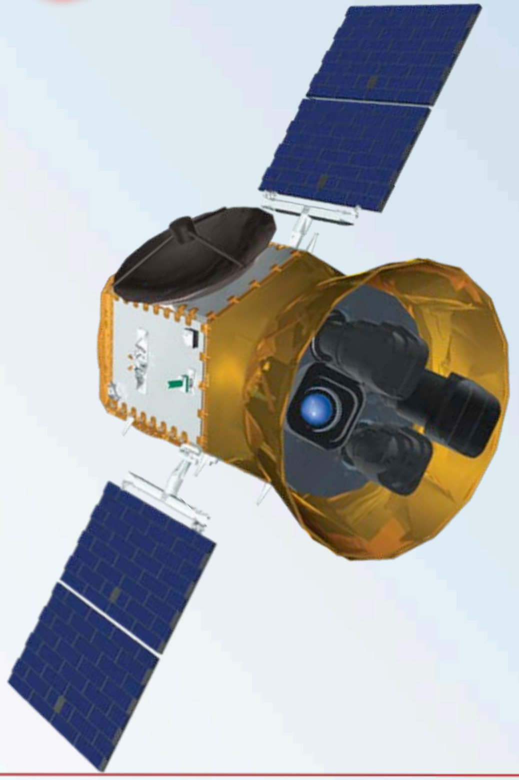
Transiting Exoplanet Survey Satellite

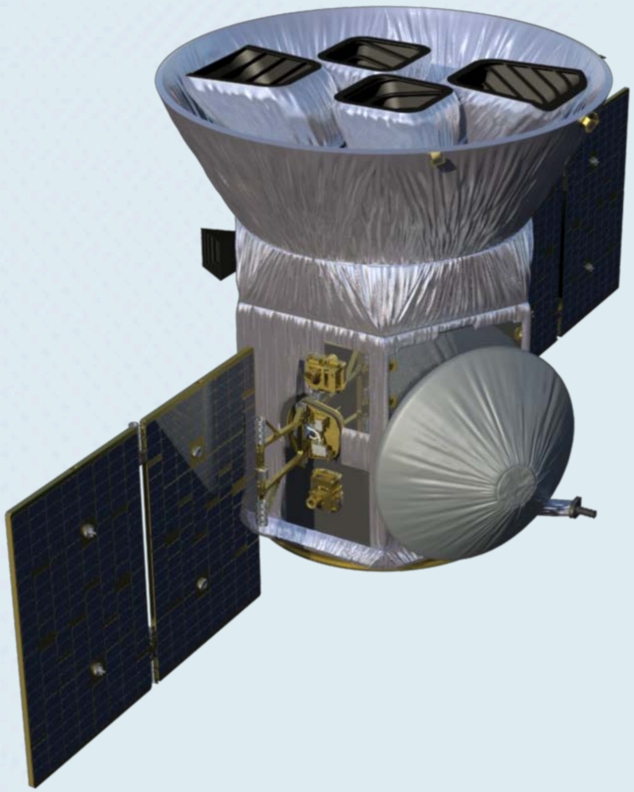


Tolerancing, alignment and test of the Transiting Exoplanet Survey Satellite (TESS) optical assembly

Brian Primeau, Michael Chrisp, Gregory Balonek, Christian Chesbrough, James Andre, Kristin Clark

This work is sponsored by the National Aeronautics and Space Administration under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government.

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

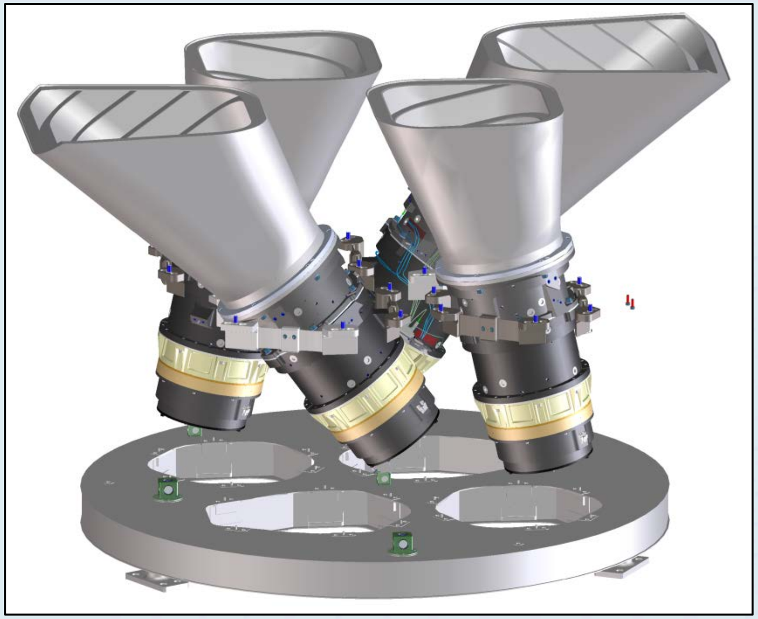


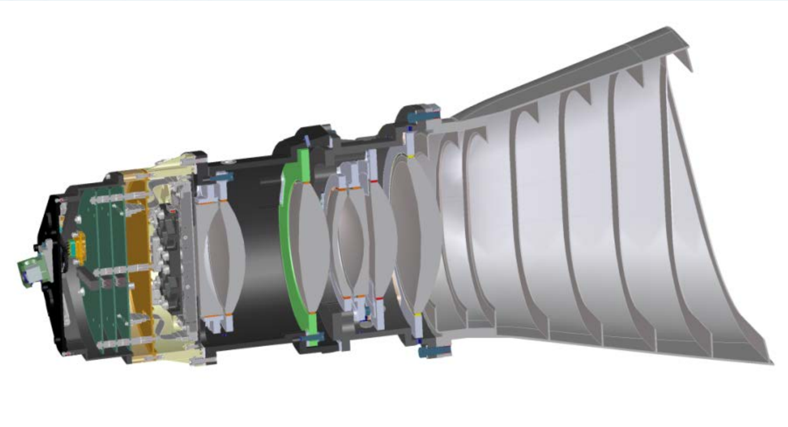
- NASA Explorer Mission
  - *August 2017 Launch*
  - *2 year mission*
  - *$228M Mission Cost*

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

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

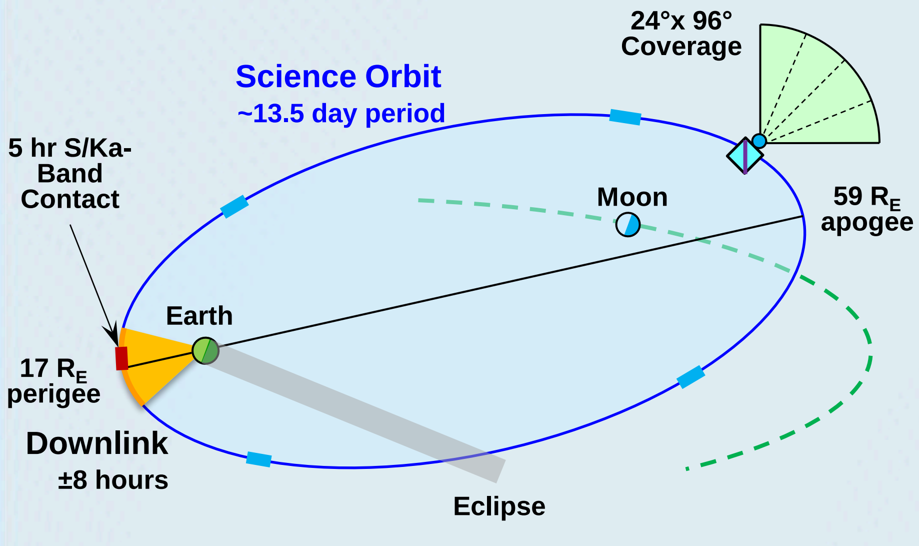




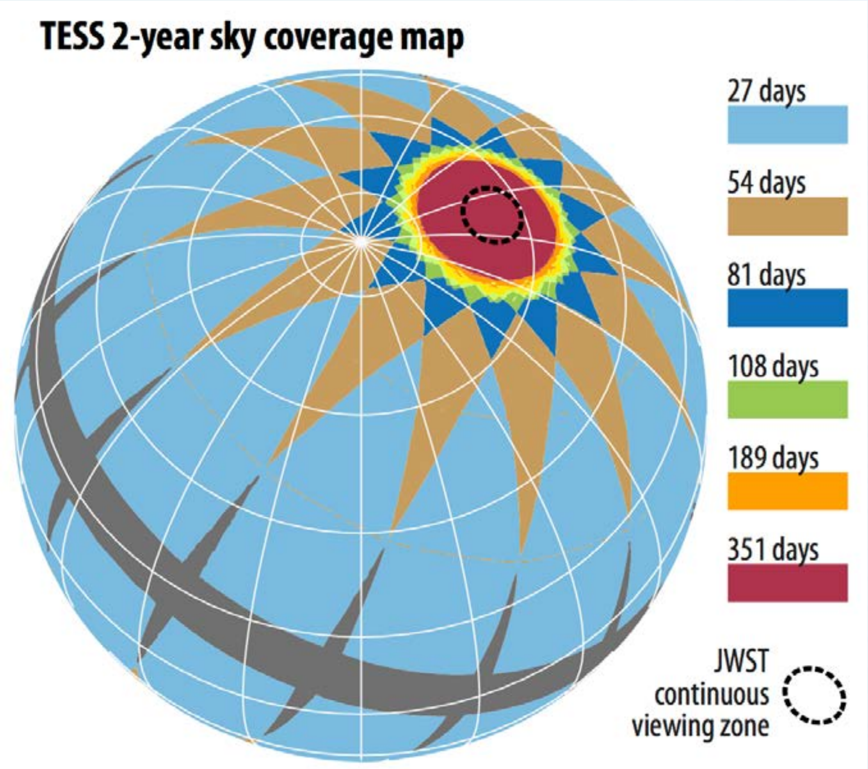
- Detector Assembly
  - *Dedicated Focal Plane Electronics*
  - *CCD focal plane 4096x4096 pixels*
- Lens Assembly
  - *24˚ x 24˚ FOV (>90% sky coverage)*
  - *146 mm focal length f/1.4*
  - *Optimized over 600-1000 nm*
- Lens Hoods (12˚, 36˚)
  - *Reduce scattered light*
  - *Thermal radiator*

