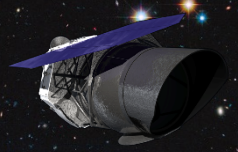


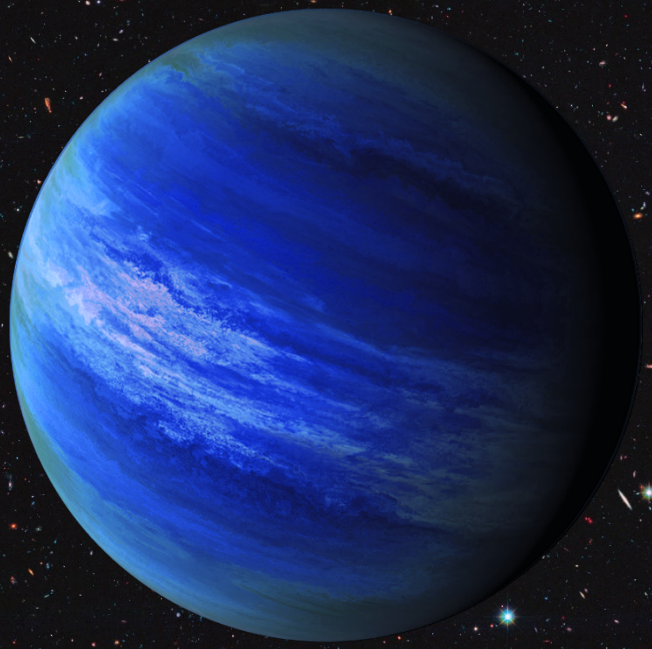
The EMCCD as imaging and spectrograph sensor for the WFIRST Coronagraph Instrument

September , 2017

Presented by Richard Demers

Coronagraph Flight Systems Manager

Jet Propulsion Laboratory



Jet Propulsion Laboratory
California Institute of Technology

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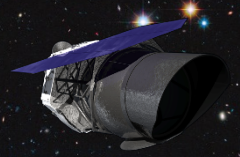
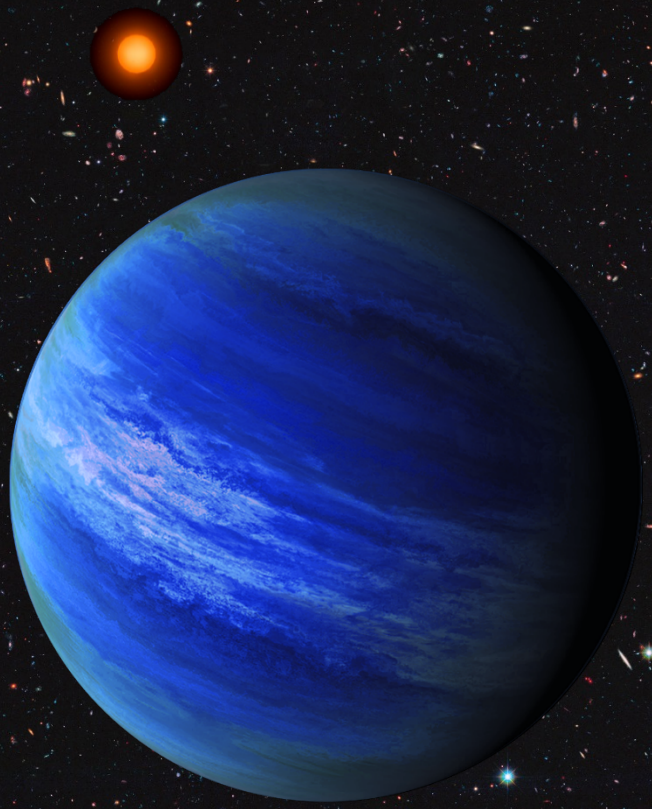


WFIRST Coronagraph Camera Team

Patrick Morrissey, Leon Harding, Michael Bottom, Bobby Effinger, Leo Neat, Richard Demers
Jet Propulsion Laboratory

Nathan Bush, David Hall, Andrew Clarke, Ross Burgon, Andrew Holland
Open University, Center for Electronic Imaging

Bijan Nemati
University of Alabama at Huntsville



Jet Propulsion Laboratory
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Outline

- WFIRST
- What is a coronagraph?
- WFIRST Coronagraph cameras
  - Science cameras
  - LOWFS camera
- Radiation testing
- Planned design mods
- Conclusion

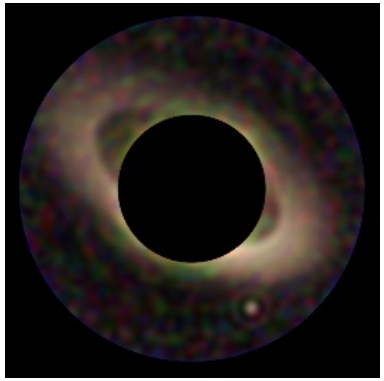
WFIRST Summary

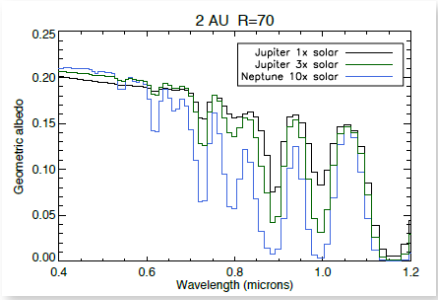
WFIRST = Wide Field InfraRed Survey Telescope

- 2.5 Meter Telescope
- Wide Field Instrument
- Coronagraph Instrument

Coronagraph Science

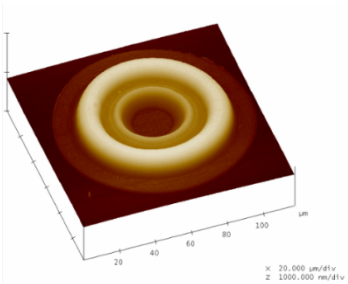
- Direct Exo-planet imaging
- Atmospheric compositions of planets
- Characterize debris disks around nearby stars



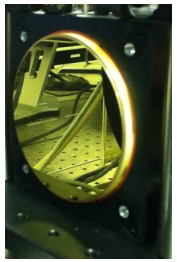


Coronagraph Unique Status

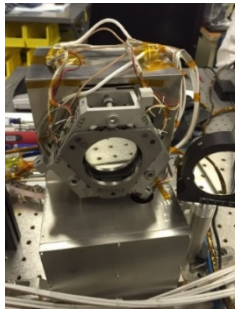
- Both a science instrument & technology demonstration
- L1 Baseline Science Requirements
  - Designed & costed to meet science requirements
- L1 Threshold Technology Requirements
  - Advances critical technology for future missions
- WFIRST CGI is the only activity planned by NASA to image and spectrally characterize exoplanets for the next decade



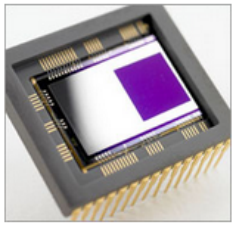
HLC mask image with an atomic force microscope



Xinetics 48 x 48 DM used in JPL's HCIT



Fast-steering mirror



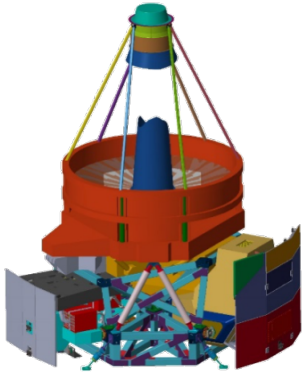
E2V EMCCD used in photon-counting mode

WFIRST Coronagraph Team

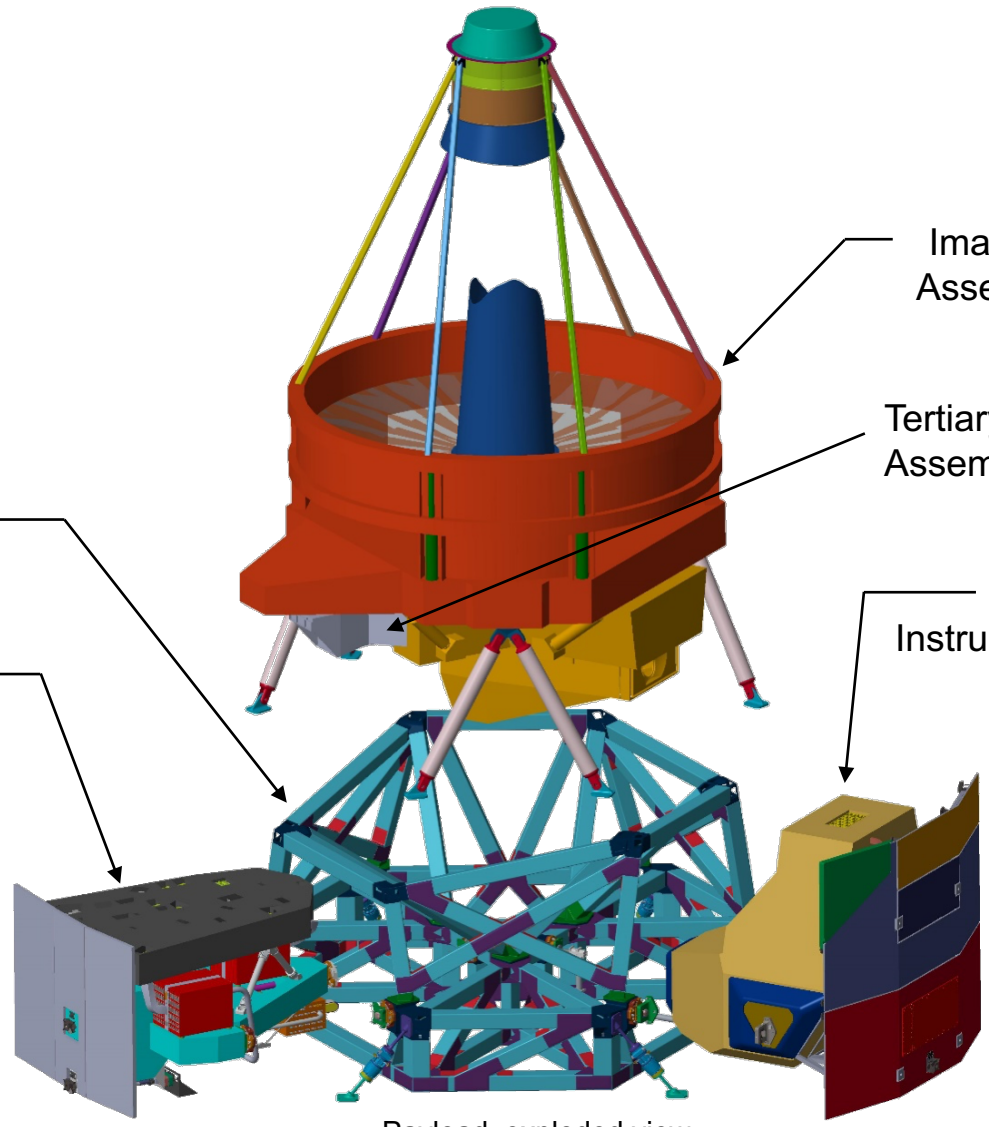
Coronagraph partner institutions:

- NASA GSFC (provided test-bed integral field spectrograph)
- Science Centers:
  - IPAC/Caltech, STScI

