# AFTA Coronagraph Update

Stuart Shaklan, Marc Foote, Mike Underhill, Marie Levine (JPL)
Mike Rodgers (Synopsys)

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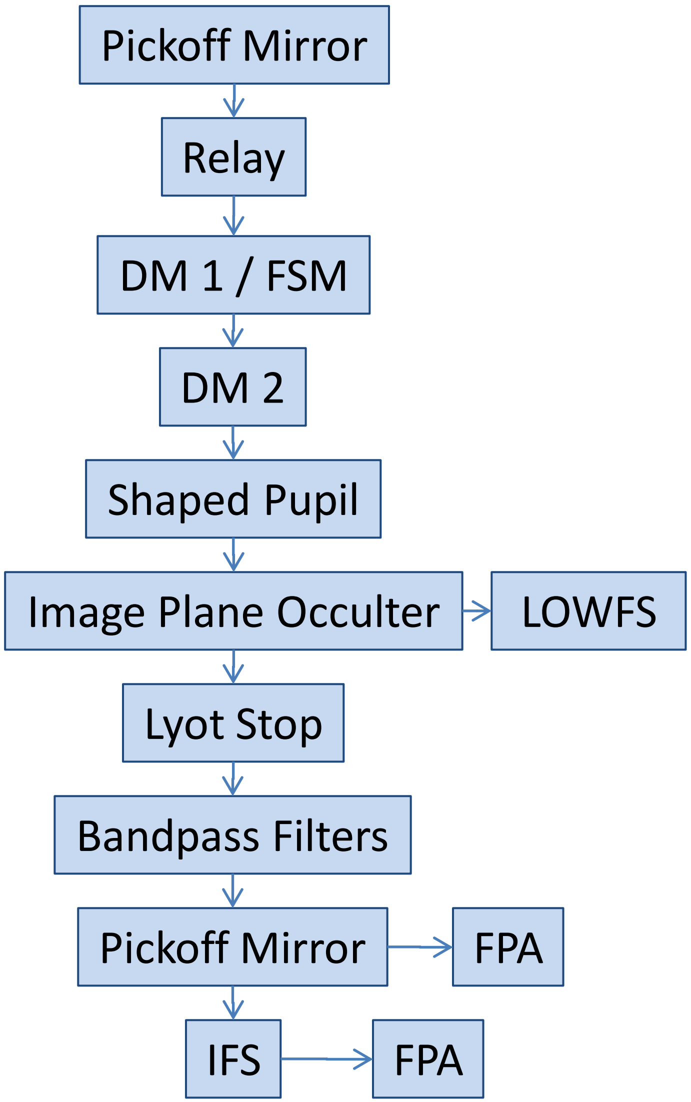
# Coronagraph Performance Goals

| | | |
|---|---|---|
| Bandpass | 400-1000 nm | Measured sequentially in five 18% bands |
| Inner Working Angle | 100 mas | at 400 nm, 3 $\lambda$/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 $\lambda$400 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<br>Low Order Wavefront Sensor: E2V 39 (TBR), 24 um pixels<br>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 |

# Coronagraph Block Diagram




Transfer on-axis beam to instrument.

Phase control and pointing

Amplitude control via phase.

Apodization for struts and secondary

Nearly-band-limited mask, central spot feeds low order wavefront sensor.

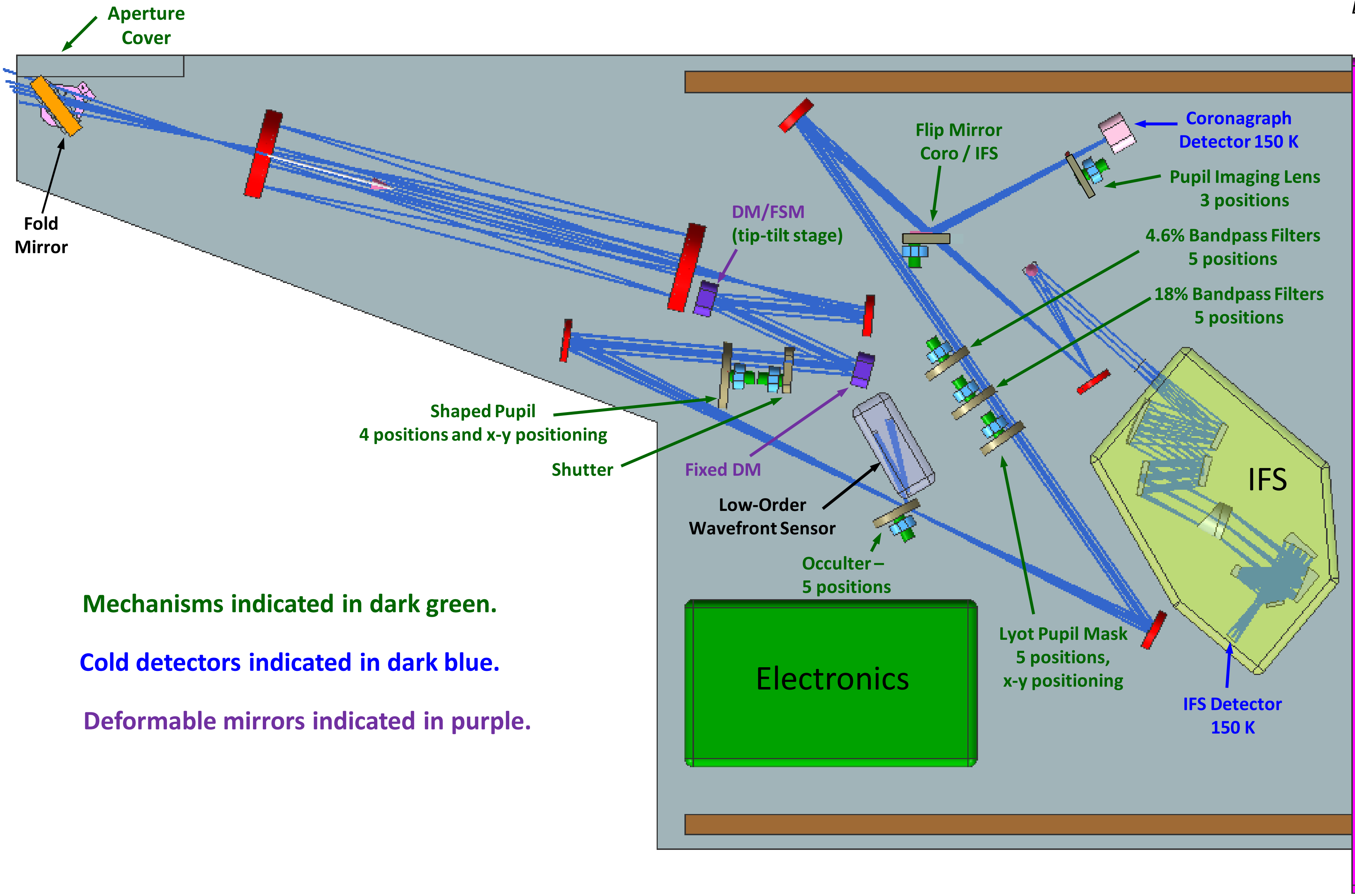
Blocks diffraction from image plane occulter

