Optical Design of Camera for Transiting Exoplanet Survey Satellite (TESS)

Michael Chrisp, Kristin Clark, Brian Primeau, Michael Dalpiaz, Joseph Lennon

SPIE Conference

June 7, 2015

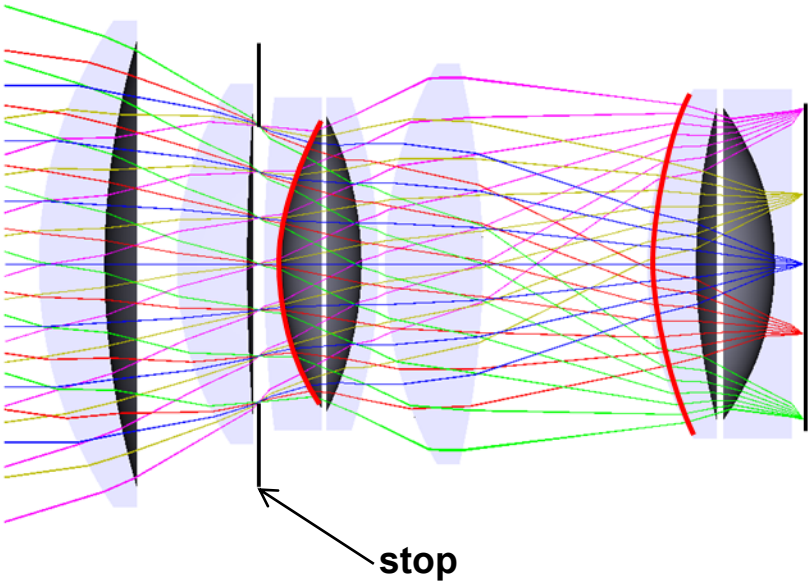
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

244 Wood Street, Lexington MA 02420

*DISCLAIMER: This work is sponsored by the Department of the Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

Introduction

- Design drivers
  - Maximum light gathering for size and volume constraints
  - Cryogenic operation at -75°C
  - Wavelength range 600 – 1000 nm
- Design features
  - Seven element hybrid Petzval design
  - No vignetting
  - Two aspheric surfaces



Parameter	Value
FOV	24° x 24°
FL, f/#	146 mm, f/1.4
EPD	105 mm
Wavelengths	600-1000 nm
CCD	2 x 2 detector arrays 4k x 4k pixels
Detector arrays	2048 x 2048 15 micron pixels
Transmittance	86.5% (including filter)
Mass	9.3 kg
Dimensions	17.0 cm diameter 21.1 cm long