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

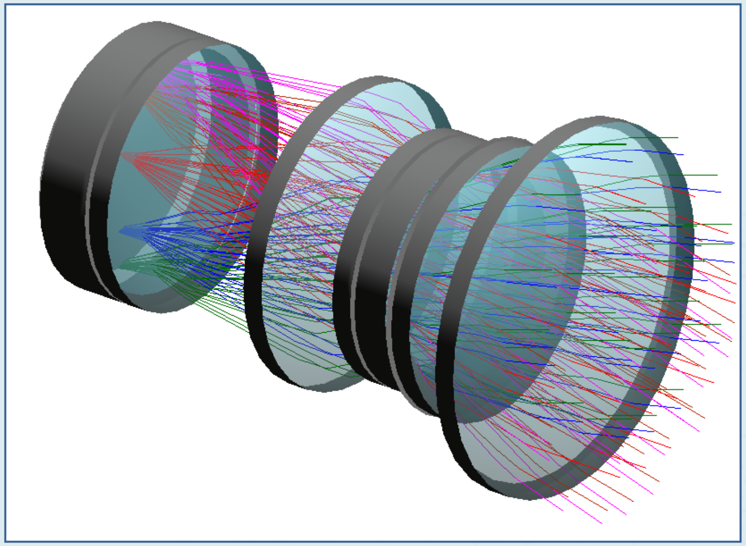


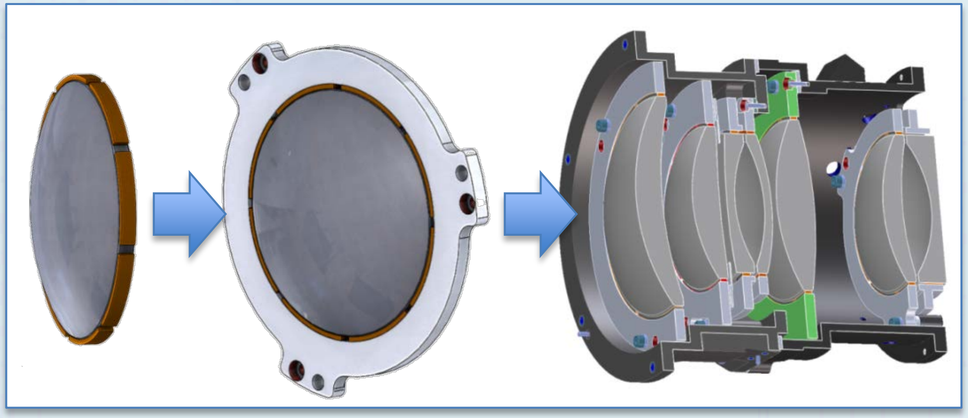
TESS Orbit

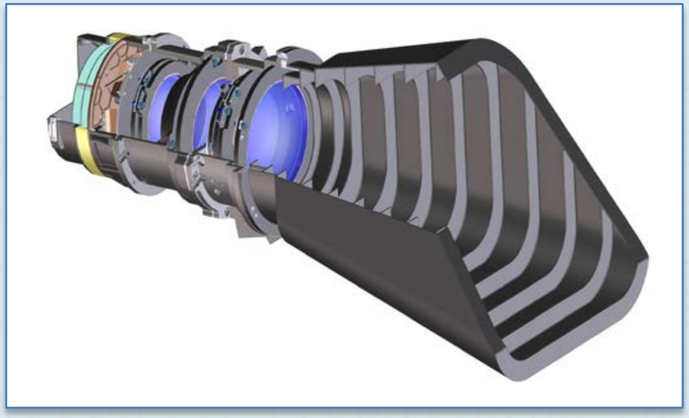


Optical Design Overview

- Lens Assembly
  - *24° x 24° FOV*
  - *146 mm, f/1.4 lens*
    - *EPD = 105 mm*
  - *7 elements*
    - *Two aspheric surfaces*
  - *Optimized over 600-1000 nm*







Lens Assembly Design Tolerances

Specification / As-Built RRU

Lens	Sur.	Fringes (power)	Fringes (irregularity)	dN (melt comp.)	dV (melt comp.)	Lens wedge (ETD µm)	Lens thickness (µm)	Axial position (µm)	Radial decenter (µm)	Lens tilt (arc min)
1	1	3 / 0.52	0.5 / 0.28	±0.00004	±0.02%	5 / 3	±25 / +20	±35 / 0	20 / 4	0.40 / 0.29
	2	3 / 0.67	0.5 / 0.33							
2	3	3 / 0.07	0.5 / 0.22	±0.00004	±0.02%	5 / 3	±25 / +9	±35 / -13	20 / 3	0.40 / 0.25
	4	3 / 0.62	0.5 / 0.16							
3	6	3 / 1.95	0.5 / 0.16	±0.00004	±0.02%	10 / 5	±50 / -10	±35 / +18	20 / 9	0.40 / 0.32
	7	3 / 1.50	Asp							
4	8	3 / 1.20	0.5 / 0.43	±0.00004	±0.02%	5 / 3	±25 / +23	±35 / -13	20 / 2	0.40 / 0.29
	9	3 / 1.70	0.5 / 0.23							
5	10	3 / 0.00	0.5 / 0.14	±0.00004	±0.02%	5 / 5	±25 / +18	±35 / +3	20 / 3	0.40 / 0.38
	11	3 / 2.00	0.5 / 0.25							
6	12	3 / 1.50	Asp	±0.00004	±0.02%	10 / 5	±50 / -36	±35 / -23	20 / 1	0.40 / 0.05
	13	3 / 1.80	0.5 / 0.20							
7	14	3 / 1.50	1 / 0.46	±0.00004	±0.02%	5 / 0	±25 / +13	±35 / 0	20 / 7	0.40 / 0.15
	15	3 / 0.07	1 / 0.07							

ETD – maximum edge thickness minus minimum edge thickness (TIR)

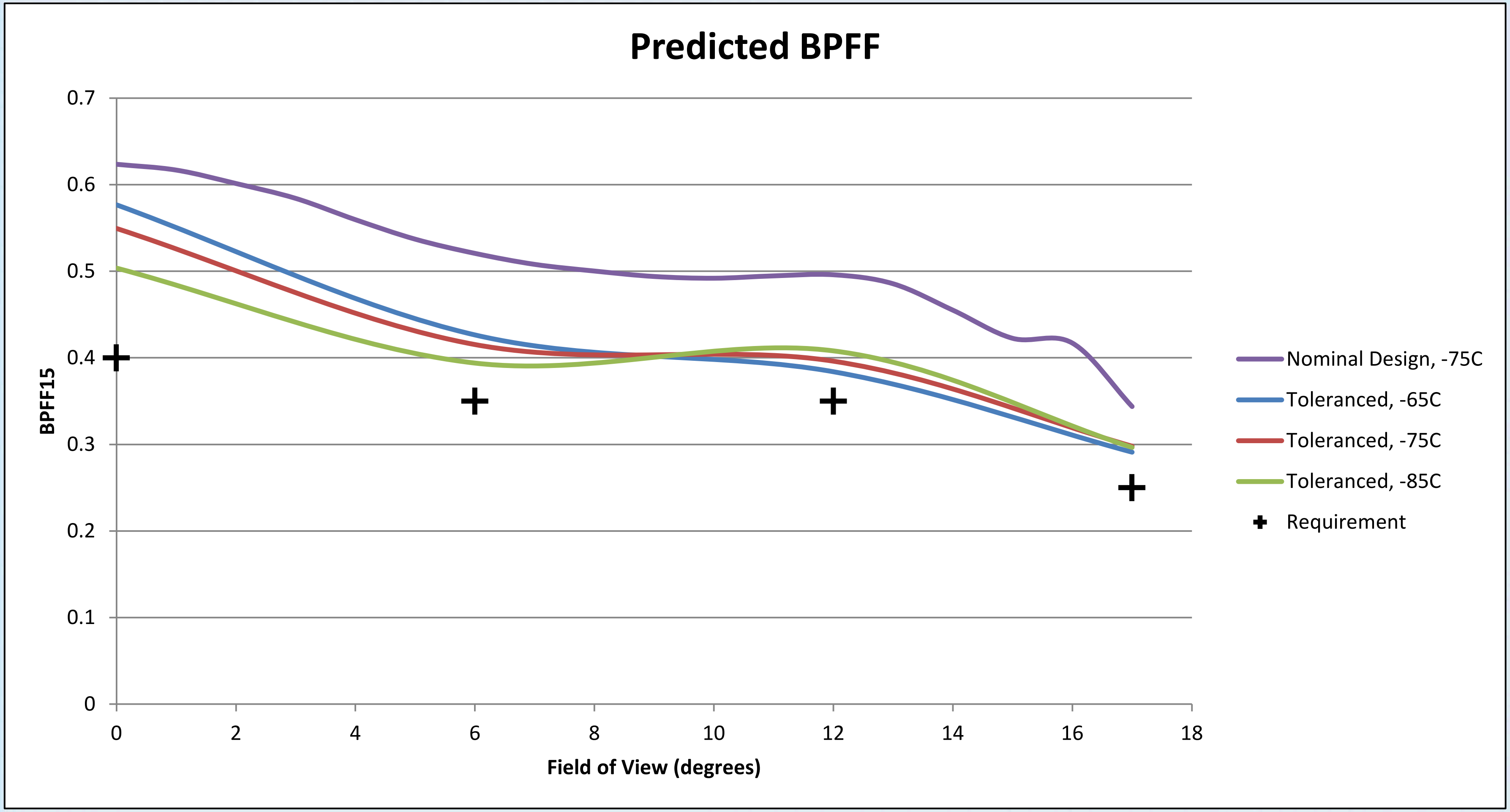
Fringes power and irregularity – difference from test plate @ 632 nm

dN – refractive index difference, dV- Abbe number change

Surface 7 Asphere Tolerance: less than 0.07 microns peak to valley over any 14mm diameter subaperture (RRU met spec).

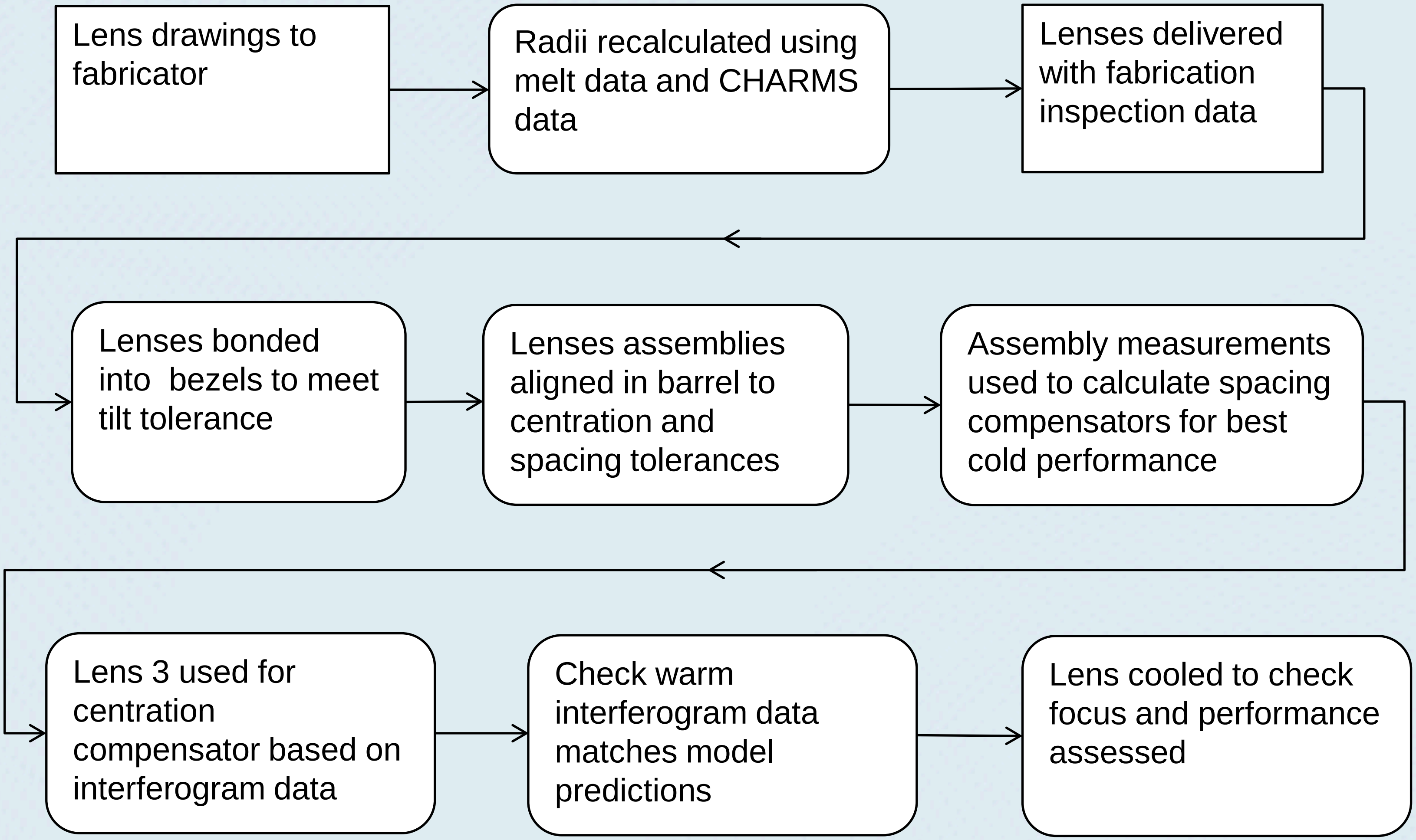
Surface 12 Asphere Tolerance: less than 0.05 microns peak to valley over any 17mm diameter subaperture (RRU met spec).

