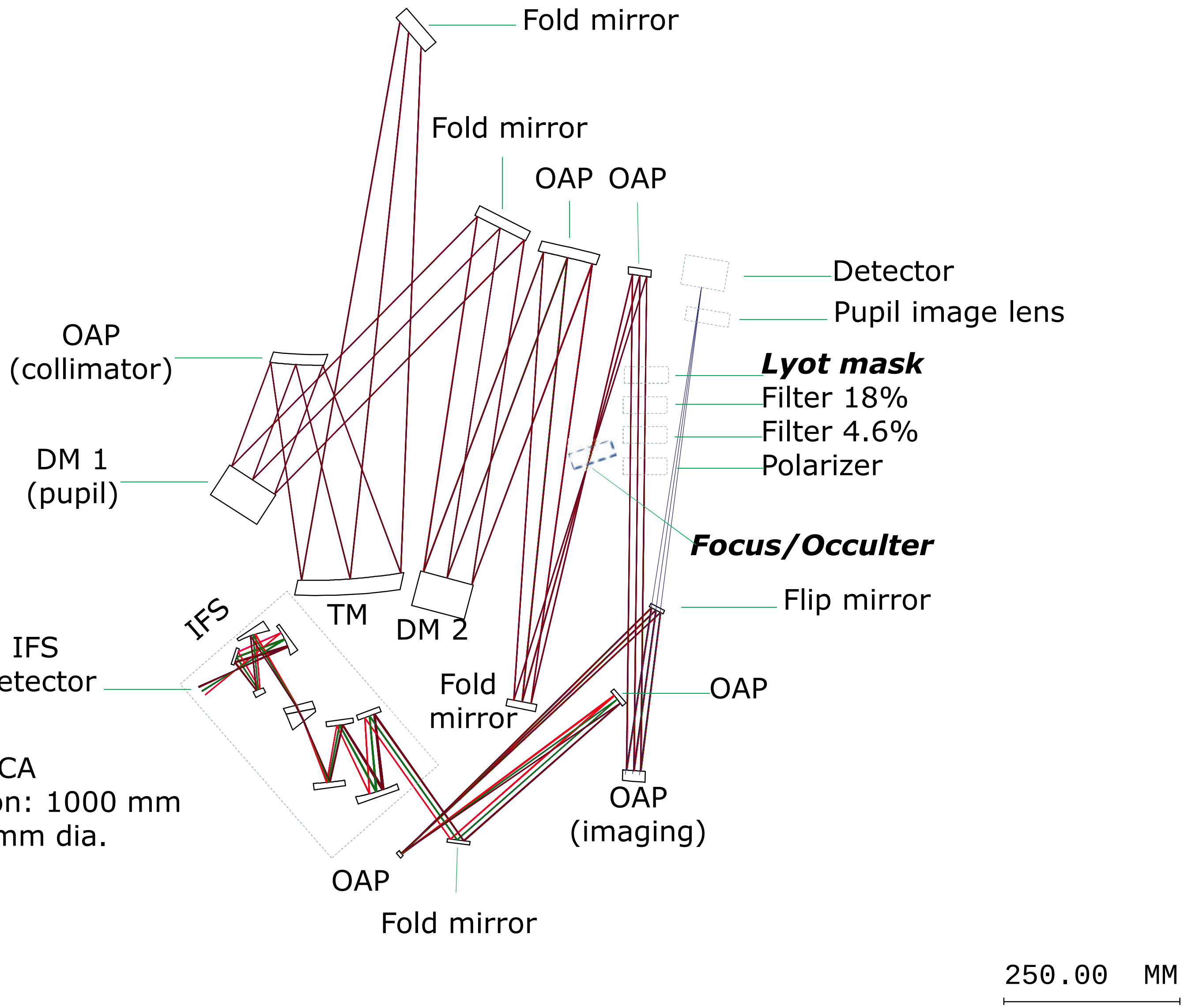




Coronagraph Optical Layout (July 2013)



