Transiting Exoplanet Survey Satellite (TESS): Designing a Sensor for Full Sky Mapping Exoplanet Detection

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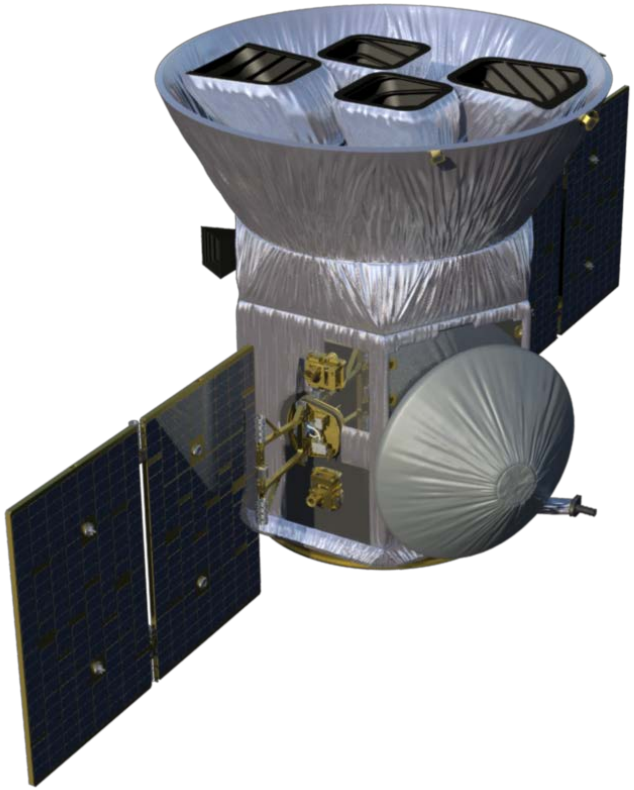
Transiting Exoplanet Survey Satellite (TESS)

TESS Goal: Find the *Nearest Earth-Like* Planets



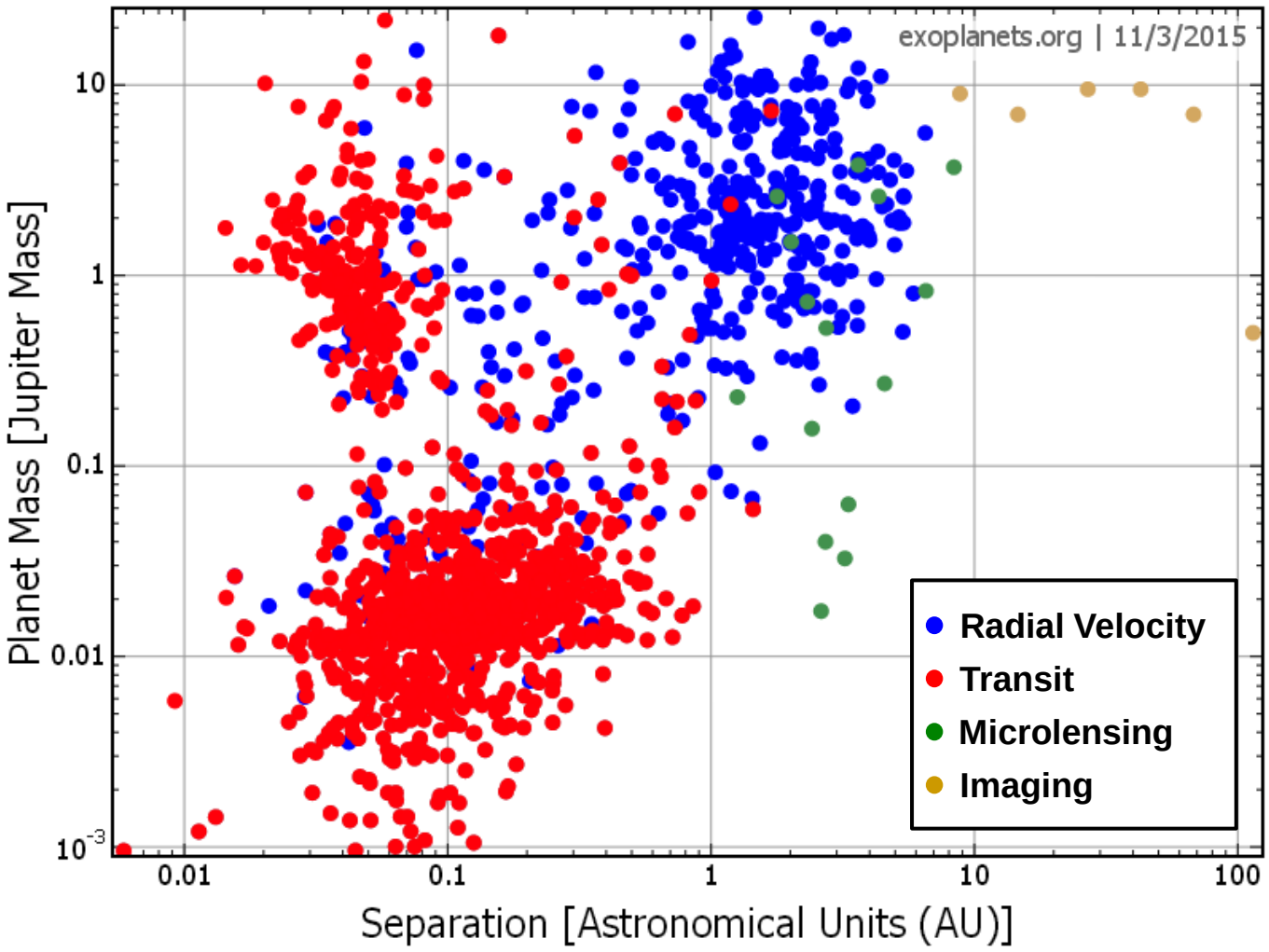
- **NASA Explorer Mission**
  - **–August 2017 Launch**
  - **–2 year mission**
  - **–$228M Mission Cost**

TESS is a complementary, logical follow-on to Kepler and pre-cursor to James Webb Space Telescope (JWST) spectroscopy of exoplanets

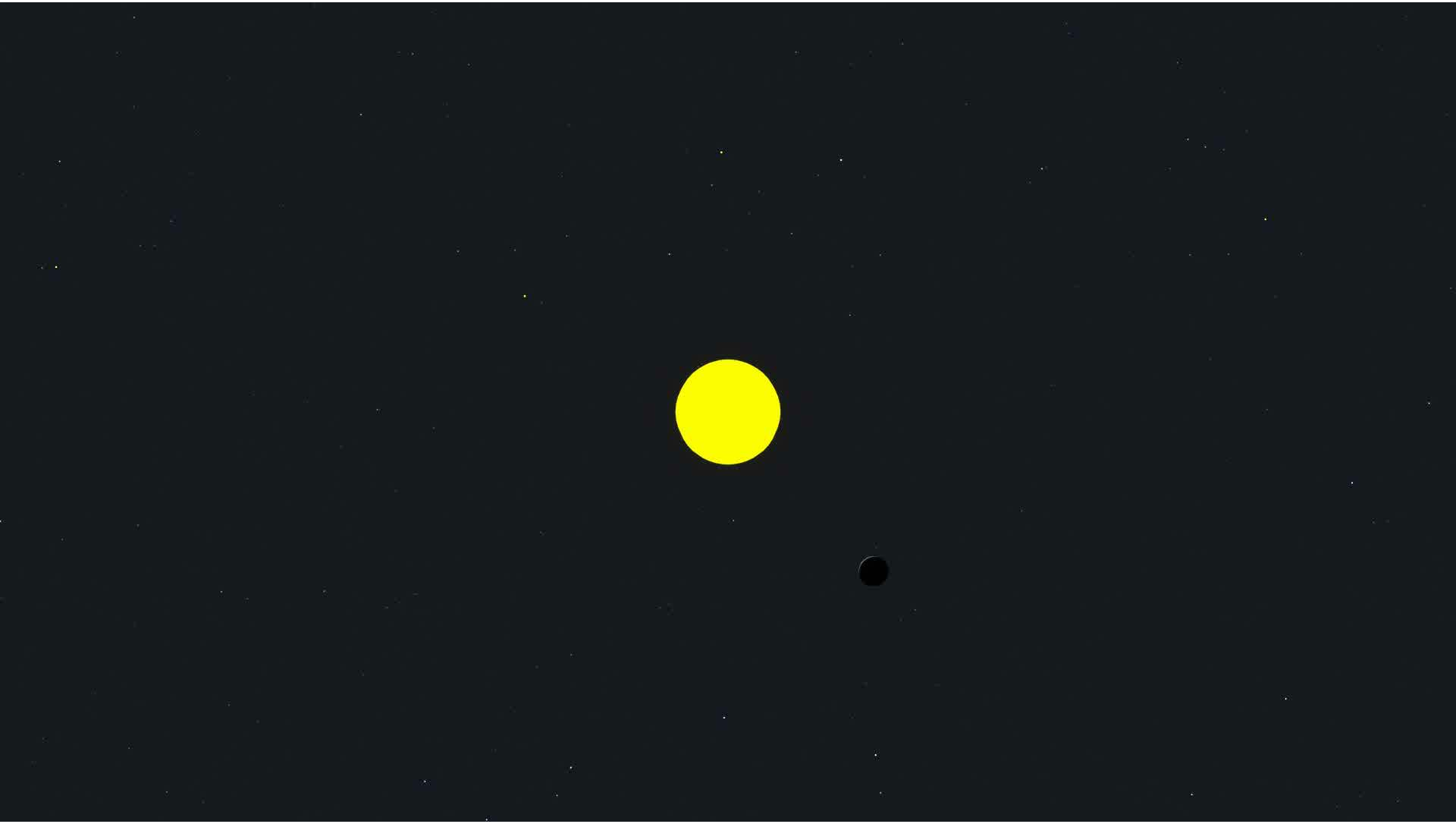
Outline

- **Science and Environment**
- **Instrument Design/Analysis**
- **Instrument Build/Test**
- **Path Forward**
- **Summary**

A Bit of Background

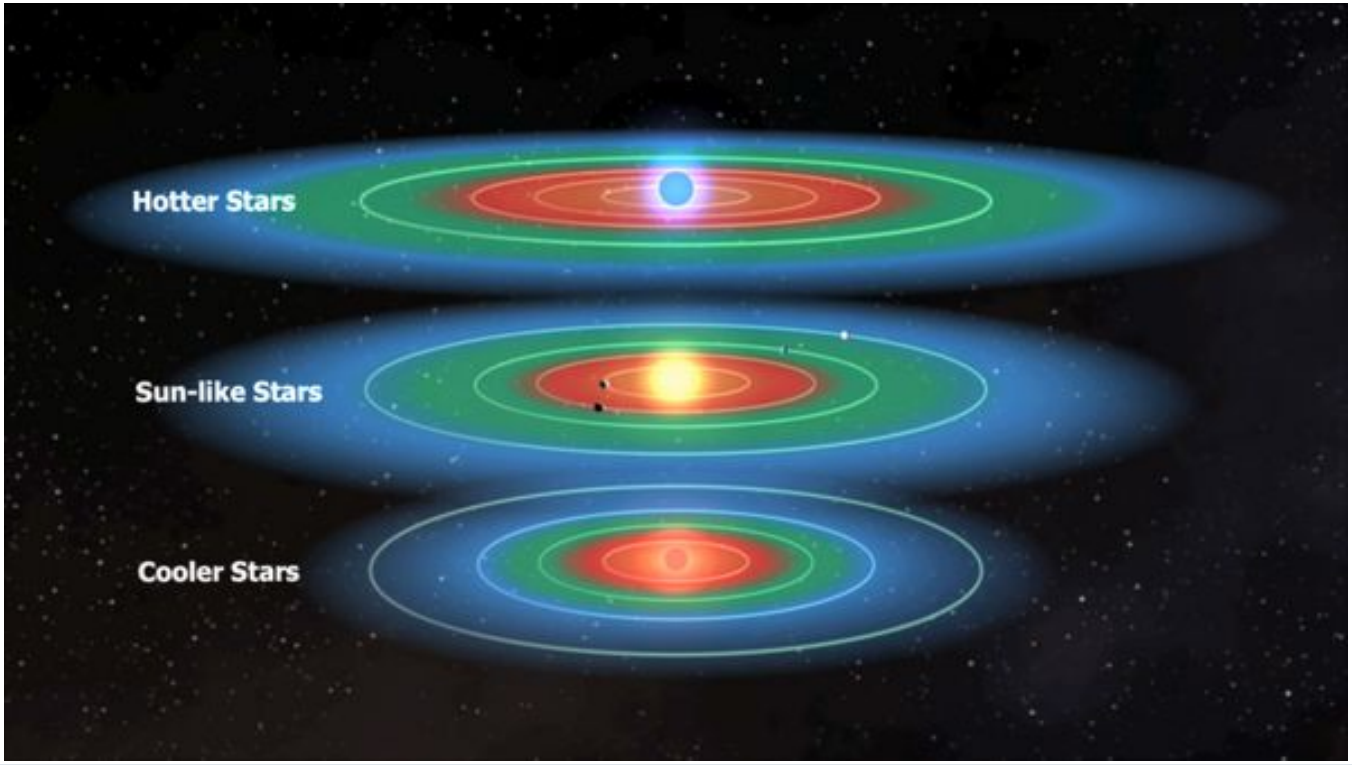


Transit Method



TESS Detection Goals and Target Stars

- **Discover transiting earths and super earths**
  - **Orbiting bright, nearby stars**
  - **Rocky planets and water worlds**
  - **Habitable planets**