CGI in WFIRST Payload



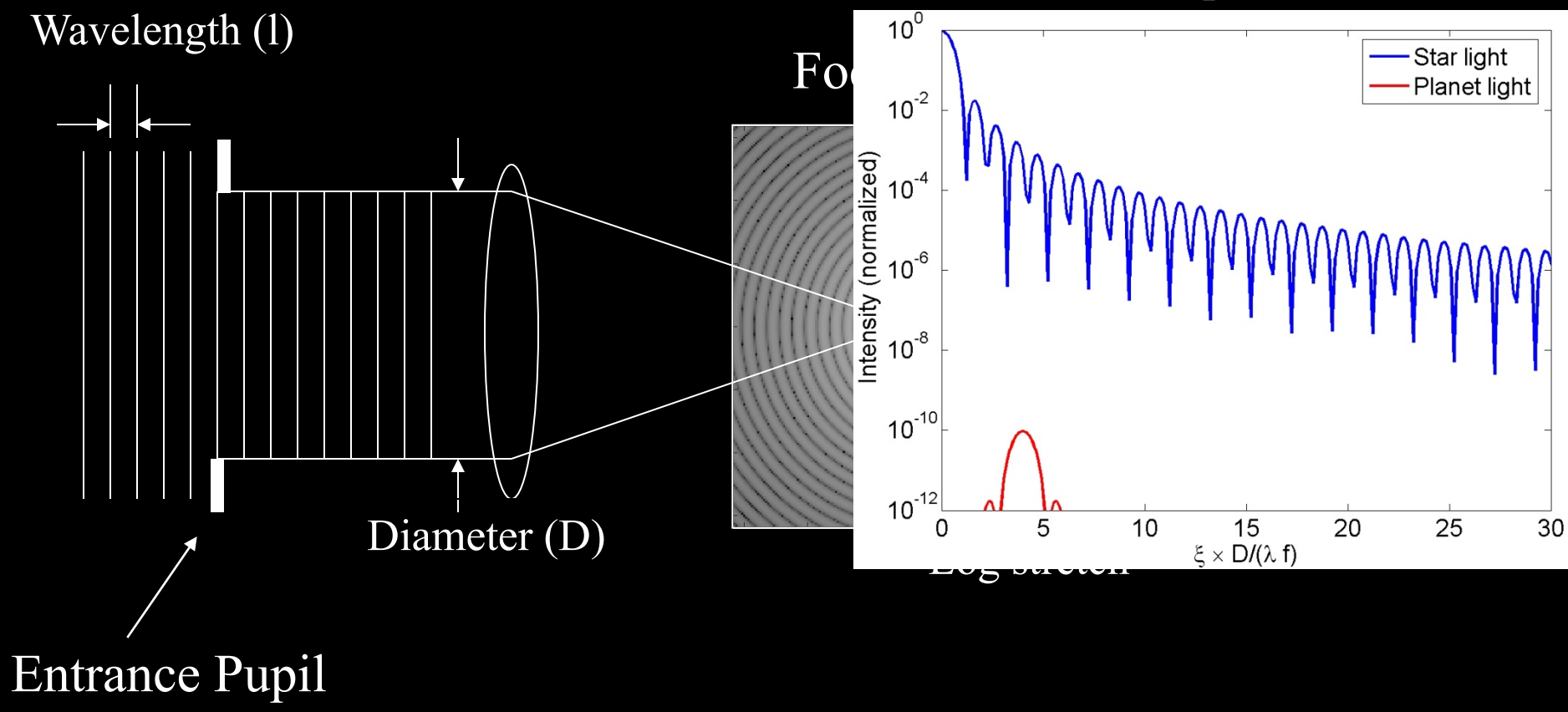
Payload, integrated

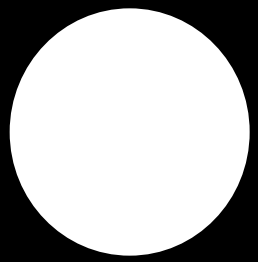


Payload, exploded view

Diffraction

Unfortunately, the planet would be





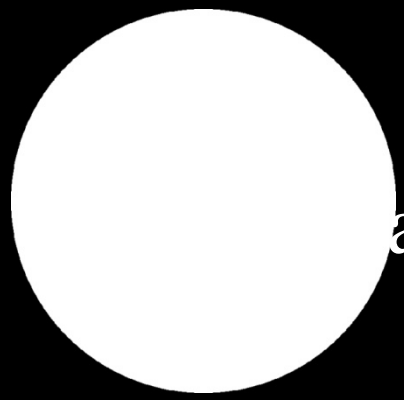
The Lyot Coronagraph

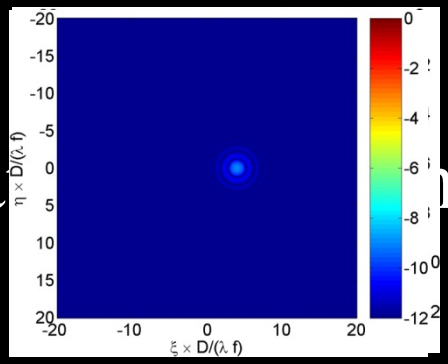
Entrance pupil

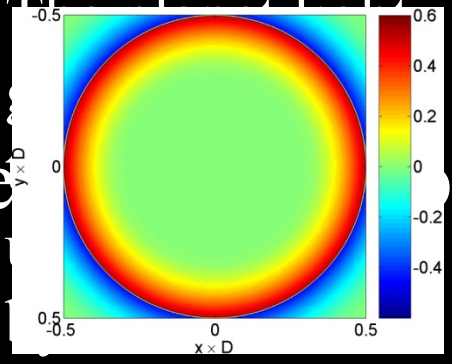
Occulter

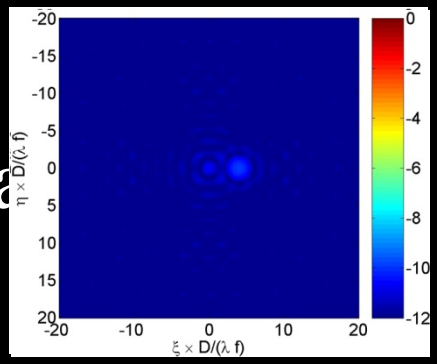
Lyot stop

Image plane

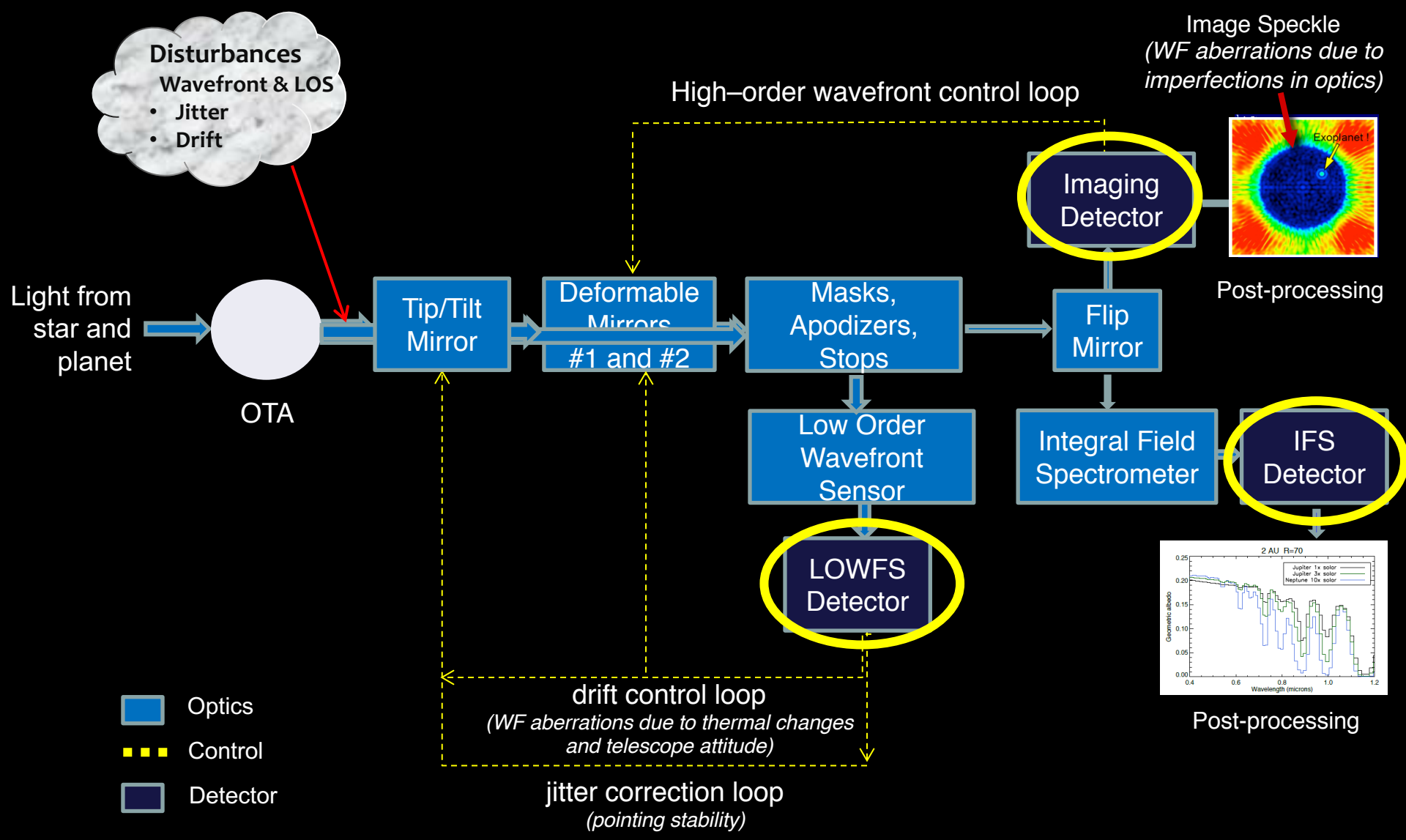






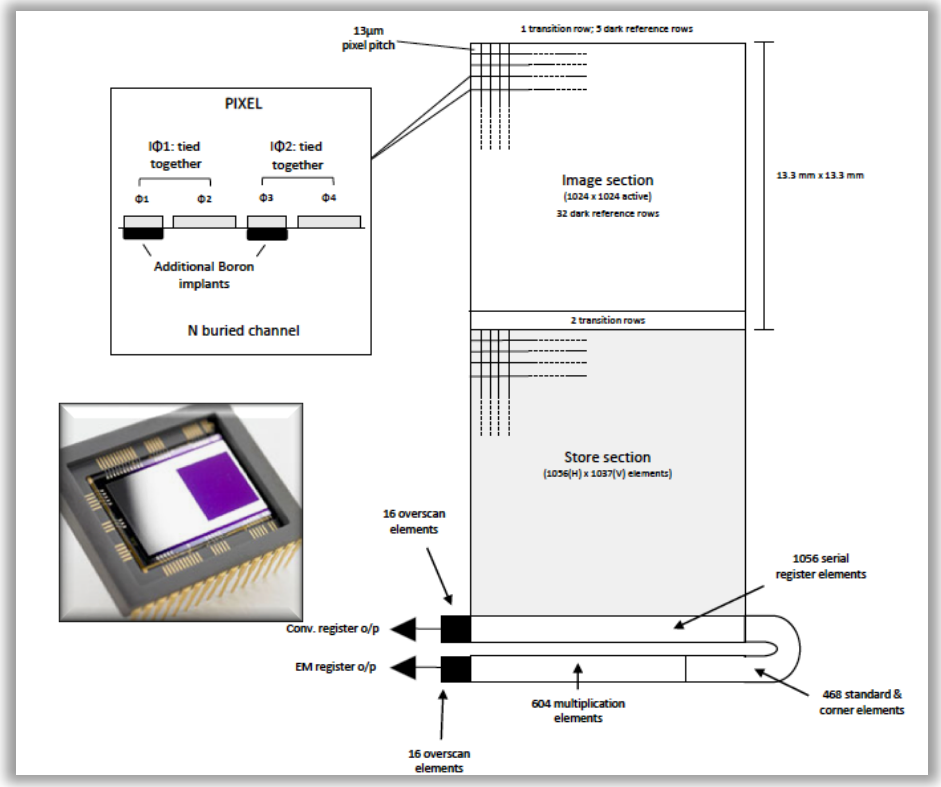


How the WFIRST Coronagraph Works



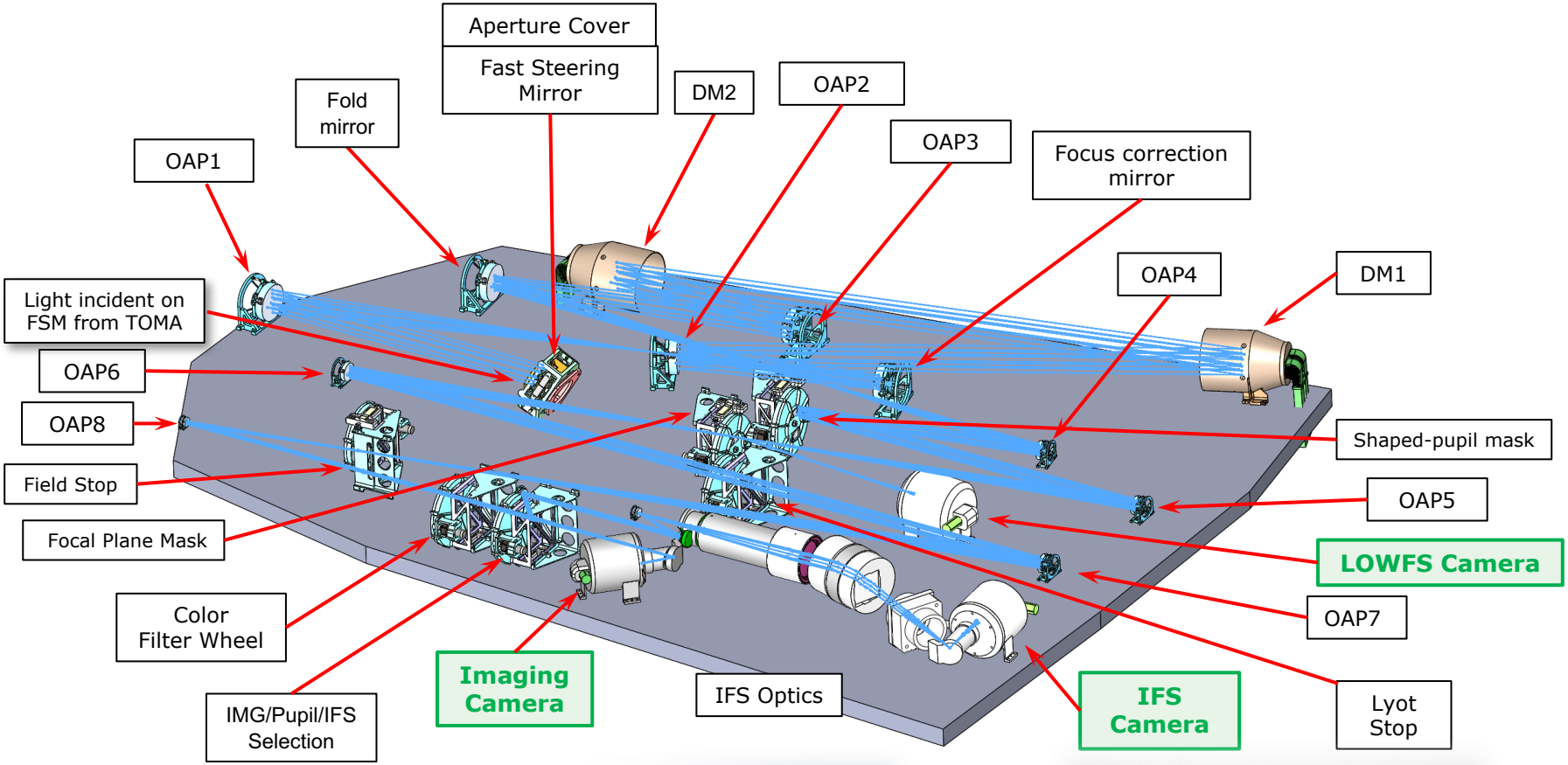
CGI Cameras

- Two science cameras
  - Direct imaging camera (DICAM)
  - Integral field spectrograph camera (IFSCAM)
- One engineering camera
  - LOWFS camera (LOCAM)
- Science cameras detect ultra-low flux (~1 ph/pix/15 min)
  - ~100 sec frames
- LOWFS camera detects higher flux
  - 1kHz frame rate
- Teledyne-e2V EMCCD 201-20 baselined for CGI cameras
- 201-20 version has been extensively tested
  - Electro-optical parameters
  - Radiation exposure
  - Low flux image characterization

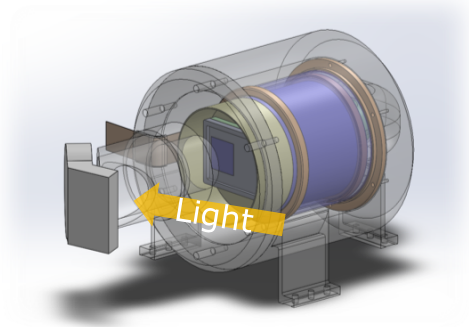


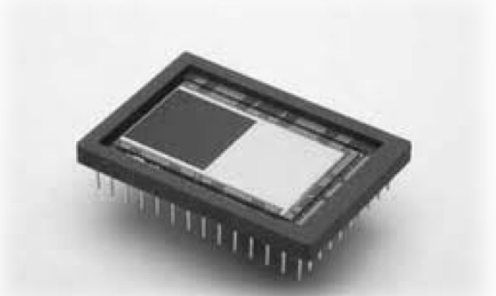