Coronagraph Layout

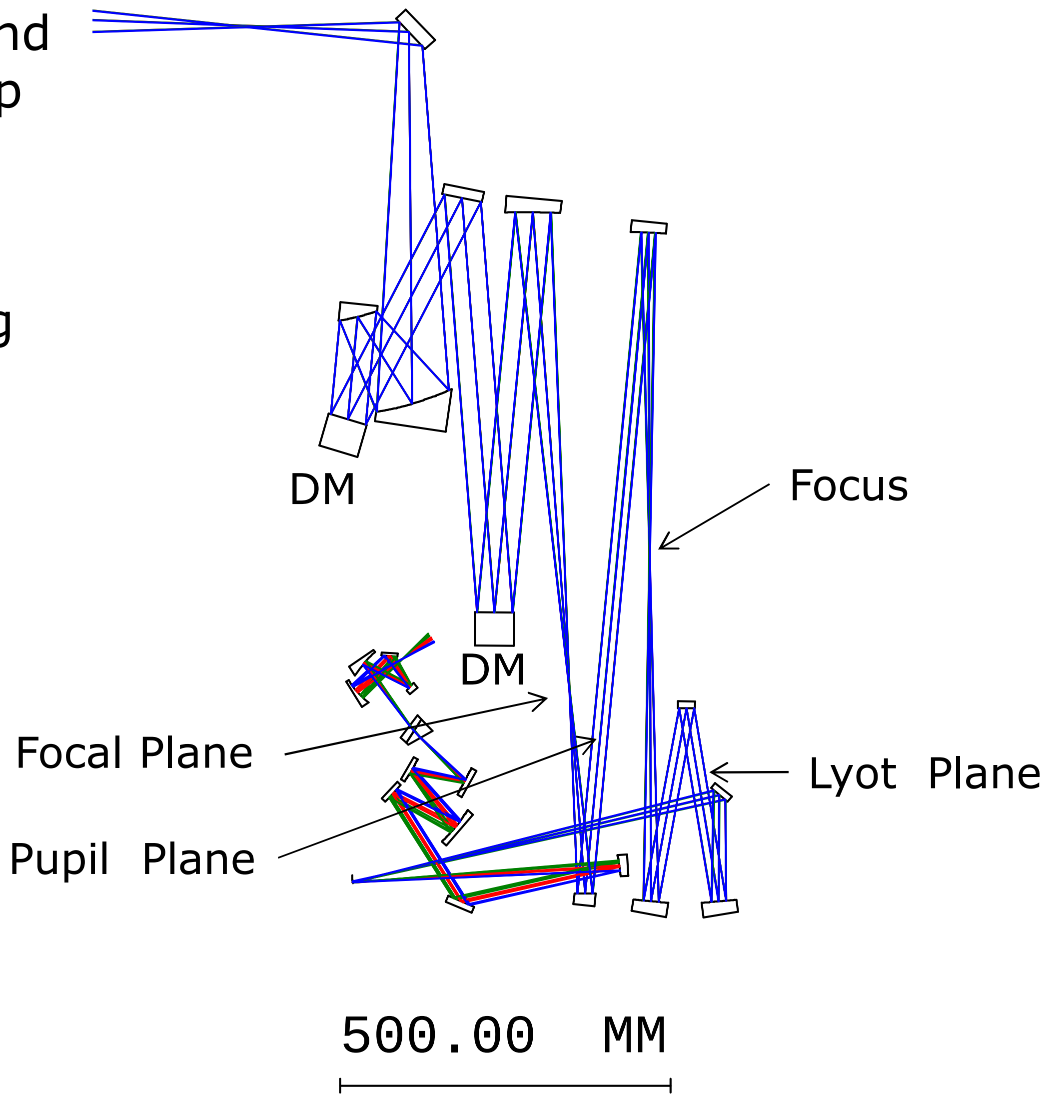


- DM 1 & 2: 64 mm CA
- DM 1 & 2 separation: 1000 mm
- Pupil 2 (Lyot): 20 mm dia.
- Imaging: F/35
- Compressor: F/15