Expected BPFF15 with tolerances



- Expected performance (84% probability)

Fabrication and Alignment Procedure



Melt Compensated Optimization

- Catalog index and dispersion data does not extend to -75C
- NASA Goddard Cryogenic, High Accuracy Refraction Measuring System (CHARMS) capable of measuring refractive index of materials down to 10K

Cryogenic Refractive Indices of S-LAH55, S-LAH55V, S-LAH59, S-LAM3, S-NBM51, S-NPH2, S-PHM52, and S-TIH14 Glasses

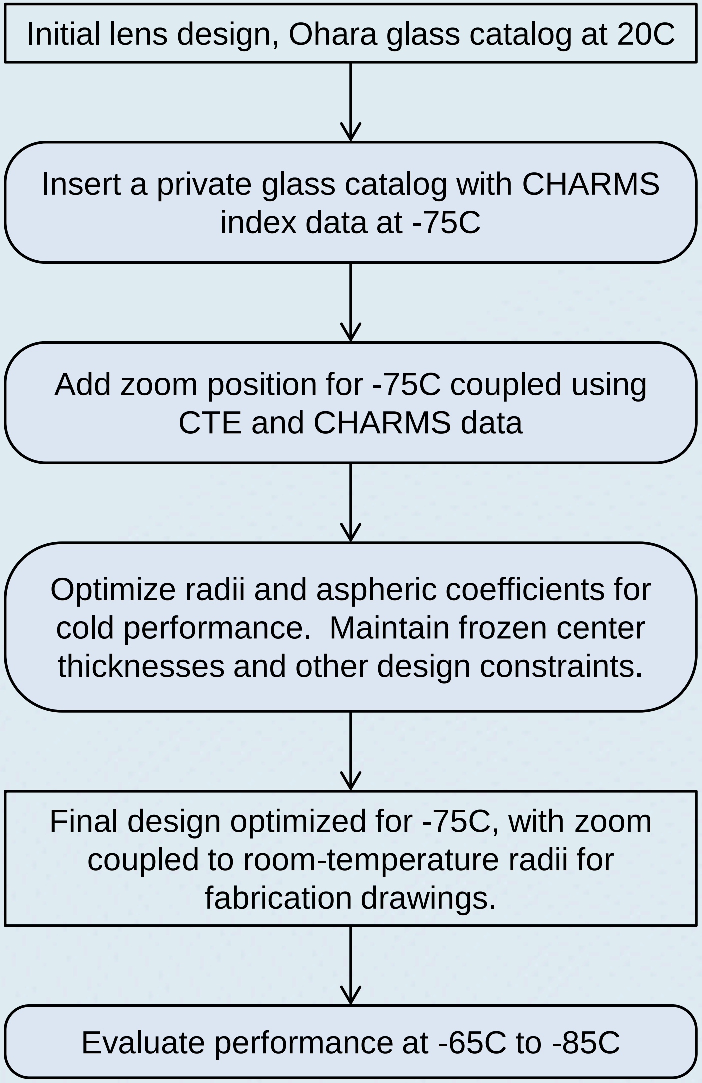
Kevin H. Miller,[1] Manuel A. Quijada, and Doug Leviton

Goddard Space Flight Center, 8800 Greenbelt Road
Greenbelt, MD 20771;

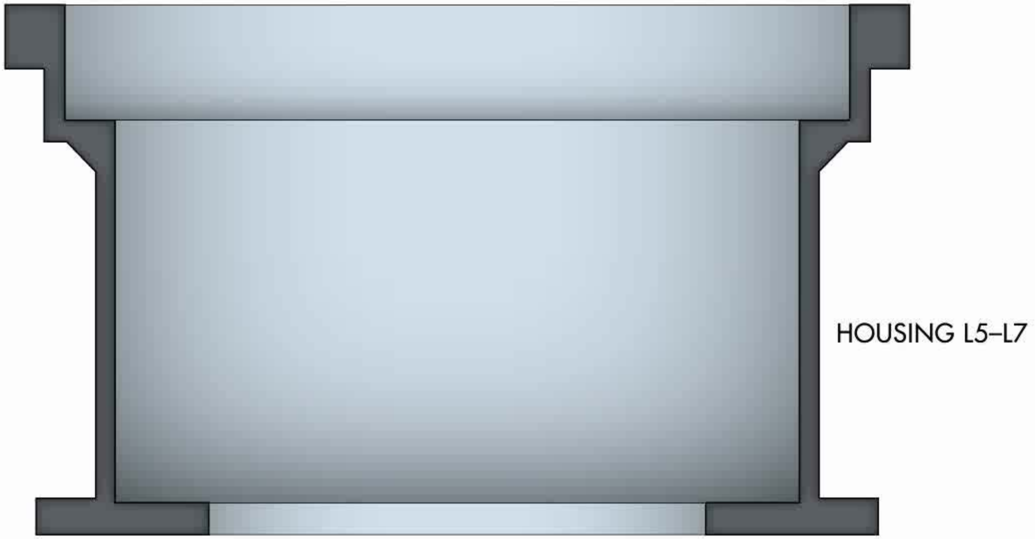
ABSTRACT

The Transiting Exoplanet Survey Satellite (TESS) is an explorer-class planet finder, whose principal goal is to detect small planets with bright host starts in the solar neighborhood. The TESS payload consists of four identical cameras with seven optical elements each that include various types of Ohara glass substrates. The successful implementation both panchromatic and thermal lens assembly designs for these cameras requires a fairly accurate (up to 1E-6) knowledge of the temperature and wavelength dependence of the refractive index in the wavelength and temperature range of operation. Hence, this paper is devoted to report on measurements of the refractive index over the wavelength range of 0.42—1.15 um and temperature range of 110—310 K for the following Ohara glasses: S-LAH55, S-LAH55V, S-LAH59, S-LAM3, S-NBM51, S-NPH2, S-PHM52, and S-TIH14. The measurements were performed utilizing the Cryogenic High Accuracy Refraction Measuring System (CHARMS) facility at NASA's Goddard Space Flight Center. A dense coverage of the absolute refractive index for the title substrates in the aforementioned wavelength and temperature ranges was used to determine the thermo-optic coefficient (dn/dT) and dispersion relation (dn/dλ) as a function of wavelength and temperature. A comparison of the measured indices with literature values, specifically the temperature-dependent refractive indices of S-PHM52 and S-TIH14, will be presented.

Keywords: S-LAH55, S-LAH55V, S-LAH59, S-LAM3, S-NBM51, S-NPH2, S-PHM52, S-TIH14, CHARMS, cryogenic refractive index