- EMCCD enables high QE CCD imaging and zero read noise photon counting.
- Low light level multi-stage serial register at elevated voltage (~50V) amplifies signals well above the level of the read noise.
- Amplified data are sent to a photon counting discriminator, eliminating read noise.

Optical Module Bench



Completely enclosed,
1cm Ta Shield Concept



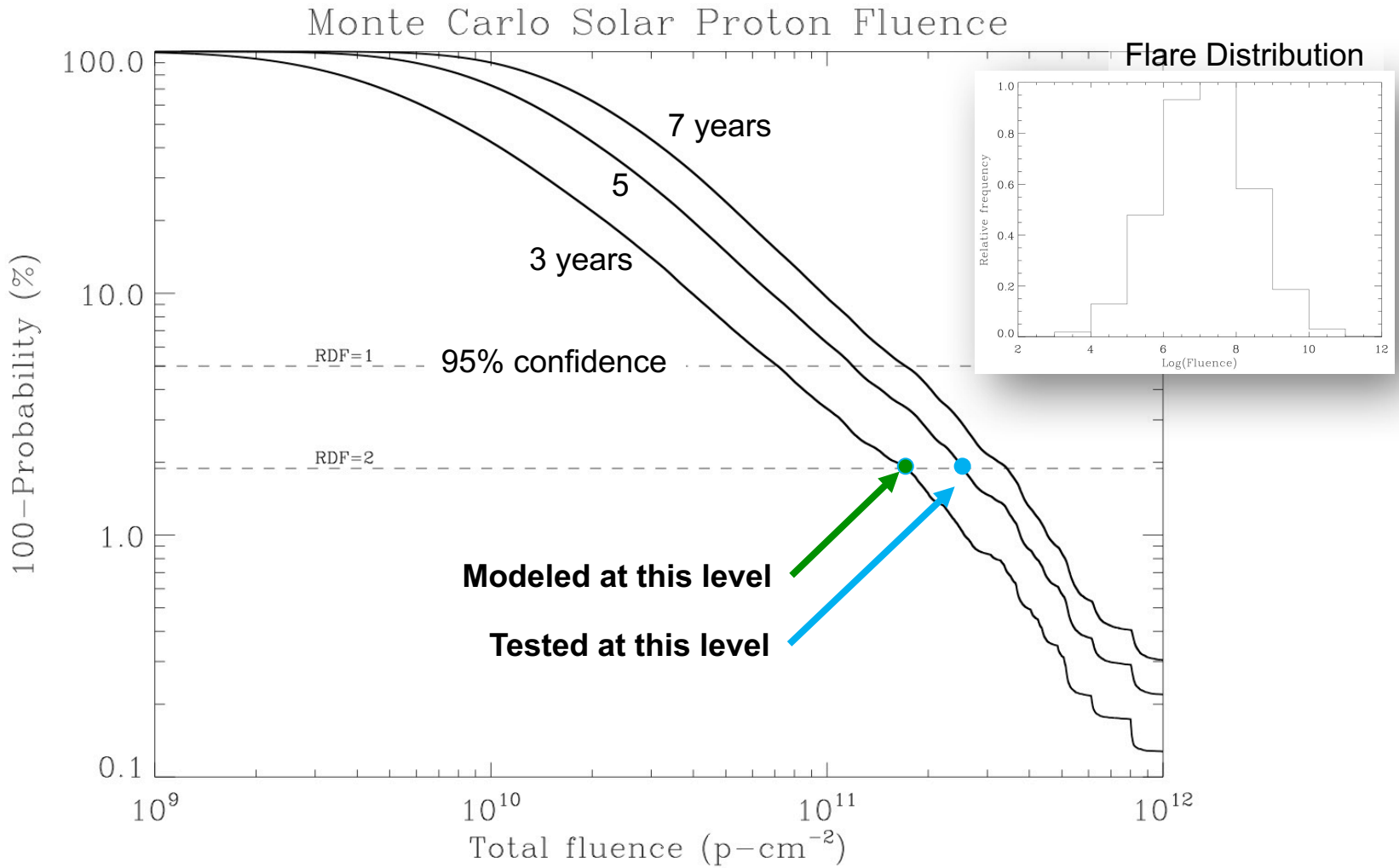


CCD201: 1K×2K format 13.3 × 26.6 mm

Camera Requirements

- LOWFScam
  - <5 e- read noise requirement
  - 50,000 e- full well requirement
  - 1000 fps operation of a 50x50 pixel region requirement
  - Latency of <1ms requirement
- DIcam/IFScam
  - Minimum flux detection limit ~ 1 photon/pixel/15 min
  - dQE > 60% (TBR)at mid-life, 95% confidence level
  - Read noise (gain = 1, 1000) = 55, 75 e- RMS
  - Dark current (BOL, EOL) < 1 , 2 e-/pix/hr
  - CIC < 0.01 e-/pix/frame
- COTS version EMCCD 201-20 meets requirements
- 201-20 selected for all three cameras for cost efficiency

L2 Orbit Radiation Environment



Radiation Test Program

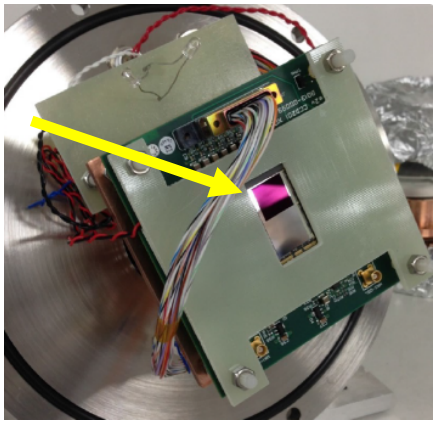
WFIRST expected radiation environment at L2 (Kepler, JWST).