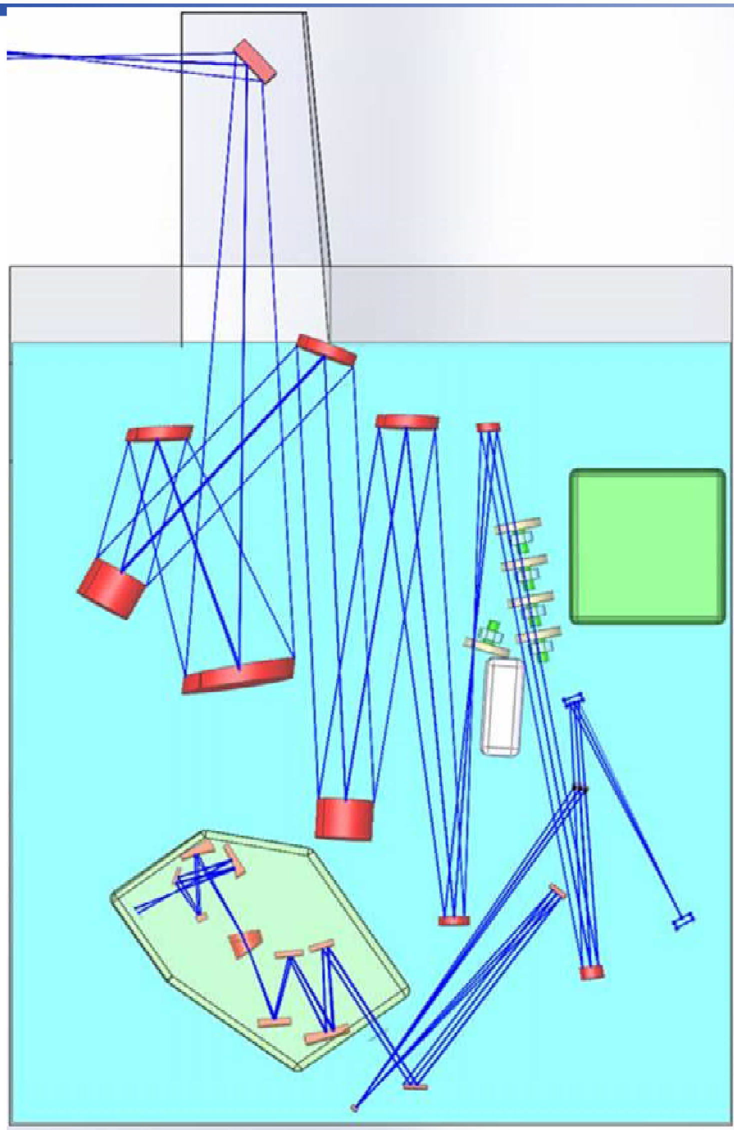
Layout with Additional Planes

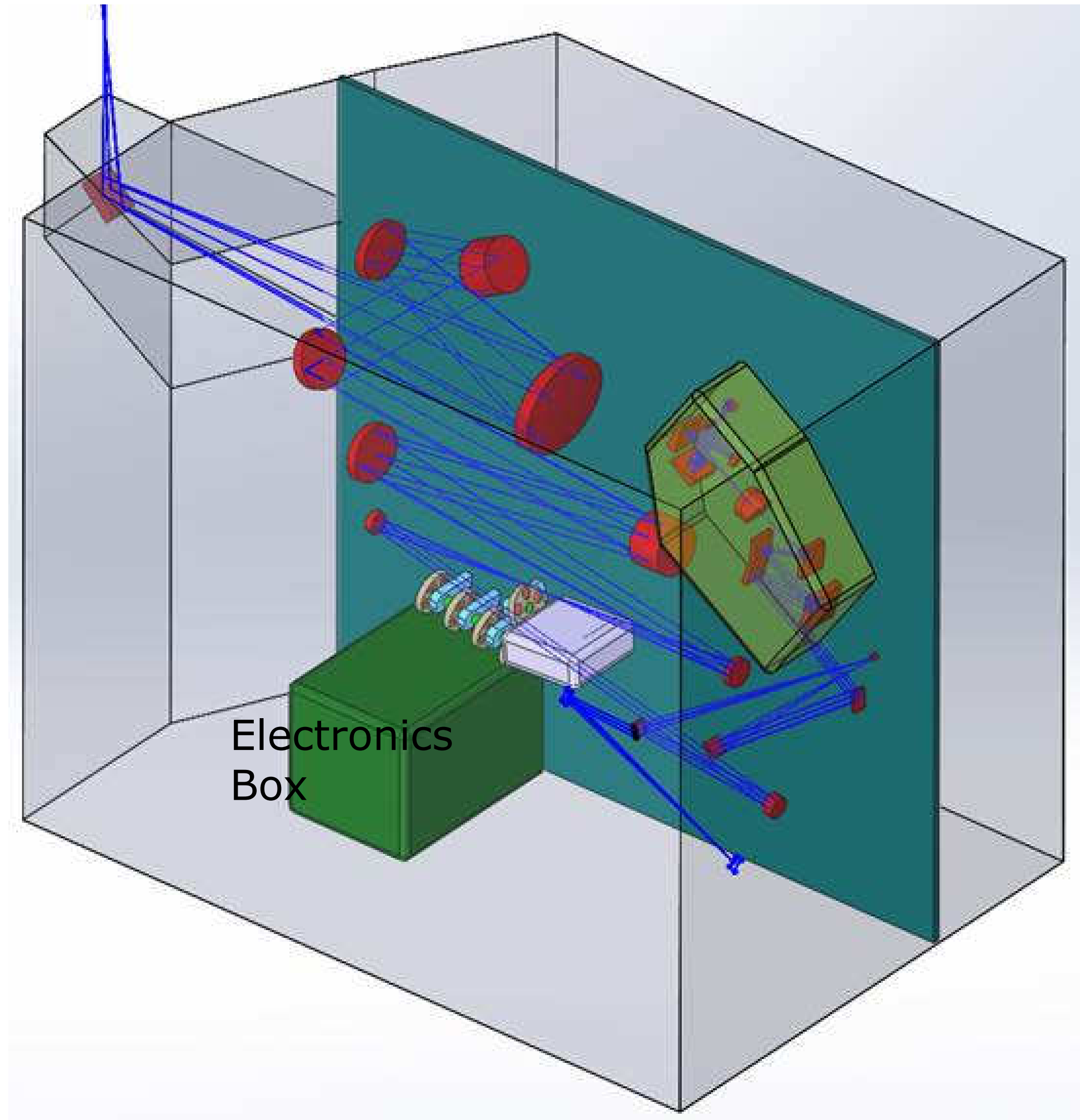
One additional reflection upstream of the occulter and another before the Lyot stop provide flexibility:

-Focus for field stop in Lyot
-Pupil plane for transmitting apodizer in VV and SP coronagraphs



Coronagraph within Allocated Volume





Potential Coronagraph Approaches

- There are 5 types of coronagraphs being considered for AFTA:
  - *Hybrid Band Limited*: circular mask, dielectric compensator, combination of Lyot Stop and sequential DMs to achieve high contrast (Trauger)
  - *Vector Vortex*: Single charge 4 mask, requires annular pupil apodization to deal with central obscuration, shaped pupil for secondary mirror supports, and sequential DMs (Serabyn, Mawet, Pueyo)
  - *Shaped Pupil*: binary apodized pupil with ‘islands’, likely a mirror with black silicon technology, sequential DMs to suppress frequency folding (Kasdin)
  - *PIAA-CMC*: (Complex mask coronagraph). Semi-transparent image plane mask for achromatization, on-axis PIAA optics, not limited by struts (Guyon, Belikov)
  - *Visible Nuller*: interferometric sheared 2-stage nuller with segmented DM and fiber/lenslet spatial filter array (Lyon, Clampin)

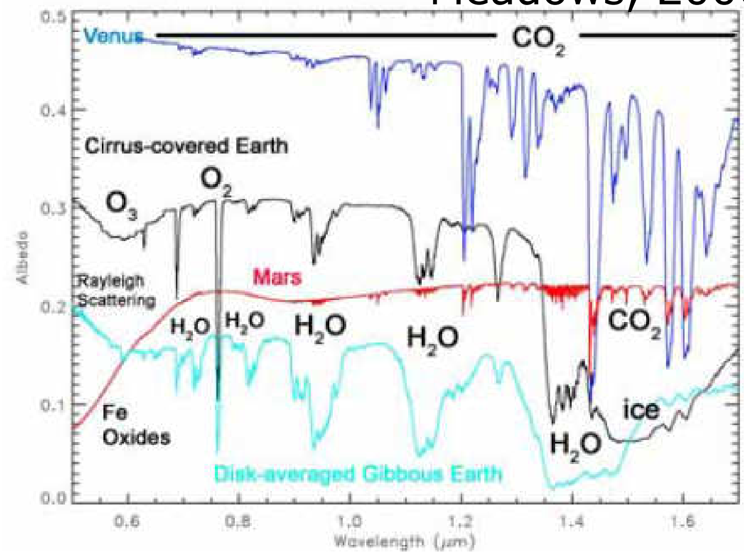
Relative Coronagraph Merits

- *Hybrid Band Limited*: moderate throughput, moderate bandwidth, heritage linked to 5e-10 contrast @ 4 l/D broad-band linear mask achieved on unobscured aperture
- *Vector Vortex*: Single polarization for moderate throughput, broad bandwidth, used in many ground-based telescopes
- *Shaped Pupil*: low throughput, large IWA, broad bandwidth, likely least sensitive to aberrations, 1e-9 broadband demo @ 4 l/D
- *PIAA-CMC*: highest throughput, unknown bandwidth for AFTA-type solution, demo'd 1e-8 contrast in few % bandwidth
- *Visible Nuller*: moderate to low throughput, moderate bandwidth, demo'd small few e-9 dark hole with half the device (no spatial filters, one nulling channel). Flew a channel on PICTURE (limited telemetry returned).
- ***Upcoming downselect to two approaches by January 2014***

Integral Field Spectrograph

- Follows design principles of ground-based IFS instruments, e.g. CHARIS (Princeton), GPI, SPHERE. OSIRIS
- 140 x 140 lenslet array. Designed to disperse 20% band over 24 detector pixels (SR ~70).
  - Accommodates 0.4 – 1 um range using 5 bandpass filters (one at a time)
  - 17 mas 'spaxel' pitch.