18% and 4% filters

Choose imaging FPA or IFS

Resolve 18% bandpass with R=70

# Coronagraph Mechanical Layout

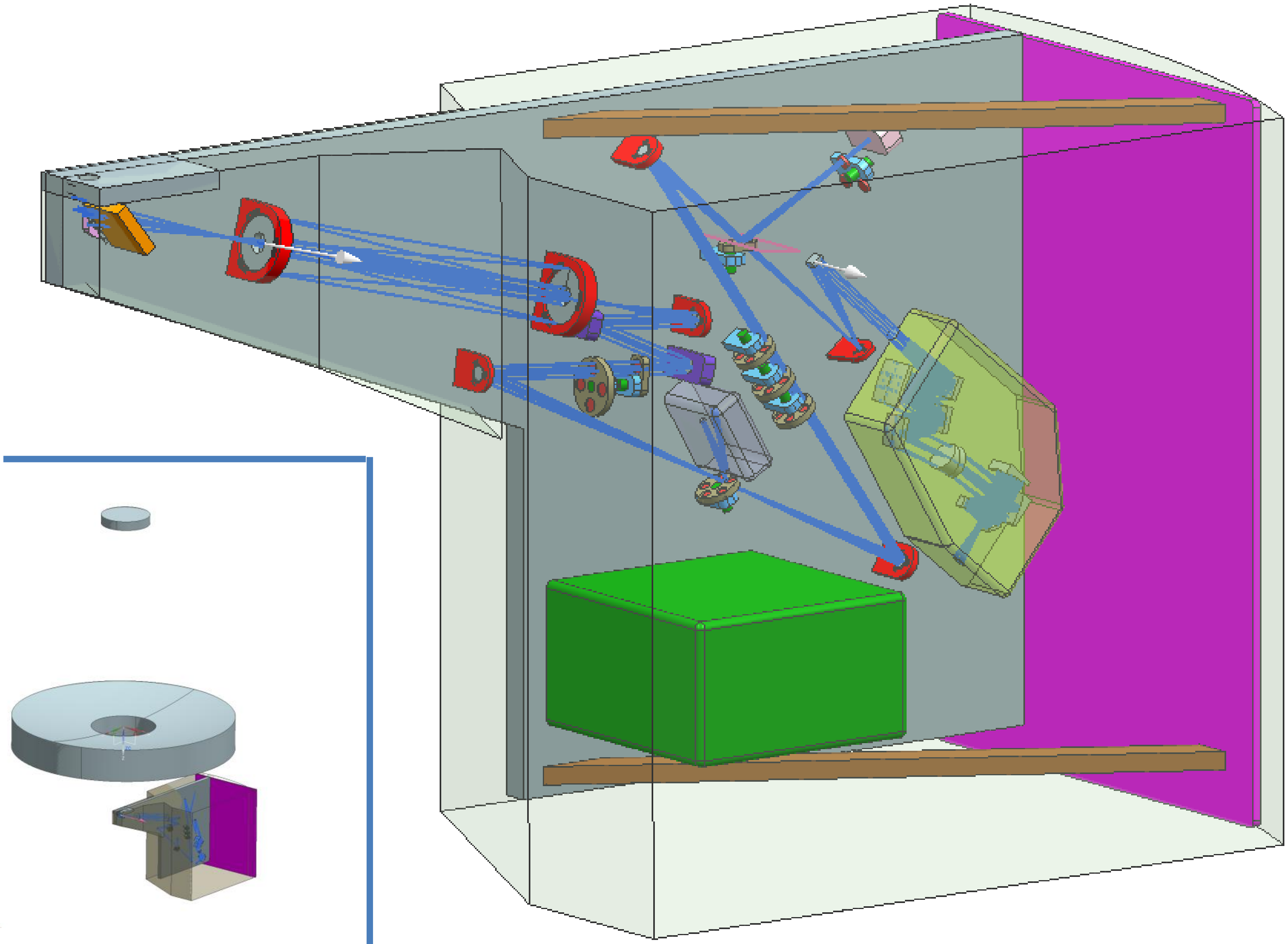



Mechanisms indicated in dark green.

Cold detectors indicated in dark blue.

Deformable mirrors indicated in purple.

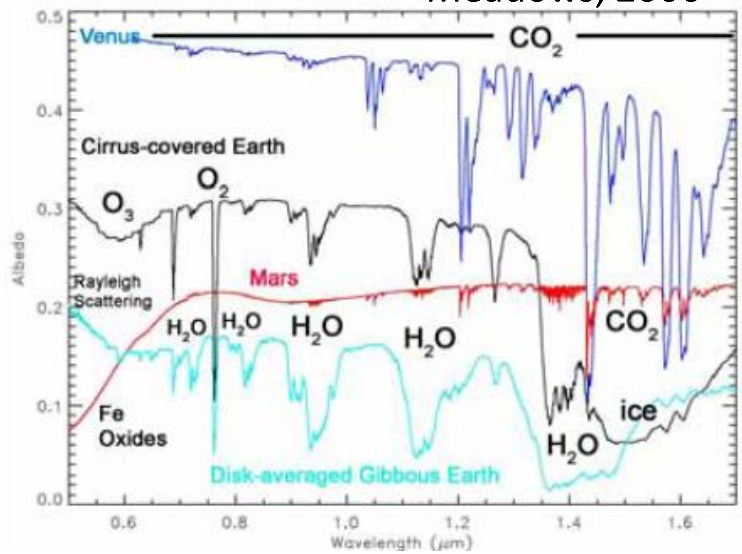
# Coronagraph and IFS Packaging



# Integral Field Spectrograph

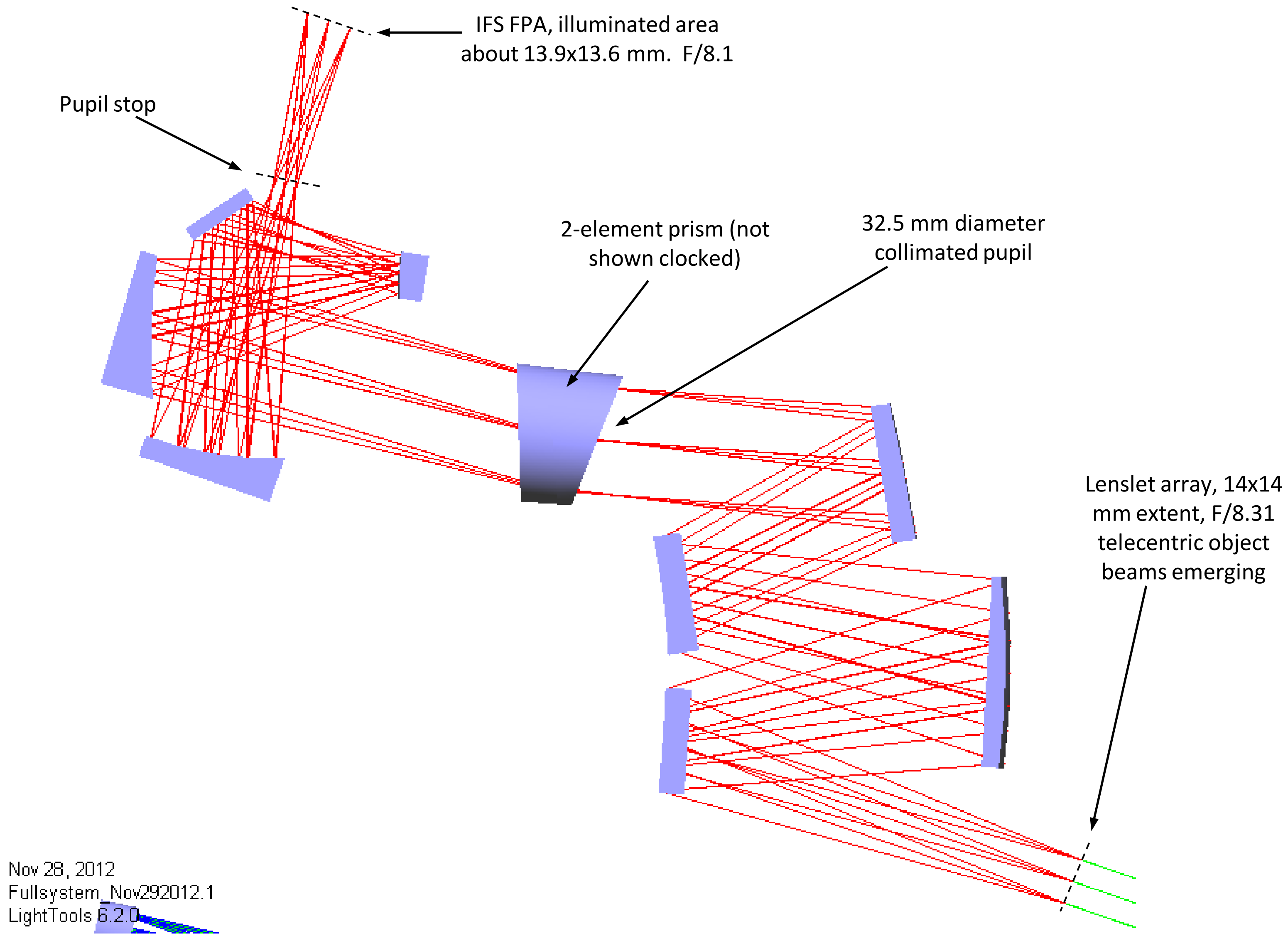
- Follows design principles of ground-based IFS instruments, e.g. CHARIS (Princeton), GPI, SPHERE. OSIRIS
- 140 x 140 lenslet array. Designed to disperse 20% band over 24 detector pixels (SR ~70).
  - Accommodates 0.4 – 1 um range using 5 bandpass filters (one at a time)
  - 17 mas 'spaxel' pitch.