Transits/year

<<1

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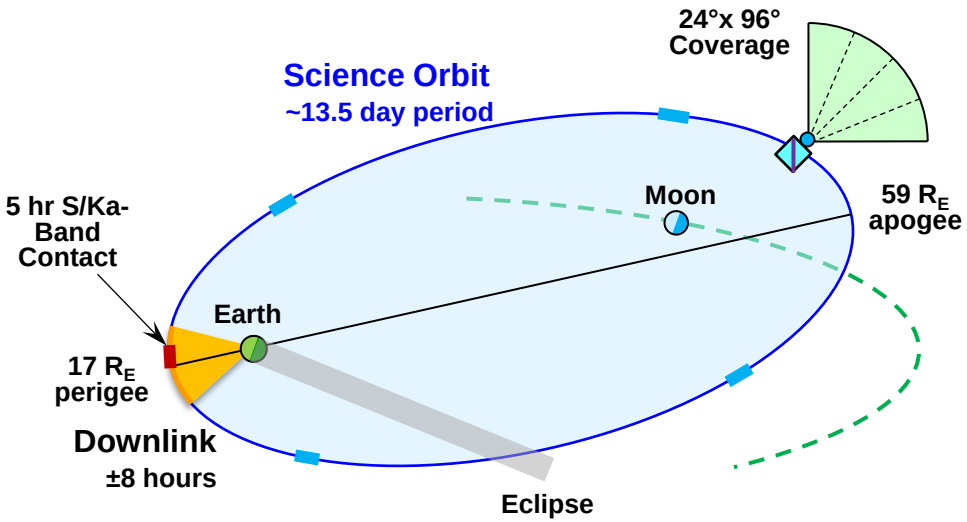
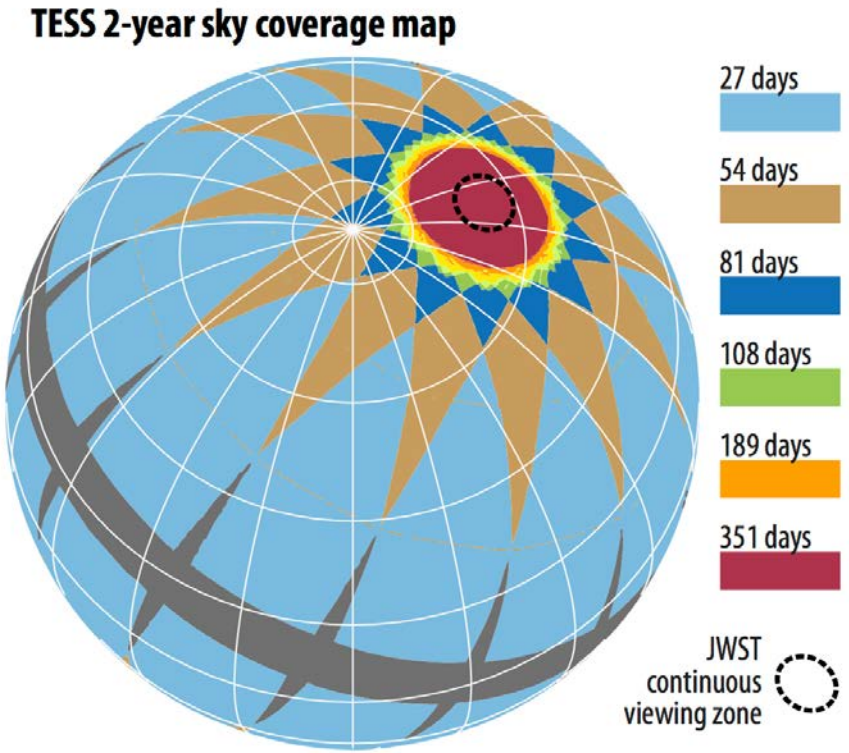
TESS Coverage and Environment

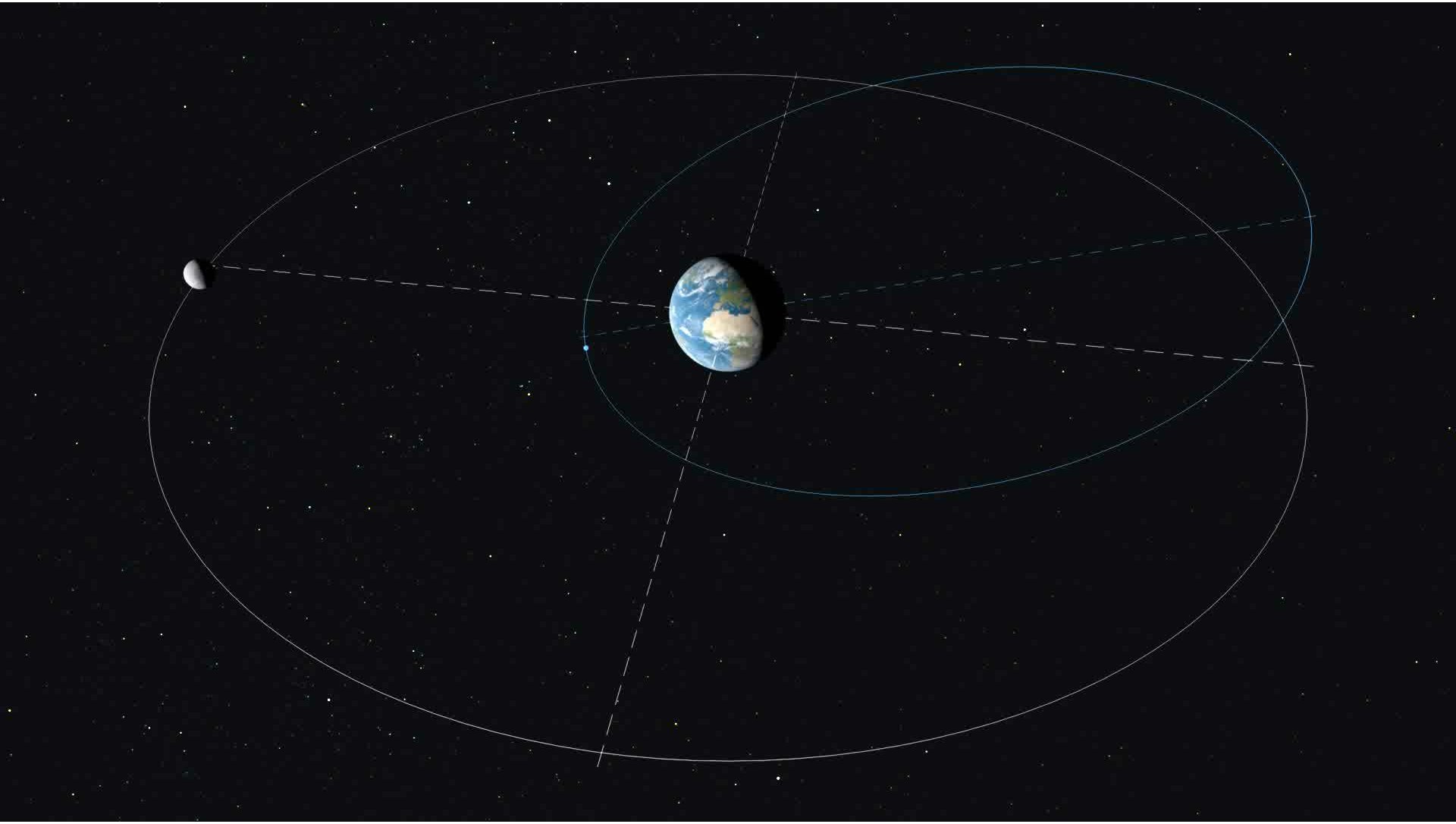
- **Highly Elliptical Orbit provides extremely stable thermal environment**
  - **Attitude change for data downlink creates a temperature pulse**
- **Wide field-of-view and step stare observing provide near full sky coverage**
  - **Science orbit instrument pointing fixed in inertial space**



TESS Orbit

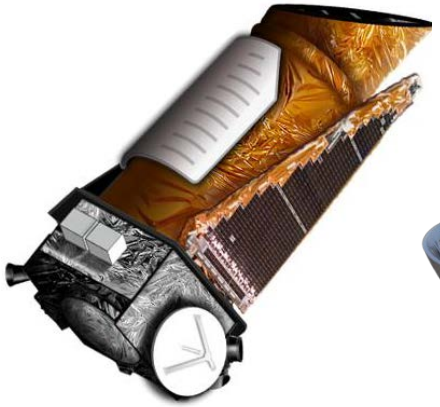


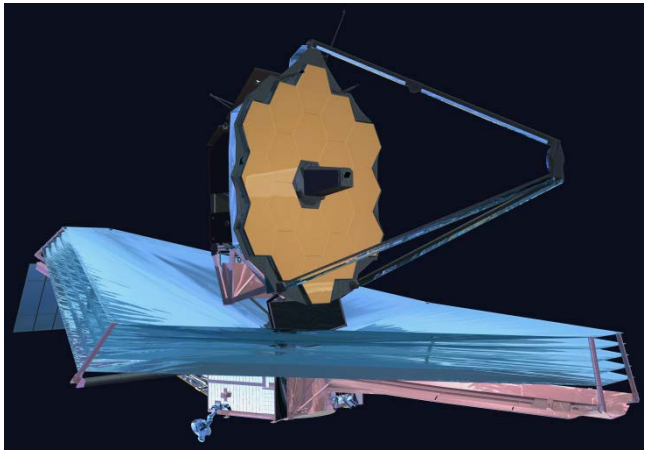
TESS Orbit and Sky Scan



TESS Piece of the Exoplanet Puzzle

- **Kepler**
  - **Estimate statistical population of exoplanets**
    - **Field-of-View (FOV) : 12 degrees**
    - **Faint stars (magnitude +12 to +16)**
- **TESS**
  - **Provide catalog of exoplanets for further observation**
    - **Large FOV : Full sky coverage**
    - **Bright stars (magnitude +4 to +12)**
- **JWST**
  - **Atmospheric characterization of exoplanets**
    - **Small FOV : Arc minutes**
    - **Star magnitudes (magnitude +4 to +14)**



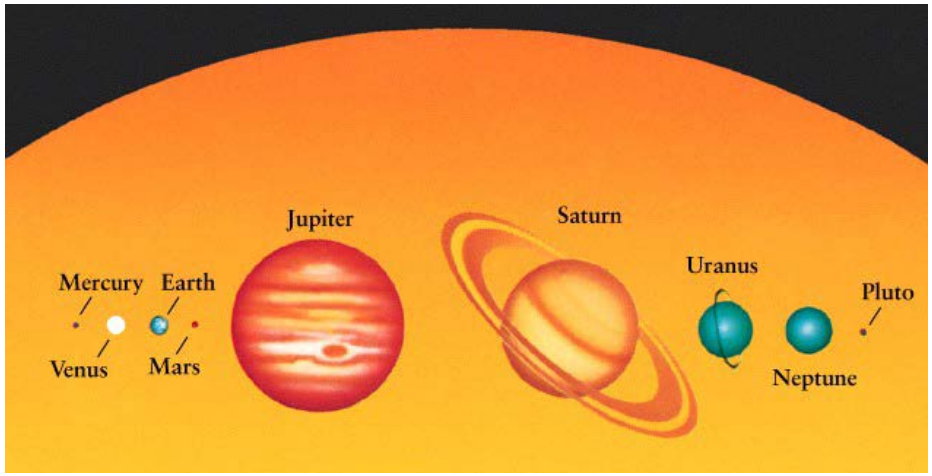


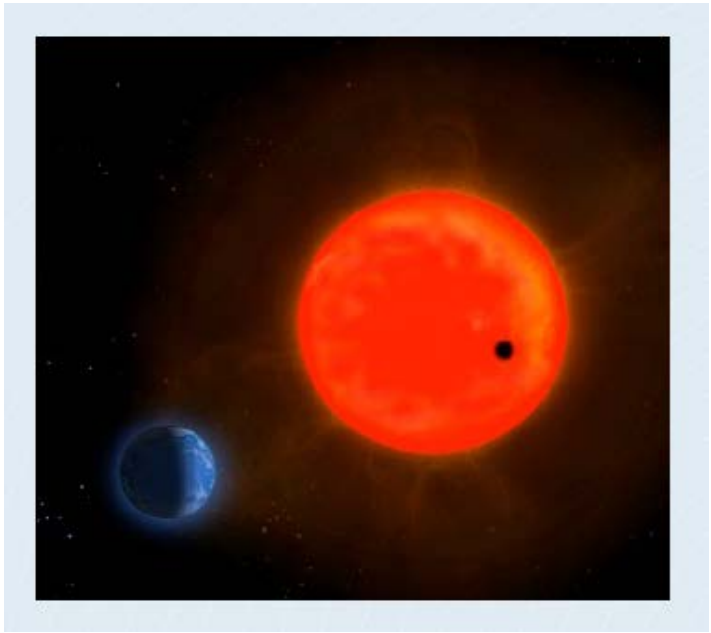
Instrument Design Study Outputs

Mission Choice	System Impact	TESS Choices
Full Sky Coverage	Number of Cameras	Field-of-View 4 x (24˚x24˚)
F,G,K,M Dwarf Stars	Spectral Band (600-1000nm)	O'Hara glasses 100μm Si depth CCD
Earth-Like Planets	Camera Sensitivity	Read Noise <20 e-
+4 to +12 Magnitude	Camera Dynamic Range	Full Well Capacity >150,000 e-
Light Curve Planet Detection	Imaging Performance	Brightest Pixel Flux Fraction >40% (on-axis)

Expected TESS Planet Detection Yields

- **In two years, TESS is expected to discover:**
  - **~30 Earth-sized planets**
    - **Handful in habitable zone**
    - **100 small planets (R_P<2R_E) in or near JWST's Continuous Viewing Zone**
  - **~300 Super-Earth planets**
  - **~3,000 Sub-Neptunes**
  - **~25,000 Neptunes and Jupiters**