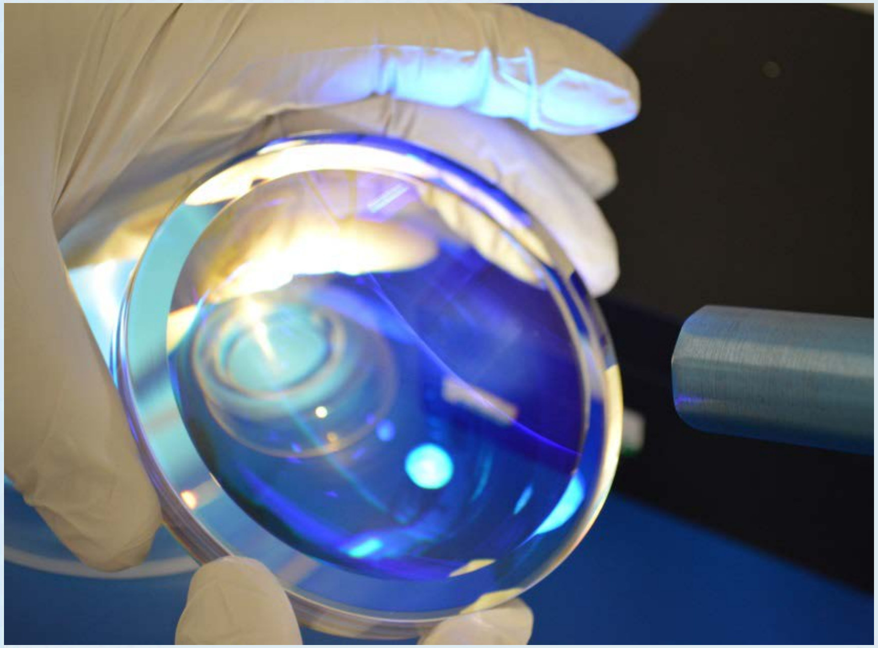


TESS Lens Assembly Build

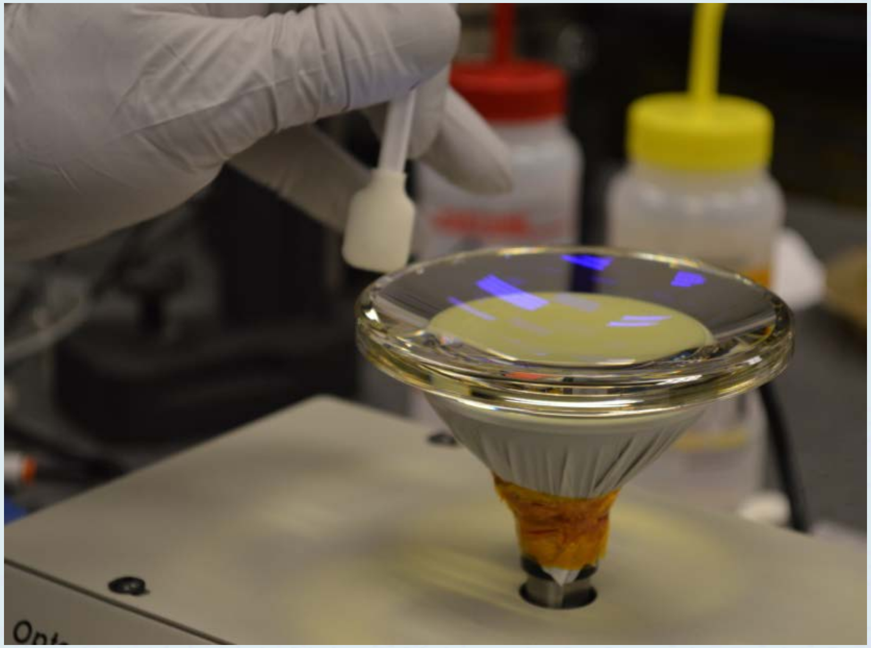


Lens Build: Lens Preparation

- RRU Lens Assembly Build – Pathfinder for Flight Build



Lens Inspection



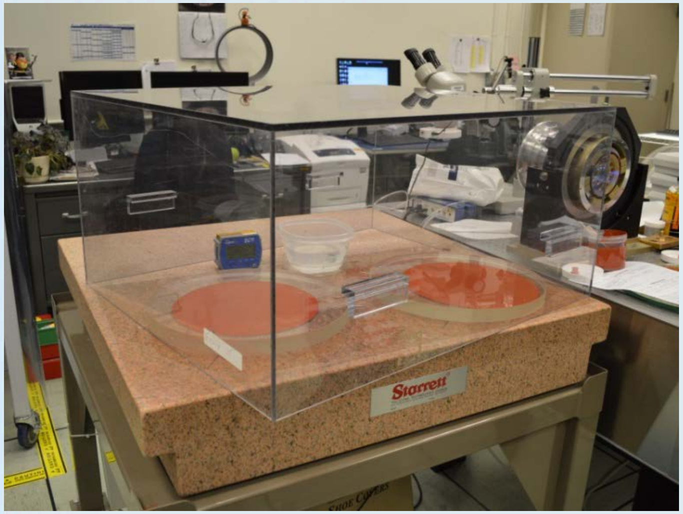
Lens Edge Preparation

Lens Build: RTV Pad Fabrication

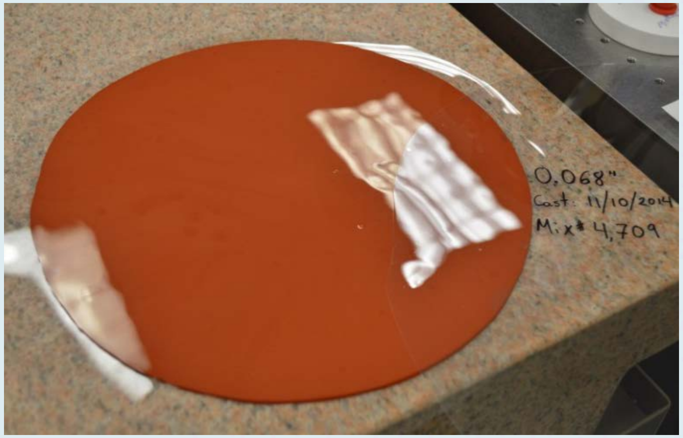
Mix

Pour

Press

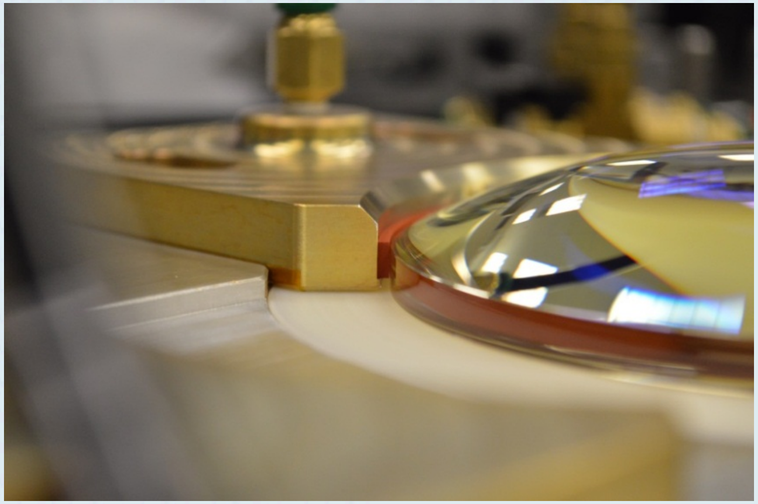


Cure

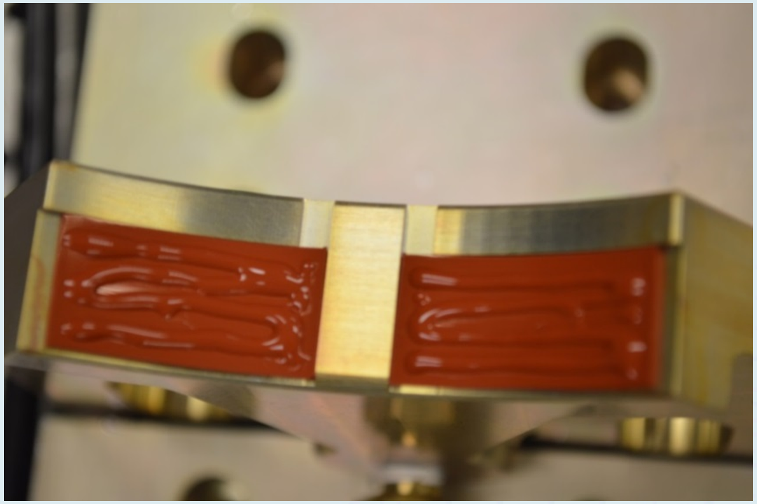


Cut

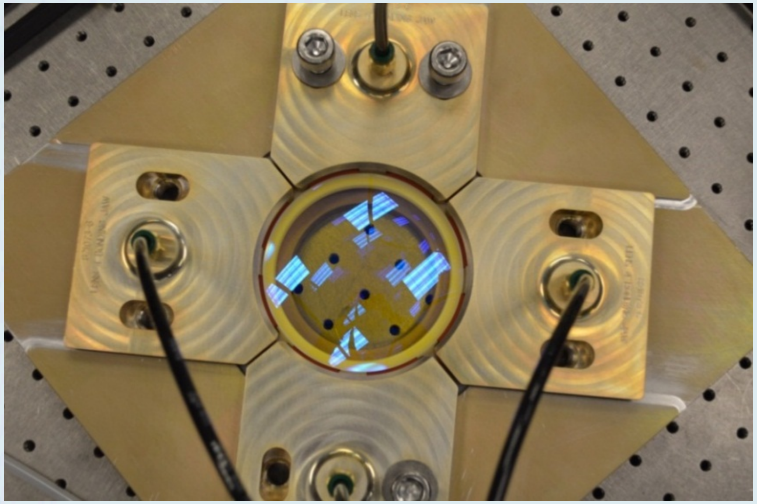
Lens Build: Lenses With RTV Pads



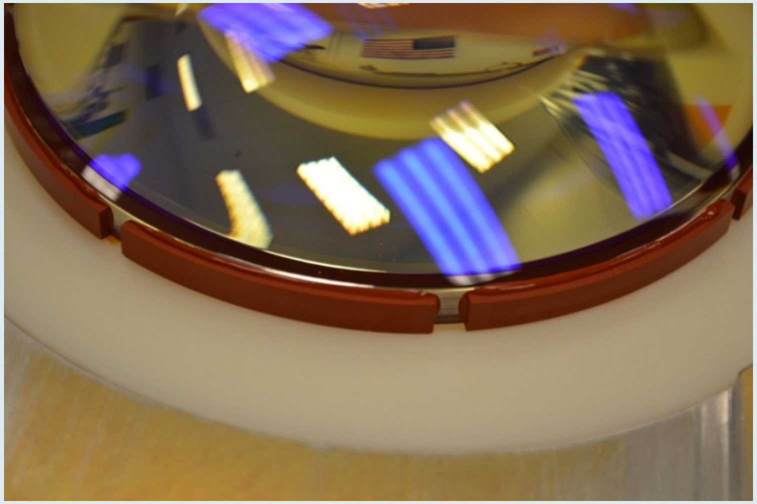
Fit Check



Pad Prep

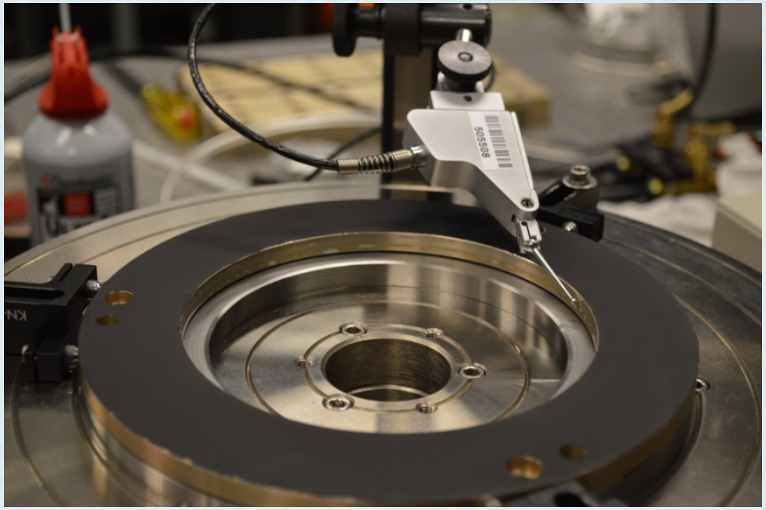


Pad Cure

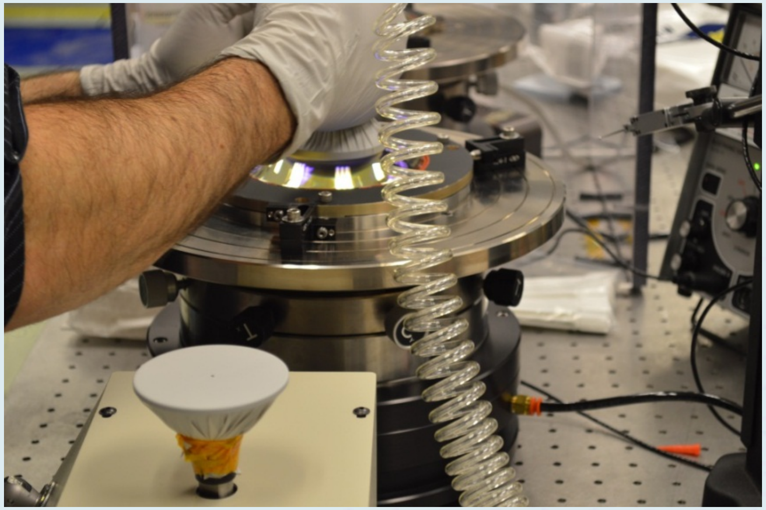


Pads on Lens

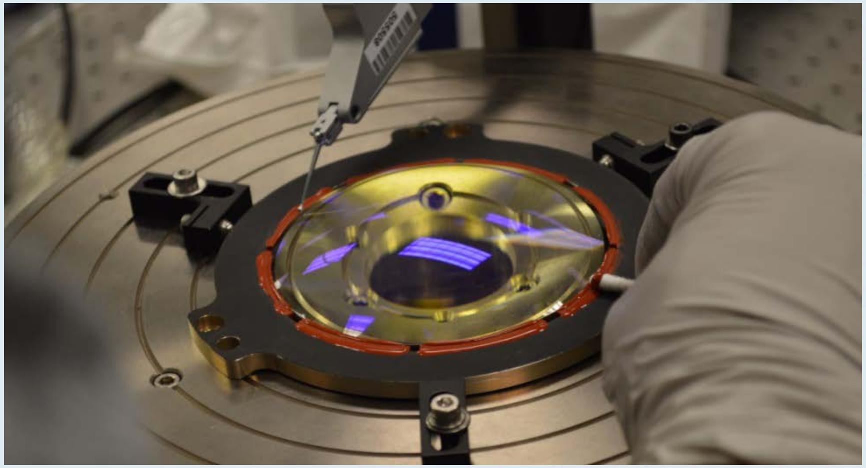