Meadows, 2006

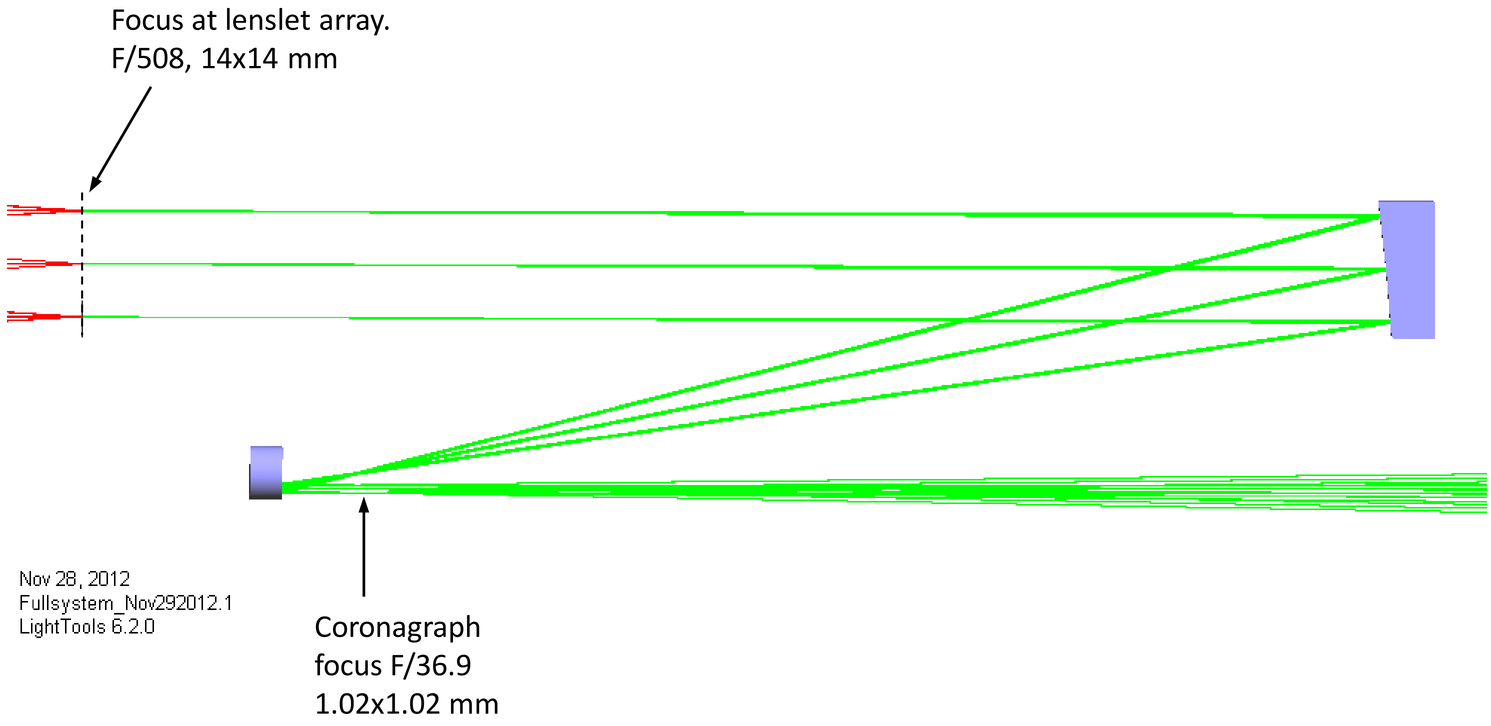



| Wavelength | Spect. Resol | Species | line depth | At this abundance level |
|---|---|---|---|---|
| 0.58 | 5 | O3 | 0.112 | 3 ppm |
| 0.69 | 54 | O2 | 0.088 | 10% |
| 0.72 | 37 | H20 | 0.13 | 1000 ppm |
| 0.73 | 57 | CH4 | 0.07 | 1000 ppm |
| 0.76 | 69 | O2 | 0.388 | 10% |
| 0.79 | 29 | CH4 | 0.032 | 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


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

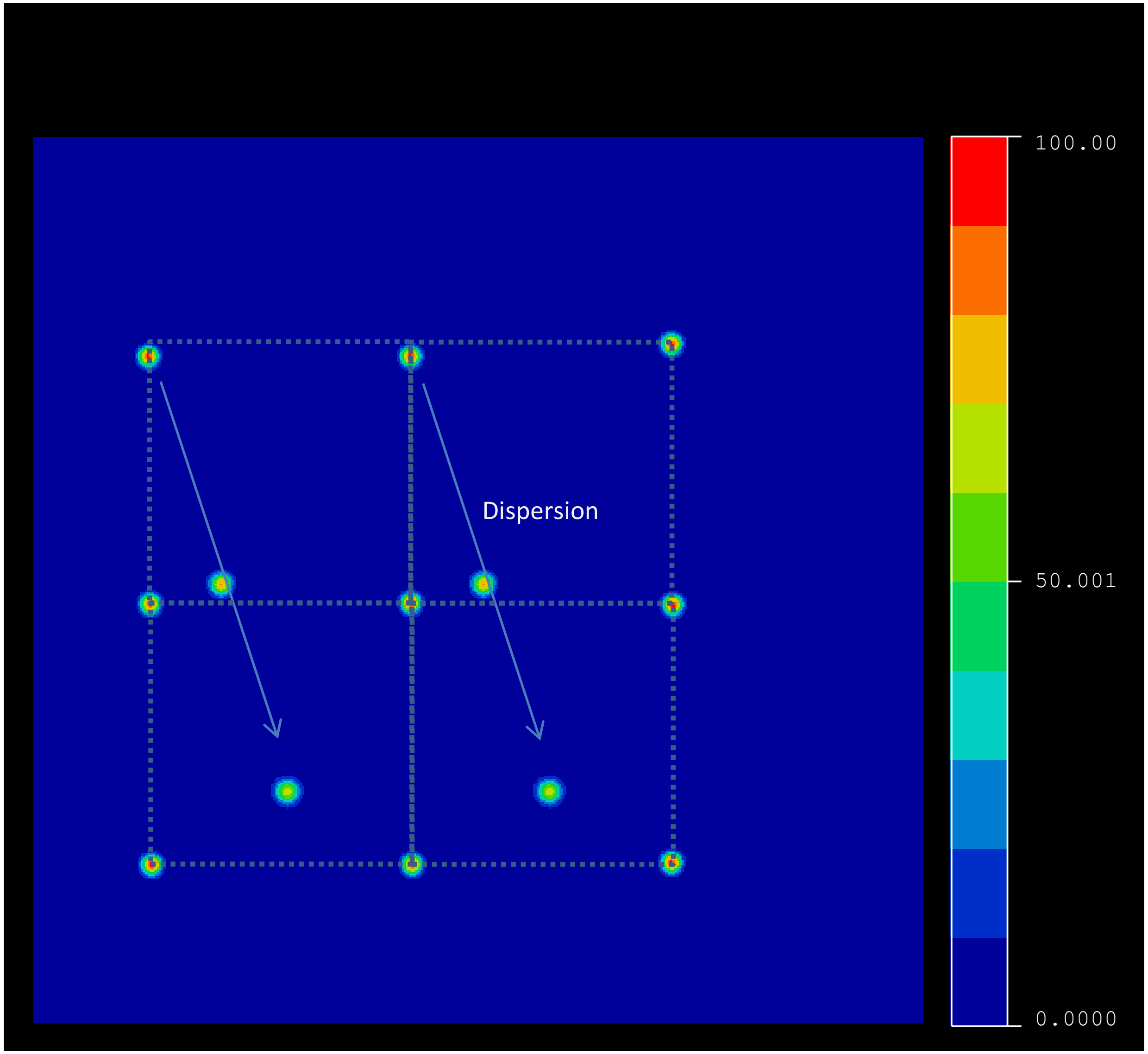
# IFS Relay from F/36.9 coronagraph focus to F/508 focus at lenslet array