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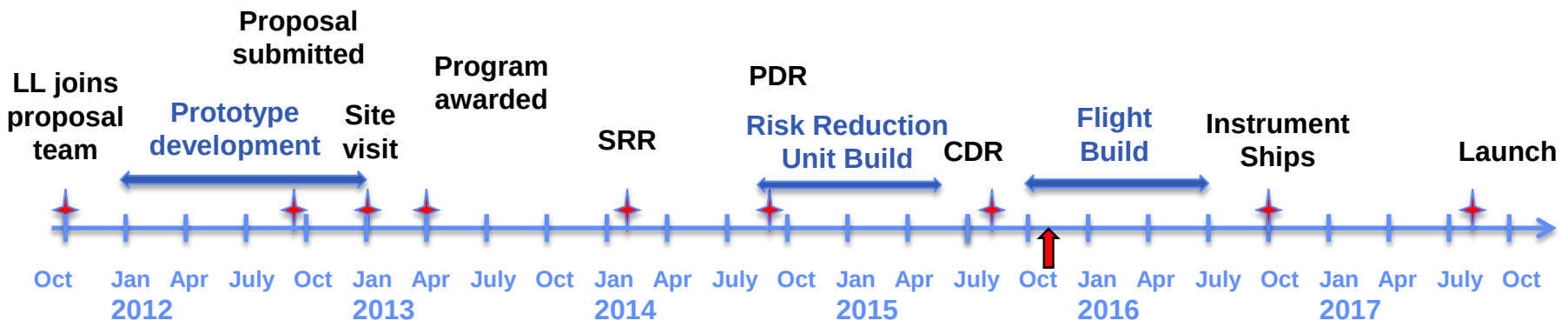
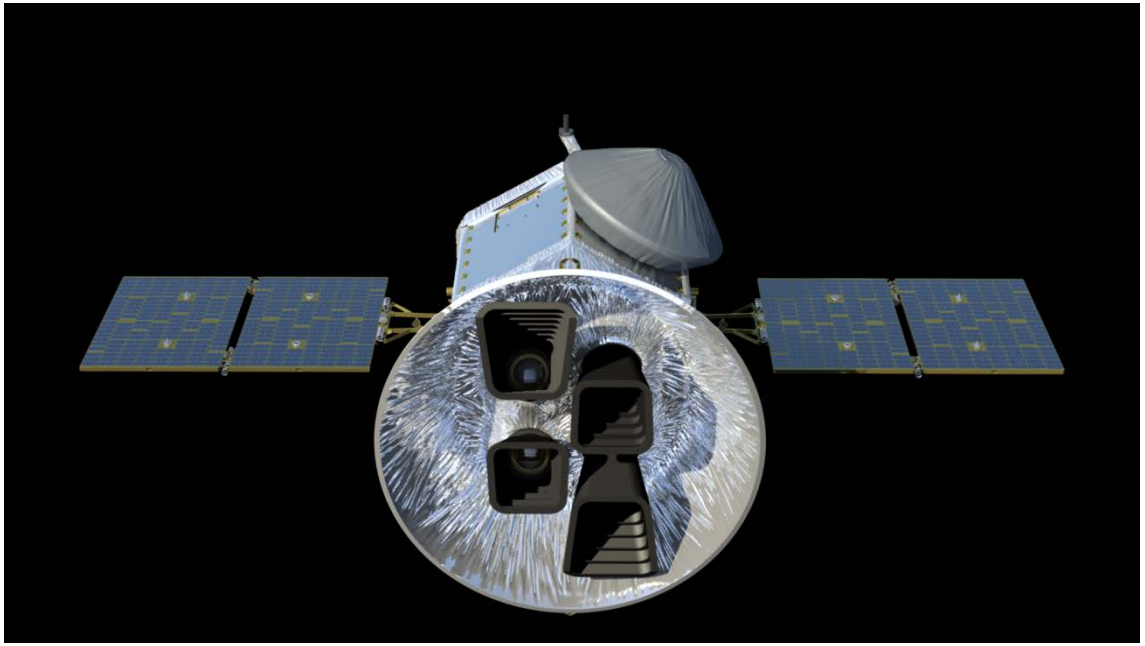
TESS Team and Timeline





MKI

NASA

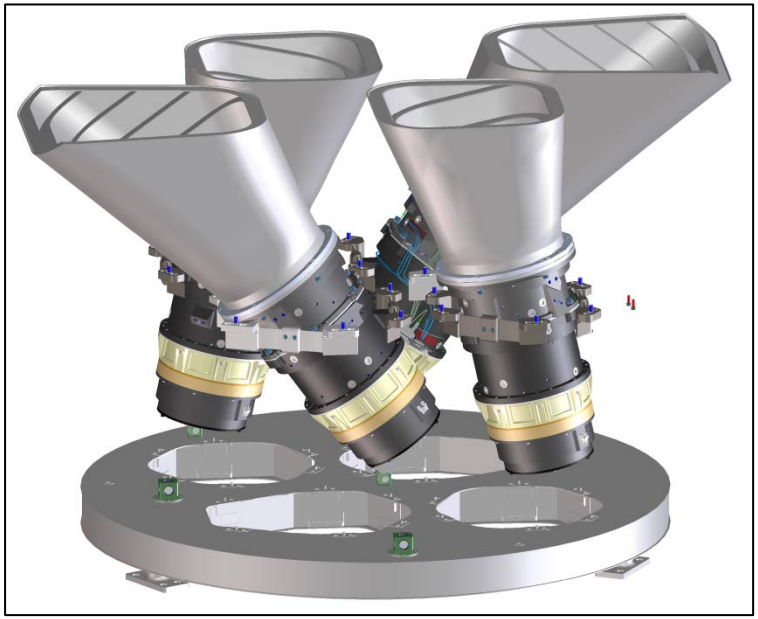
Orbital ATK

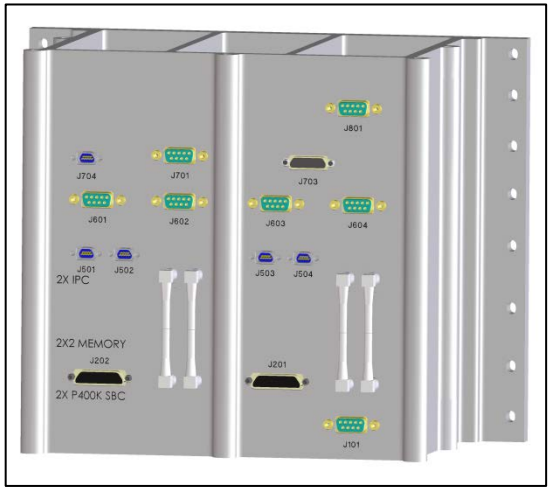
SPACEX

TESS Instrument Overview

Camera Structure Assembly (CSA)

- Four wide field-of-view cameras with flexure mounts
- Camera Plate Assembly
  - Camera Plate
  - Bipods
  - Purge Manifold
- Electrical and thermal harnesses

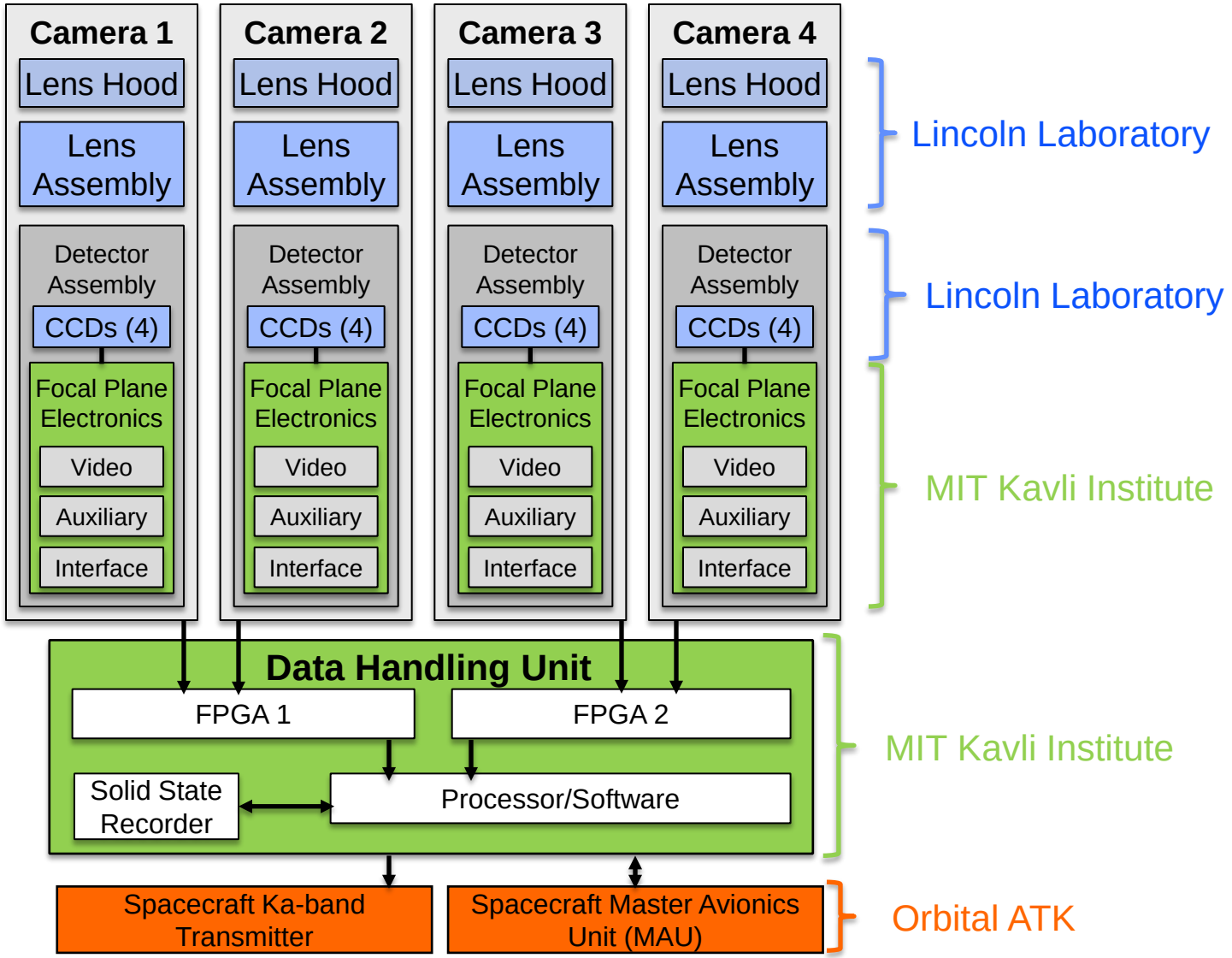




Data Handling Unit (DHU)

- Processes four camera streams simultaneously
- Processes and stores science and housekeeping data
- Generates quaternions for spacecraft fine pointing
- Processes spacecraft commands
- Passes stored science data to the Ka Transmitter

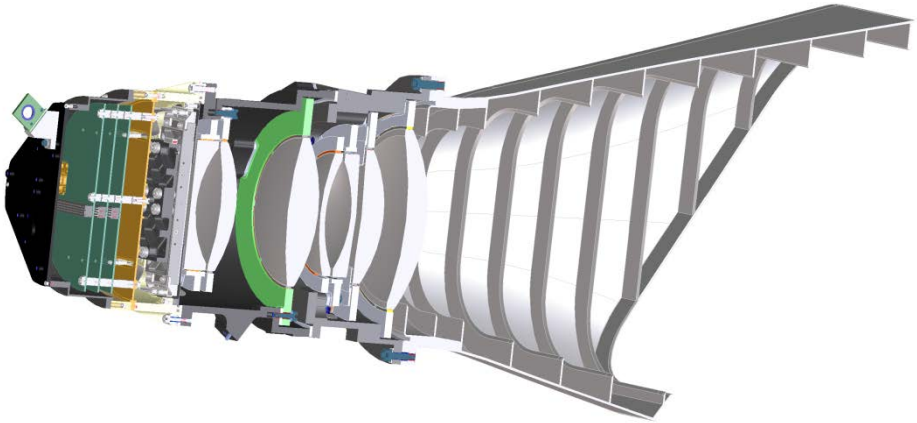
TESS Instrument Block Diagram

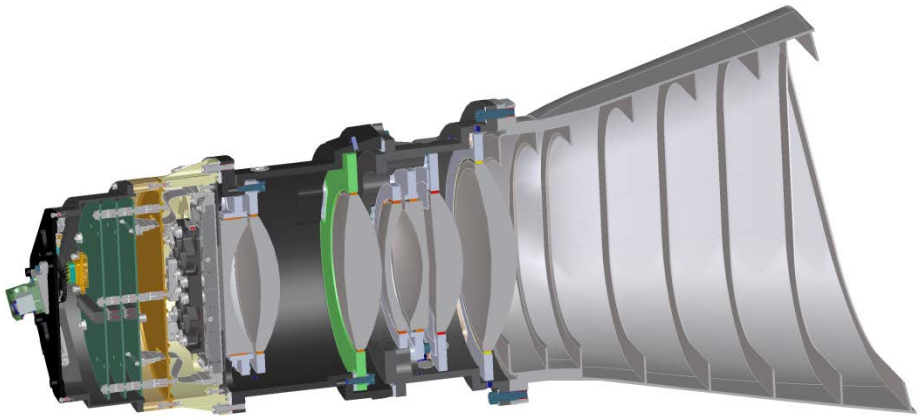


Instrument Design Challenges

- **Optical**
  - **Combine large field-of-view, spectral range, and collection efficiency**
  - **Suppress stray light (-70 dB)**
- **Mechanical**
  - **Align lens barrel to CCD**
  - **Maintain structural stability during launch**
- **Thermal**
  - **Isolate electronics (warm) from CCD/lens (cold)**
  - **Minimize thermal settling time after data downlink**
- **Structural Thermal Optical Performance (STOP) Modeling**
  - **Maintain camera pointing stability on orbit**
  - **Maintain Brightest Pixel Flux Fraction (BPFF) over field and temperature**

Instrument Design



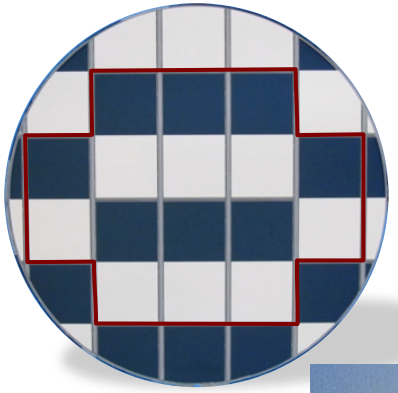


- **Detector Assembly**
  - Dedicated Focal Plane Electronics
  - CCD focal plane 4096x4096 pixels
- **Lens Assembly**
  - 24˚ x 24˚ FOV (>90% sky coverage)
  - 146 mm focal length f/1.4
  - Optimized over 600-1000 nm
- **Lens Hoods (12˚, 36˚)**
  - Reduce scattered light
  - Minimize noise floor
  - Thermal radiator
- **Instrument Assembly**
  - Maintain optical performance throughout science orbit

TESS Imager Summary

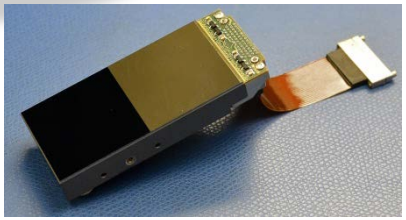
- **2048 x 2048 frame-transfer format, (2k x 4k CCD)**
- **15-µm pixels**

Performance	Value	Achieved
Well Capacity	> 150,000 e- (goal)	**> 190,000 e-**
Conversion Gain	< 10 µV/e-	**7 µV/e-**
Read Noise @ 625 kHz	< 20 e-	**< 14 e- w/FPE**
Dark Current @ -30°C	< 8 e-/pix/sec	**< 2.5 e-/p/s**
Device Thickness	100 µm (-10/+15µm)	**95 – 115 µm**
Depletion-depth control	Substrate bias	**Functional**
Targeted Spectral Range	600-1000 nm	**70% @ 950 nm**