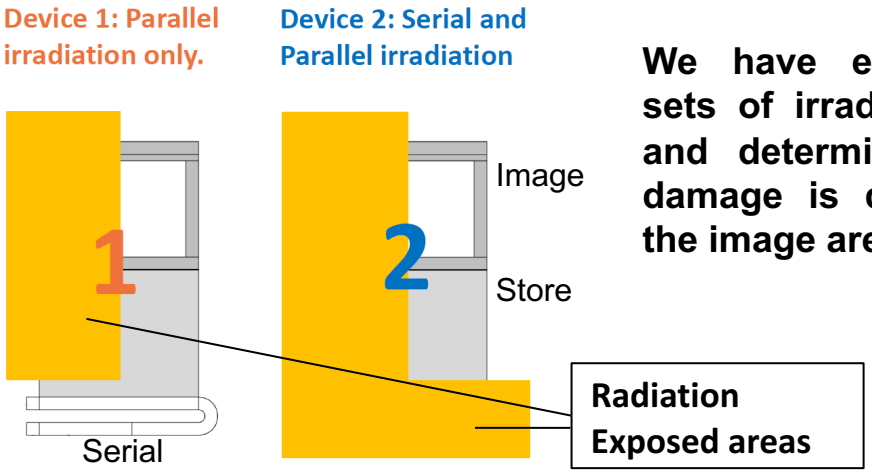
- This location is well beyond the Moon and outside the protection of the Earth's magnetosphere
- Radiation dose will be **dominated by protons from solar flares.**

EMCCD detectors exhibit charge transfer deterioration similar to other CCD detectors (e.g. HST) when the silicon lattice is damaged by energetic particles.

Collaboration with Open University, UK to evaluate the performance of commercial EMCCDs that are degraded by a flight-like radiation dose (95% confidence, 5 years, RDF=2) of protons.

EMCCD



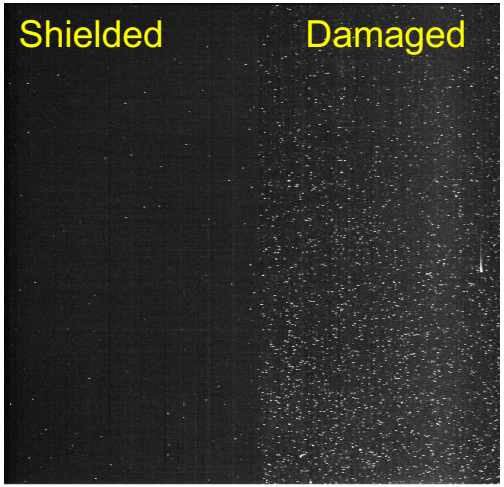


We have evaluated two sets of irradiated devices and determined that the damage is dominated by the image area.

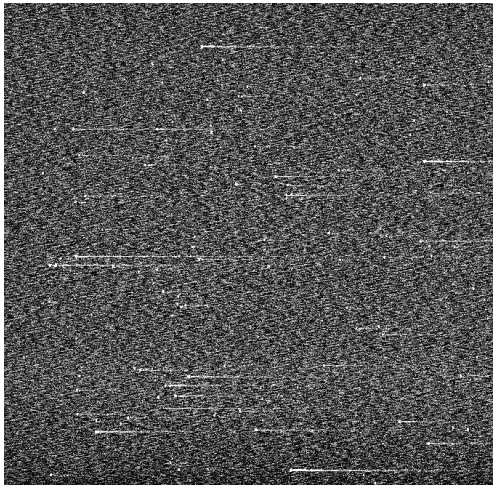
Radiation Damage

- Proton damage results in 1) hot pixels and 2) charge transfer degradation.
  1. **Hot pixels** may have much higher dark than the typical pixel (>10x), however, these pixels are ~10% of the total even at end of mission.
     - The *diffuse* dark current remains under 1 electron-px^{-1}-hour^{-1}
  2. **Charge transfer degradation** disproportionately affects faint signals since traps are efficient when they are empty.
     - *Increasing the frame time is an effective mitigation but is limited by the long tails of cosmic rays generated in the EM gain register*

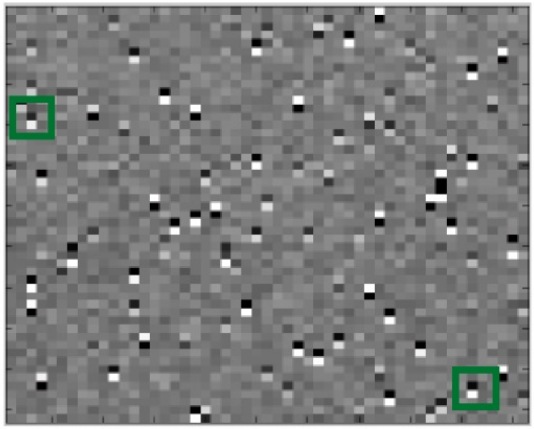
Hot Pixels



Cosmic Rays



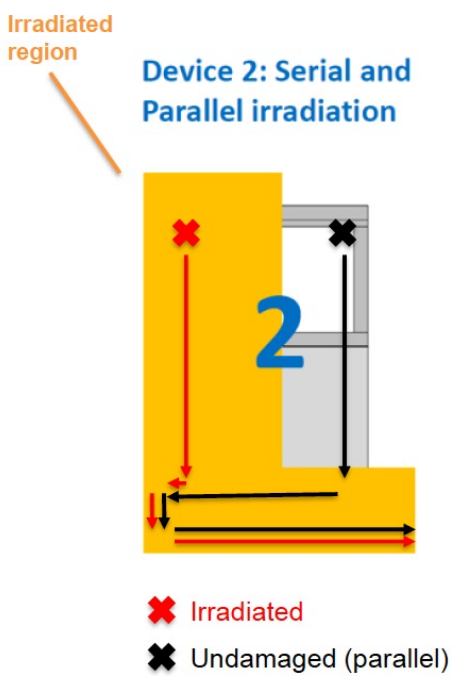
di-Vacancy traps, 50×50 window

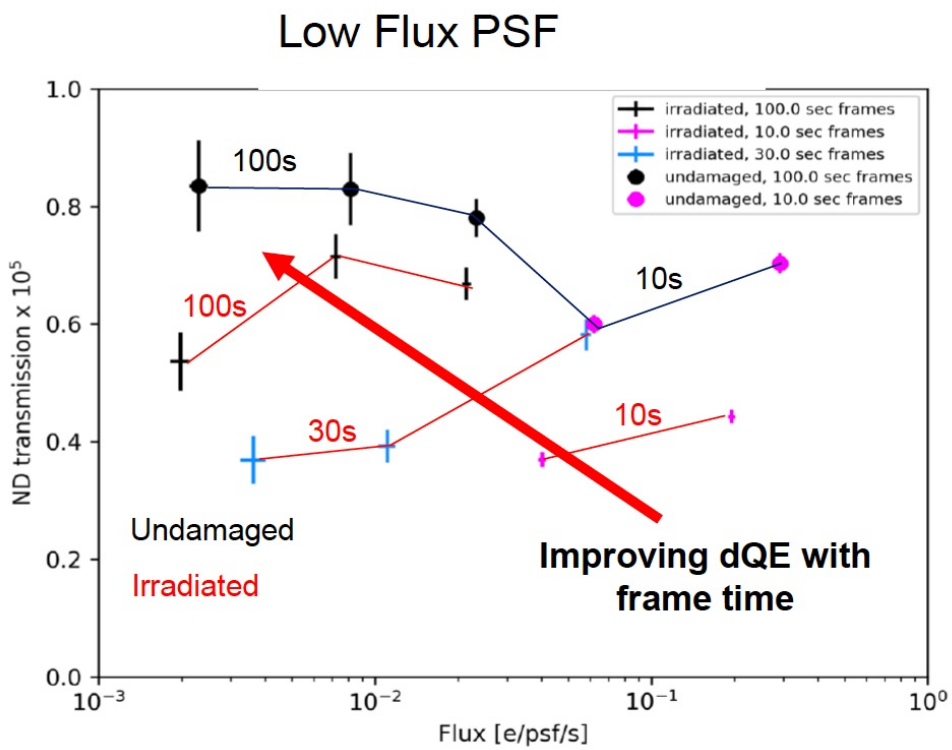


Post Irradiation: 2.5×10^9

Radiation Induced Image Degradation

- Low flux PSF measured using a scene generator and ND filters
- PSF detection is characterized using
  - Aperture photometry
  - Markov Chain Monte Carlo Model
- Input flux dependence of dQE is measured
- The radiation-damaged detector performance at 5 years meets requirements. Desirable to increase performance margin by improving the sensor design at Teledyne-e2v.