Lens Build: Lenses in Bezels



Bezel Check

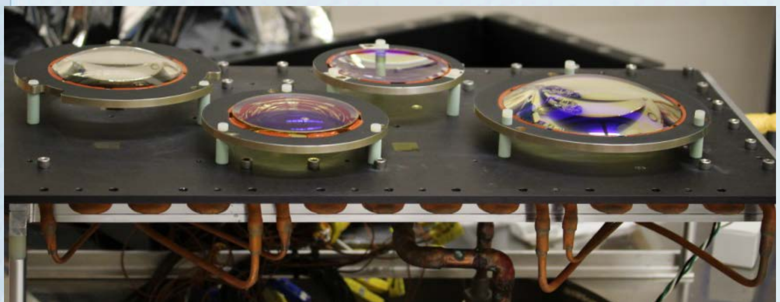


Lens Placement



Lens in Bezel Runout

Lens Build: Lens Thermal Cycling



L1, L2, L3, L4 Mounted for Test

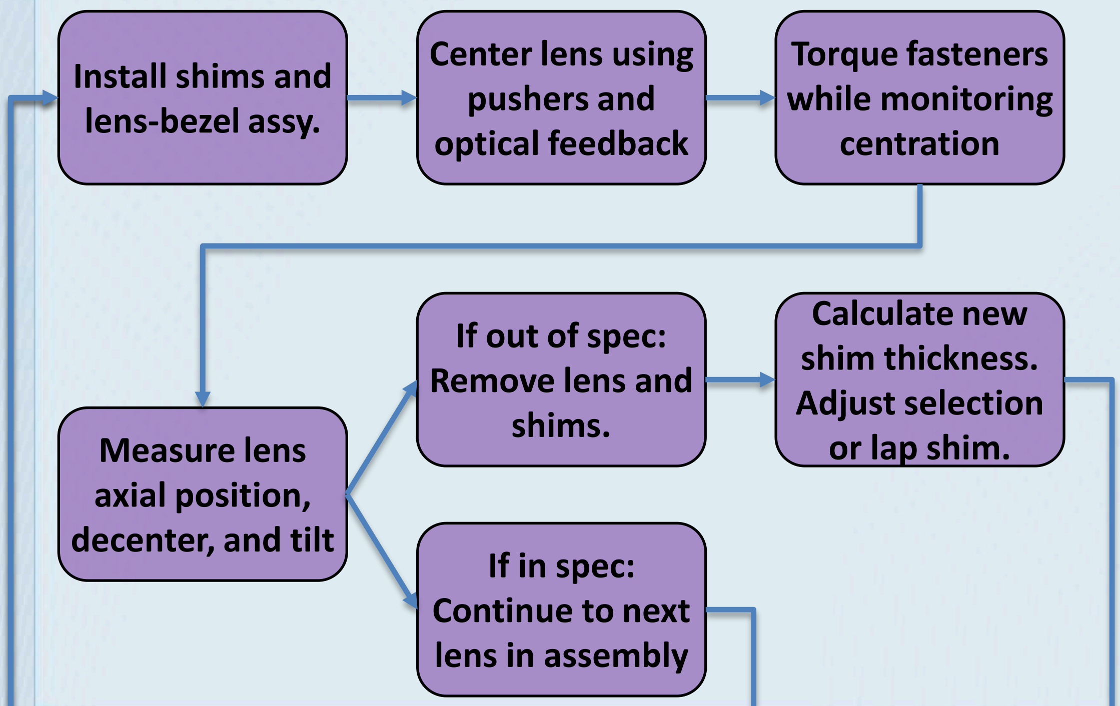
Thermal Blankets

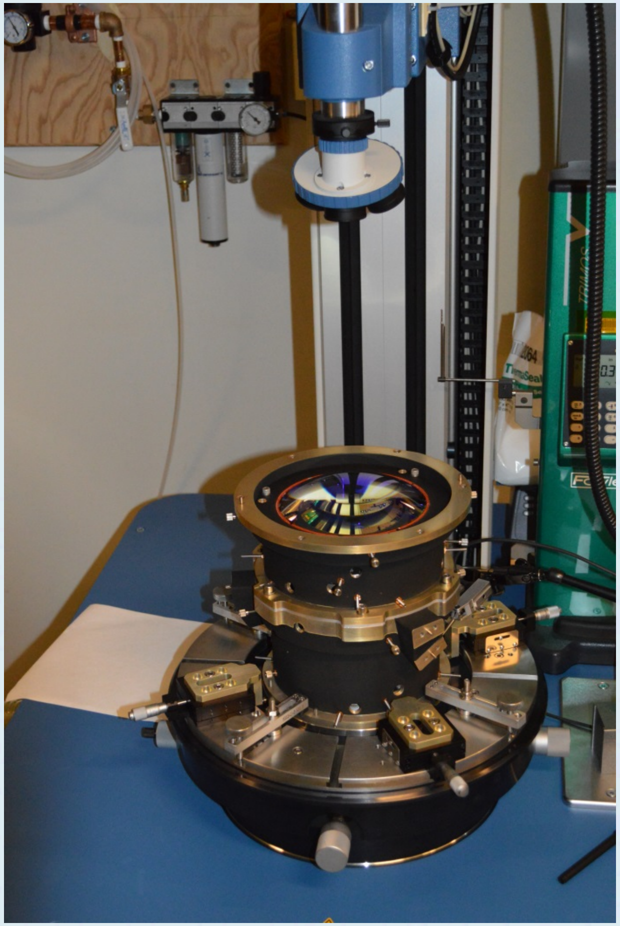
Cover (Dog-House) Installed

Thermal Chamber

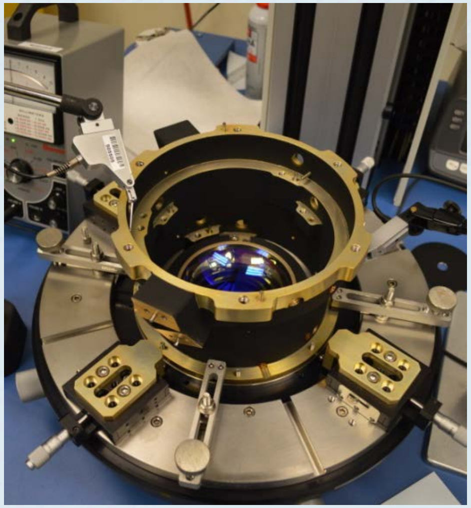
Lens Alignment

- Trioptics Lens Assembly Station
  - *Non-contact measurement of lens alignments*
  - *Procedure details developed during RRU build*
  - *Uncertainty in lens alignment: 2 microns in decenter and 1 micron axial displacement*

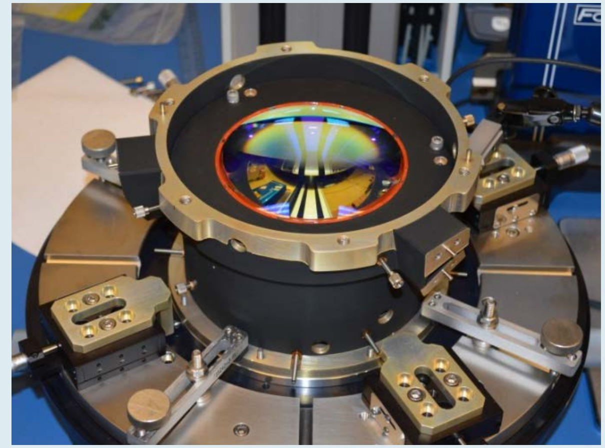




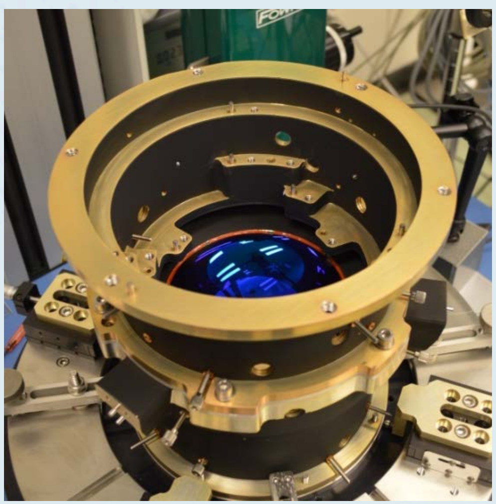
Lens Build: Barrel Assembly and Alignment