Meadows, 2006



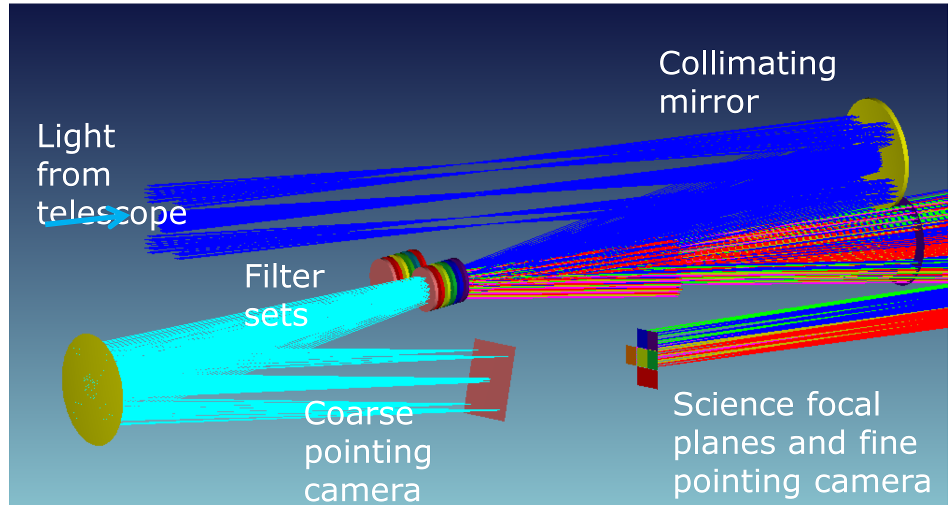
Wavelength	Spect. Resol	Species	line depth	At this abundance level
0.58	5	O3	0.112	3 ppm
0.69	54	O2	0.088	10%
0.72	37	H20	0.13	1000 ppm
0.73	57	CH4	0.07	1000 ppm
0.76	69	O2	0.388	10%
0.79	29	CH4	0.032	1000 ppm
0.82	35	H20	0.118	1000 ppm
0.89	32	CH4	0.417	1000 ppm
0.94	17	H20	0.401	1000 ppm
1.05	40	C02	0.001	1000 ppm

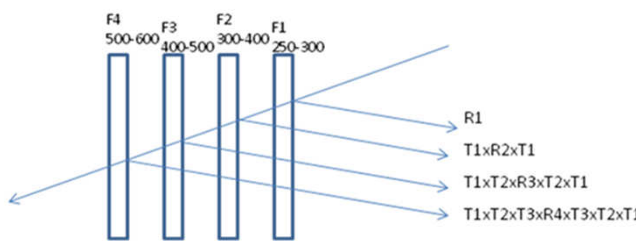
IFS Alternatives?

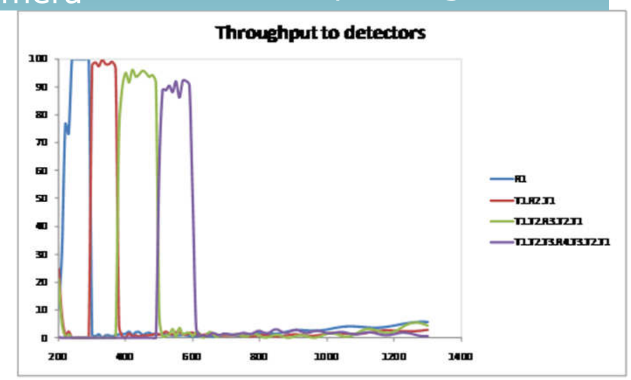
ExoPlanet Exploration Program

For broadband wavefront sensing:

Dichroic Tree
-Put four 2% beams on a detector or on separate detectors.
-The problem is we still need 4 additional filters sets in the wheel.







For spectroscopy, consider a fiber fed 1-D spectrometer. The fiber is positioned to pick off planet light using an x-y-z stage. >> throughput than an IFS and no spectral isolation problems. But not good for WFS.

Strawman Stability Allocations: Linear Drift Terms

Motion of Secondary Mirror Relative to Primary Mirror

x-rotation	6	nrad
y-rotation	6	nrad
z-rotation	2	nrad
x-translation	2	nm
y-translation	7	nm
z-translation	6	nm

Motion of Coronagraph Relative to Primary Mirror

x, y, z rotation	0.25	urad
x, y, z translation	0.25	um

Primary Mirror Deformation

Focus	33	pm
Astigmatism per axis	1.3	pm
Coma per axis	0.7	pm
Trefoil per axis	1	pm
Spherical Aberr.	4	pm
Higher order Aberr.	<1	pm each

Only contribute terms that LOWFS doesn't measure.

Pointing

Telescope Rigid Body/axis	10	mas
Centration of spot on mask	TBD	uas

Drift of zero point

Integration Time: Imaging

AFTA Integration Time Examples, 10% bandpass

For SNR=5 observation, 100 s readout, , Coronagraph throughput 0.2, Telescope throughput 0.6

V	log10(Planet Contrast)	log10(Instr. Contrast)	#Zodis (solar + exo)	Dark current (e-/pix/s), Read Noise e/pix	Bandpass	INTEG. TIME (Hours)	Comment
5	-9	-9	3	0 , 0	10%	1.37	Jupiter, Noiseless detector
5	-9	-9	3	0, **0.1**	10%	1.41	Read noise
5	-9	-9	3	0, **0.2**	10%	1.52	More read noise
5	-9	-9	3	0, **0.5**	10%	2.29	More read noise
5	-9	-9	3	**0.0001**, 0	10%	1.41	Dark Current
5	-9	-9	3	**0.0002**, 0	10%	1.45	More dark Current
5	-9	-9	3	**0.001,** 0	10%	1.74	More dark current
5	-9	**-8**	3	0, 0	10%	4.8	Instrument-limited
5	-9	**-8**	3	0.001, 1	10%	8.4	Instrument-limited
5	**-10**	-9	3	0.0001, 0.1	10%	111	exo-Earth
5	-9	-9	3	**0.001/0.5**	10%	2.7	Jupiter, RN and DC
5	-9	-9	3	**0.001/1**	10%	5.4	more RN and DC

Important: The IFS is designed for at most 18% bandwidth (selectable with a filter wheel). Characterization of planet spectra across 400-800 nm requires repeating characterization observations 5 times.