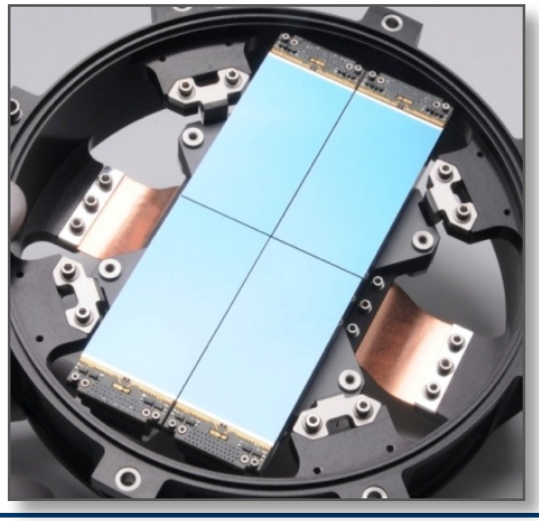


Completed 200 mm CCD Wafer

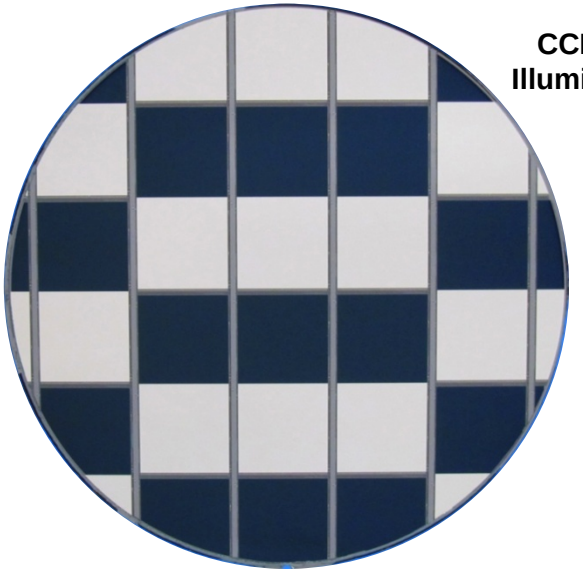
Packaged CCID-80 Imager



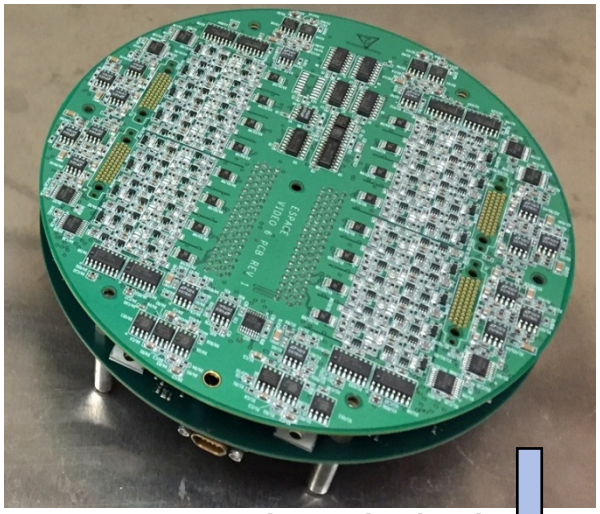
Prototype Detector Assembly



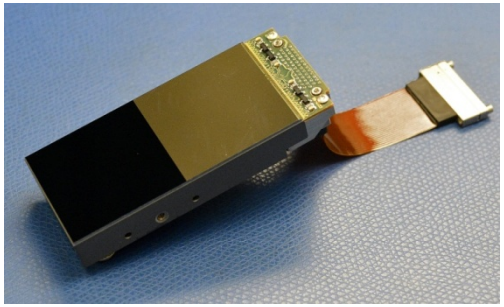
TESS Detector Assembly Summary



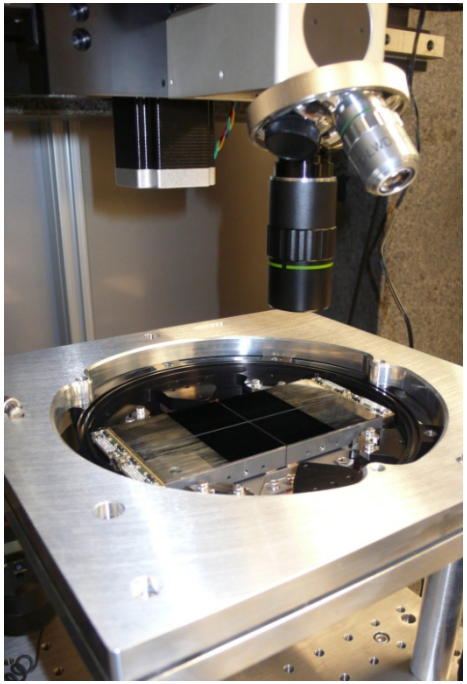
CCID-80 Back Illuminated Wafer



v6 Prototype Electronics (MKI)



Packaged CCID-80 Imager



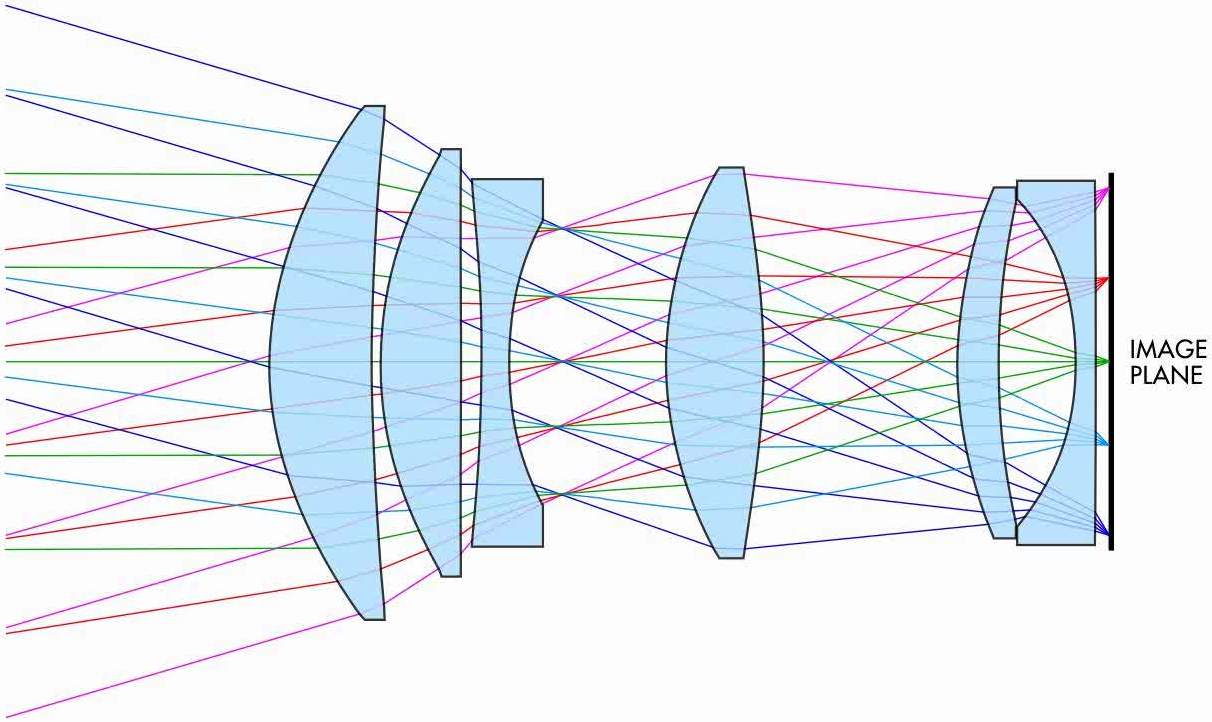
Focal Plane Array (FPA) Alignment

Detector Assembly

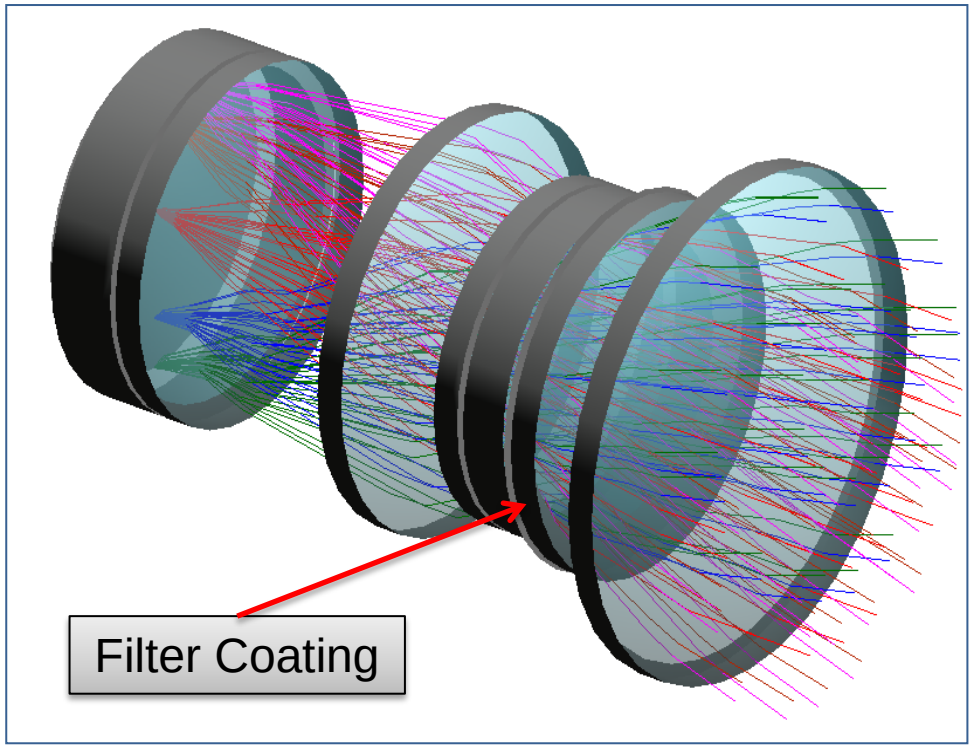
TESS Lens Design

PRELIMINARY DESIGN

6 LENSES

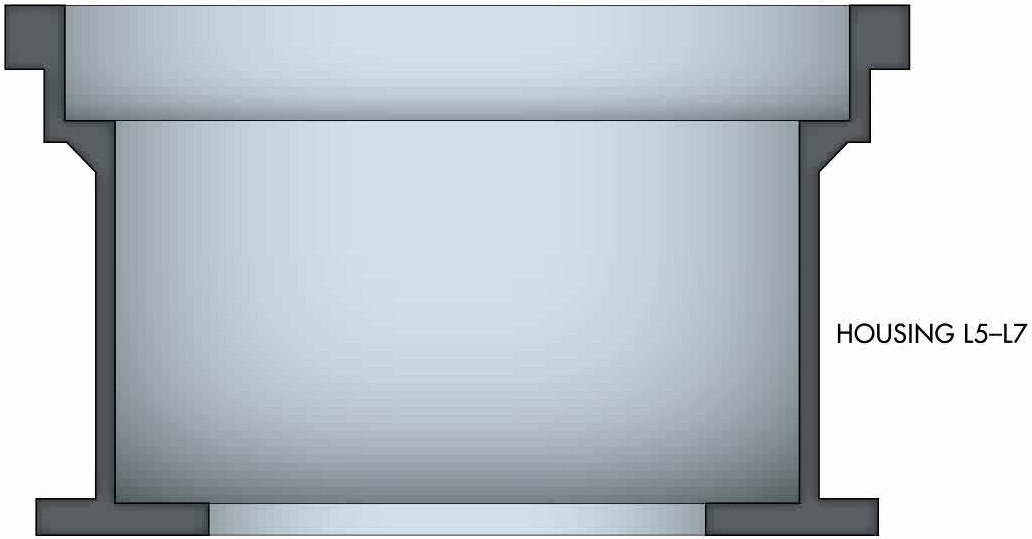


Lens Design Summary

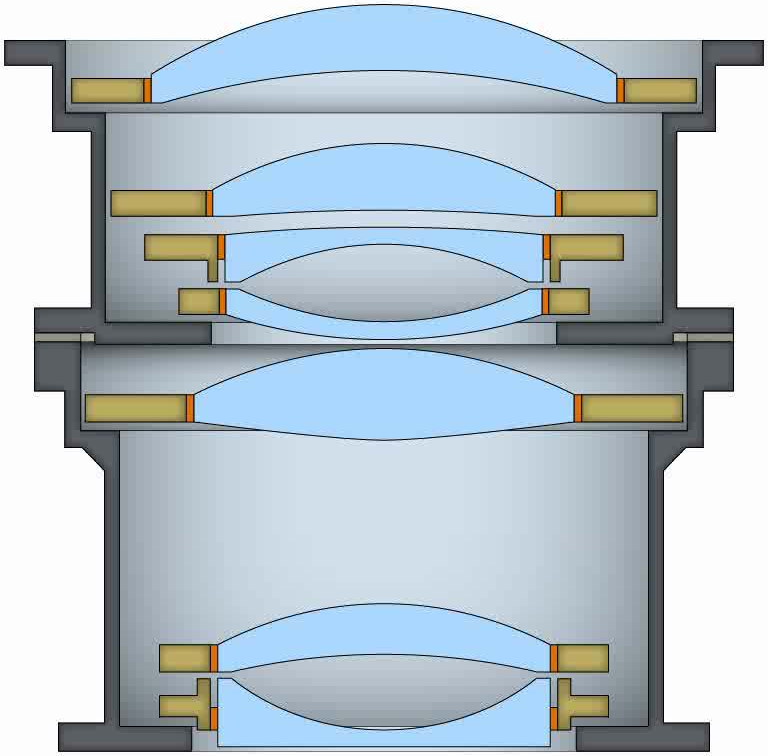


Characteristic	Value
FOV	24° x 24°
FL, f/#	146 mm, f/1.4
EPD	105 mm
Bandpass	600-1000 nm
On-axis throughput	86.5% (including filter)
Construction	7 elements (2 aspherical surfaces)
Filter	Thin-film cut-on filter (600 nm)
PSF	BPFF: 54% at 0° field angle 41% at 6° field angle 39% at 12° field angle 30% at 17° field angle
Operating Temperature	-75 C ± 10 C