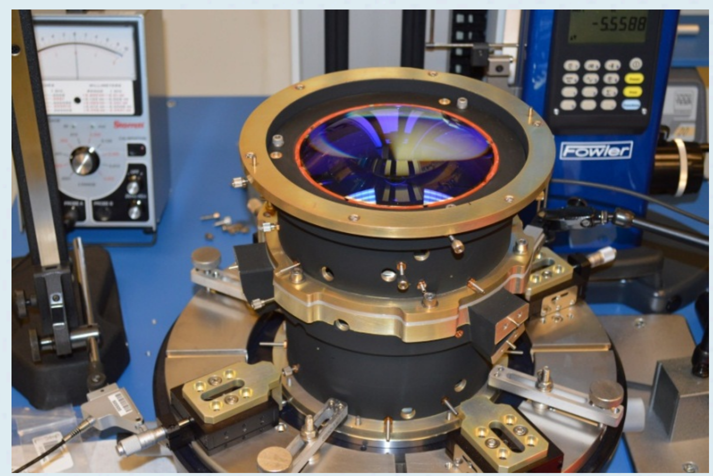
Lens install



Lower Barrel Complete

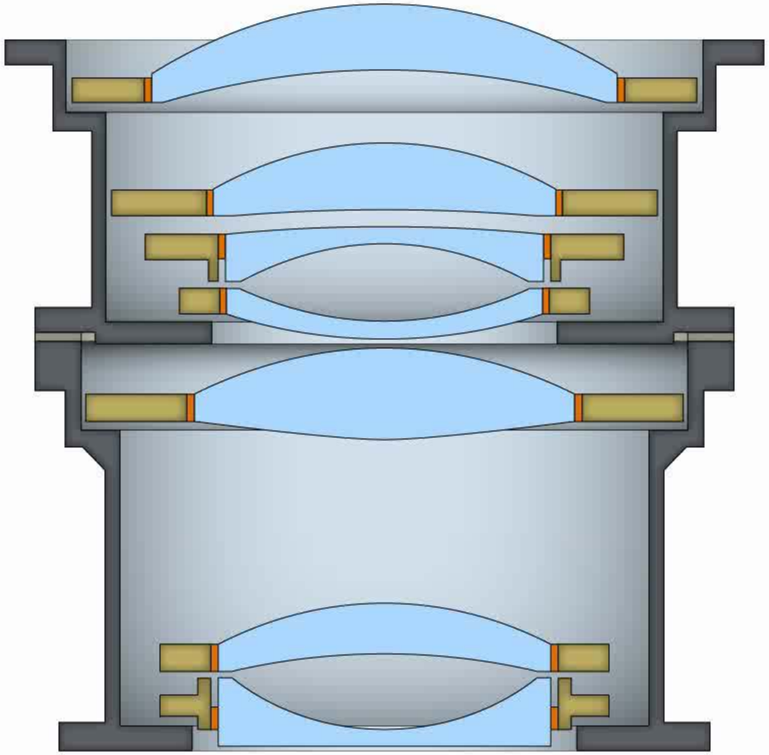


Upper Barrel



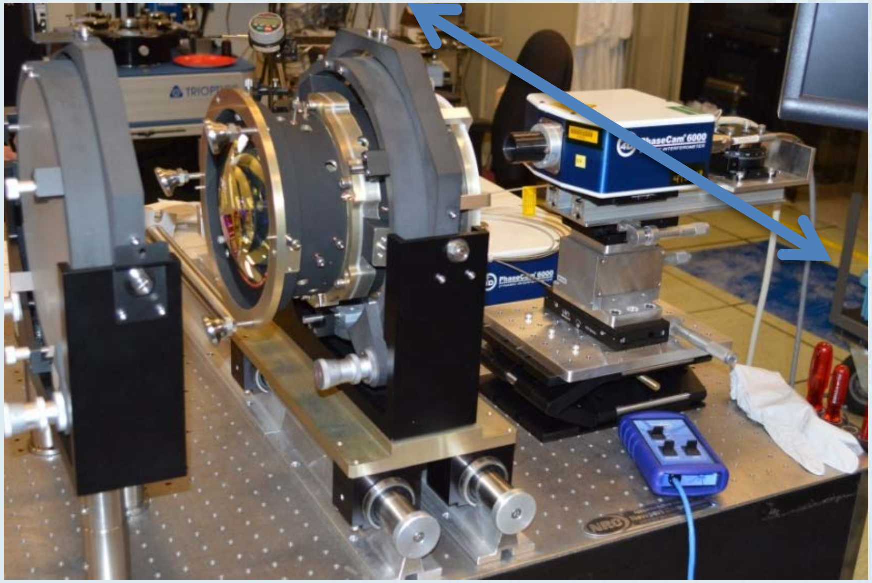
Lens Complete

TESS Optical Test



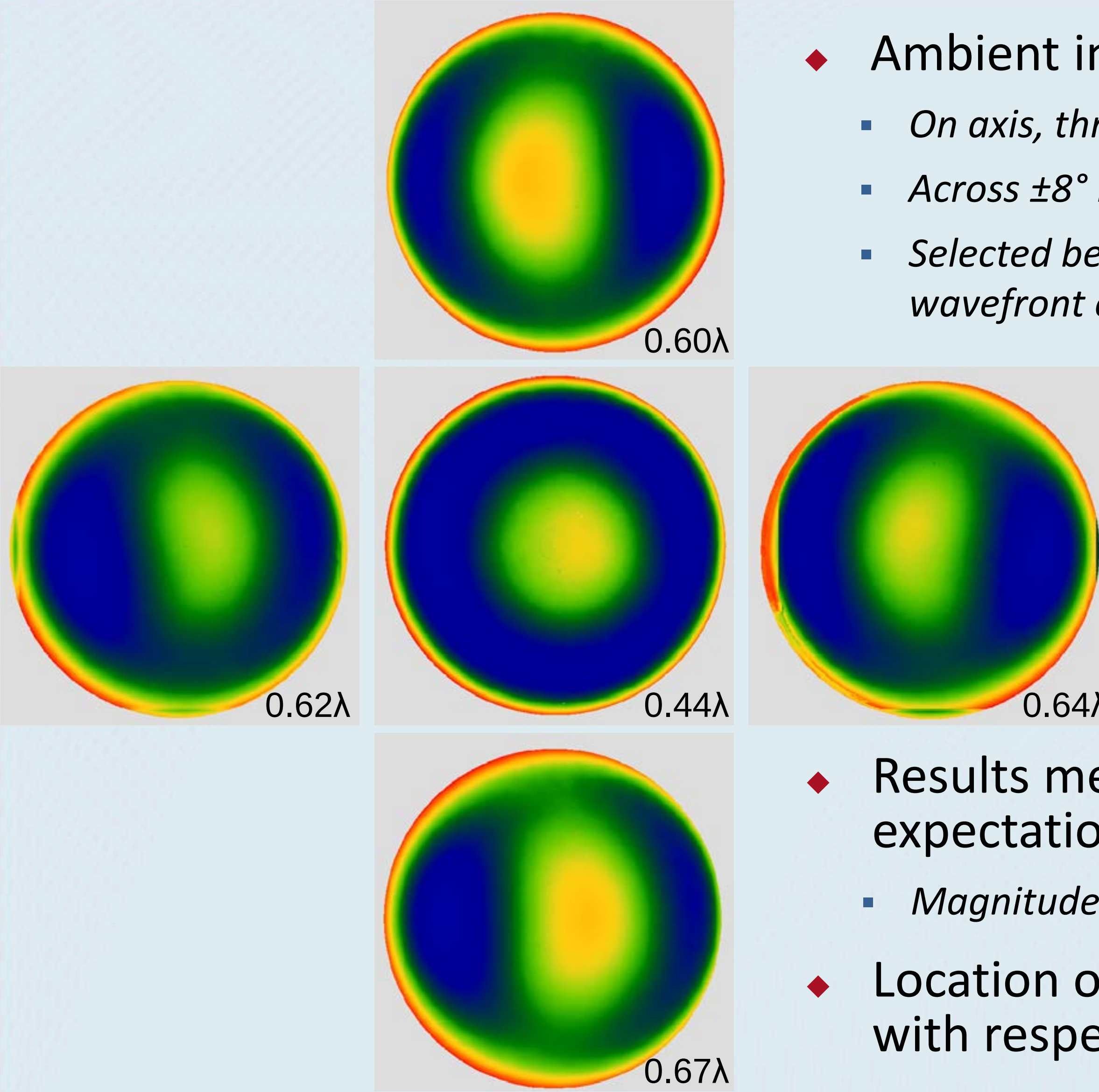
Interferometry

- Focus interferometer at focus of TESS, and return using large flat in object space
- Translate interferometer along focal plane, and follow return with large flat tilt
  - *Track interferometer location with respect to TESS lens, and track return flat angle with theodolite*
- Take interferometric data across FOV and through focus



RRU Ambient Interferometry

On axis, ± 10mm (3.9°) Wavefront Maps



- Ambient interferometry for:
  - *On axis, through focus*
  - *Across ±8° FOV (each axis)*
  - *Selected best focus figures and RMS wavefront error displayed*
- Results meet the design expectations
  - *Magnitude and aberration content*
- Location of best focus measured with respect to Lens 7

- CODE V 'ALI' used to calculate compensator adjustments
  - *Lens 1 and Focal Plane positions*

Focal Plane Only

Wavelength = 632.8 nm.

Zoom	Field	Field weight	Number of rays	RMS wavefront difference pre-align	RMS wavefront difference post-align
1	1	1.000	7796	1.7191	0.3162
1	2	1.000	7501	1.2751	0.3609
1	3	1.000	7397	1.2765	0.3555
1	4	1.000	7733	1.5489	0.2716
1	5	1.000	7665	1.5772	0.2664
1	6	1.000	7175	1.4138	0.3829
1	7	1.000	7421	1.4722	0.3229
1	8	1.000	7580	1.5710	0.1865
1	9	1.000	7520	1.4906	0.3257
1	10	1.000	7766	1.7190	0.2714
1	11	1.000	7765	1.7415	0.2596
1	12	1.000	7414	1.6074	0.3016
1	13	1.000	7505	1.5784	0.2160
TOTAL				1.5470	0.2995

Compensator type	Compensator value	RMS (a) difference	RMS (b) contribution	
* DLZ S16	0.45941E-01	0.3055	1.5177	(focus)
** DLA S16	-.68563E-04	1.5471	0.0222	(image tilt)
** DLB S16	0.17755E-03	1.5470	0.0562	(image tilt)

(a) TOTAL RMS wavefront difference assuming only one compensator is active
(b) TOTAL RMS wavefront error introduced by the one compensator

Focal Plane and Lens 1

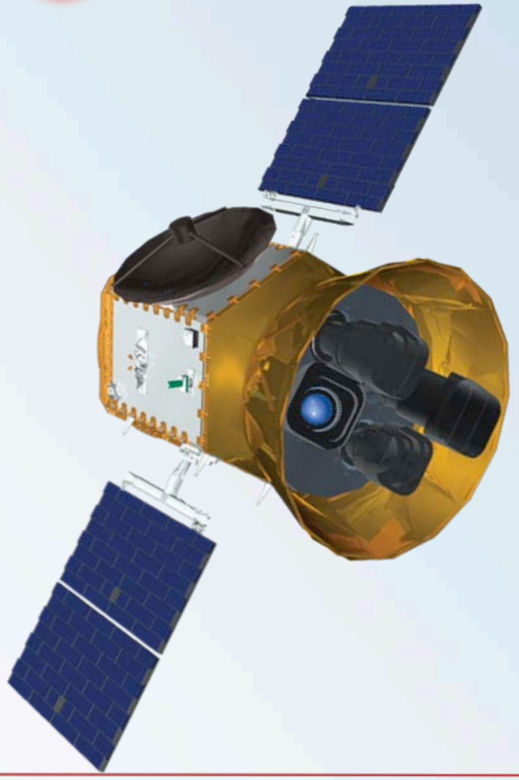
Wavelength = 632.8 nm.

Zoom	Field	Field weight	Number of rays	RMS wavefront difference pre-align	RMS wavefront difference post-align
1	1	1.000	7796	1.7191	0.1962
1	2	1.000	7501	1.2751	0.2935
1	3	1.000	7397	1.2765	0.3072
1	4	1.000	7733	1.5489	0.1818
1	5	1.000	7665	1.5772	0.2137
1	6	1.000	7175	1.4138	0.3129
1	7	1.000	7421	1.4722	0.2562
1	8	1.000	7580	1.5710	0.2057
1	9	1.000	7520	1.4906	0.2033
1	10	1.000	7766	1.7190	0.2317
1	11	1.000	7765	1.7415	0.2134
1	12	1.000	7414	1.6074	0.3367
1	13	1.000	7505	1.5784	0.2146
TOTAL				1.5470	0.2477

Compensator type	Compensator value	RMS (a) difference	RMS (b) contribution	
DSZ S1..2	-.19731 #	0.2872	1.5353	
DSX S1..2	-.14719E-01	1.5453	0.0587	
DSY S1..2	0.35073E-01	1.5428	0.1394	
* DLZ S16	-.49821E-03	1.5631	0.0165	(focus)
** DLA S16	-.27759E-03	1.5492	0.0900	(image tilt)
** DLB S16	0.82665E-04	1.5467	0.0262	(image tilt)

(a) TOTAL RMS wavefront difference assuming only one compensator is active
(b) TOTAL RMS wavefront error introduced by the one compensator
Compensator has been damped to avoid exceeding maximum value

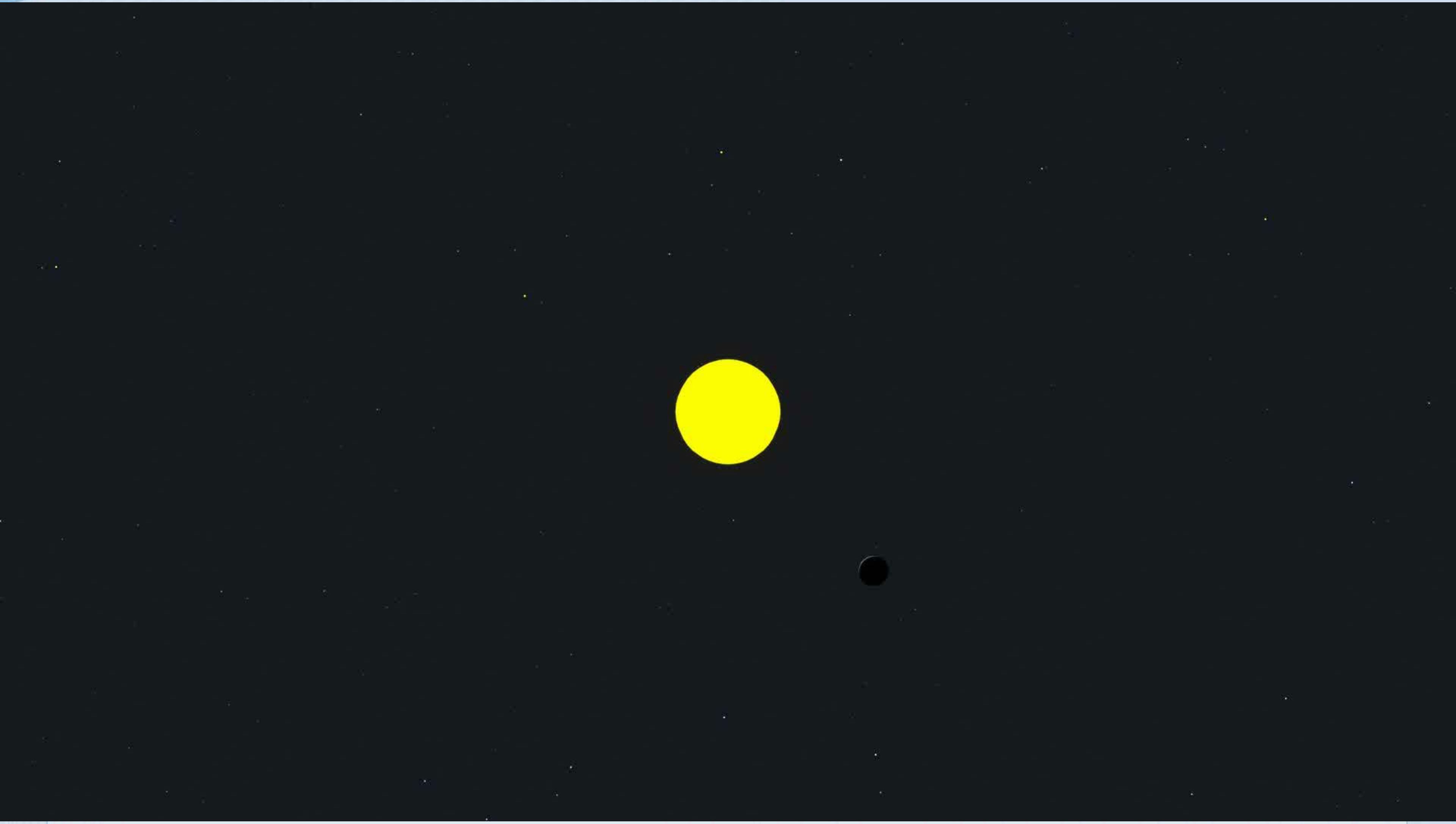
Did not adjust Lens 1 since performance predictions met BPFF specification with only focus adjustment.



Extra Slides

This work is sponsored by the National Aeronautics and Space Administration under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government.