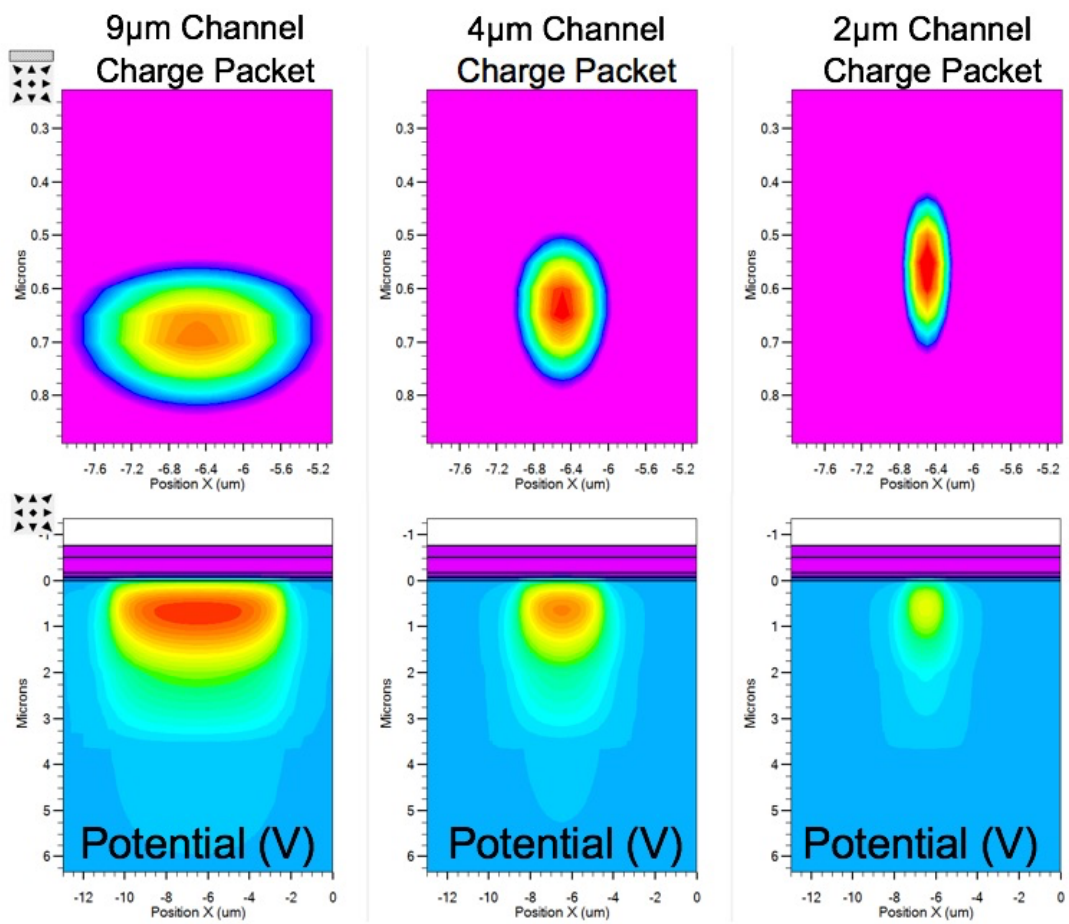


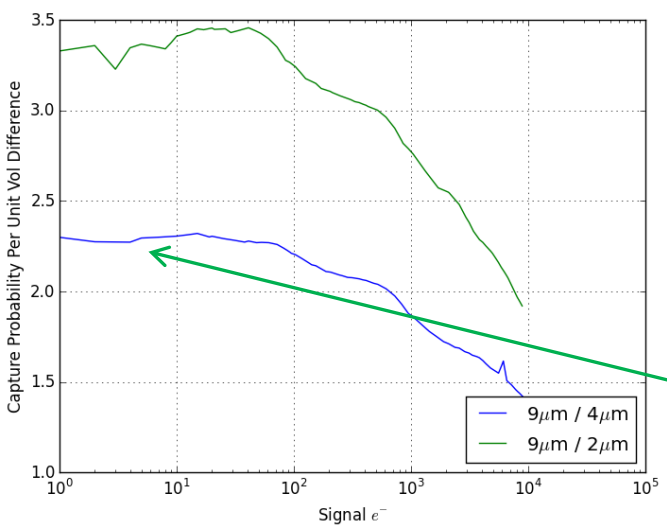


Trap mitigation: narrow channels

Narrowing the buried channel result:

- Higher density charge packets for a given signal size
- Smaller volume for a given signal size
- Change in the position of signal(y-axis) related to the change in channel parameter





2x reduction in capture probability @ 4uμm channel width

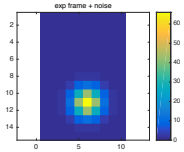
Analysis by Nathan Bush of Open University, CEI

Modeling of EMCCD Detector Improvements

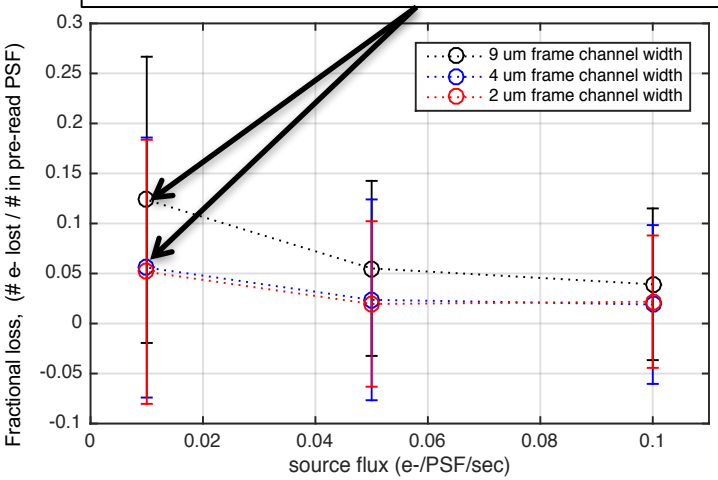
What performance improvement is expected by narrowing the channel width of frame register pixels from 9um to 4um.

Result: The detector trap model predicts that signal loss due to radiation induced traps is decreased by a factor of 2 at a flux of 0.01 c-PSF^{-1}-s^{-1} by narrowing the image pixel channel width from 9um to 4um.

Reducing the channel width further does not show much added benefit.



~2x less signal loss with 4um channel width than 9um



Analysis results by Bobby Effinger, 8/16/2017

- The effect of a 2x improvement of the detector CTI through narrowing the channel widths of the frame pixels is evaluated for the current error budget.
- The margin against the detector requirements improves from 21% to 31%

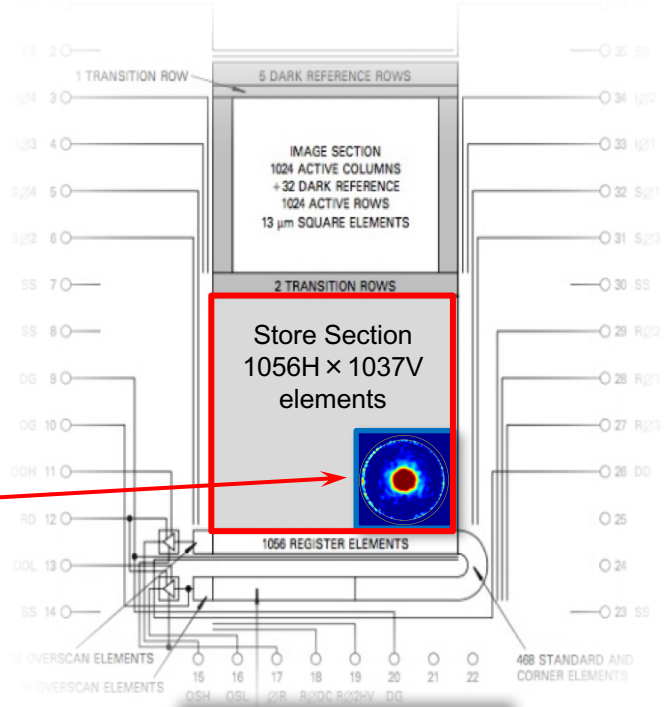
Error Budget Items	Nominal Req. (ppb)	Nominal CBE (ppb)	2x Impr. In CTI CBE (ppb)
Photometry Noise	0.50	0.41	0.36
Detector Noise	0.41	0.32	0.28
Margin against Detector Req.		21.0%	30.9%

EB results by Bijan Nemati, 8/16/2017

Planned Device modifications

Step 1 : Low risk fast turn around approach (process change only)

- Eliminate visible light shield in store section
- Reduces number of transfers to serial readout by ~1000 transfers
- Image camera only needs small window



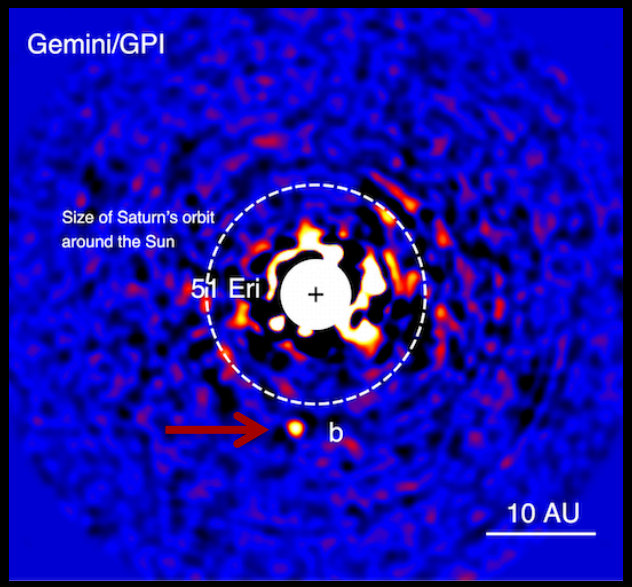
Step 2 : More aggressive approach (both process and design change)

- Two different buried channel reduced widths (3, 4 μm) in a banded array
- Notch channel design (high heritage)
- Overspill register drain dump
- High responsivity/low noise output amp

Summary

- **EMCCD technology is being advanced for the WFIRST CGI**
  - Low flux image and characterization
  - High frame rate wavefront sensing
- **Ambient and cryo-radiation testing was completed**
  - Characterized dark current, CIC, image degradation in the presence of displacement damage

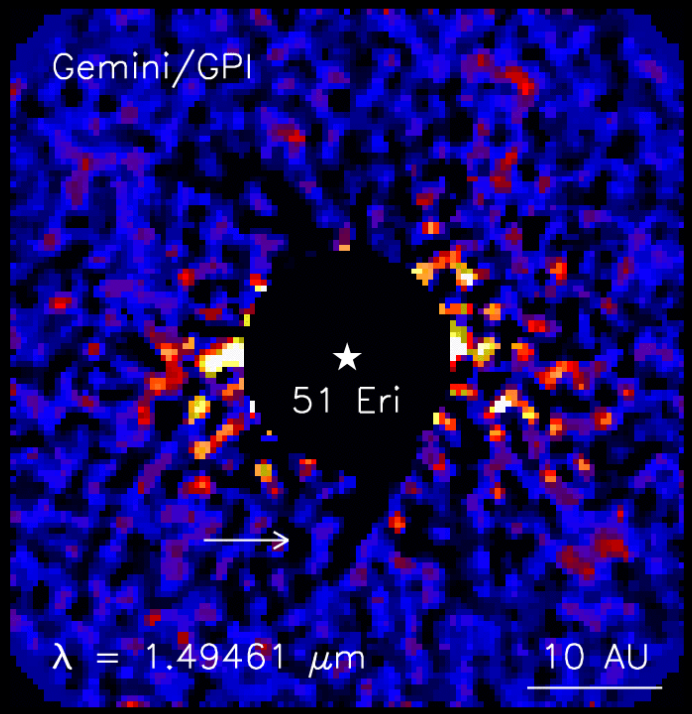
DARE MIGHTY THINGS

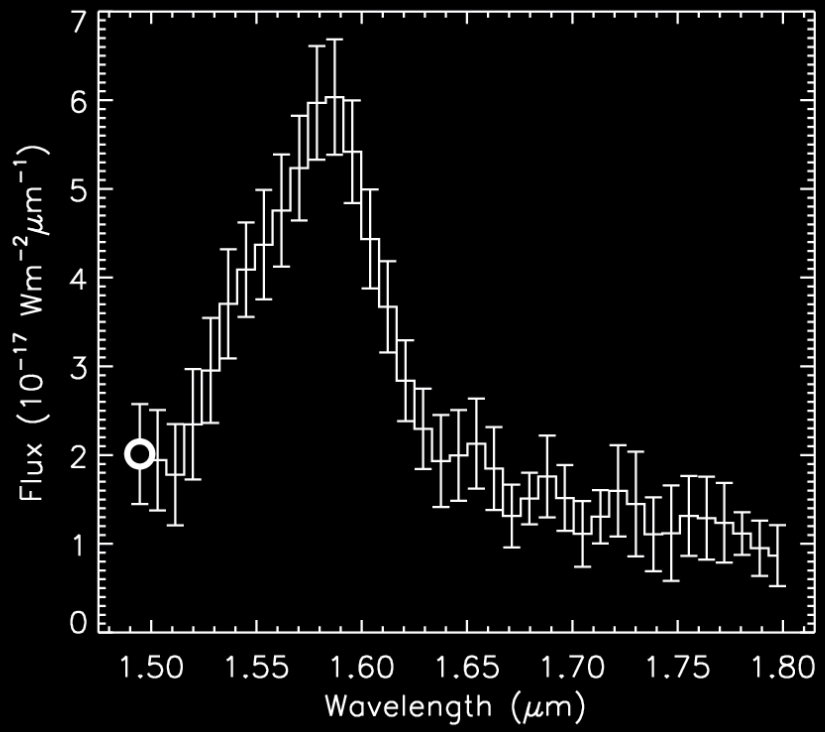


GPI image of 51 Erdiani b, Courtesy Bruce Macintosh, Stanford University

- **COTS version 201-20 meets performance requirements**
  - Various modifications are underway to increase margins
- **Next programmatic milestones**
  - System Requirements Review
  - Subsystem Definition Review