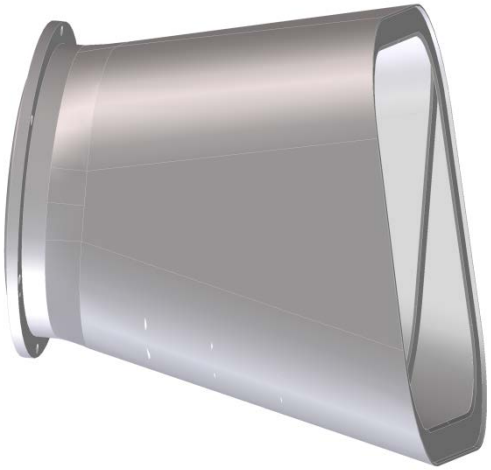
TESS Lens Assembly Build

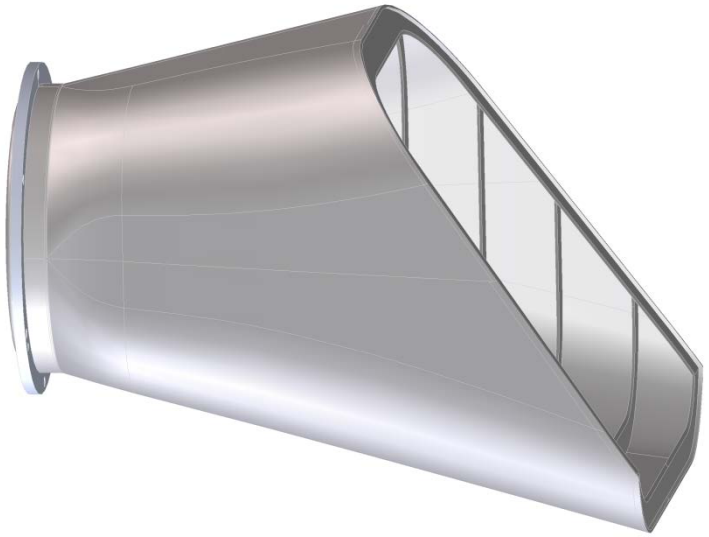


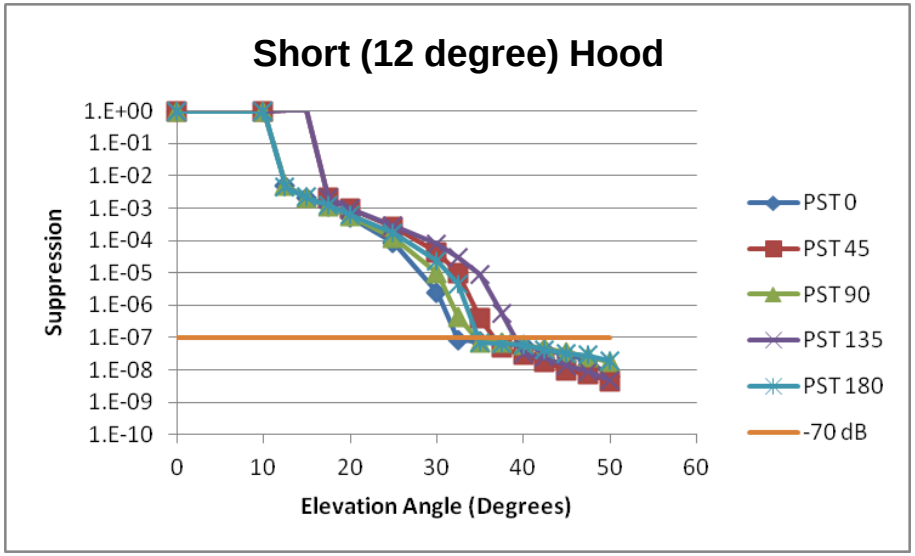
TESS Optical Test

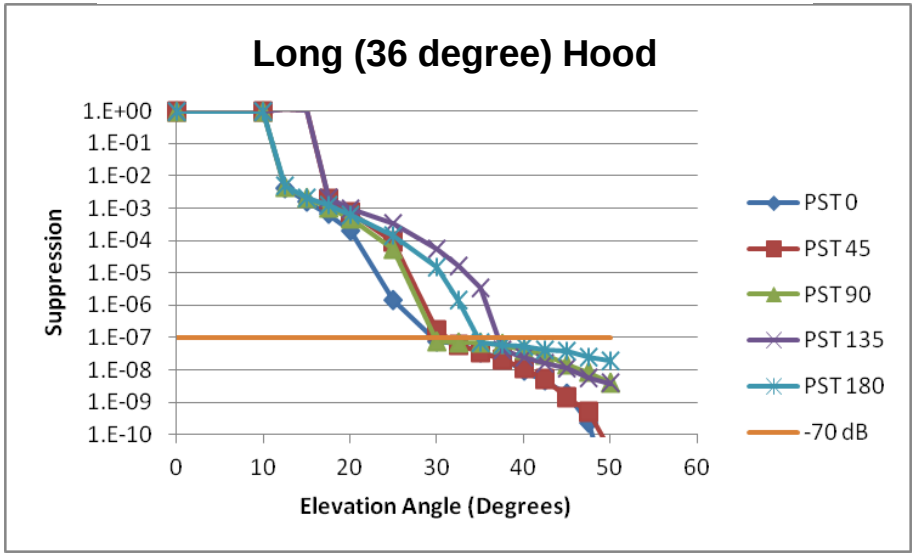


Lens Hood

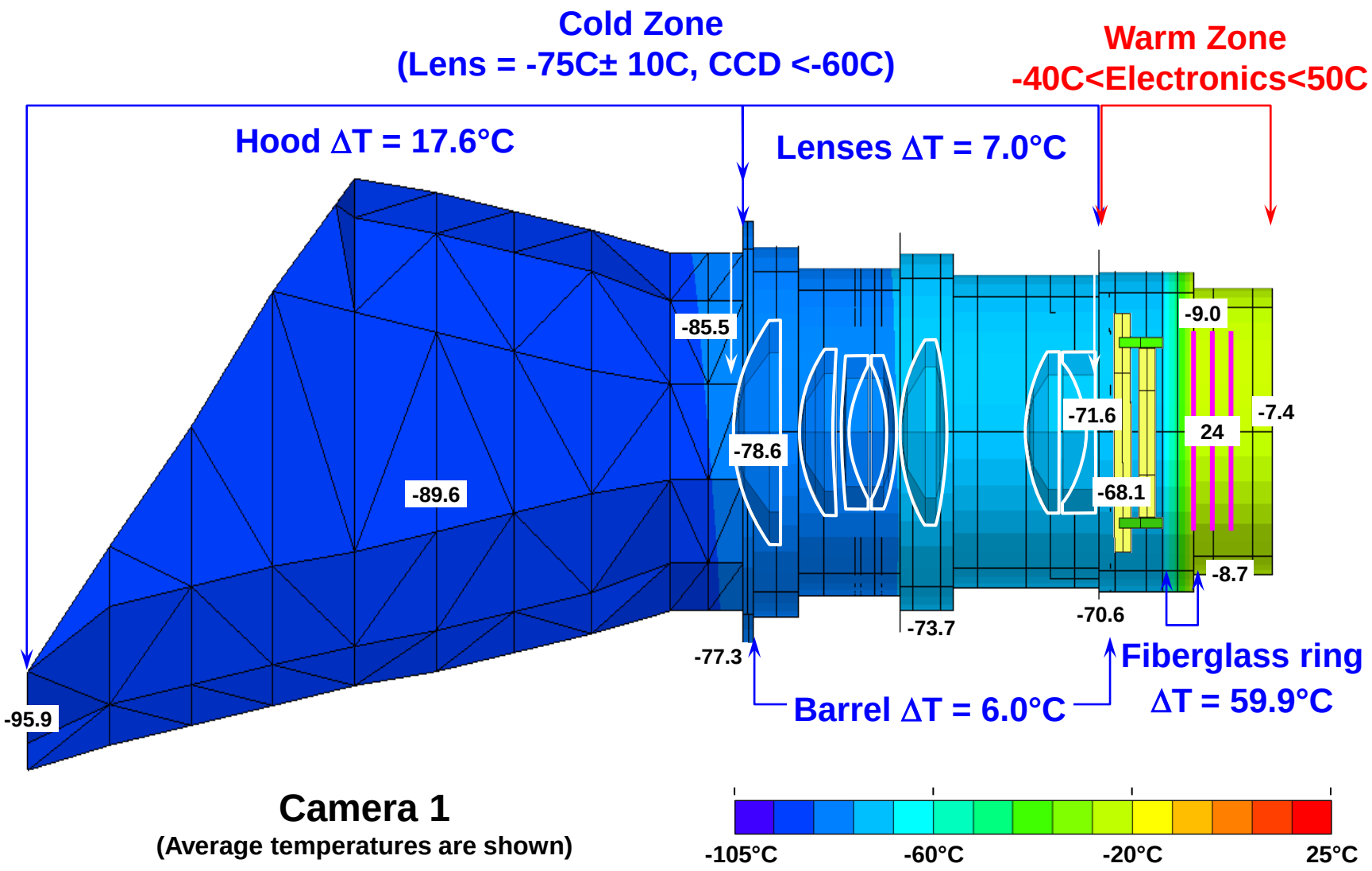





Short (12 degree) Hood
Suppression
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
0
10
20
30
40
50
60
Elevation Angle (Degrees)
PST 0
PST 45
PST 90
PST 135
PST 180
-70 dB


Long (36 degree) Hood
Suppression
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
0
10
20
30
40
50
60
Elevation Angle (Degrees)
PST 0
PST 45
PST 90
PST 135
PST 180
-70 dB

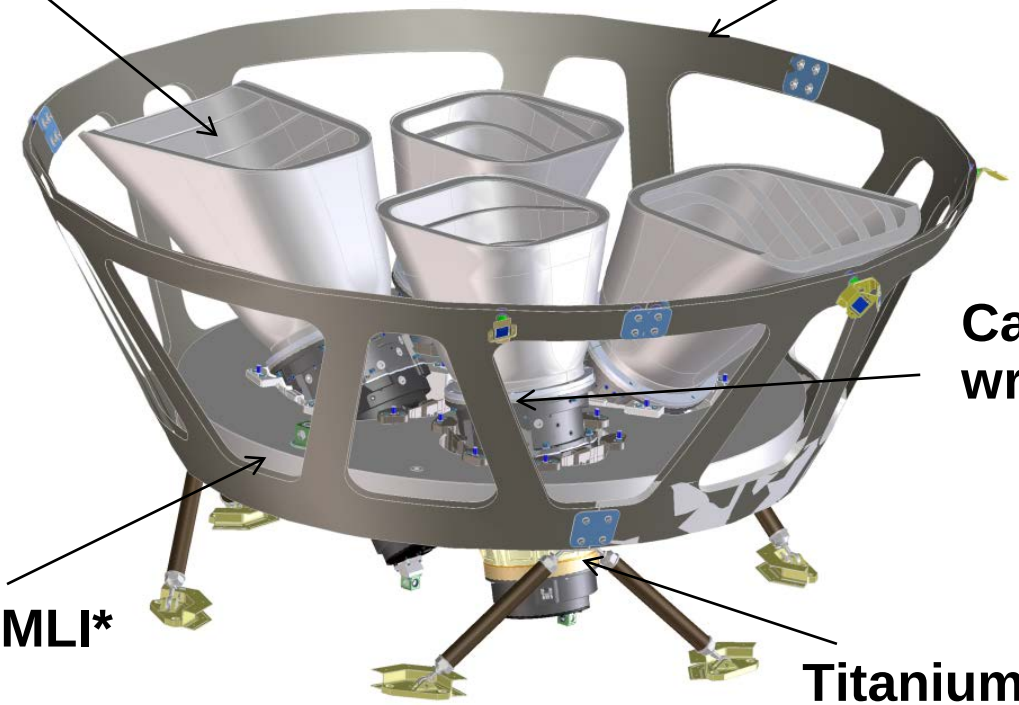
Operational Camera Temperatures



Camera 1

(Average temperatures are shown)

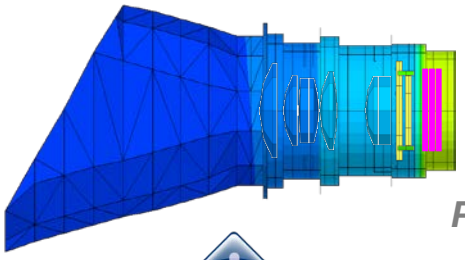
Instrument Structural / Thermal Design Features



* Multi-Layer Insulation

STOP Modeling Process

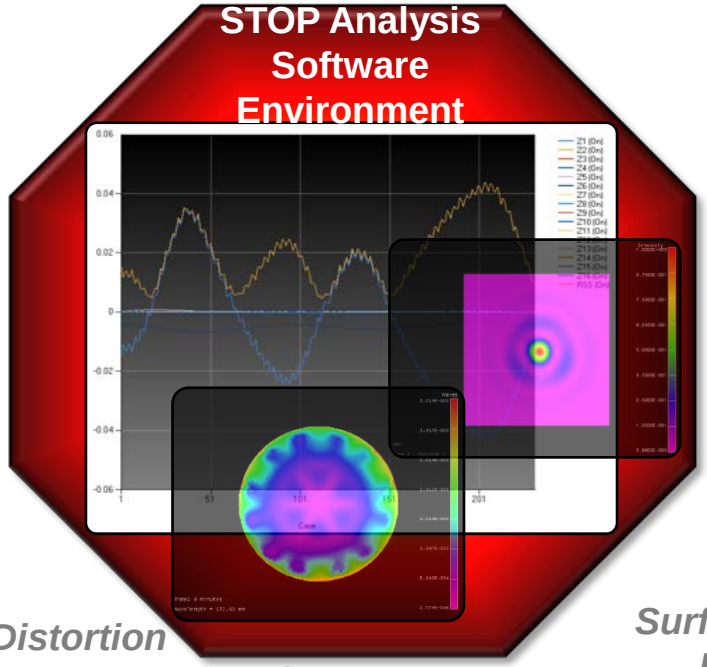
Thermal to Structural Temperature Mapping