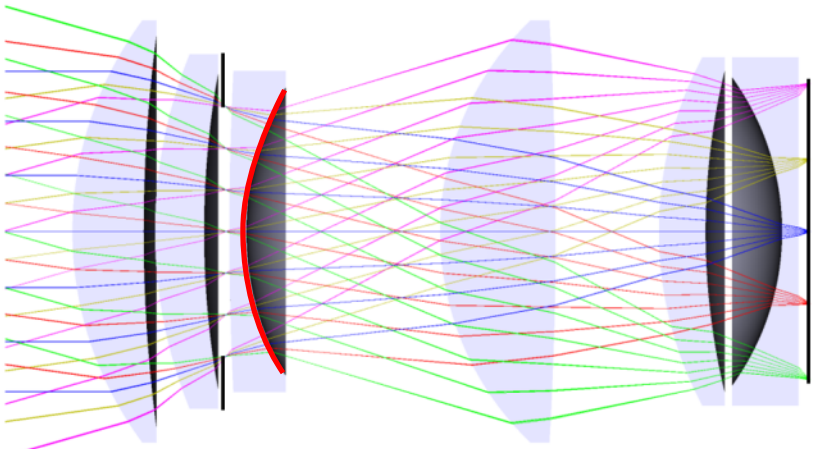
Design Evolution

Engineering Design f/1.56

6 lenses 1 aspheric

Field 22.5° x 22.5°

Pupil 101.8 mm

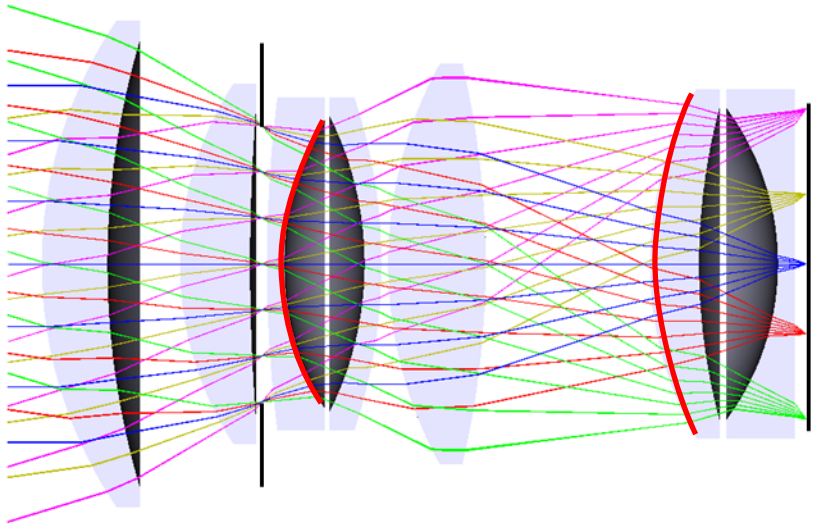


Flight Design f/1.4

7 lenses 2 aspherics

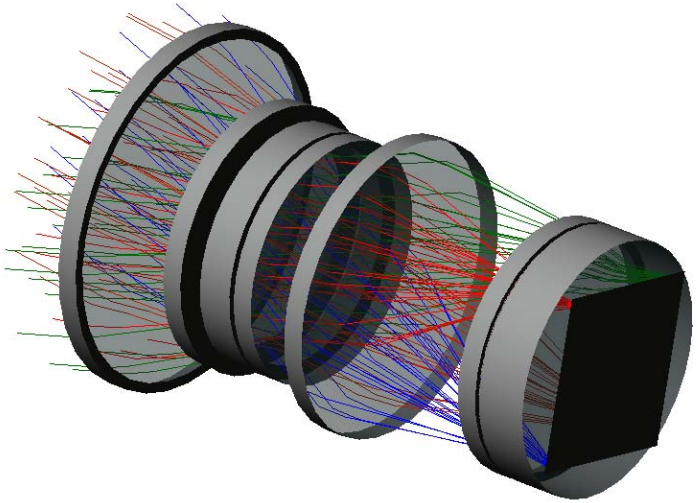
Field 24° x 24°

Pupil 105 mm



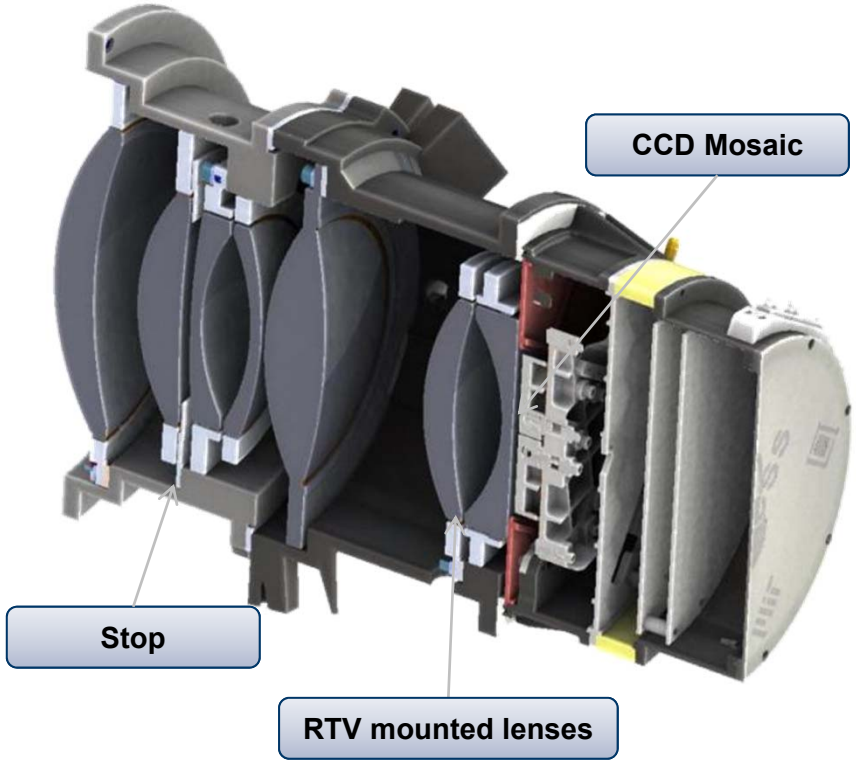
Design Implementation

Optical Design



Number of lenses	7
f-number	1.4
Pupil diameter	105 mm
Field of View	24° x 24°

Lens Assembly



Tolerances

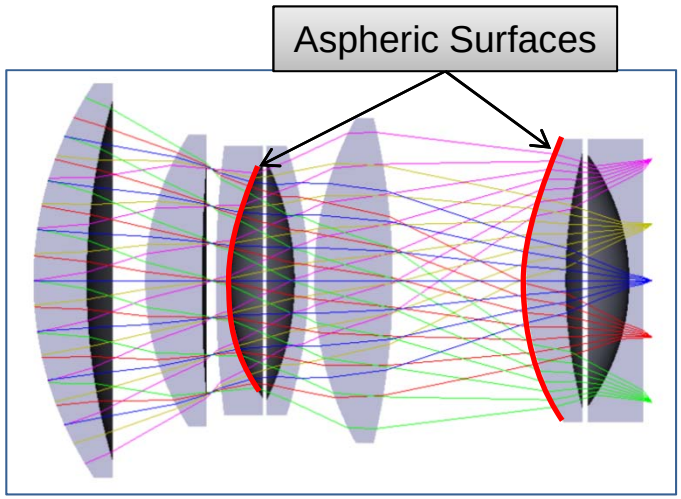
- **Melt data recalculation of design**
- **Compensators for assembly**
  - **First lens decenter and spacing**
  - **Detector focus**

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	1,2	3	0.5	±0.00007	±0.04%*	±0.005	±0.030	±0.035	±0.020	±0.4
2	1,2	3	0.5	±0.00007	±0.04%	±0.007	±0.030	±0.035	±0.020	±0.4
3	1	3	0.5	±0.00007	±0.04%	±0.010	±0.050	±0.035	±0.020	±0.4
	2	3	Asp							
4	1,2	3	0.5	±0.00007	±0.04%	±0.007	±0.030	±0.035	±0.020	±0.4
5	1,2	3	0.5	±0.00007	±0.04%*	±0.007	±0.030	±0.035	±0.020	±0.4
6	1	3	Asp	±0.00007	±0.04%	±0.010	±0.050	±0.035	±0.020	±0.4
	2	3	0.5							
7	1,2	3	1	±0.00007	±0.04%	±0.007	±0.025	±0.035	±0.020	±0.4

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

Best Aspheric Surface Search

- Performed search for best aspheric surfaces using Forbes polynomials
  - QSL numbers are equivalent to the interferometric fringe density (difficulty of asphere)
- Solution from CODEV Asphere Expert has an RMS Error Value of 45
  - 20% larger RMS spot sizes than the search result and difficult aspheres
- Best solution from search had an RMS error value of 35