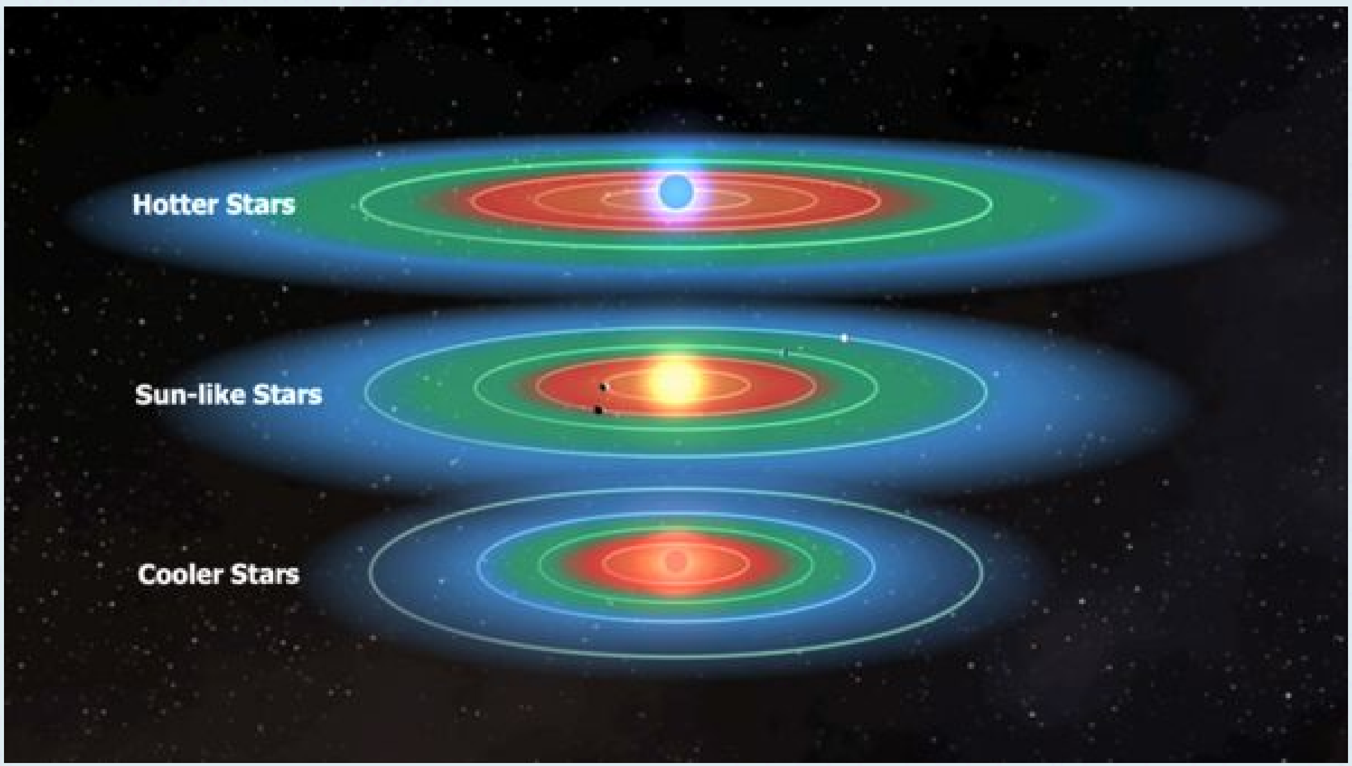
Transit Method



TESS Detection Goals and Target Stars

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

Habitable Zone



Transits/year

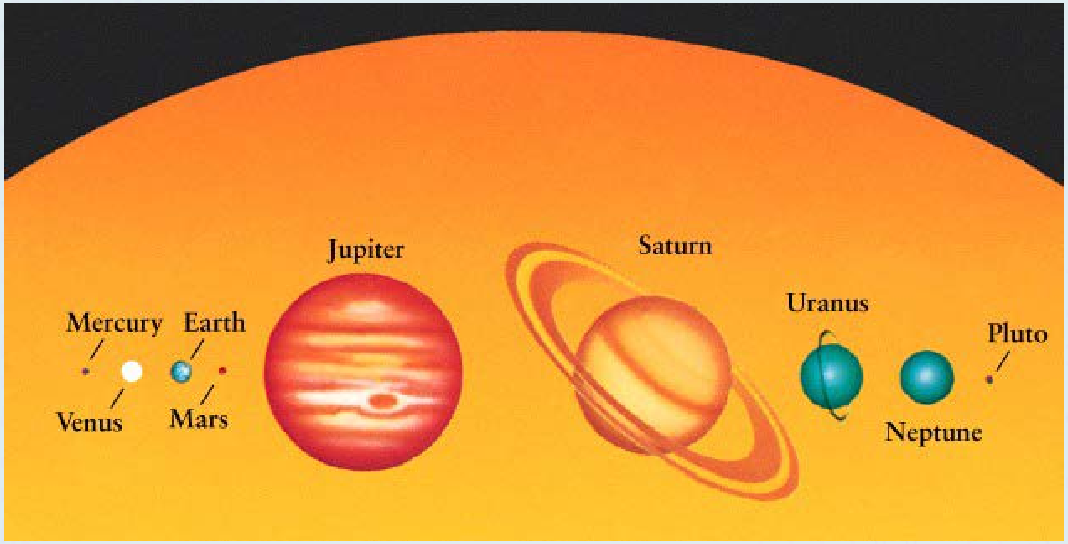
<<1

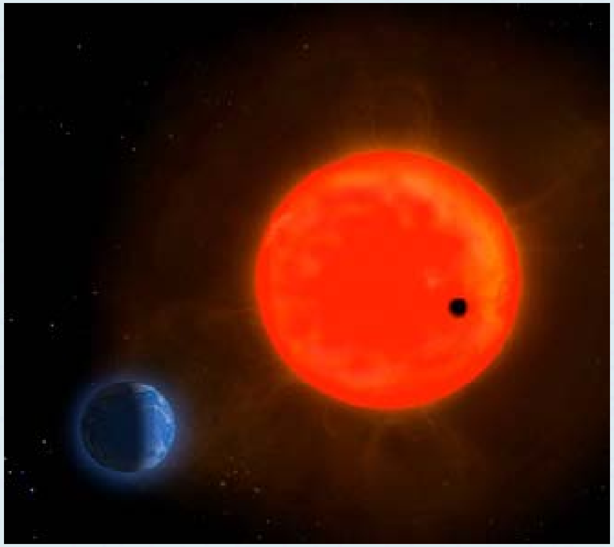
~1

>>1

Expected Planetary Detections

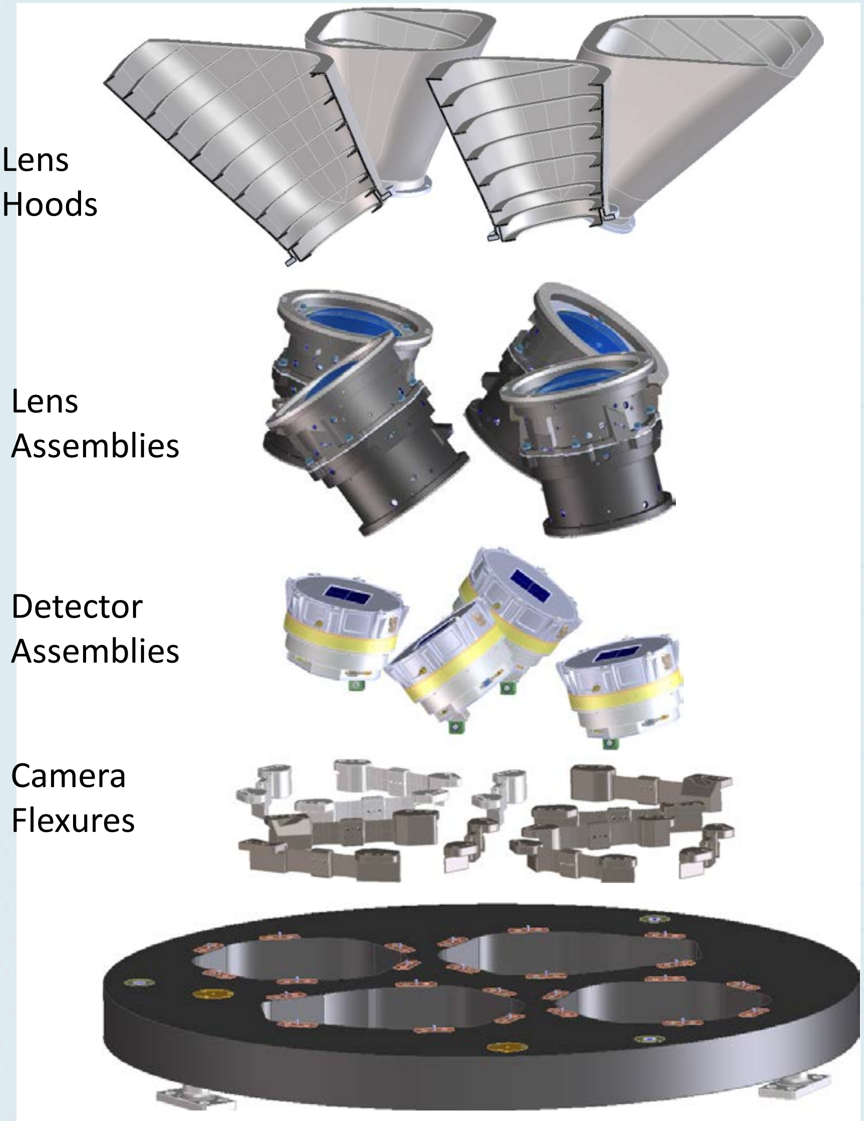
- With a 2 year mission duration, TESS is expected to discover:
  - *30 Earth-sized planets*
    - *10-20% inside the habitable zone*
    - *20-30% inside JWST's Continuous Viewing Zone*
  - *300 Super-Earth (2·R_E) planets*
  - *Tens of thousands of larger planets*