Thermo-Elastic Distortion Analysis

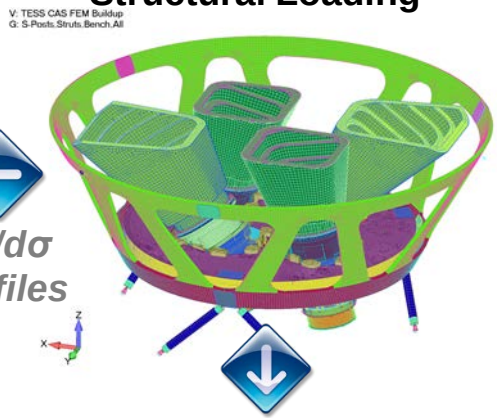
dn/dT Profiles

STOP Analysis Software Environment



Surface Distortion Rigid Body Displacements

Structural Loading

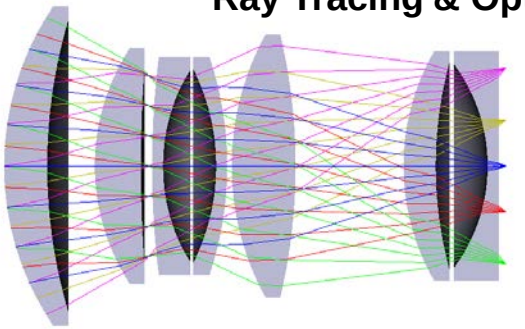


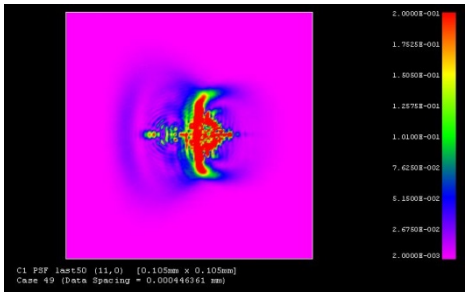
Structural Analysis

dn/dσ Profiles

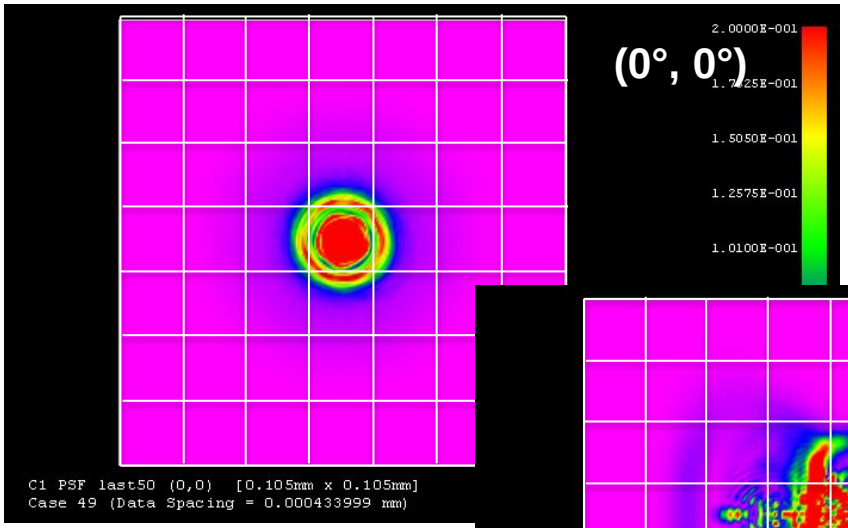
Surface Distortion Rigid Body Displacements

Ray Tracing & Optical Analysis

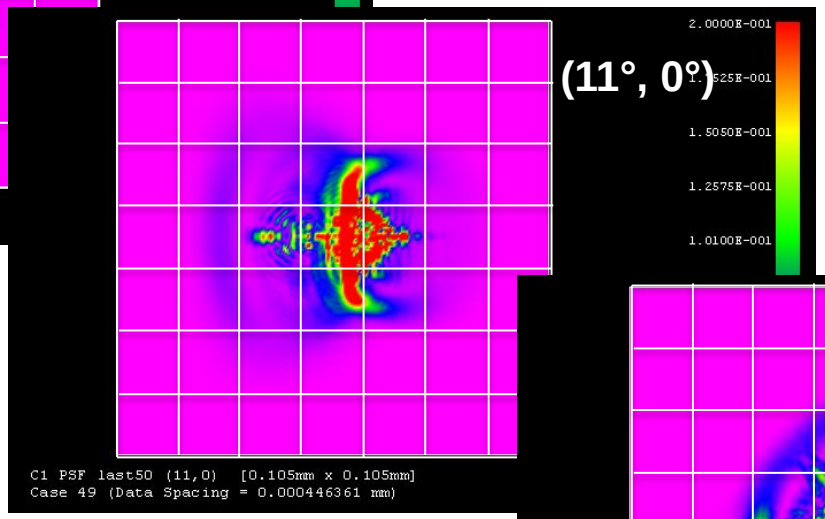




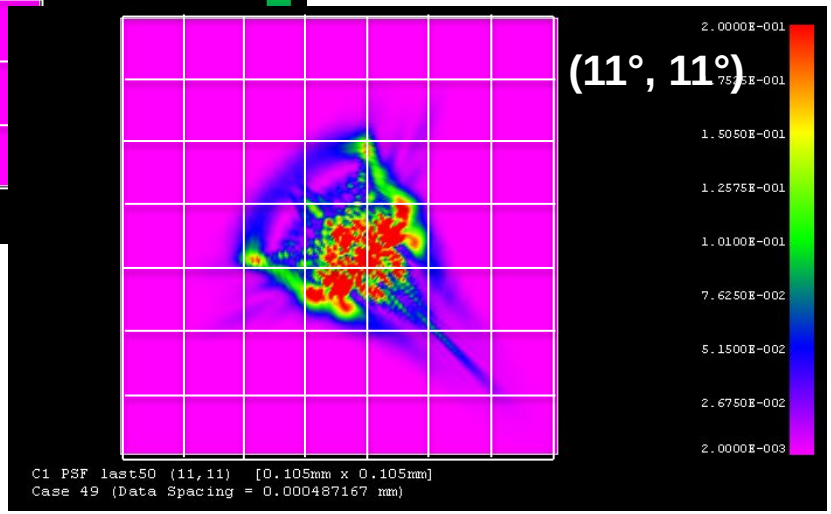
Imaging Performance on Orbit



Ensquared Energy =55%



Ensquared Energy =23%



Ensquared Energy =18%

15 micron pixel

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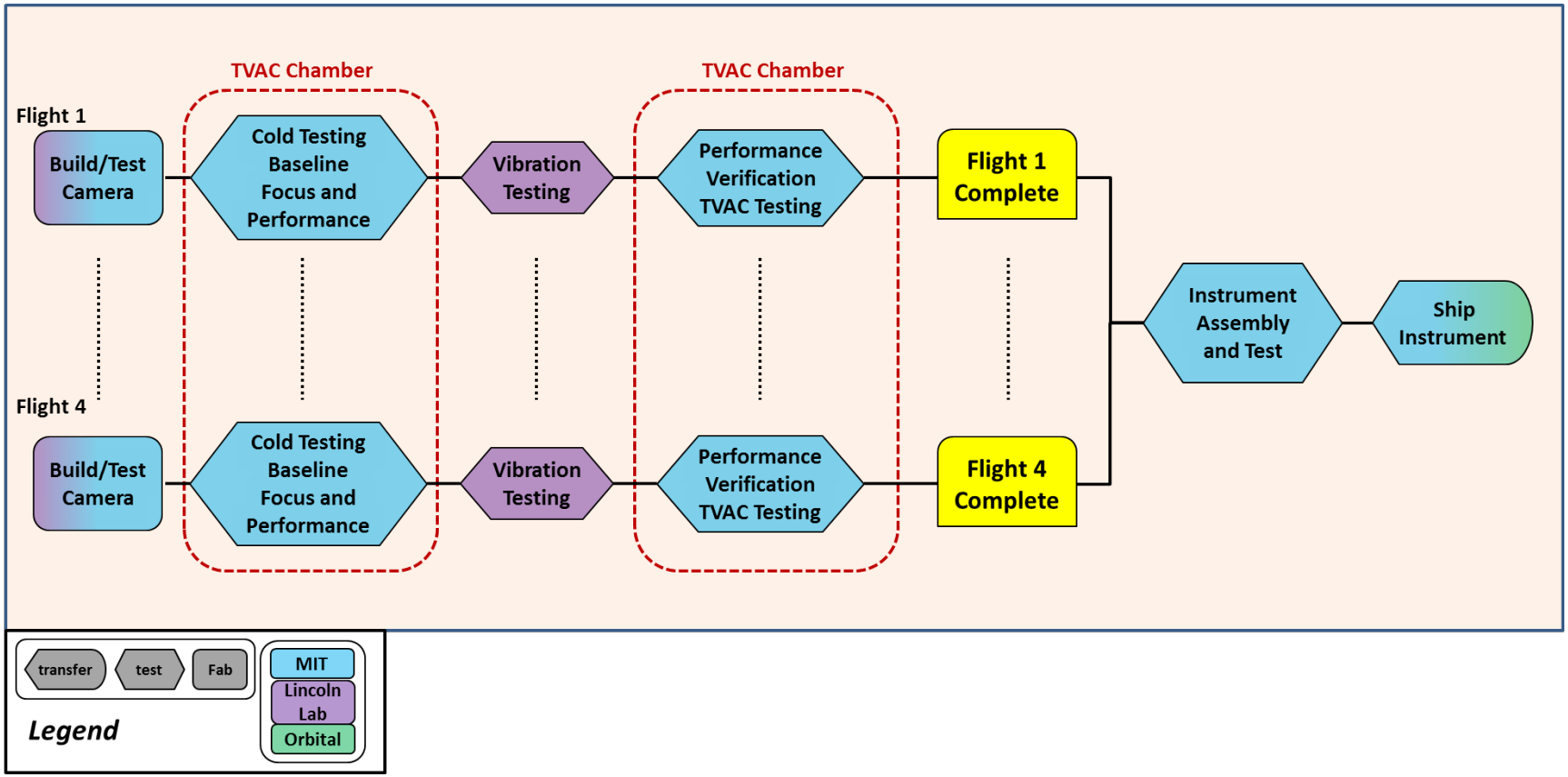
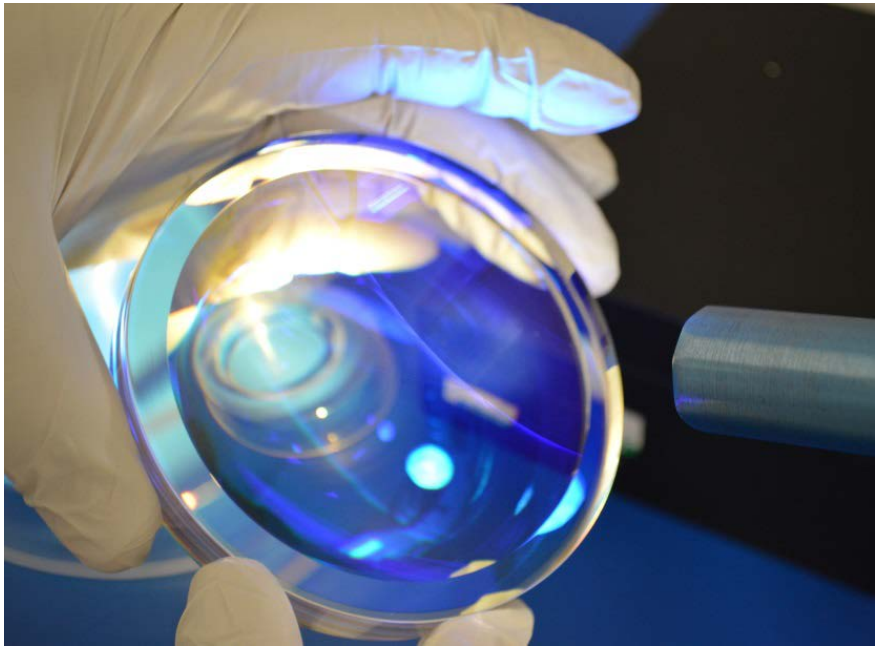
Instrument AI&T Flow