High Contrast Spectrum - GPI

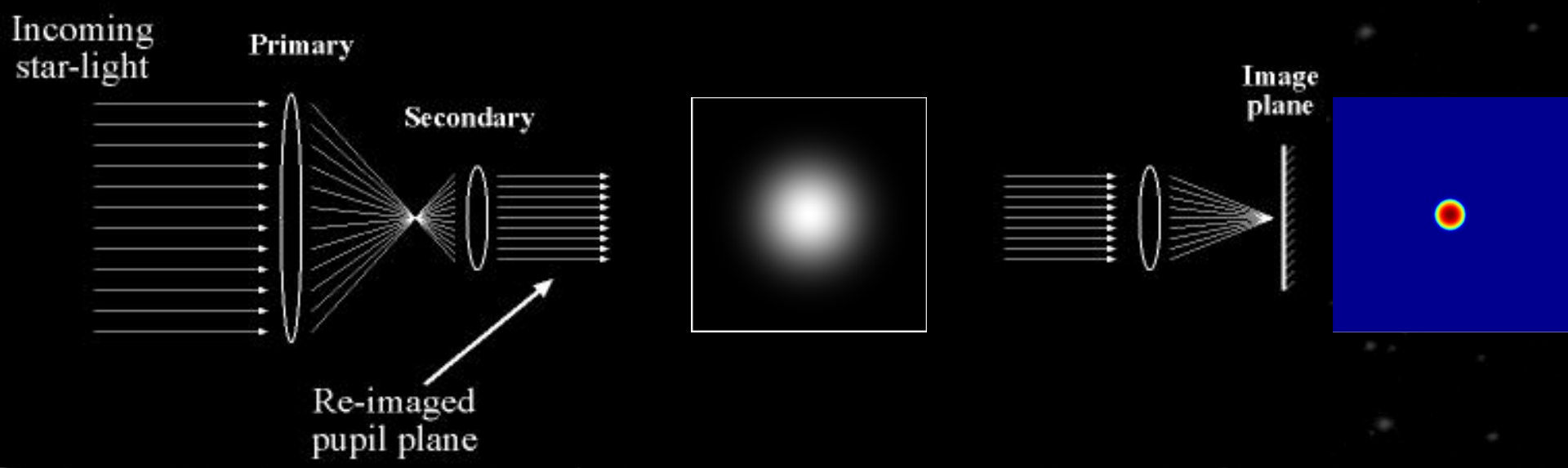




GPI image (2015) of 51 Erdiani b, provided by Bruce Macintosh, Rob deRosa & Christian Marois, UC Berkeley

RESERVE SLIDES

The Apodized Pupil Coronagraph



Cryo Radiation Test Summary

Parameter	Units	Org.	Pre-Irradiation	Post-Irradiation 2.5×10^9 pr/cm^2	MS-7 Requirement
Image area Dark Current	e-/pix/sec	JPL	$(3.00\pm0.40)\times10^{-5}$	$(7.00\pm0.0)\times10^{-4}$	1.0×10^{-3}
Effective Read Noise	e-/pix/frame	JPL	$(1.70\pm0.0)\times10^{-6}$	$(1.70\pm0.0)\times10^{-6}$	1.0
Total CIC	e-/pix/frame	JPL	$(2.1\pm0.2)\times10^{-3}$	$(2.3\pm0.2)\times10^{-3}$	—
EPER Parallel CTI (10e- signal)	-	CEI	$(8.88\pm0.49)\times10^{-6}$	$(8.32\pm0.52)\times10^{-4}$	—
EPER Serial CTI (10e- signal)	-	CEI	$(1.65\pm0.47)\times10^{-5}$	$(6.84\pm0.15)\times10^{-4}$	—
X-Ray Parallel CTI (1 event/2700 pix)	-	CEI	$(0.569\pm1.0)\times10^{-6}$	$(1.31\pm0.05)\times10^{-4}$	—
X-Ray Serial CTI (1 event/2700 pix)	-	CEI	$(1.65\pm2.08)\times10^{-6}$	$(4.12\pm0.35)\times10^{-5}$	—

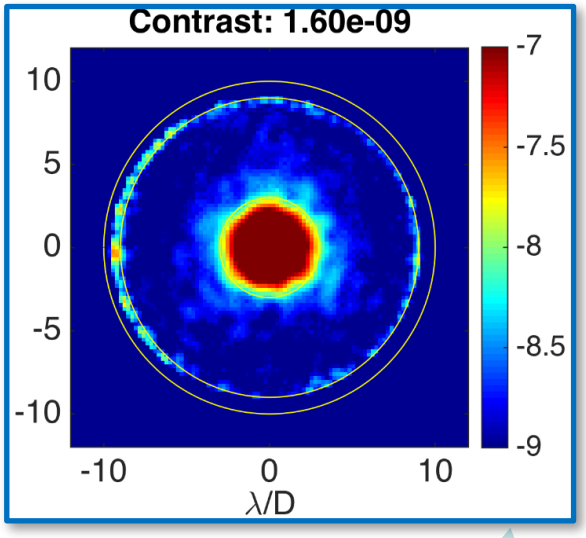
NOTES

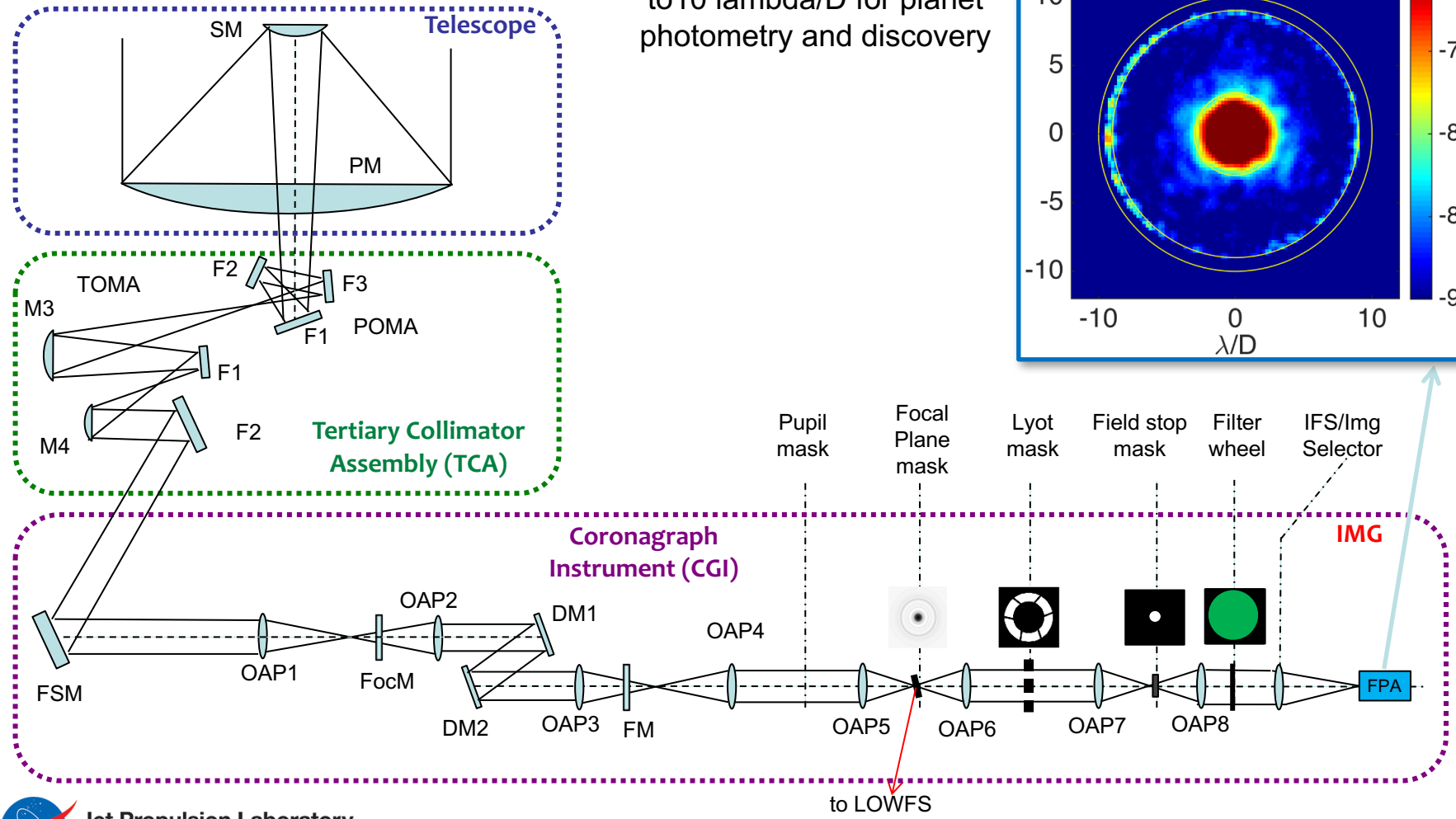
1. CEI measurements made at 165K using XCAM commercial electronics, not performance optimized
2. JPL measurements made at 168K using NüVü flight-like commercial electronics, performance optimized
3. CEI read noise measurement (not shown) made in analog mode with low gain
4. JPL read noise measurement made in photon counting mode with high gain
5. JPL EOL measurements are optimized for extremely low flux detection and result in slightly higher dark current.