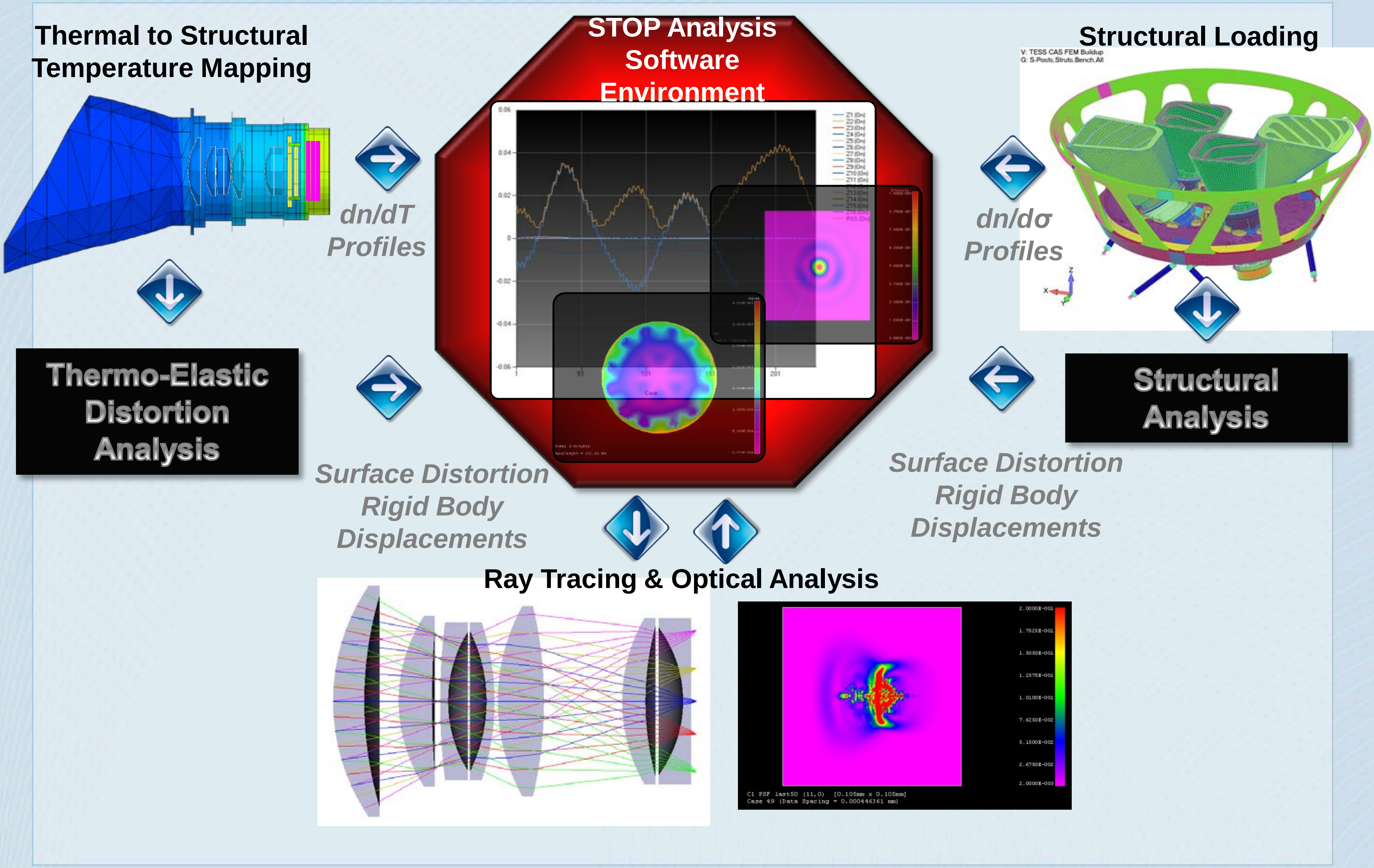


Instrument Level Overview

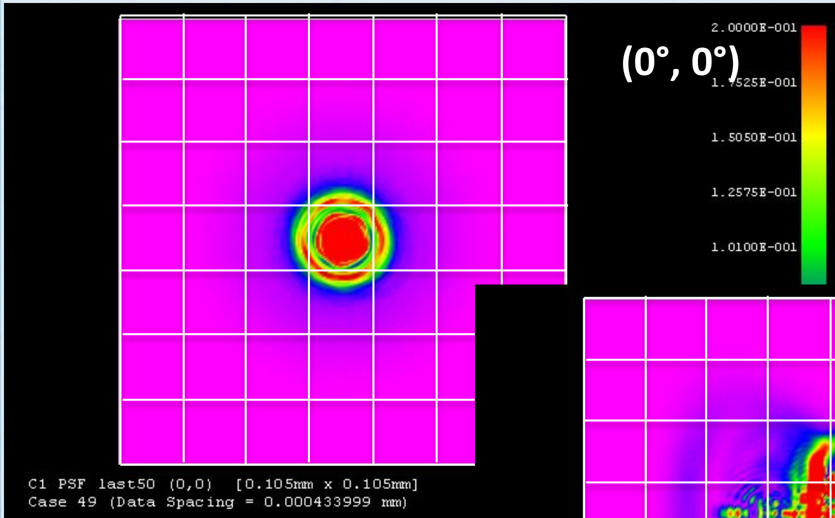
- TESS Instrument consists of 5 primary mechanical subsystems:



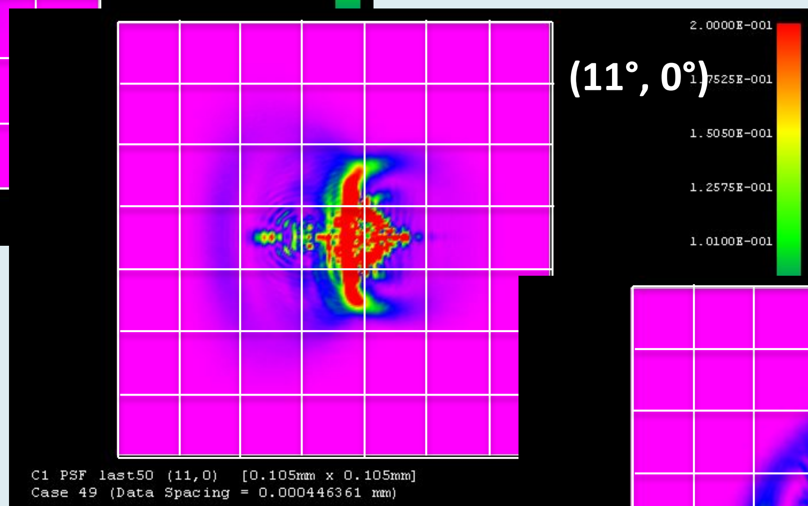
STOP Modeling Process



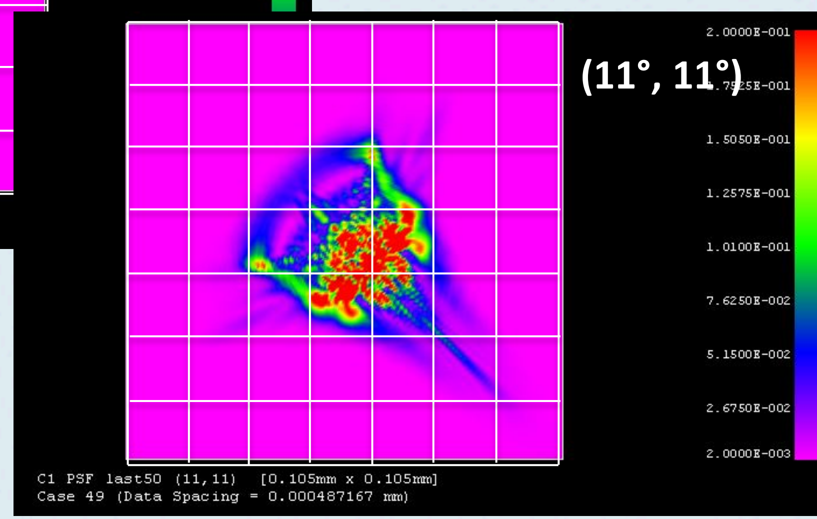
Imaging Performance on Orbit



Ensquared Energy =55%



Ensquared Energy =23%



Ensquared Energy =18%

15 micron pixel

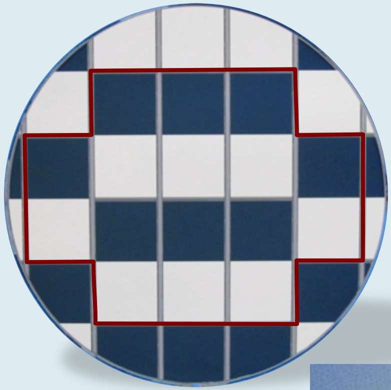
TESS Imager

Parameter	Requirement
CCD	2 x 2 detector arrays
Detector Array	2048 x 2048
Pixel Size	15 microns
CCD Active Area Size	63.482 mm x 63.482 mm
CCD active area diagonal semi-height	44.88 mm

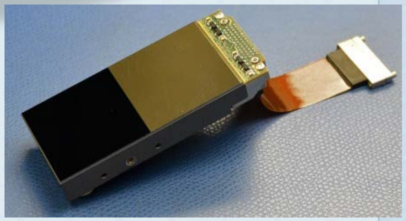
TESS Imager Summary

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

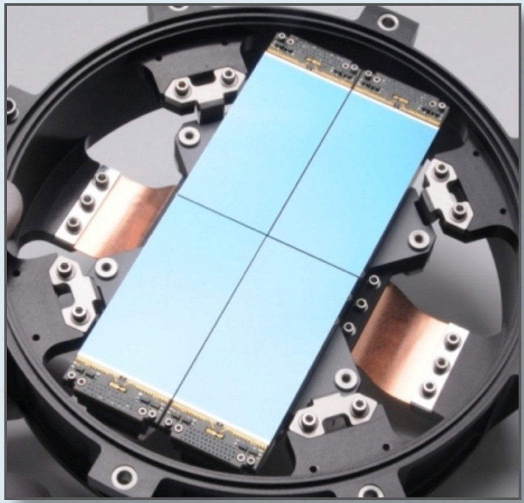
Performance	Value	Achieved
Well Capacity	> 150,000 e- (goal)	**> 190,000 e-**
Conversion Gain	< 10 µV/e-	**7 µV/e-**
Read Noise @ 625 kHz	< 20 e-	**< 14 e- w/FPE**
Dark Current @ -30°C	< 8 e-/pix/sec	**< 2.5 e-/p/s**
Device Thickness	100 µm (-10/+15µm)	**95 – 115 µm**
Depletion-depth control	Substrate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



Completed 200 mm CCD Wafer



Packaged CCID-80 Imager



Prototype Detector Assembly

Lens Assembly Design Tolerances

Lens	Sur.	Fringes (power)	Fringes (irregularity)	dN	dV	Lens wedge (ETD mm)	Lens thickness (mm)	Axial position (mm)	Radial decenter (mm)	Lens tilt (arc min)
1	1	3	0.5	±0.00004	±0.02%	±0.005	±0.025	±0.035	±0.020	±0.4
	2	3	0.5					comp.	comp.	
2	3	3	0.5	±0.00004	±0.02%	±0.005	±0.025	±0.035	±0.020	±0.4
	4	3	0.5							
3	6	3	0.5	±0.00004	±0.02%	±0.010	±0.050	±0.035	±0.020	±0.4
	7	3	Asp							
4	8	3	0.5	±0.00004	±0.02%	±0.005	±0.025	±0.035	±0.020	±0.4
	9	3	0.5					comp.		
5	10	3	0.5	±0.00004	±0.02%	±0.005	±0.025	±0.035	±0.020	±0.4
	11	3	0.5							
6	12	3	Asp	±0.00004	±0.02%	±0.010	±0.050	±0.035	±0.020	±0.4
	13	3	0.5							
7	14	3	1	±0.00004	±0.02%	±0.005	±0.025	±0.035	±0.020	±0.4
	15	3	1					comp.		

ETD – maximum edge thickness minus minimum edge thickness (TIR)
Fringes power and irregularity – difference from test plate @ 632 nm
dN – refractive index difference, dV- Abbe number change

Surface 7 Asphere Tolerance: less than 0.07 microns peak to valley over any 14mm diameter subaperture.
Surface 12 Asphere Tolerance: less than 0.05 microns peak to valley over any 17mm diameter subaperture.

RRU As-Built Fabrication + Alignment Results

Lens-Serial#	Sur.	Fringes (power)	Fringes (irregularity)	dN, dV*	Lens wedge (ETD mm)	Lens thickness (mm)	Axial position (mm)	Radial decenter (mm)	Lens tilt (arc min)
1-SN3	1	0.52	0.281	Comp.	0.003	+0.020	0	0.0042	0.285
	2	0.67	0.329						
2-SN10	3	0.07	0.221	Comp.	0.003	+0.009	-0.013	0.0032	0.252
	4	0.62	0.156						
3-SN1	6	1.95	0.156	Comp.	0.005	-0.010	+0.018	0.0093	0.323
	7	1.50	Asp**						
4-SN2	8	1.20	0.433	Comp.	0.003	+0.023	-0.013	0.0020	0.288
	9	1.70	0.227						
5-SN1	10	0.00	0.143	Comp.	0.005	+0.018	+0.003	0.0031	0.378
	11	2.00	0.250						
6-SN3	12	1.50	Asp**	Comp.	0.005	-0.036	-0.023	0.0013	0.052
	13	1.80	0.200						
7-SN1	14	1.50	0.464	Comp.	0.000	+0.013	0	0.0068	0.153
	15	0.07	0.069						

Fabrication and alignment results good to a fraction of tolerance allocation! Compensation of Lens 1 and barrel-to-barrel spacing were not necessary. Qual/Flight goal is to build to the above tolerances and avoid difficult and time intensive interferometric active alignment.