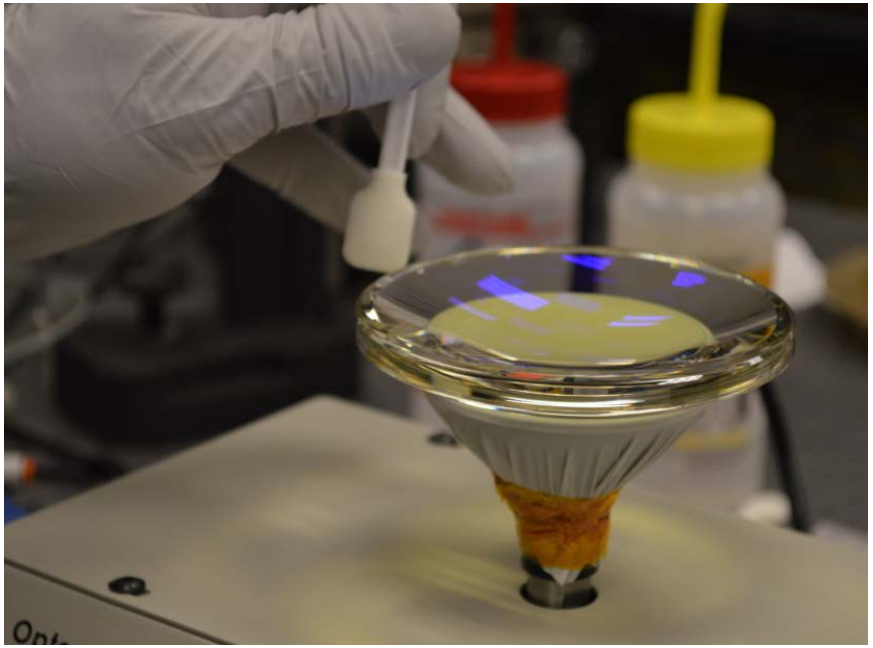


Risk Reduction Unit (RRU) Lens Build – Lenses

- **RRU Lens Assembly Build – Pathfinder for Flight Build**



Lens Inspection



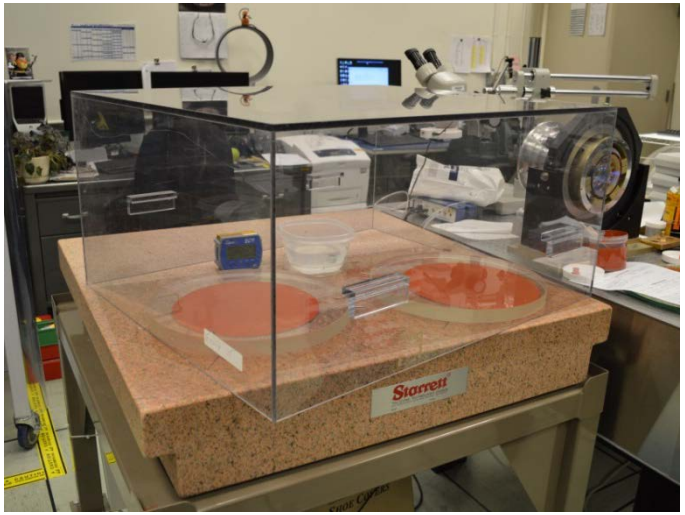
Lens Edge Preparation

RRU Lens Build: RTV Pad Fabrication

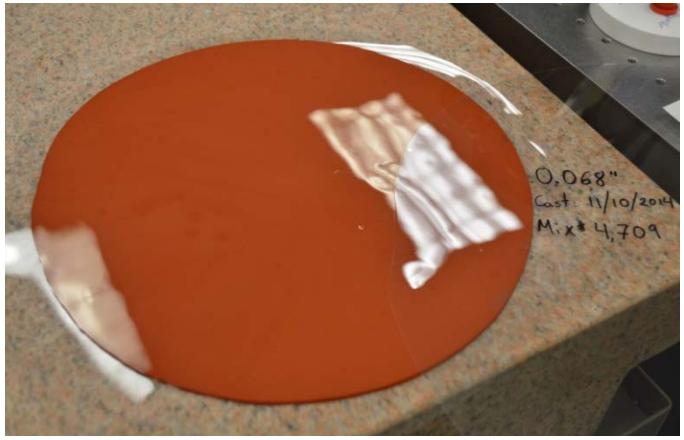
Mix

Pour

Press

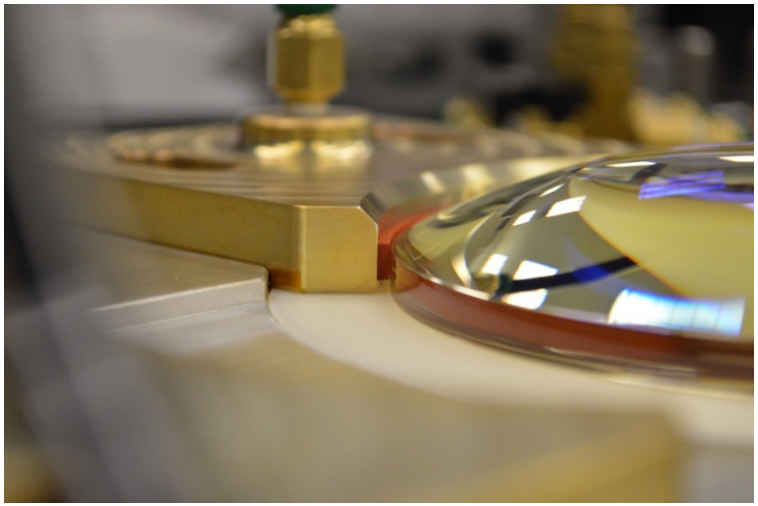


Cure

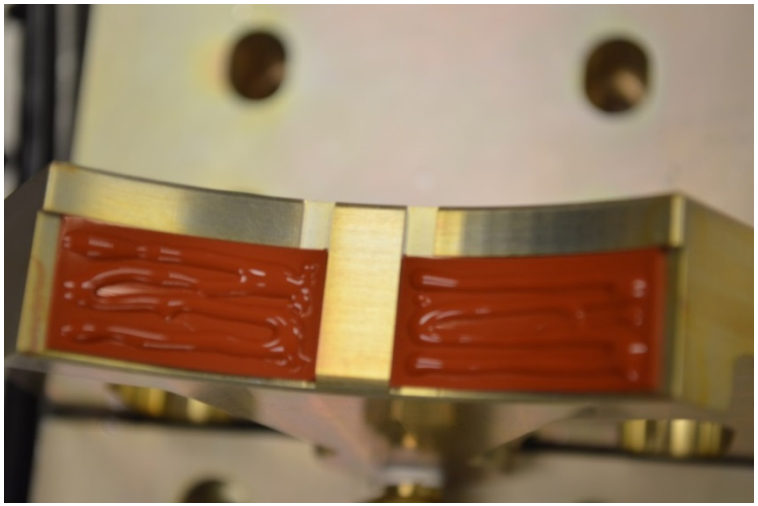


Cut

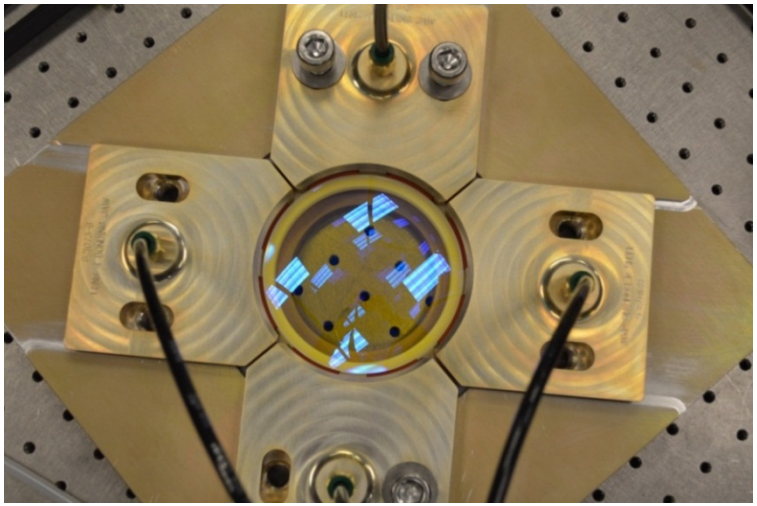
RRU Lens Build – Lenses with RTV Pads



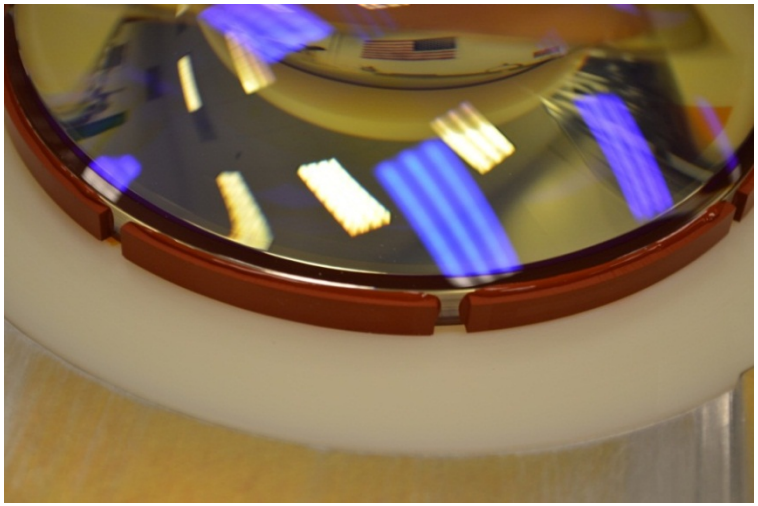
Fit Check



Pad Prep

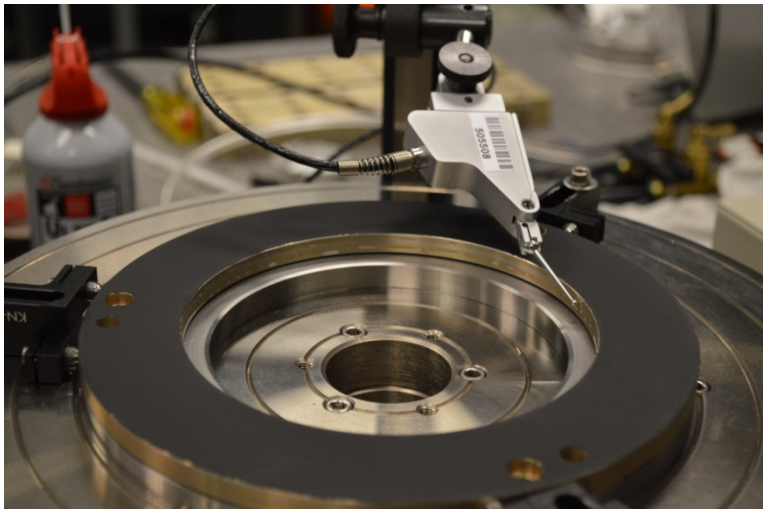


Pad Cure

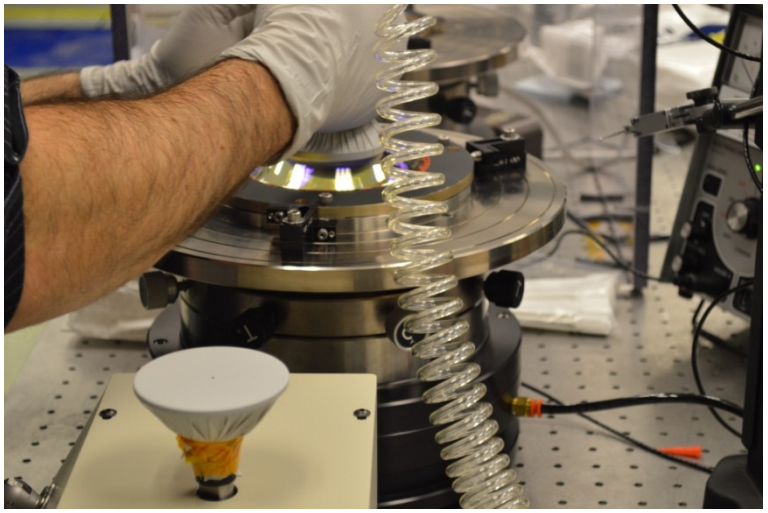


Pads on Lens

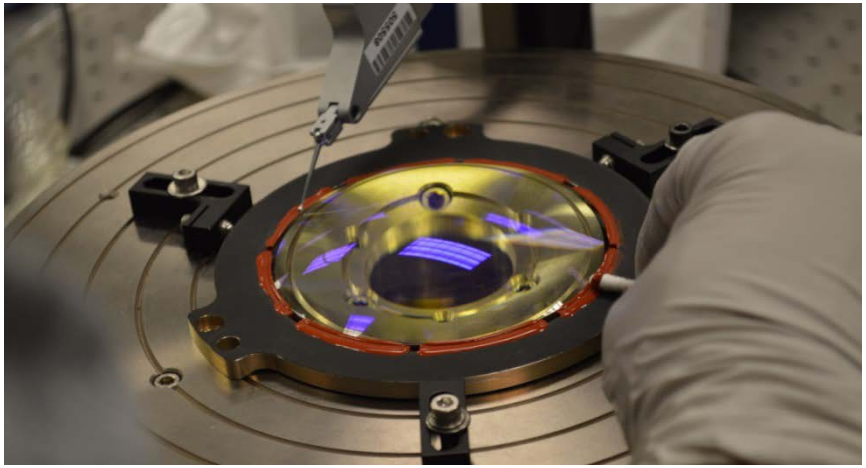
RRU Lens Build – Lenses in Bezels



Bezel Check

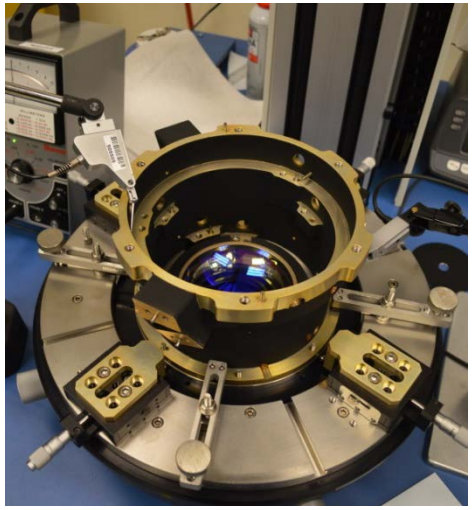


Lens Placement

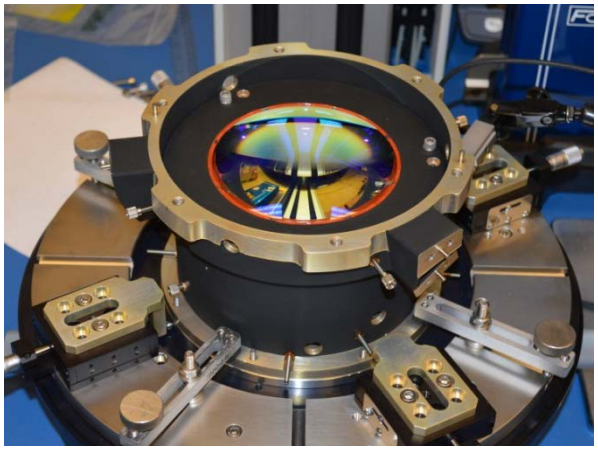


Lens in Bezel Runout

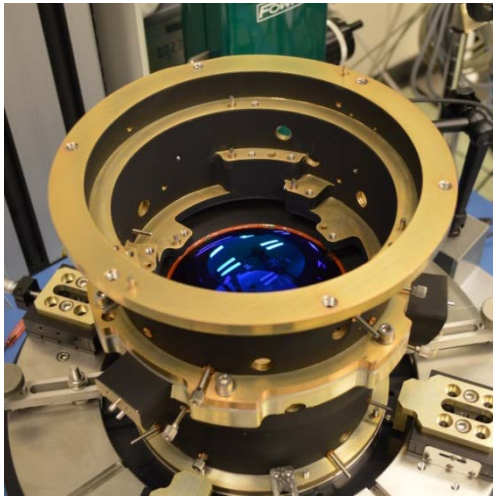
RRU Lens Build – Barrel Assembly and Test