Integration Time: Spectroscopy

AFTA Integration Time Examples, 2% bandpass

For SNR=5, 100 s readout, , Coro throughput 0.2, Telescope throughput 0.6, IFS throughput =0.5

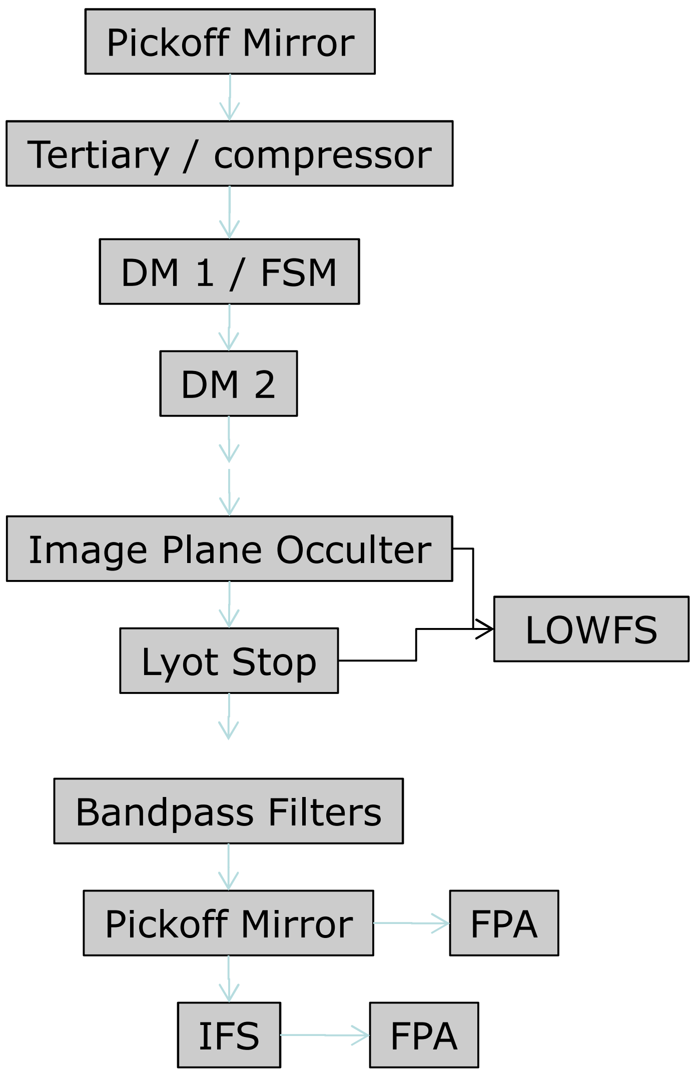
V	log10(Planet Contrast)	log10(Instr. Contrast)	#Zodis (solar + exo)	Dark current (e-/pix/s), Read Noise e/pix	Bandpass	INTEG. TIME (Hours)	Comment
5	-9	-9	3	0 , 0	2%	13.7	Jupiter, Noiseless detector
5	-9	-9	3	0, **0.02**	2%	13.9	Read noise
5	-9	-9	3	0, **0.05**	2%	14.6	More read noise
5	-9	-9	3	0, **0.1**	2%	17.4	More read noise
5	-9	-9	3	**0.00005**, 0	2%	15.6	Dark Current
5	-9	-9	3	**0.0001**, 0	2%	17.4	More dark Current
5	-9	-9	3	**0.001,** 0	2%	50	More dark current
5	-9	**-8**	3	0, 0	2%	47	Instrument-limited
5	-9	**-8**	3	**0.0001/0.1**	2%	55	Instrument-limited
5	**-10**	-9	3	0.0001, 0.1	2%	1770	exo-Earth
5	-9	-9	3	**0.0001/0.1**	2%	21	Jupiter, RN and DC
5	-9	-9	3	**0.001/0.5**	2%	142	more RN and DC

Important: The IFS is designed for at most 18% bandwidth (selectable with a filter wheel). Characterization of planet spectra across 400-800 nm requires repeating the characterization observations 5 times.

Conclusions

- Layouts accommodate various forms of coronagraphs.
- A decision on the type of coronagraph to be flown will happen in January, 2014.
- A LOWFS can significantly relax the requirements
  - Must study how well the LOWFS needs to work.
- The hard part about the coronagraph is likely to be opto-mechanical stabilization when we have:
  - A room temperature coronagraph mounted on rails in a
  - colder instrument carrier, adjacent to a colder WFIRST instrument
  - all sitting behind a moderate temperature primary mirror.
  - And a geosychronous orbit.
- It is important to keep the instrument background at or below the level of the zodi, to keep integration times down.

Coronagraph Block Diagram



Transfer off-axis beam to instrument.

Aspheric terms, 48 or 64 mm beam

Pupil: Phase control and pointing

Amplitude control via phase.

Hybrid-band-limited mask
Blocks diffraction from image plane occulter
LOWFS may be image plane or pupil plane
DMs are integral part of diffraction control.