# IFS Dispersion Plot



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




Dispersion of two adjacent spaxels, 690-760-830 nm

# AFTA Coronagraph Mechanisms (1 of 2)

| Mechanism | Description |
|---|---|
| Aperture Cover Mechanism | Moves aperture cover in and out of position to cover opening in front of fold mirror in neck. Open when coronagraph is in use. Closed during launch and any long periods when coronagraph is unused. Closed during servicing. |
| Shutter | 2-position shutter.<br>Beam is 2 cm diameter<br>Blocks light to coronagraph and IFS detectors for background checks and to block light during reads. |
| Tip-Tilt Stage | Tips and tilts first DM at pupil +/- 3 arc-sec (25 mas-sec telescope pointing control x120 magnification in coronagraph, /2 in mirror angle, x2 for margin)<br>resolution of 60 mas (to correct telescope pointing to 1mas = 120mas in coronagraph = 60mas (0.3 micro-rad) in mirror angle. Dynamic range = 6 as / 60 mas = 100.<br>For pointing control. Operates at up to 100 Hz based on feedback from low-order wave-front sensor. Compensates for reaction wheel vibration. |
| Lyot Image Plane (Occulter) Mask Changer | 5 positions (4 masks and open)<br>Masks are 1 cm diameter<br>At image plane<br>Angled, with reflected light going to low-order wave-front sensor.<br>Removes star image from coronagraph light path, directs it to low-order wave-front sensor. |

# AFTA Coronagraph Mechanisms (2 of 2)

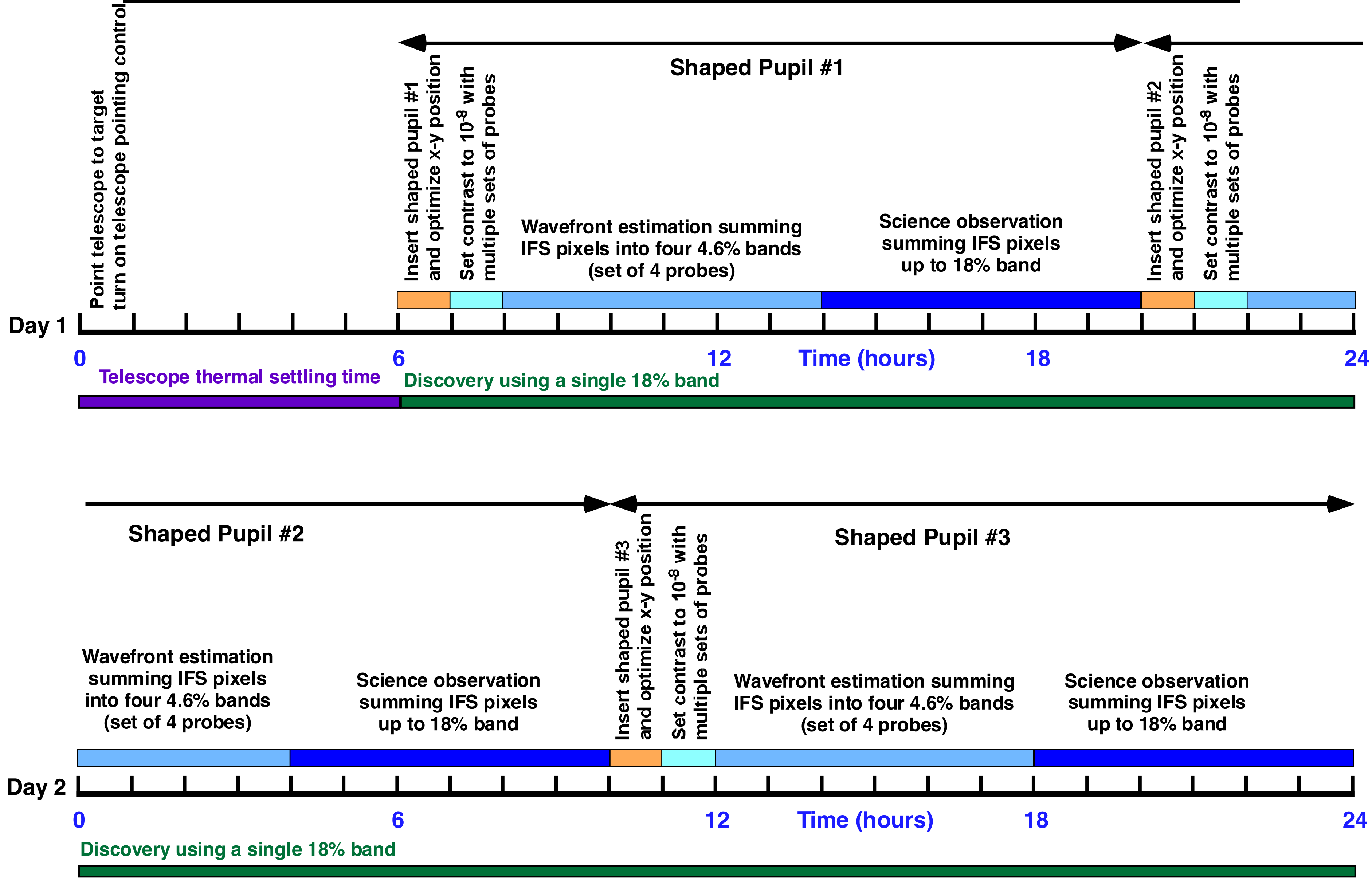


| Mechanism | Description |
|---|---|
| Lyot Stop (Pupil) Mask Changer | 5 positions (4 masks, open)<br>Masks are 1.5 cm diameter |
| Lyot Stop (Pupil) Mask X-Y Positioner | x-y adjust to 10 microns for alignment of Lyot stop mask |
| Shaped Pupil Mask Changer | 4 positions (3 masks, open)<br>Masks are 2 cm diameter |
| Shaped Pupil Mask X-Y Positioner | x-y adjust to 10 microns for alignment of shaped pupil mask |
| 18% Bandpass Filter Changer | 5 positions (4 filters, open)<br>Filters are 1.5 cm diameter |
| 4.6% Bandpass Filter Changer | 5 positions (4 filters, open)<br>Filters are 1.5 cm diameter |
| Flip Mirror for Coronagraph / IFS | 2 positions<br>To redirect light to coronagraph image detector or allow it to go straight through to IFS |
| Pupil Imaging Lens Changer | 3 positions<br>Lenses are 1.5 cm<br>To allow coronagraph imaging detector to image pupil. |