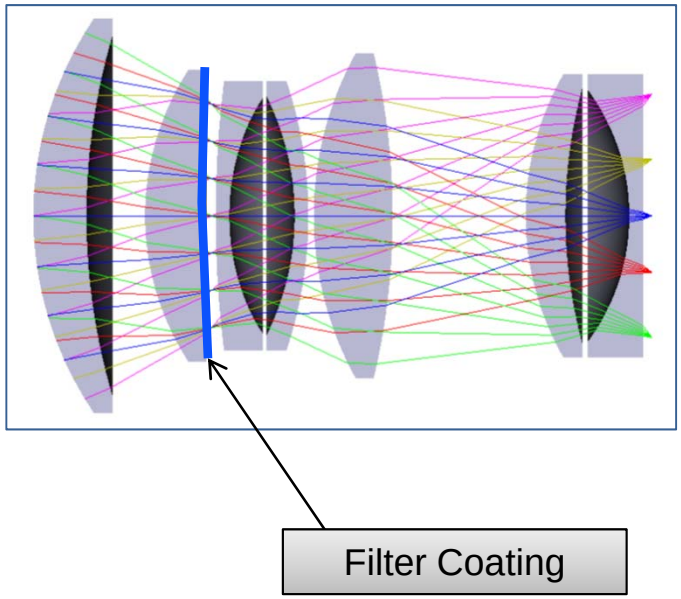


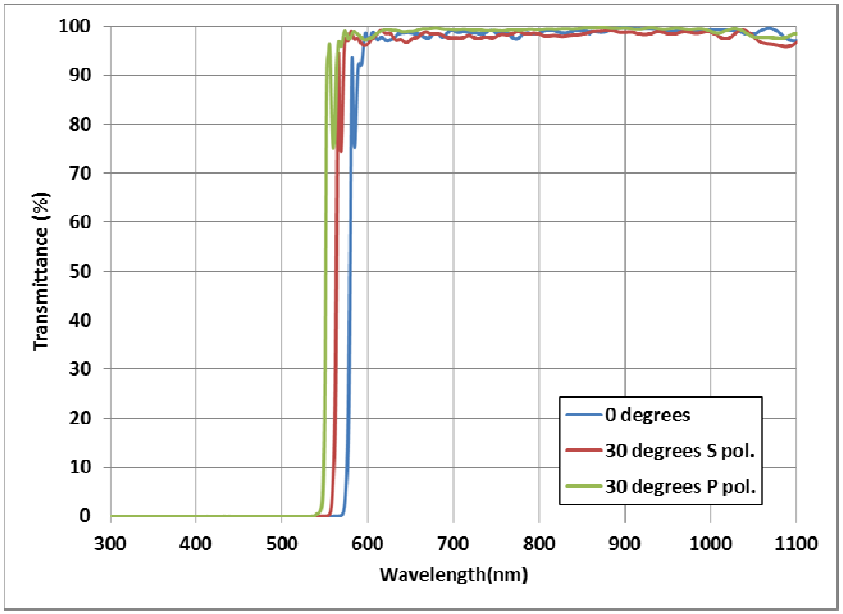
Aspheric Surfaces	RMS Error Value	QSL1	QSL
No aspherics	97	NA	NA
Single asphere L3, S2	59	401	NA
CODEV ASPHERE EXPERT surface L4, S1 and L5, S1	45	1077	1719
Surfaces L3, S2 and L6, S1	36	451	308

The two aspheric surfaces reduce the RMS spot sizes by 60% compared with the spherical design

Short Wave Rejection Filter

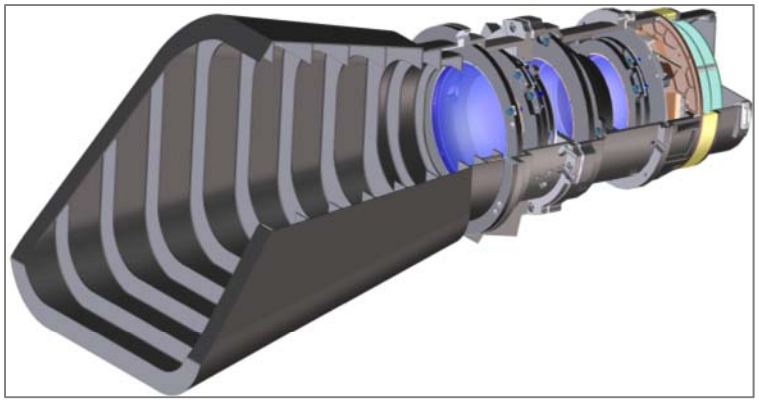
- **Filter coating on lens saves weight compared with separate filter ahead of lens**
- **Coating operates over an angle of incidence from 0° to 30°**
- **High blocking of >10^{-5} for wavelengths <530 nm**