10% and 2.5% filters

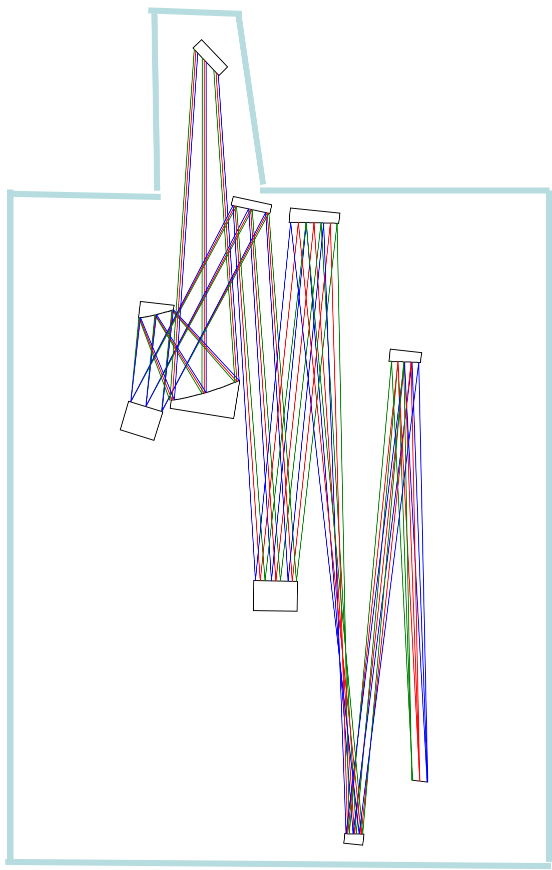
Choose imaging FPA or IFS

Resolve 10% bandpass with R=70

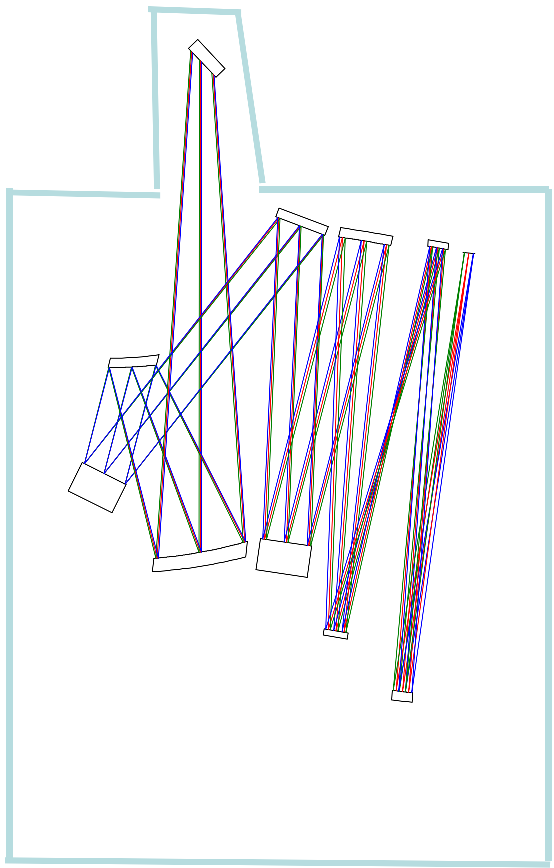
48 vs 64 mm Beam

ExoPlanet Exploration Program

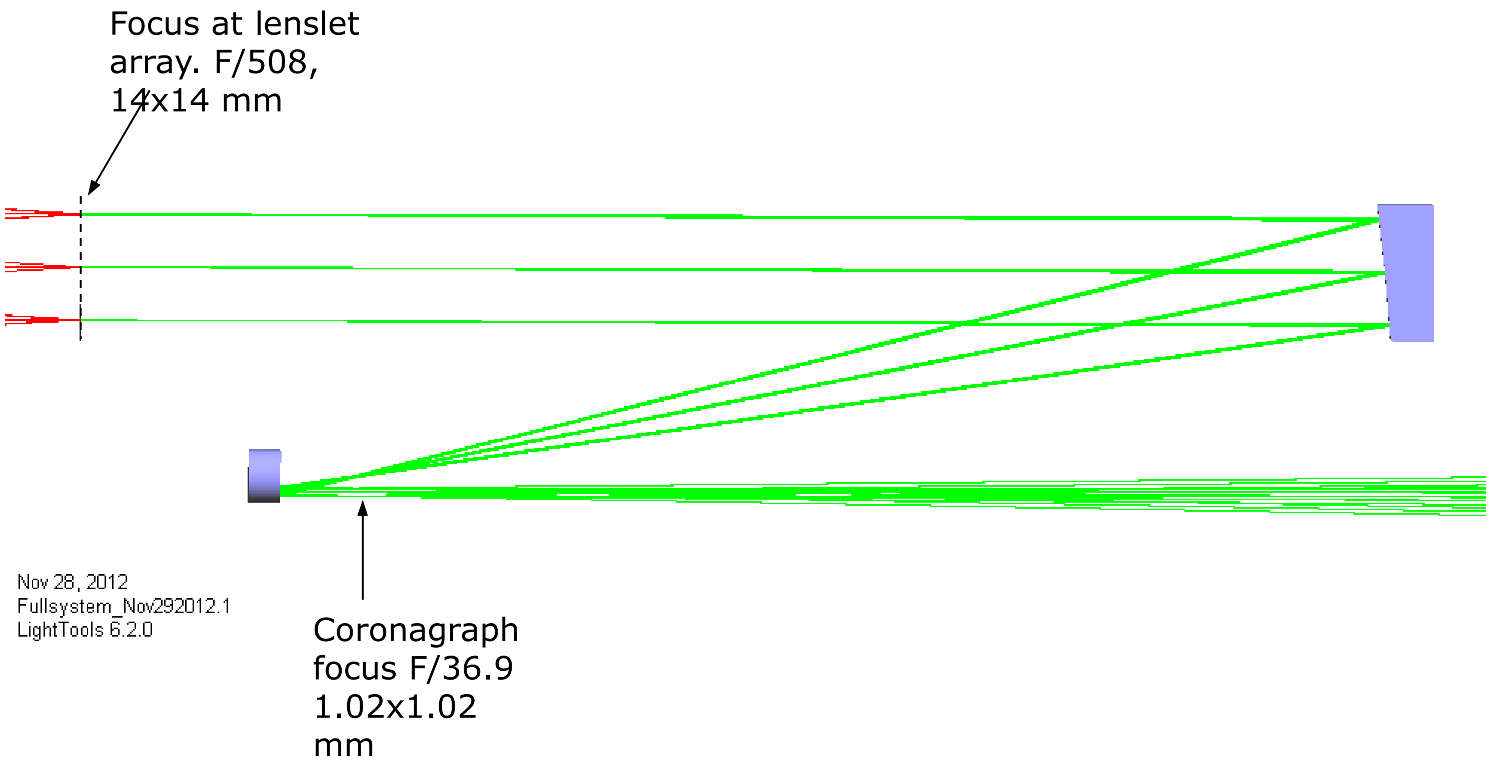
With 48 mm DM



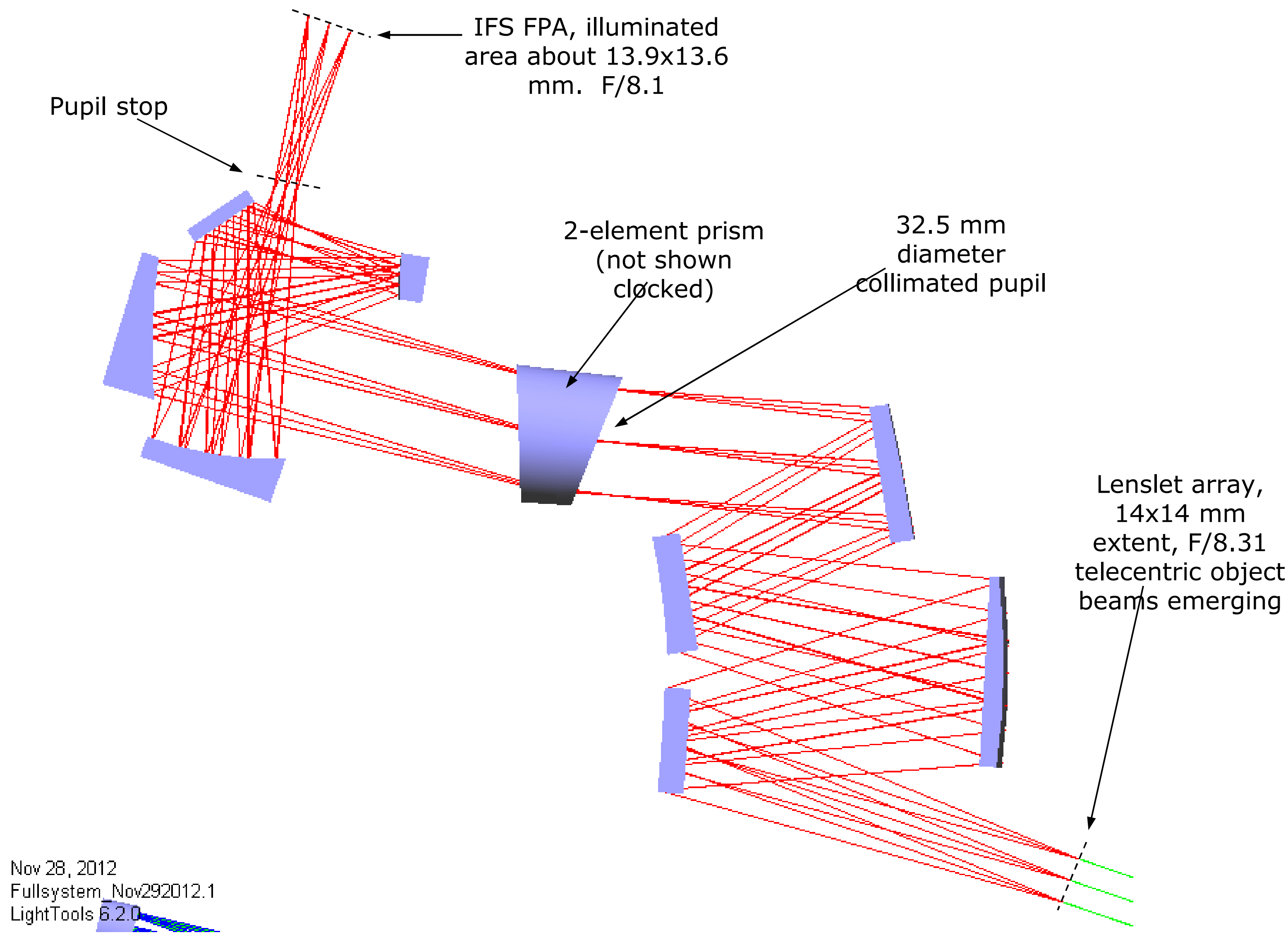
With 64 mm DM



IFS Relay from F/36.9 coronagraph focus to F/508 focus at lenslet array



IFS



IFS FPA, illuminated area about 13.9x13.6 mm. F/8.1
Pupil stop
2-element prism (not shown clocked)
32.5 mm diameter collimated pupil
Lenslet array, 14x14 mm extent, F/8.31 telecentric object beams emerging
Nov 28, 2012
Fullsystem_Nov292012.1
LightTools 6.2.0