# Coronagraph Conceptual Operations Timeline Assumptions

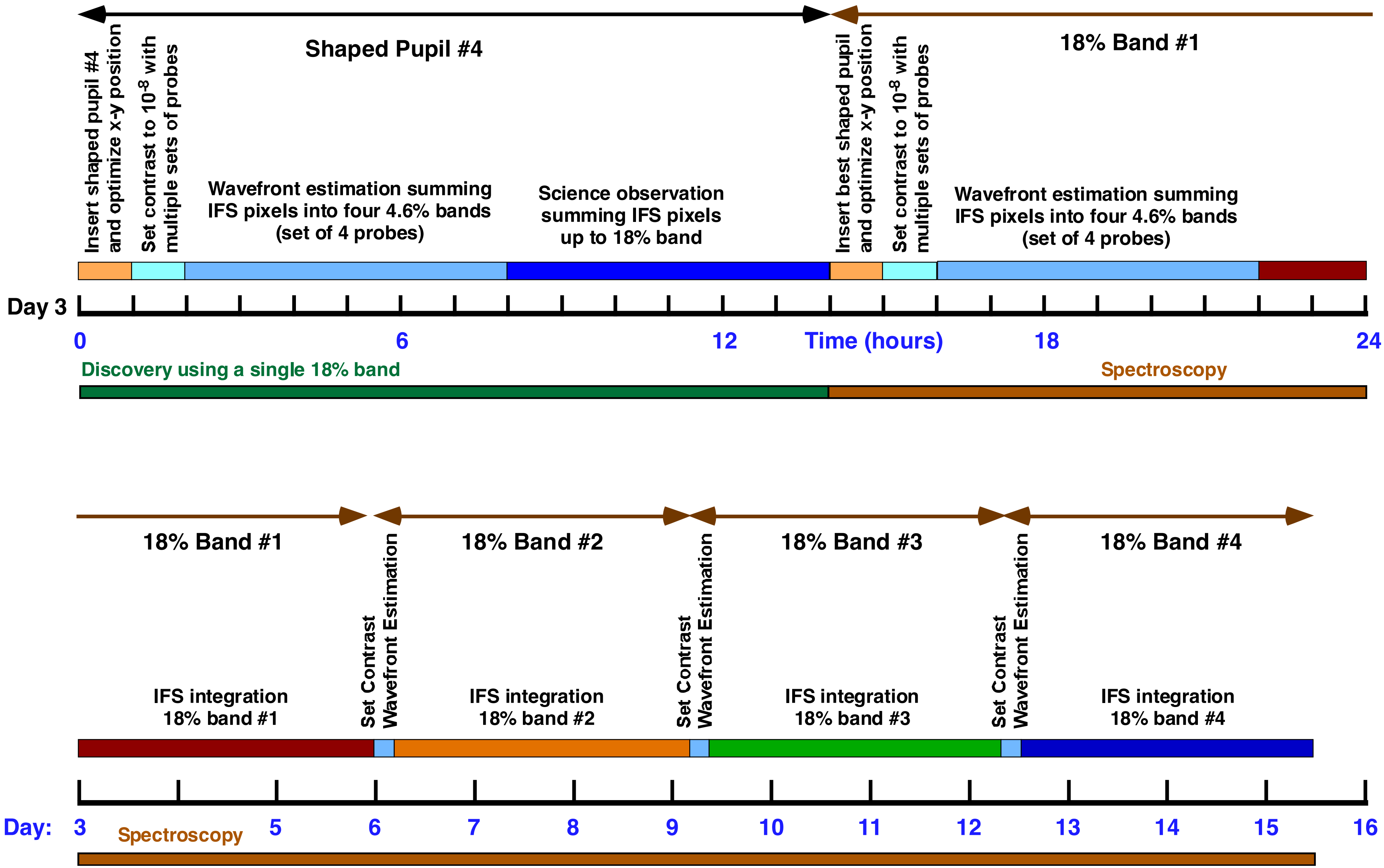
- $10^{-8}$ instrument contrast
- 4.83 mag star at 10 pc
- $10^{-9}$ contrast planet
- SNR=5
- 100 sec integrations for cosmic ray rejection
- EMCCD detectors with 0.001 e-/pixel/frame read noise, $10^{-5}$ e-/pixel/sec dark current

# Coronagraph Conceptual Operations Timeline (1)



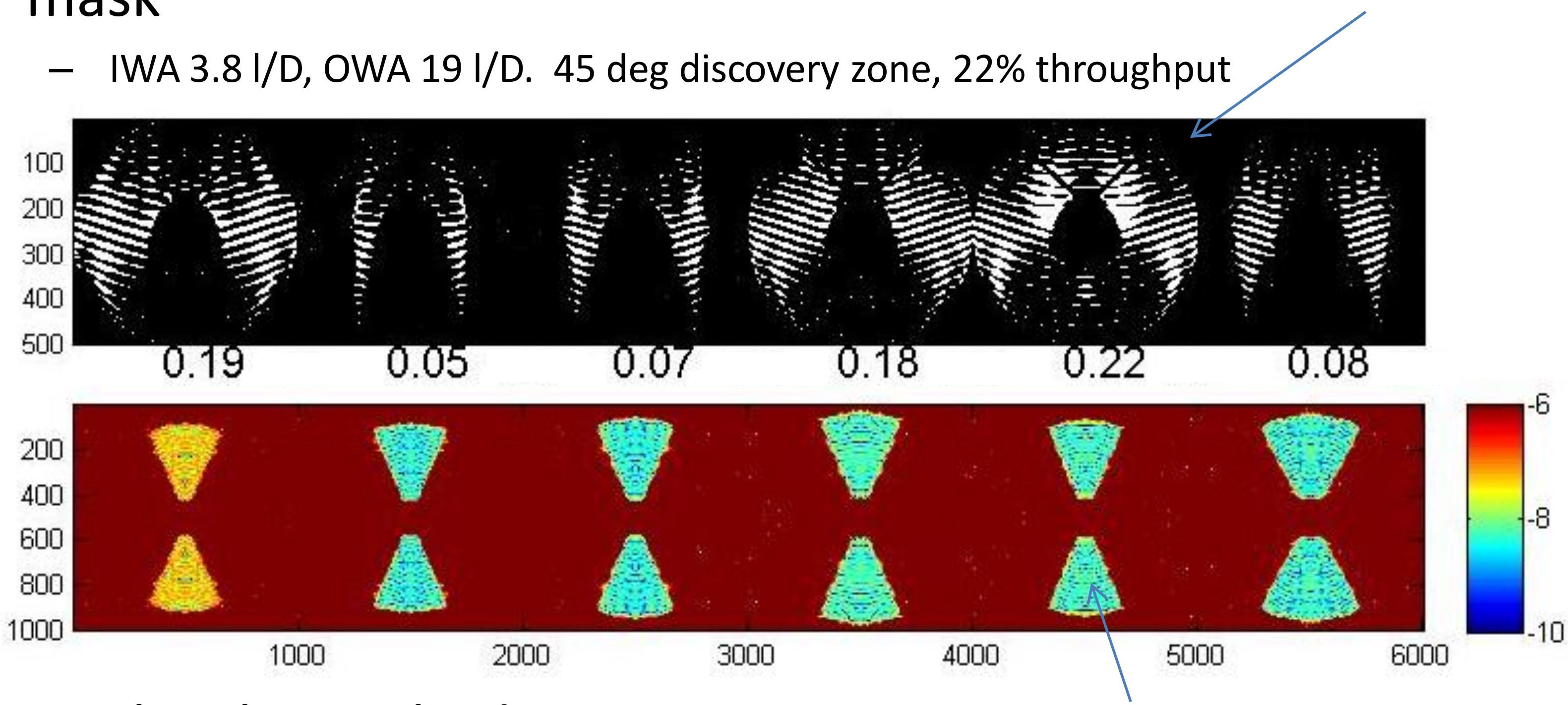
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

# Coronagraph Conceptual Operations Timeline (2)



# Aberration Sensitivity Modeling

- We have modeled the aberration sensitivity of a shaped-pupil mask
  - IWA 3.8 l/D, OWA 19 l/D. 45 deg discovery zone, 22% throughput