CGI Modes – Hybrid Lyot

Hybrid Lyot Mode

360deg dark hole from 3 to10 lambda/D for planet photometry and discovery

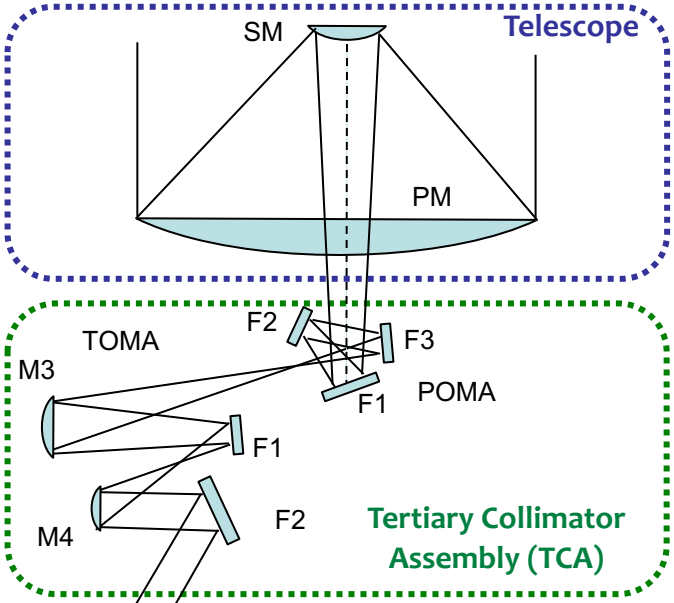


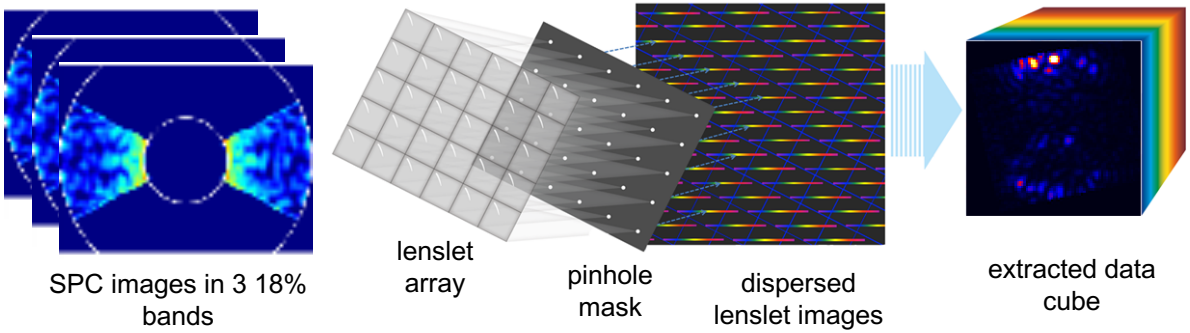


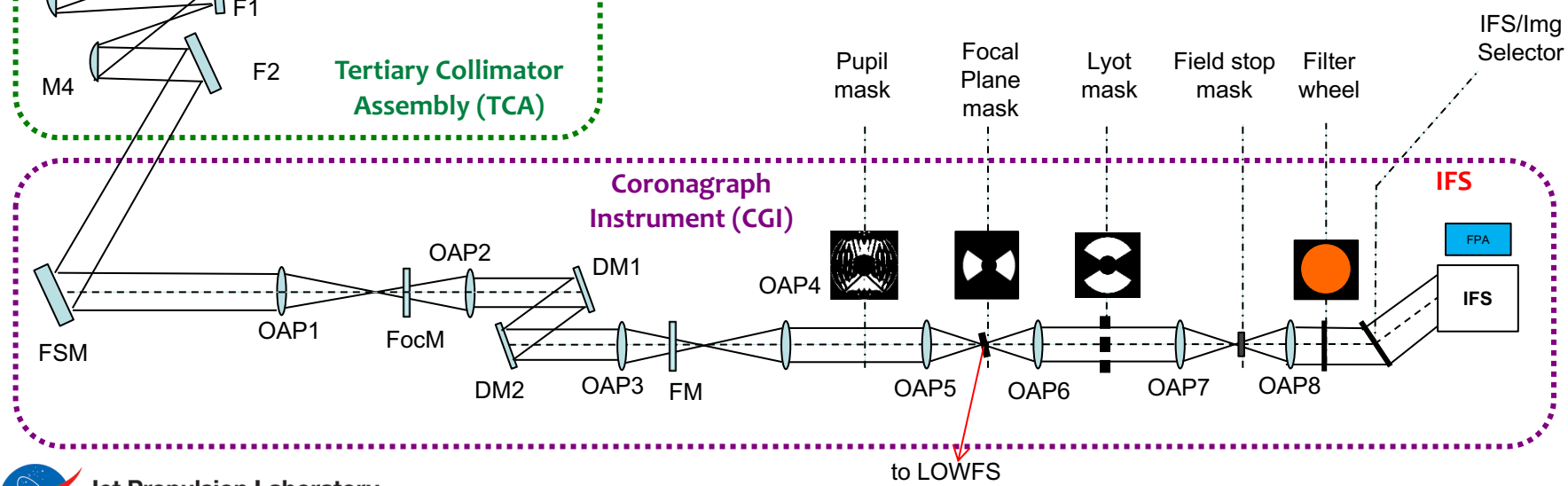
CGI Modes – Shaped Pupil Spectroscopy

Shaped Pupil Spectroscopy Mode

The IFS uses 3 18% bands to produce R=50 spectra from 600 to 970nm





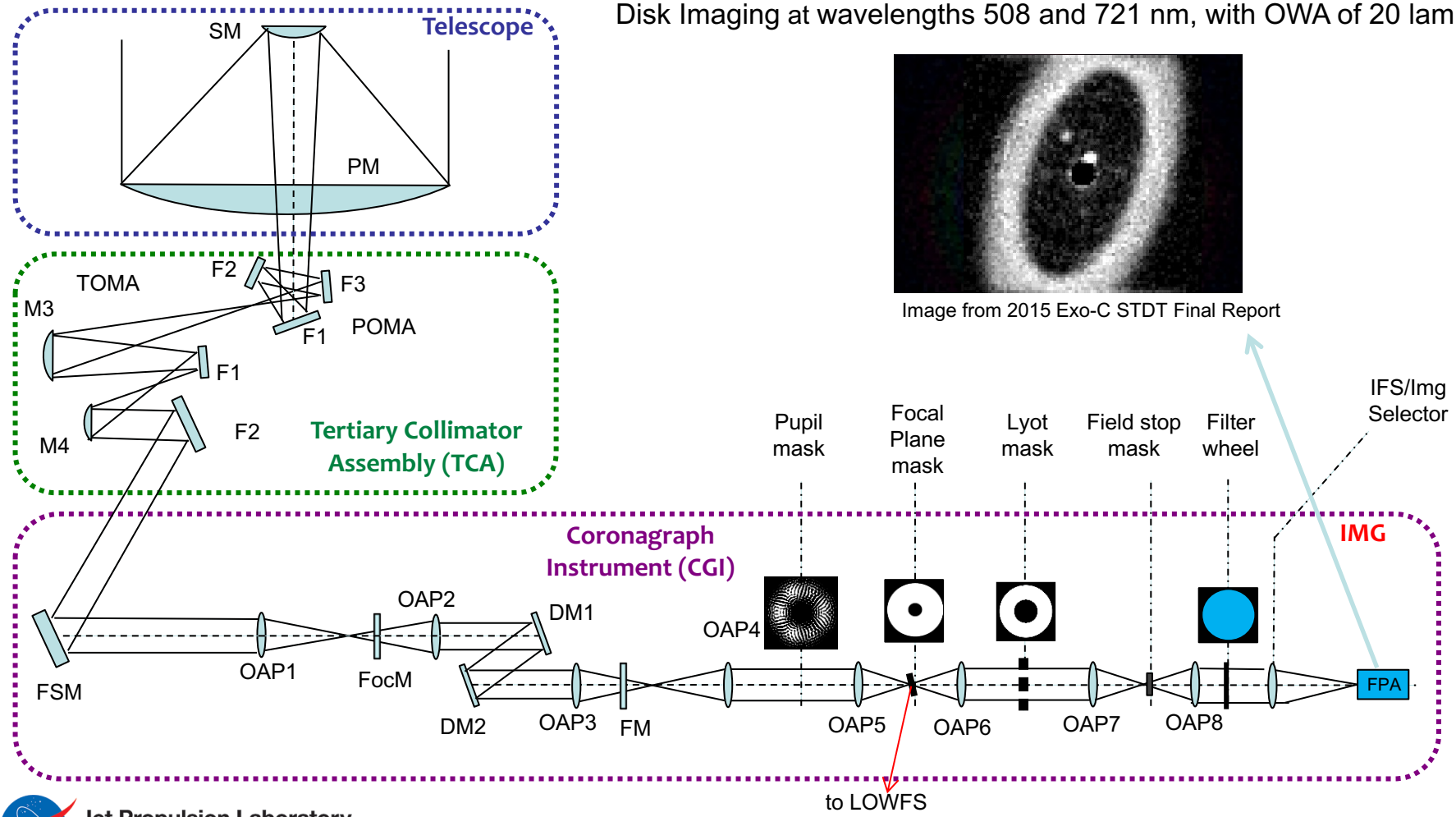


CGI Modes – Shaped Pupil Disk

Shaped Pupil Disk Imaging Mode

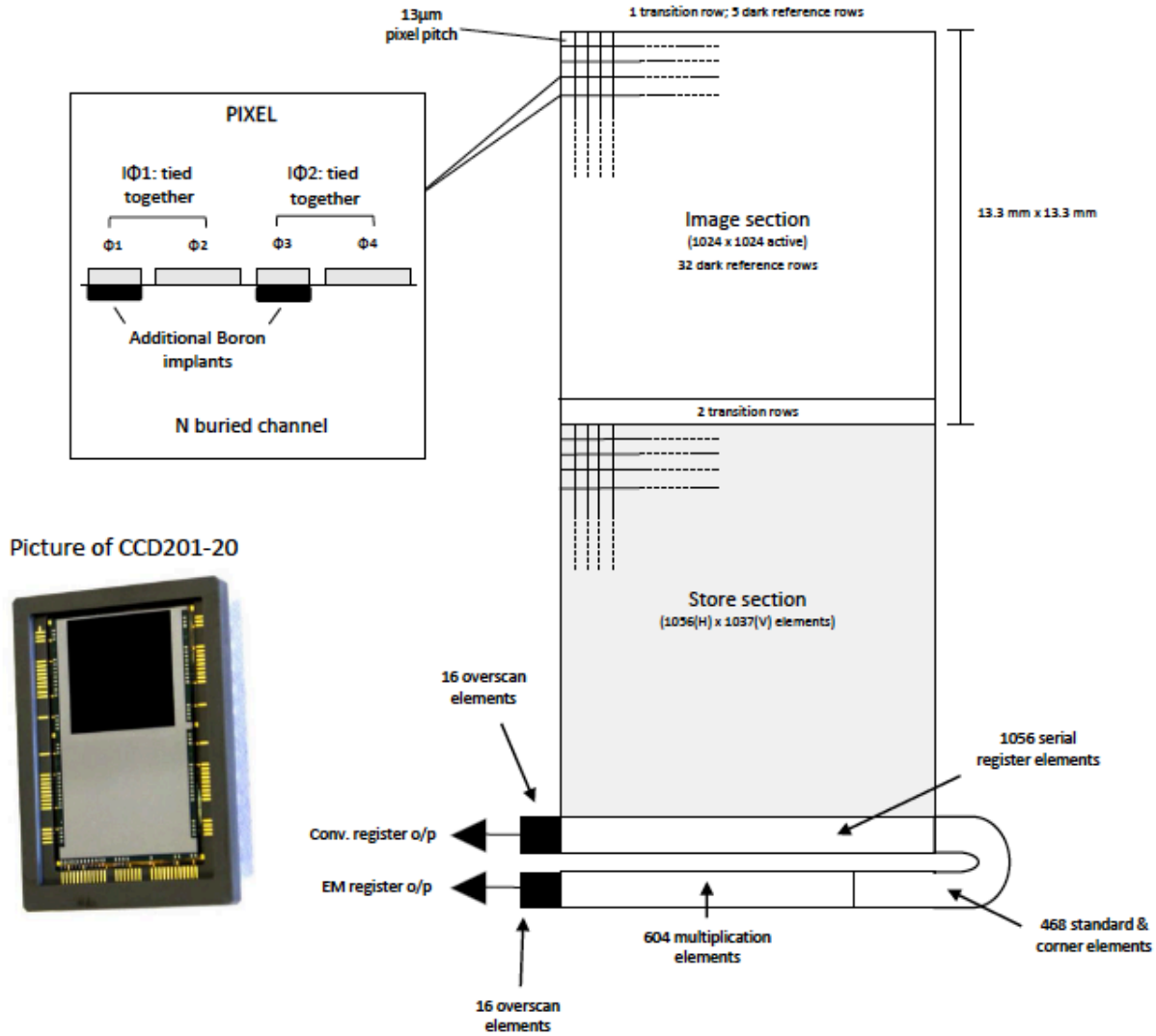
Disk Imaging at wavelengths 508 and 721 nm, with OWA of 20 lambda/D