Spectral Characterization

Source: WFIRST-AFTA STDT Report, May, 2013

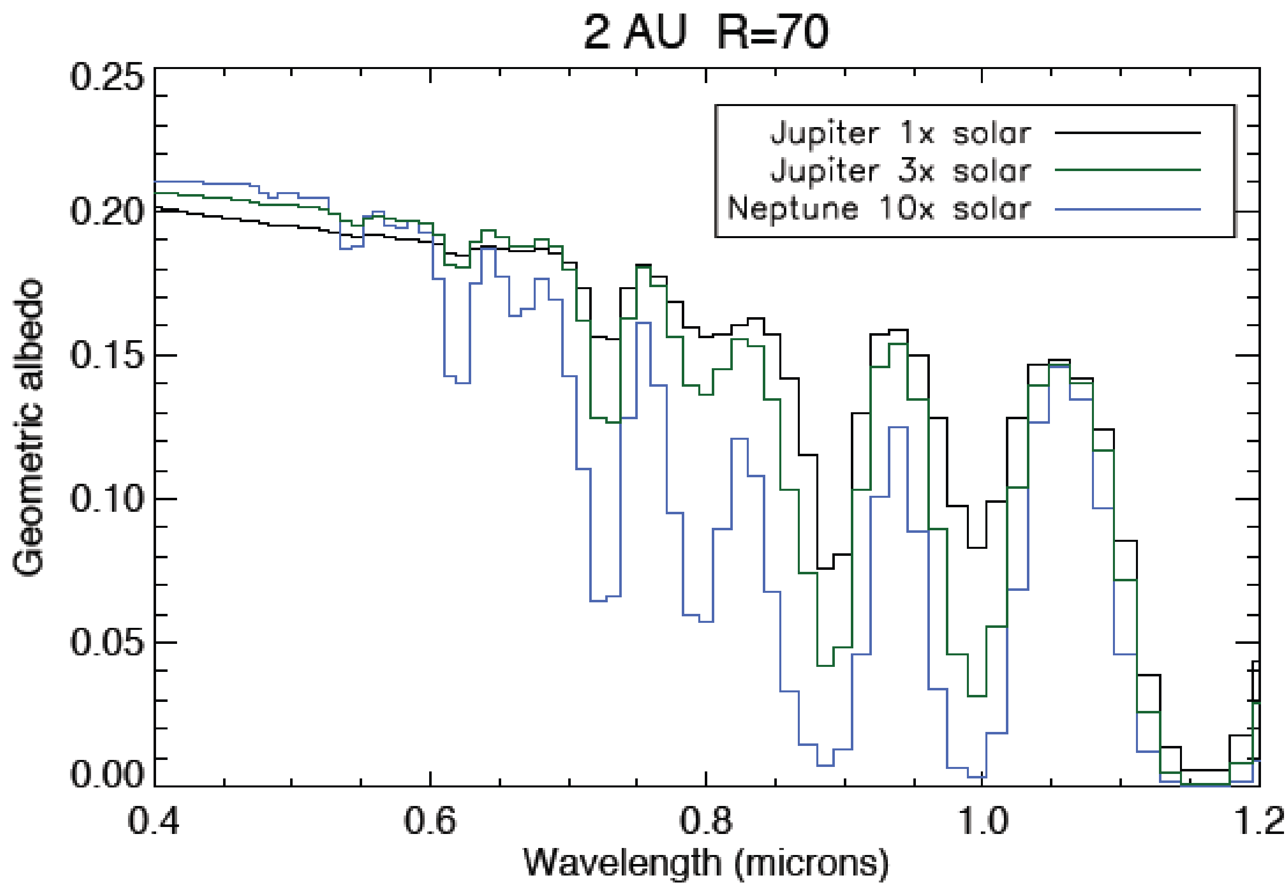
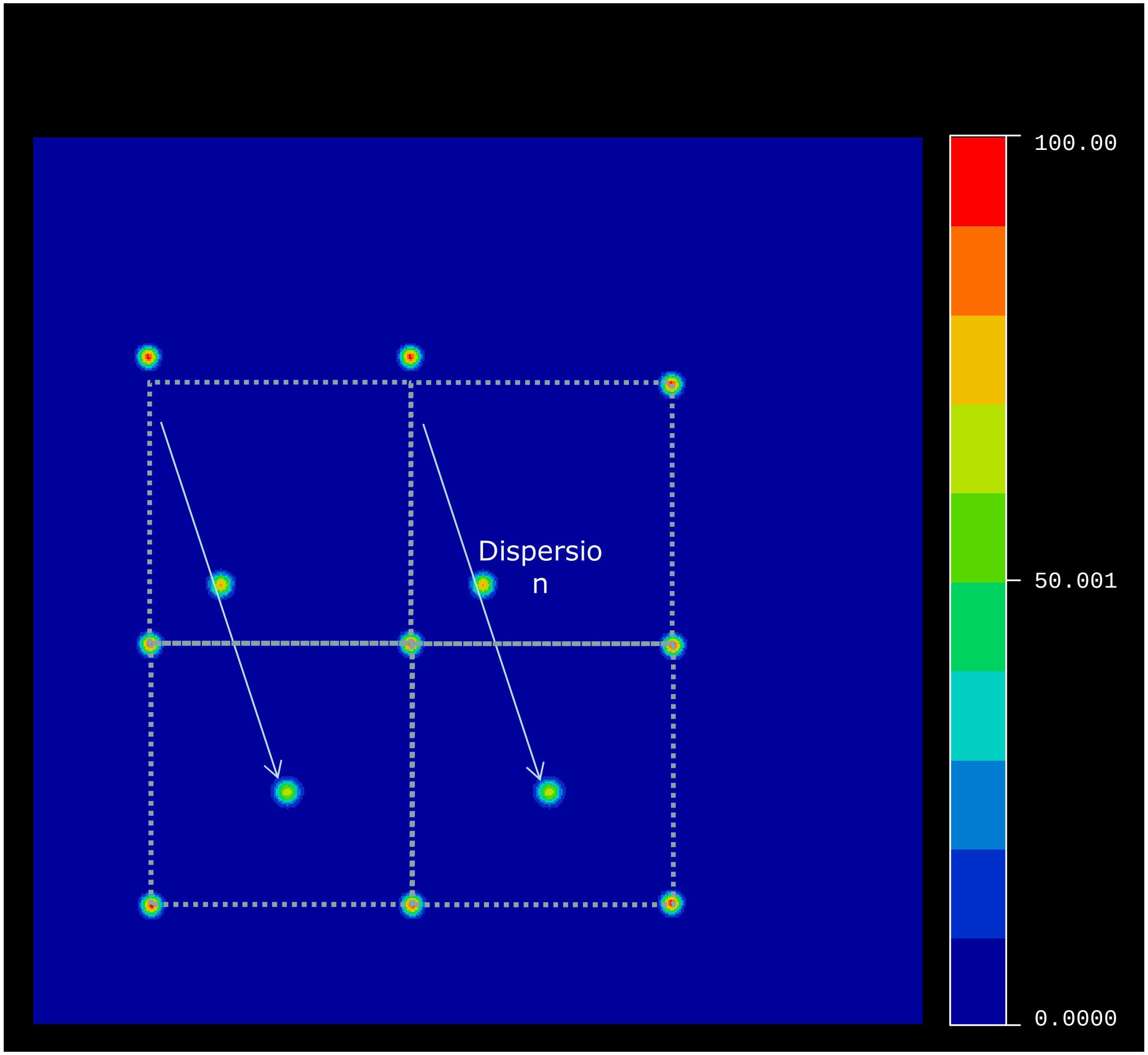


Figure 2-22: Model exoplanet spectra (Cahoy et al 2010) for a Jupiter-mass planet with stellar metallicity (1x solar) and one enhanced in heavy elements by formation (3x), and a Neptune-like planet (10x). Spectra have been binned to the resolution of the WFIRST-2.4 coronagraph spectrometer, $\lambda/\Delta\lambda$ = 70. The three classes of planets are easily distinguishable.

9 spaxels, two shown dispersed 690-760-830 nm



Dispersion of two adjacent spaxels, 690-760-830 nm (15 pixels horizontal separation)