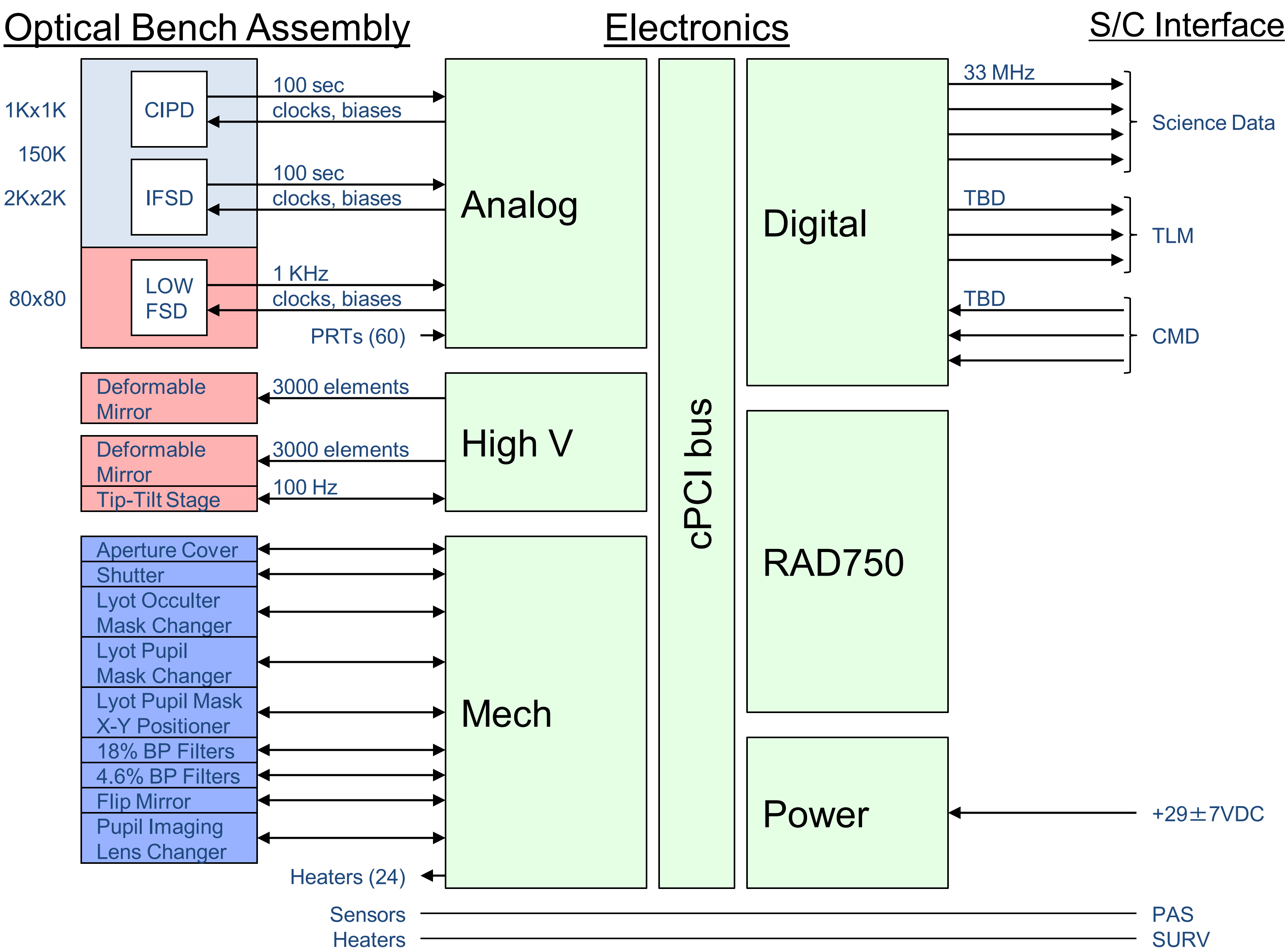



- Top level error budget parameters were:
  - 1e-8 instrument background, 1e-9 planet, and 2e-10 contrast stability

# Requirements imposed on the Telescope

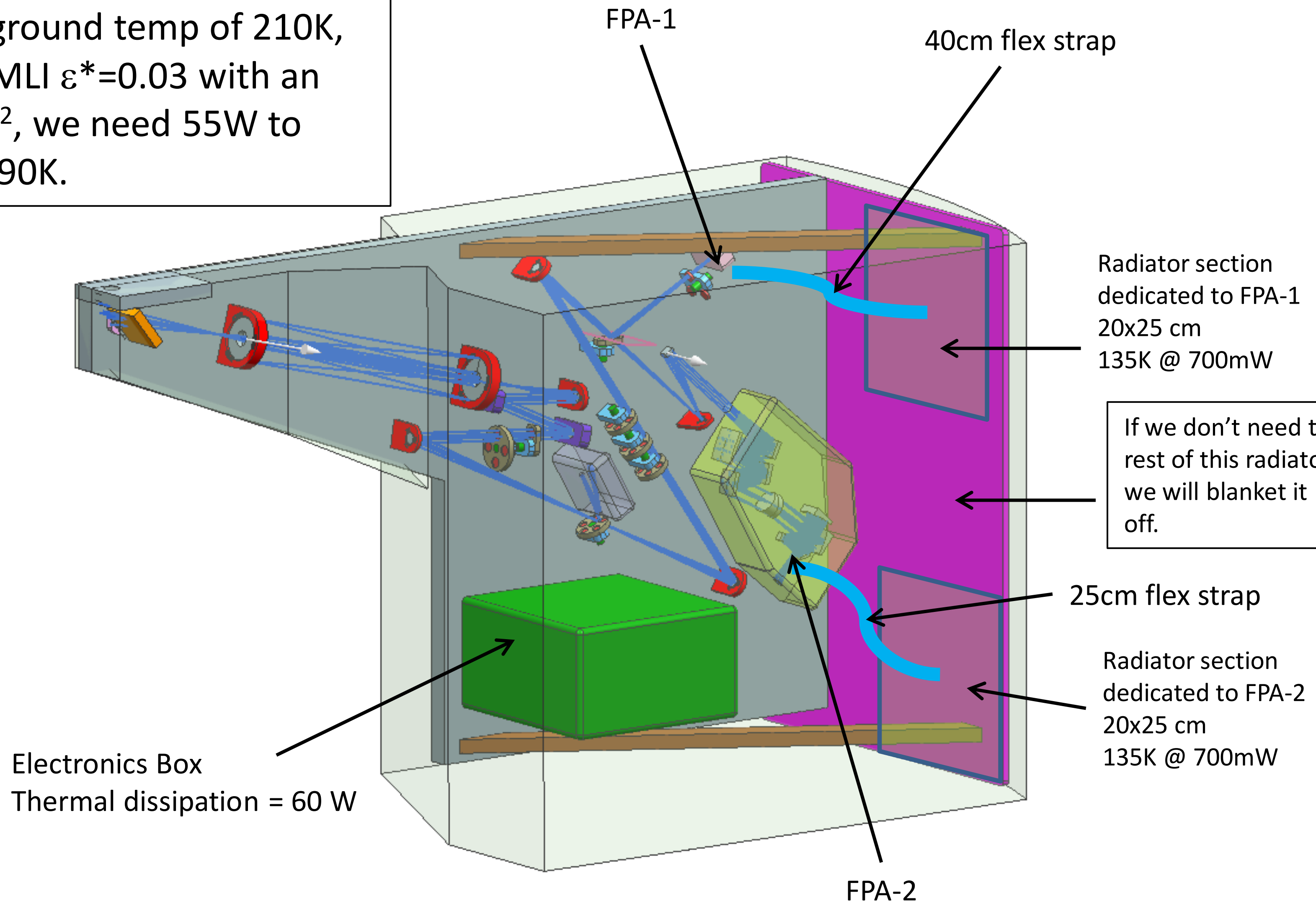
- For the duration of an observation (a few hours), the rms drift requirements are:
  - Pointing: LOS 1-sigma rms 10 mas/axis (linear drift)
  - Secondary mirror motion relative to primary mirror: 3 nrad per axis, 3 nm per axis
  - Primary mirror bending:
    - Focus, coma, astigmatism, trefoil: 5 pm rms
    - Higher order, e.g. spherical, secondary trefoil, tertiary spherical…: 1 pm rms
- With a low-order wavefront sensor handling tip-tilt, focus, coma, astigmatism, and trefoil, the pointing, secondary mirror motion, and low-order PM bending modes are significantly relaxed.
  - This is the key to success

# Coronagraph Electronics Block Diagram



# Coronagraph Preliminary Thermal Control Concept

Assume MLI covering instrument sides.
With background temp of 210K, Assuming MLI $\varepsilon^*=0.03$ with an area of $6m^2$, we need 55W to maintain 290K.