Image from 2015 Exo-C STDT Final Report



e2V CCD201-20 Architecture

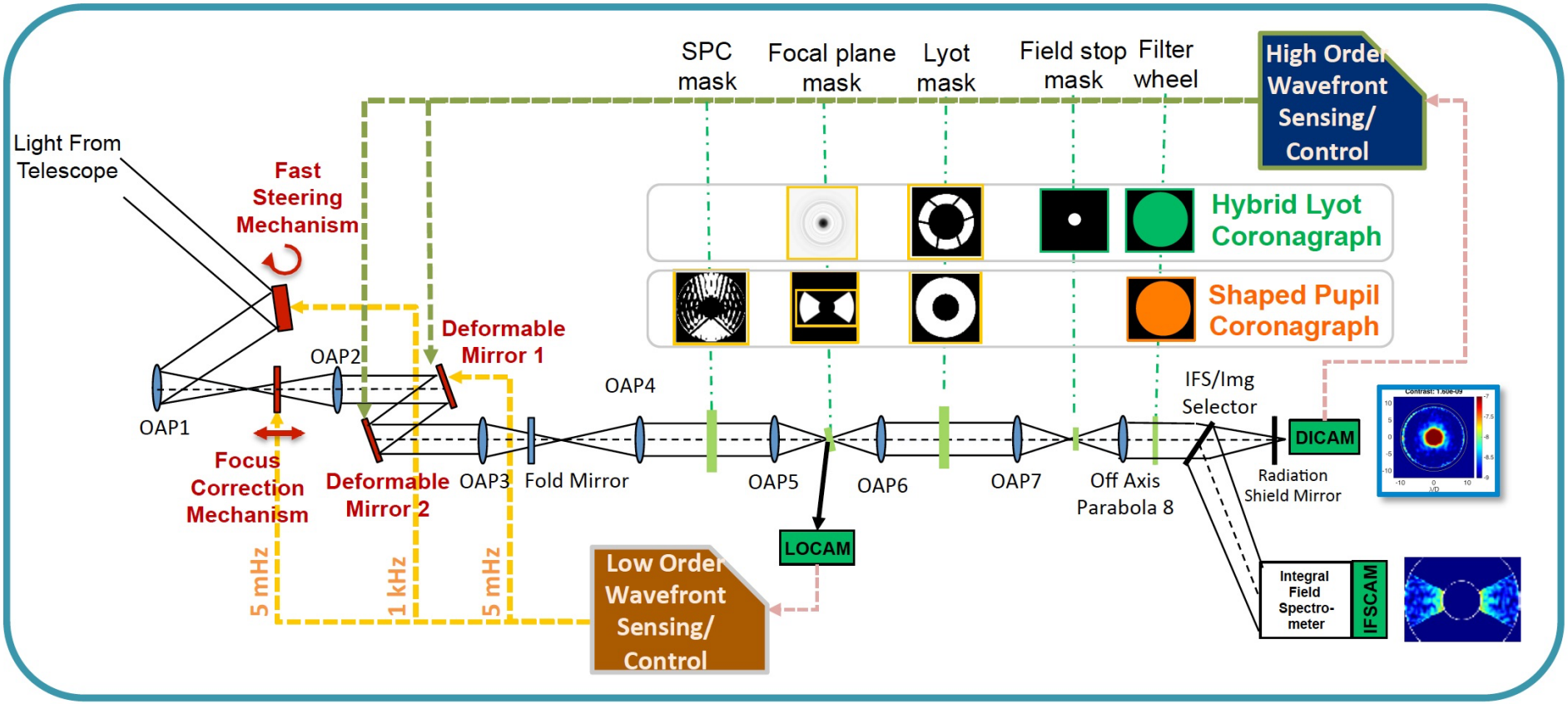
- Frame transfer configuration
- High Responsivity (HR) output – conventional CCD operation
- Large Signal (LS) output – EM gain operation
- Standard & Corner elements
  - Bend-around to reduce die size
  - 468 selected to balance the 1056 element row and thus act as buffer (with 604 elements) to increase readout speed

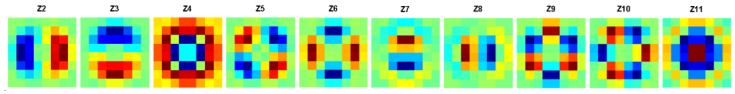


Picture of CCD201-20

Taken from *Harding & Demers, et al. (2016)*

1st Actively Controlled Optical Imaging Instrument w/ Coronagraph Masks in Space





- Active components
  - Fast steering mirror (FSM) for line-of-sight control
  - Focus correction mechanism (FocM) for focus control
  - Deformable mirrors (DM1, DM2) for wavefront error control
- Control loops
  - High-order wavefront sensing control (HOWFS/C) loop for initially achieving starlight suppression
  - Low-order wavefront sensing control (LOWFS/C) loop for continuously maintaining starlight suppression

Acronyms

- CGI = Coronagraph Instrument
- DICAM = Direct Imaging Camera
- DM = Deformable Mirror
- FocM = Focus Control Mechanism
- FSM = Fast Steering Mirror
- FSW = Flight Software
- I/C = Interface Card
- IFS = Integral Field Spectrograph
- IFSCAM = IFS CAMera
- LOCAM = Low Order wavefront sensor CAMera
- OAP = Off-Axis Parabola
- OTA = Optical Telescope Assembly
- PCU = Power Conditioning Unit
- POMA = PickOff Mirror Assembly
- TOMA = Tertiary Optical Mirror Assembly
- TCA = Tertiary Collimator Assembly

MECHANISMS

- SPWM = Shaped Pupil Wheel Mechanism
- OCWM = Occulter Wheel Mechanism
- LSWM = Lyot Stop Wheel Mechanism
- FSWM = Field Stop Wheel Mechanism
- CFWM = Color Filter Wheel Mechanism
- CSWM = Camera Selector Wheel Mechanism

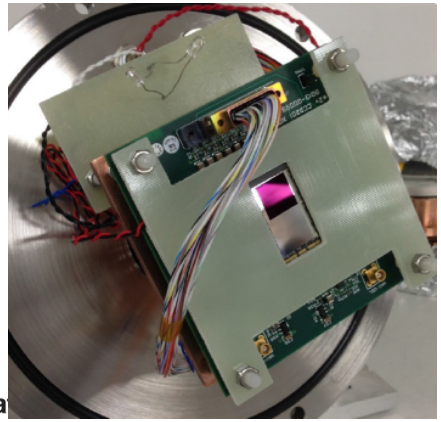
Radiation Testing : Phase I

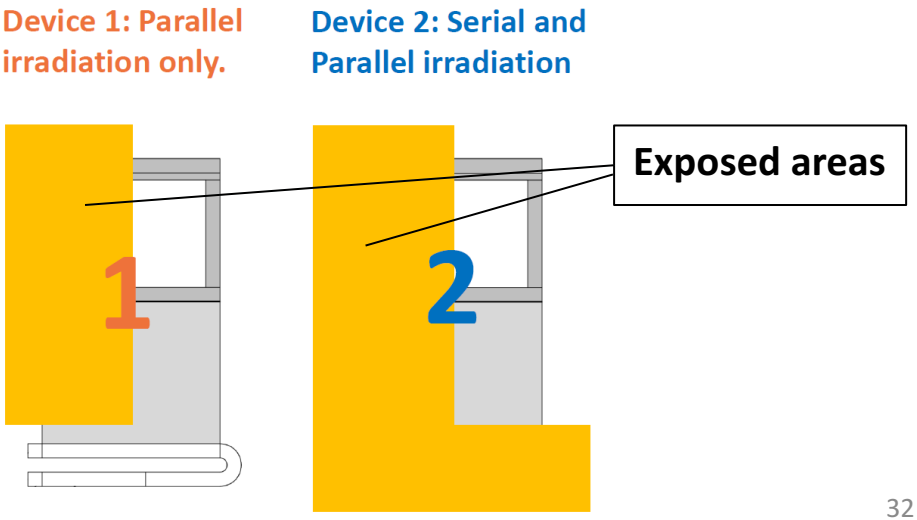
Single Displacement Damage Dose (DDD)

Single exposure of Displacement Damage Dose (DDD) at room temperature

- **Survivability test of detector for 2.5 x 10^9 protons cm^{-2} dose [10 MeV equivalent]**
  ~Corresponds to 6 years at L2 orbit with Ta shielding
- DUT engineering-grade EMCCD: e2V m/n CCD201-20
- Paul Scherrer Institute Beamline, Switzerland in April 2015
- Assessed degradation of:
  - Read Noise, EM gain, Clock Induced Charge, Dark current, Charge Transfer Inefficiency
- T = 293 K during irradiation;
- 165 ±2 K during post exposure measurement
- Unbiased during exposure
- Frame time = 100 sec
- Inverted Mode Operation (IMO): suppression of large surface dark current
- Serial readout rate of 700kHz (some exceptions)

DUT = device under test





Radiation Testing: Phase II

Incremental Displacement Damage Dose (DDD) at Cryo

Four separate exposures of Displacement Damage Dose (DDD) at cryo-temp

- **Characterize the performance degradation at intermediate points in 6 year life cycle**
- DUT science-grade EMCCD: e2V m/n CCD201-20
- Performance fully characterized before campaign and after each of four doses
- Facility: Helios 3 Beamline, Harwell, UK
- T = 165 ±2 K for irradiation; (±5 K during measurements)
- Biased during exposure to monitor flatband voltage shift
- Inverted Mode Operation (IMO): suppression of large surface dark current
- Serial readout rate of 700kHz (some exceptions)
- Applied bias voltages during test same as for Phase I for comparison*
  - * Except for the two voltages driving EM gain
  - Four cumulative doses summing to 7.5 x 10^9 pr/cm^2 [10 MeV equivalent]
    - Fourth dose smaller than prescribed due to facility failure
      - Reported but not used in analysis
  - Performance fully characterized **before** campaign and **after each** of four doses
    - Dark current, CIC, EM gain, RN, X-ray CTI, EPER, amplifier responsivity

Exposure Dose [10^9 protons/cm^{-2}]	Cumulative Dose [10^9 protons/cm^{-2}]
0	0
1	1
1.5	2.5
2.5	5
2.5	7.5

Rad-hard modifications

Design Parameter	Units	A	B	C	Comments
Image & store pixel channel width	μm	Standard	3, 4, 6, SBC* (TBC)	3, 4, 6, SBC* (TBC)	*3 or 4 different channel widths to be used. Exact widths TBC and can be confirmed in initial design definition
Image & store pixel well depth	e-	Standard	TBC	TBC	Assumed to be non-critical
Serial pixel channel width	μm	Standard (24 μm)	9 to 12**	9 to 12**	**TBC following design definition phase
AR coating		Standard	Multi-2	Multi-2	Must be flight qualified; deemed low risk
Output amplifier gain (EM output)	μV/e-	Standard	Standard	~3 μV/e-[†]	[†]Highest responsivity that can be made with 10 MHz output frequency
Visible light blocking layer (over store area)		None	None	None	VIS blocking layer covering serial register, corner elements and EM register; blockage of a few pixel rows at bottom of array is acceptable
Silicon thickness in store region	μm	~12 μm	~12 μm	~12 μm	Edge of thick silicon to be a few (<10) rows into the store region. Metal store shield to cover the serial register, corner elements and EM register only
On-chip temperature sensor		None	None	None	To be incorporated into flight package, not on-chip
Barrier implant		Standard	Standard	Standard	
Overspill register		Recombines with signal	Dump into a drain	Dump into a drain	
Dump Drain (DD)		Yes	Yes	Yes	No change will occur to DD if serial register is not modified