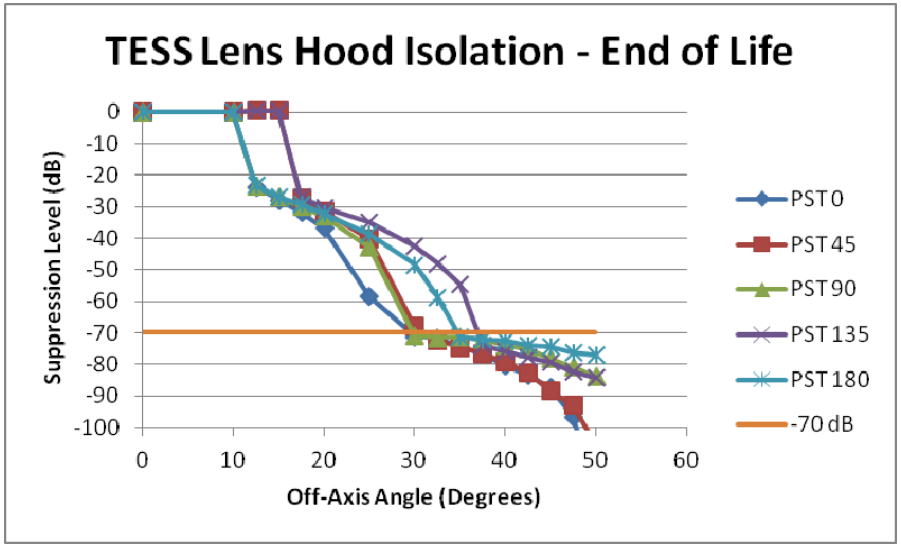


Stray Light

- Lens hood design blocks Earth- and moonshine from reaching the detector plane
  - Two lens hood lengths (required by spacecraft keep-out volume)
- Lens hood model
  - Z302 black paint in lens barrel
  - IEST-STD-CC1246D level 500A contamination specified on external surfaces
- Baffle achieves 70 dB isolation at 37° range for corner fields



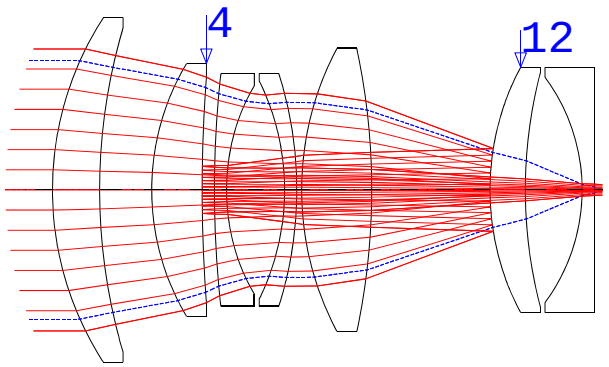
Long Lens Hood



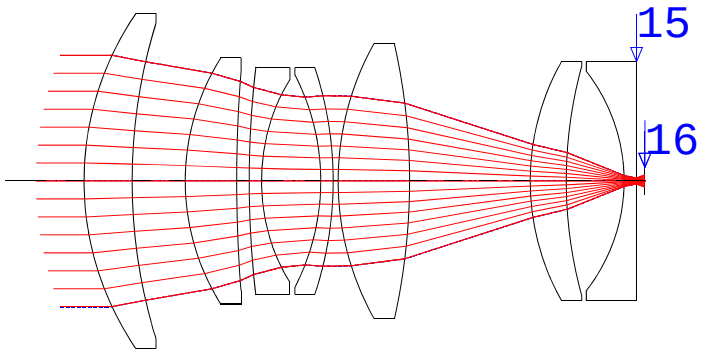
Ghost Image Analysis

Paraxial ghost analyses showed two paths of interest

Front of Lens 6 → Filter → Detector



Detector → Back of Last Lens →Detector



Ghost	Peak Irradiance (100% transmittance)	Transmittance	Peak Irradiance (with transmittance)	Ghost Irradiance relative to Image
Image	2.2×10^{8} W cm^{-2}	0.84	~1.8×10^{8} W cm^{-2}	
Surfaces 12→4	4.8×10^{3} W cm^{-2}	3.5×10^{-4}	~1.7 W cm^{-2}	<~10^{-8}
Surfaces 16→15	5.6×10^{2} W cm^{-2}	10^{-3}	0.6 W cm^{-2}	<~10^{-8}

Ghost images not significant, irradiance <10^{-8} w.r.t. primary image

Conclusion

- Hybrid Petzval design with no vignetting proved to have the best light gathering under the volume and weight constrictions
- Two aspheric surfaces improve the r.m.s. spot size by 60% compared with the non-aspheric design.
- Internal short wave rejection filter coating successfully replaced an external filter
- The lens hood design has met stray light rejection requirements
- Lens has been fabricated and assembled, with initial results matching the performance predictions