# Coronagraph Electronics Mass and Power Estimates

RAD750
- 9 W 116.5MHz processing

Analog
- 1 W CIPD interface
- 1 W IFSD interface
- 2 W LOWFSD interface
- 1 W HK subsystem

Digital
- 4 W FPGA
- 1 W LVDS interfaces
- 2 W SDRAM/Flash memory

Mechanism
- 3 W quiescent
- 1 W average actuation

High Voltage
- 2 W Tip-Tilt driver
- 9 W Deformable mirror drivers
- 9 W Deformable mirror drivers

Power
- 15 W DC/DC converter efficiency (75%)

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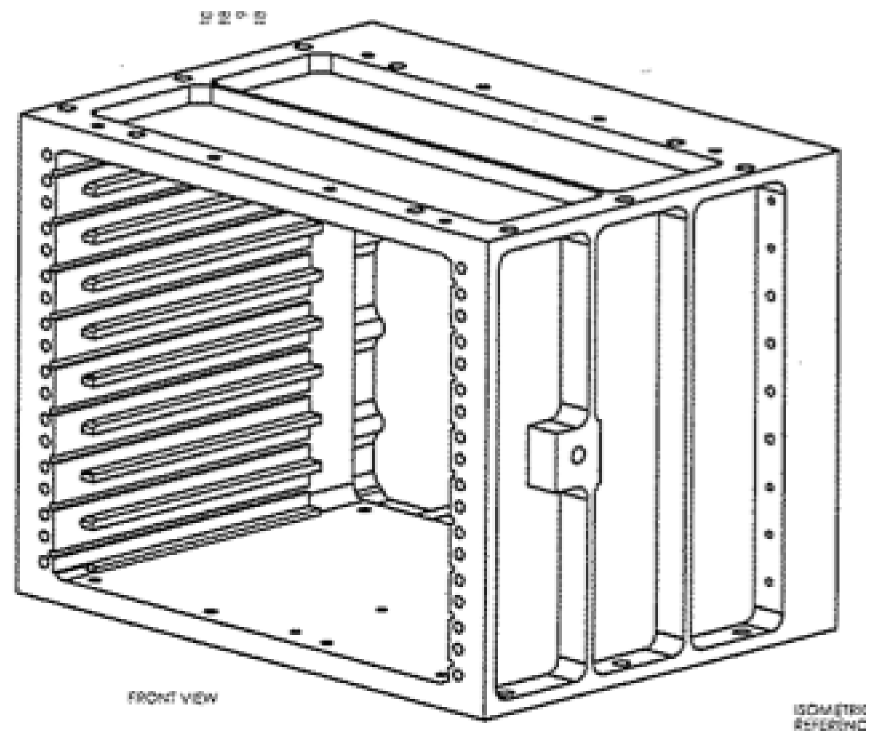
- 60 W electronics (not including heaters)

Electronics chassis:
- 28cm x 20cm x 20cm




- 11 kg (chassis)
- 10 kg (cables and connectors)

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- 21 kg electronics

# Coronagraph Preliminary Mass and Power Estimates

## Mass

| Item | CBE (kg) | Maturity Margin | CBE + Margin (kg) | Notes |
|---|---|---|---|---|
| Structure | 51.00 | 50% | 76.50 | |
| Optical Elements | 11.00 | 50% | 16.50 | |
| Optical Mounts | 6.50 | 50% | 9.75 | |
| Mechanisms | 15.00 | 50% | 22.50 | |
| Thermal Hardware | 14.00 | 50% | 21.00 | |
| Electronics | 21.00 | 50% | 31.50 | |
| Total | 118.5 | | 177.8 | |

## Power

| Item | CBE (W) | Maturity Margin | CBE + Margin (W) | Notes |
|---|---|---|---|---|
| Electronics | 60 | 50% | 90.0 | |
| Additional Heater Control Power | 30 | 50% | 45.0 | Electronics heat will help maintain instrument temperature |
| Total | 90.0 | | 135.0 | |

# Preliminary Coronagraph Data Rate

- WFIRST SDT report 2012 estimates 1.3 Tbits/day for WFIRST
- Coronagraph ideally produces small fraction of WFIRST data volume
- Coronagraph Mode
  - 1kx1k pixels (or fewer) at 12 bits
  - Downlink 100 sec integrations for cosmic ray avoidance (TBD)
  - 2x compression
  - 5.2 Gbits/day
- IFS Mode
  - 2.56kx2.16k pixels at 12 bits
  - Downlink 100 sec integrations for cosmic ray avoidance (TBD)
  - 2x compression
  - 29 Gbits/day
- Low-Order Wavefront Sensor Diagnostics
  - 80x80 pixels at 12 bits
  - 1 kHz frame rate
  - 2x compression
  - 0.14 Tbits/hour

➢ 30 Gbits/day would allow downlinking of continuous coronagraph or IFS data; 0.14 Tbits/day would allow 1 hour/day of LOWFS diagnostic data.

➢ Could be higher or lower based on frame rate required for cosmic ray avoidance and whether cosmic ray rejection can be done automatically in instrument

# Coronagraph Detector Candidates (1)

- E2v Electron Multiplying CCDs (EMCCDs)
  - Currently most viable candidate
  - Read noise is 1e-3 e-/pixel/frame in photon counting mode. Frame rate must be high enough to ensure ≤ 1 photon/pixel/frame in region of interest, and to allow for cosmic ray suppression.
  - At 170K dark current noise is 3e-6 e-/pixel/sec. 0.1 e-/pixel for 8 hours of integration.
  - Current arrays up to 1k x 1k. 4k x 4k under development.
  - Caltech plans balloon experiment in 2015 to increase TRL level.
- Geiger-Mode Avalanche Photodiodes
  - May provide read-noise-free photon counting
  - Current arrays too small – 512x512 under development
- BAE/Fairchild Scientific CMOS
  - 1.2 e- read noise. Sampling-up-the-ramp technique could provide reduced read noise and cosmic ray suppression, but contact at BAE says non-destructive reads are not possible
  - 2k x 1k array development
  - CMOS detectors are typically more radiation hard than CCDs

# Coronagraph Detector Candidates (2)

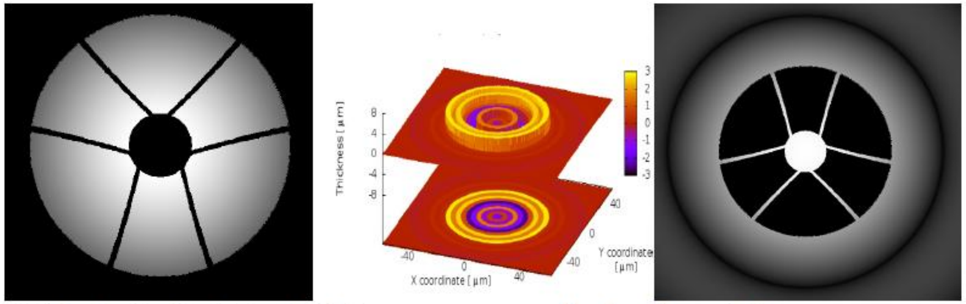
- Microwave Kinetic Inductance Devices (MKIDs)
  - Under development in JPL Microdevices Laboratory and UC Santa Barbara
  - True photon counting with energy sensitivity for spectroscopy, enabling simpler optical system with greater throughput
  - Still in early development – pixels ≈ 100 microns; largest array size ≈ 2000 pixels with 70% yield
  - Operation at ≈ 100 mK
  - Theoretical spectral resolution 100, but demonstrated resolution is 20 (254 nm) and 10 (1 micron)
  - QE 60% at 0.4 microns, 25% at 1 micron. High QE theoretically possible.