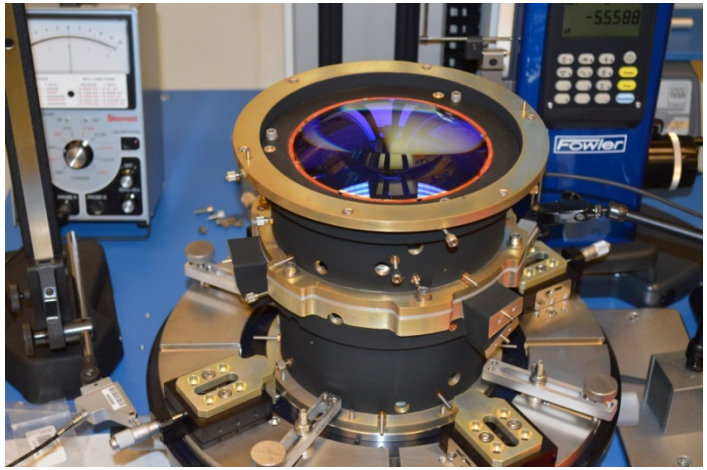
Lens Install



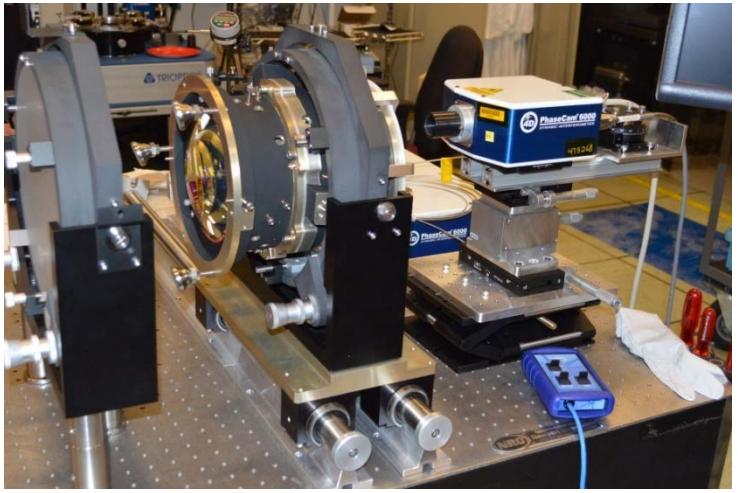
Lower Barrel Complete



Upper Barrel

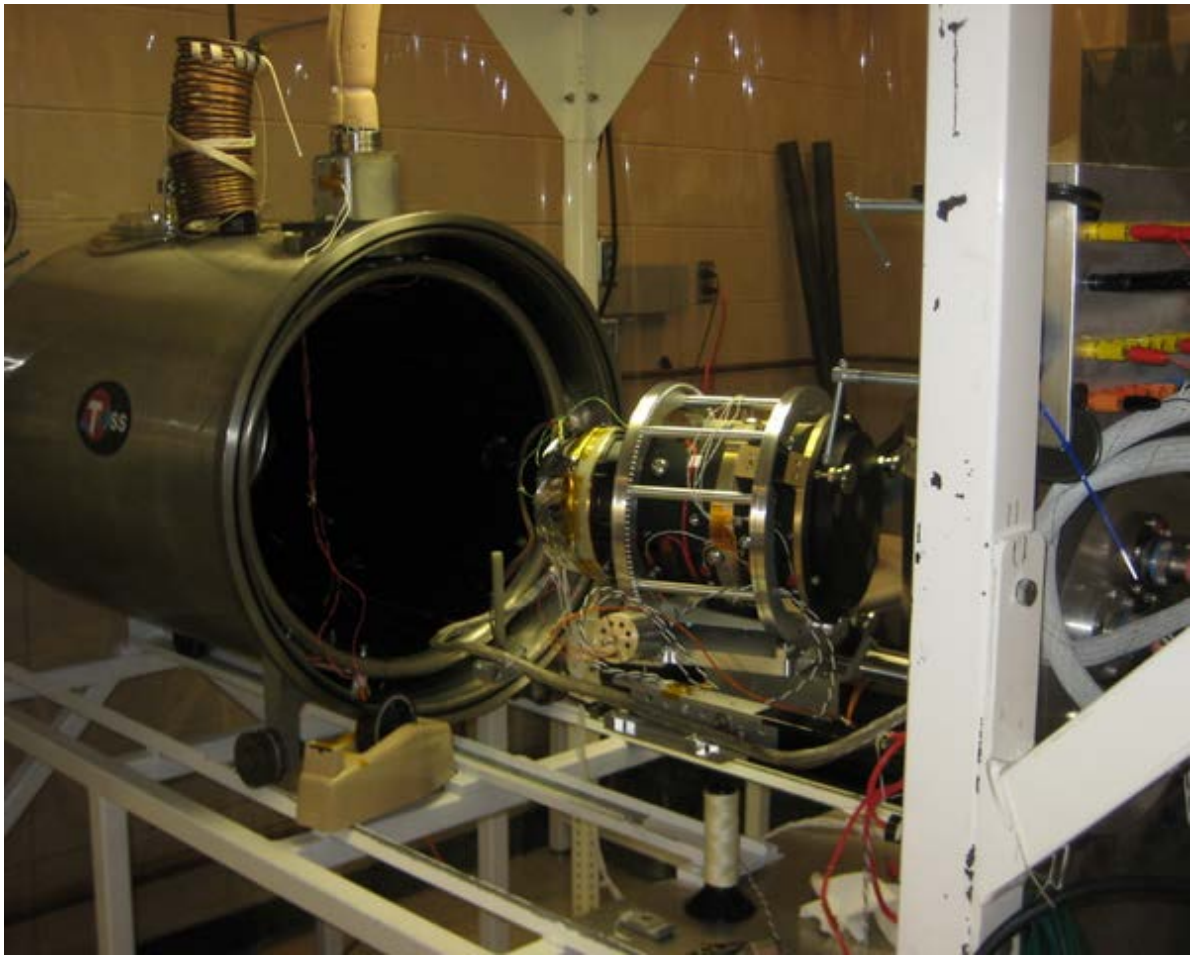


Lens Complete



Interferometry

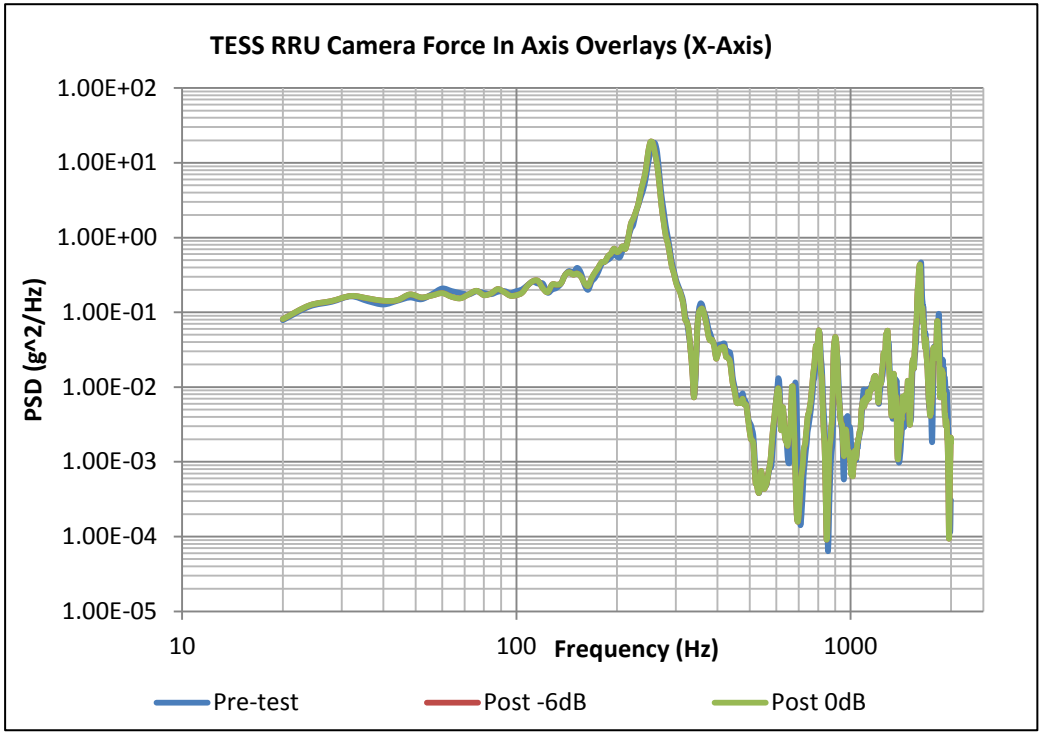
RRU Build – Completed Camera

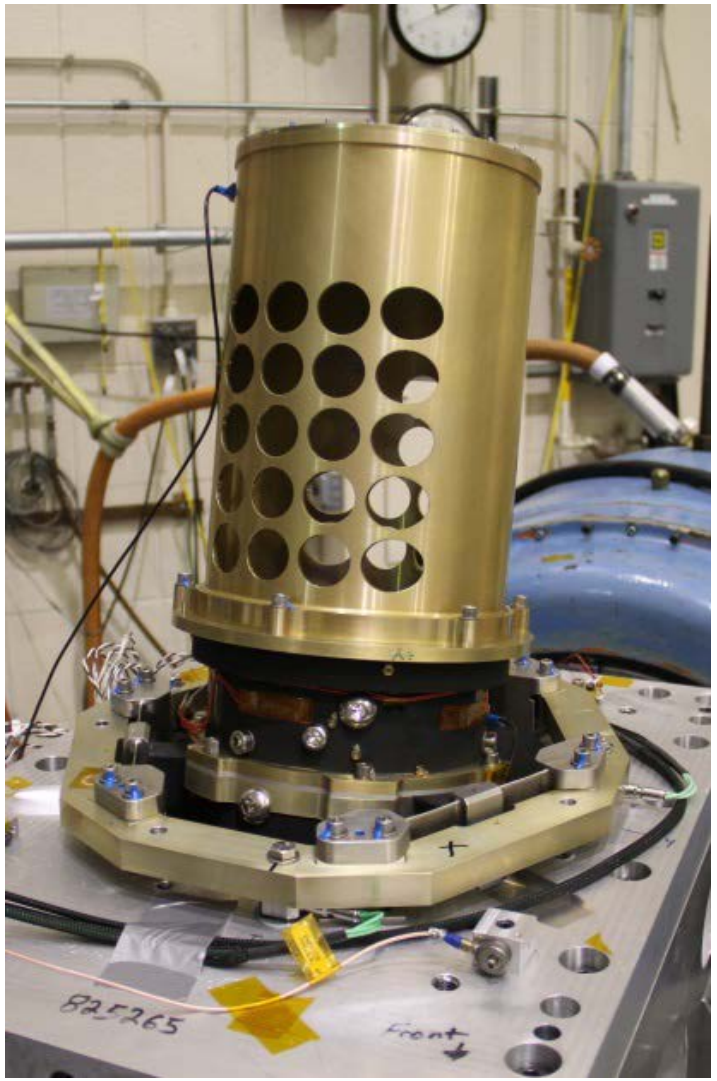


Camera Installation in Thermal Vacuum Chamber

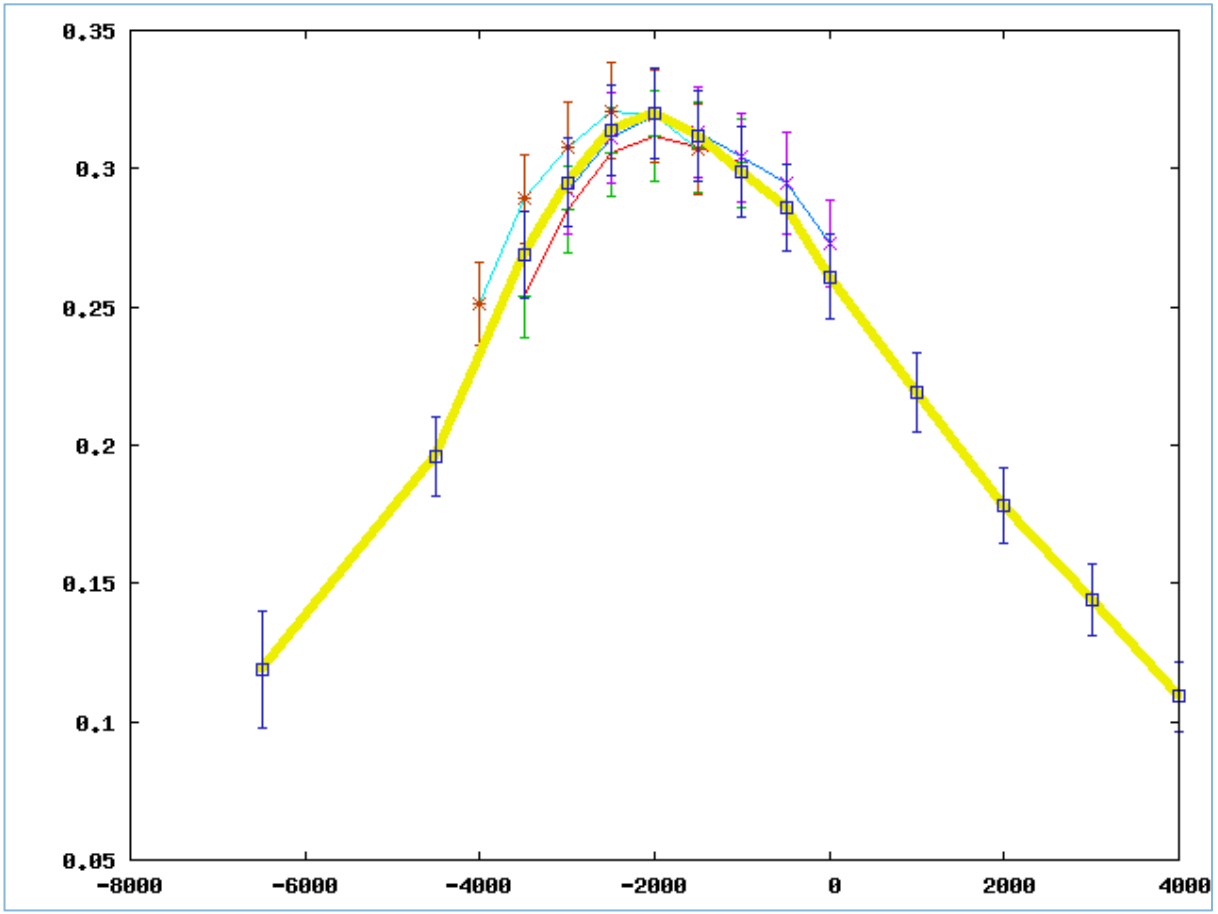
RRU Build – Vibration Testing

- **Primary objective – confirm lens build method**





RRU Test Results – Pre/Post Vibration Testing



Outline

- Science and Environment
- Instrument Design/Analysis
- Instrument Build/Test
- **Path Forward**
- **Summary**

Path Forward

- **Risk Reduction Unit testing successfully completed**
- **First flight camera build underway**

Thank You!!

- Division 7
  - Greg Allen
  - Jim Andre
  - Greg Balonek
  - Michael Beard
  - Cheryl Bourget
  - Daniel Bud
  - Jim Caisse
  - Chris Chesbrough
  - Michael Chrisp
  - Joe Dabrowski
  - Michael Dalpiaz
  - Joe D'Arco
  - Keith Doyle
  - Shelly Hazard
  - Melissa Hodson
  - James Hwang
  - Alexandra Karlicek
  - Jack Kartel
  - Frank Laquaglia
  - Eui-In Lee
  - Chuck Lewis
  - Josh Lennon
  - Bob MacDonald
  - Tony Mormile
  - Chris Nutting
  - Jocelyn O'Brien
  - Allison Pinosky
  - Brian Primeau
  - Justin Rey
  - Michael Rolla
  - Tom Roy
  - Ralph Semonian
  - Vishwa Shukla
  - Pamela Wright
- Division 9
  - Greg Berthiaume
  - Tony Smith
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  - Deb Woods
- Division 8
  - Barry Burke
  - Joe Ciampi
  - Mike Cooper
  - Kay Johnson
  - Renee Lambert
  - Debbie Landers
  - Mo Neak
  - Kevin Newcomb
  - Dan O'Mara
  - Ilya Prigozhin
  - David Volfson
  - Keith Warner
  - Doug Yong
  - Microelectronics Lab
- Safety, MAO & PSO
  - Tom Bondaruk
  - Joe Kairouz
  - Parker Kimball
- Kavli Institute
  - Roland Vanderspek

Summary

- **TESS promises to be a very productive, exciting science mission**
- **Multi-division, cross-discipline expertise has resulted in a robust, high performance design**
- **Risk Reduction Unit has paved the way for a smooth transition to flight build**
- **Looking forward to launch in 2017!**