# Technology Development Needed

- E2v EMCCDs
  - Increase in array size from 1k x 1k to ≥ 2k x 2k – under development.
  - Qualification for flight. Caltech plans balloon experiment in 2015.
- Boston Micromachines Co. MEMS Deformable Mirrors
  - Increase in number of actuators from 1k to 3k – under development through funded Phase II SBIR.
  - Qualification for flight.
- System Demonstration
  - Demonstrate a coronagraph compatible with the AFTA aperture that can achieve better than 1e-8 background and good throughput at 3 $\lambda/D$.
  - Demonstration of closed-loop low-order wavefront correction at level needed for coronography
  - Demonstrate Wavefront estimation and control using an IFS
  - Demonstrate ability to detect a planet below the speckle background

# Next Steps

- Investigate PIAA-CMC design
  - Higher throughput, lower instrument floor, smaller working angle, larger discovery space
- Start working I&T plan
- Develop cost and schedule



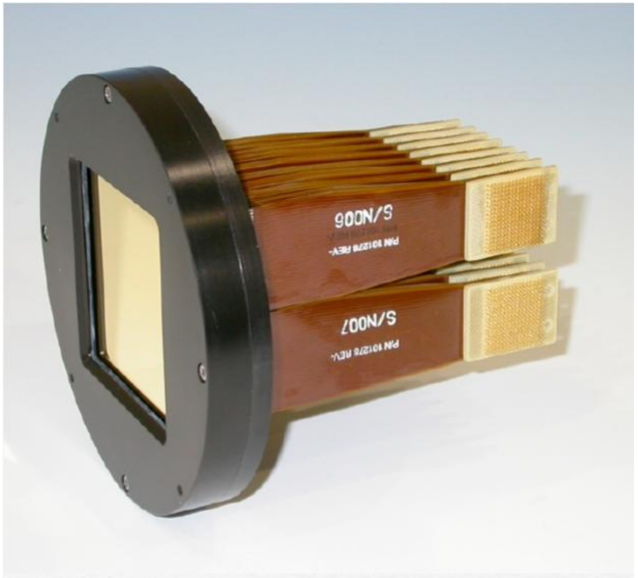
***EXACT's PIAACMC coronagraph design. The telescope pupil is first remapped into a slightly apodized pupil (left) using lossless aspheric optics. A phase focal plane mask (center), optimized for broadband operation, diffracts light outside the pupil (right), which can then be masked by a Lyot stop.***

Guyon et al, 2013

Design:
1e-8 background
40% bandwidth
Central spot 0.9 l/D radius
High throughput

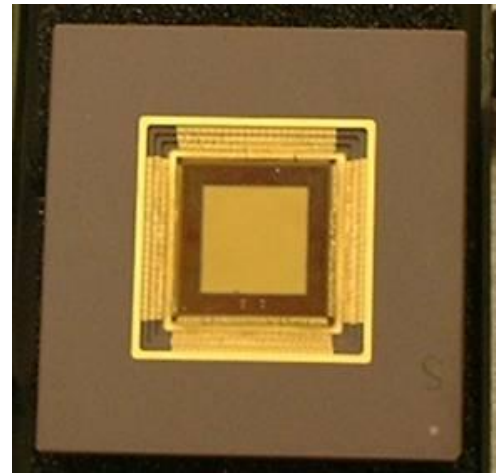
# Backup Slides

# Deformable Mirrors for Picometer Aberration Control



## Xinetics, 64x64 DM

In hand: several 32x32, one 48x48,
One 64x64 currently in use in HCIT
- pixel pitch: 1000 um
- stroke: ~1.5 um
- Mirror segment: glass on PMN



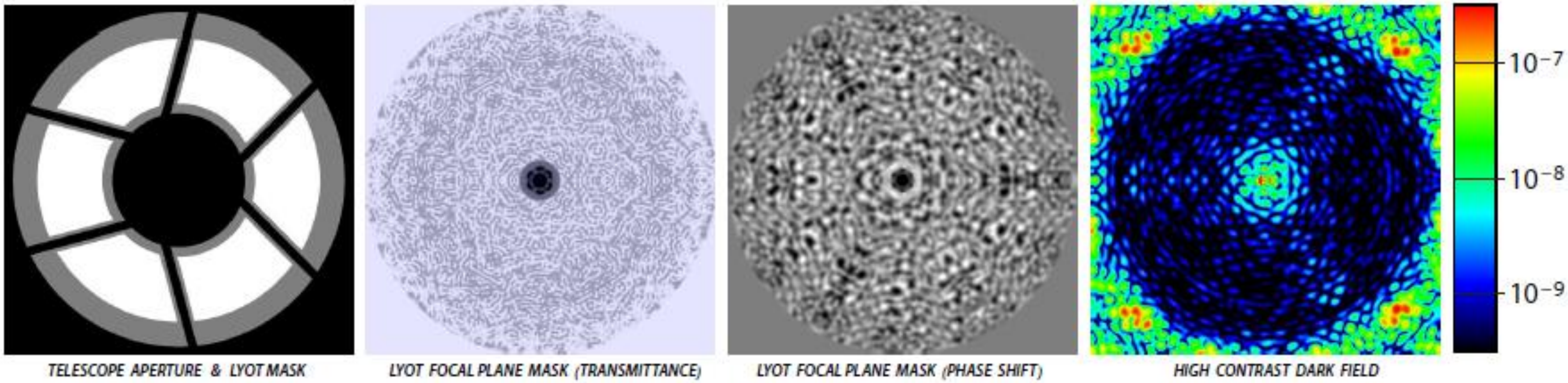
## Boston Micromachine 32 x32 MEMS

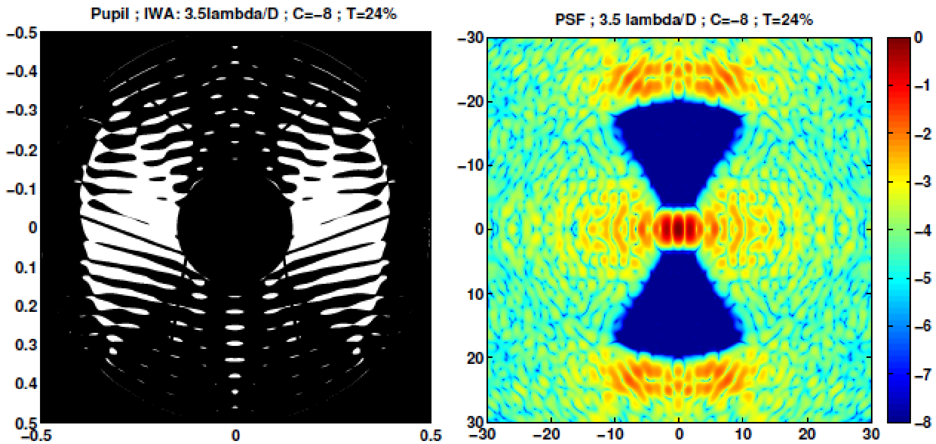
Phase II SBIR has begun. Delivery of 3000 element continuous facesheet MEMS DM in 2014.
- pixel pitch: 300 um
- stroke : 1.5 um
- Mirror segment material: silicon

Many 32x32 devices in use: Princeton, LLNL, UA, UH, ARC

# Coronagraph Masks

Lyot Coronagraph: complex mask (amplitude and phase) to address obscured aperture. A monochromatic solution has been found and is shown here. Broad band solution is being addressed. *Courtesy of J. Trauger and D. Moody, JPL.*




Shaped Pupil Masks: A binary apodization in the pupil plane is optimized to provide high-contrast attenuation over a prescribed region of the image plane. Naturally broad band, trades IWA, throughput, contrast, and discovery area.
*Courtesy J. Kasdin and A. Carlotti, Princeton.*