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

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ABSTRACT

The optical design of the wide field of view refractive camera, 34 degrees diagonal field, for the TESS payload is described. This fast f/1.4 cryogenic camera, operating at -75°C, has no vignetting for maximum light gathering within the size and weight constraints. Four of these cameras capture full frames of star images for photometric searches of planet crossings. The optical design evolution, from the initial Petzval design, took advantage of Forbes aspheres to develop a hybrid design form. This maximized the correction from the two aspherics resulting in a reduction of average spot size by sixty percent in the final design. An external long wavelength pass filter was replaced by an internal filter coating on a lens to save weight, and has been fabricated to meet the specifications. The stray light requirements were met by an extended lens hood baffle design, giving the necessary off-axis attenuation.

Keywords: optical design, telescopes, space instrumentation, cameras, sensors

1. INTRODUCTION

The Transiting Exoplanet Survey Satellite (TESS) will search for planets transiting bright and nearby stars and has been selected by NASA for launch in 2017 as an Astrophysics Explorer mission. The science details of this mission are given in a paper[1] by the principal investigator George Ricker and the team. The mission and overall satellite information are described thoroughly on NASA's TESS website[2].

On the satellite are four cameras of the same optical design, arranged so that their individual 24°x 24° fields of view sum to cover a 48°x 48° field of regard. Each of these cameras has a lens hood baffle, which due to the arrangements on the spacecraft are of two different lengths. The cameras operate at a cryogenic temperature of -75°C and the performance given here is at that temperature. The focal planes for the cameras consist of 4 CCDs closely spaced in a square arrangement giving a frame size of 2k x 2k pixels.

This paper will cover the details on the optical design of the cameras including their expected performance. Also included are the stray light performance for baffles and the optical filter coating, enabling the optical system to meet the science requirements.

2. OPTICAL DESIGN

The challenge, in the optical design for the camera, was to get as much as light as possible onto the detector focal plane, given the constraints on volume, weight and image performance: volume, because the four cameras have to fit in the diameter and depth available on the satellite's camera platform, weight, to meet the overall budget for the satellite, and image performance, so that the light gathered from a star is concentrated on a small number of pixels.

The light gathering is determined by the entrance aperture diameter, which was made as large as possible within the constraint limits. This resulted in fast f/1.4 optical system, found by exploring a number of lens arrangements to reach the optimal solution. Unlike a typical wide-angle camera used in photography, where 50% vignetting is allowed at the edge of the frame, the TESS camera is designed with no vignetting to maintain the same sensitivity over the whole of the detector.

The optical design has evolved during two generations of the camera. First the engineering unit was designed and built. Then after studying the performance of the engineering unit and a change in specifications, the flight camera design was generated and built. The engineering camera is interesting for tracing the design evolution, but the flight camera is the one that will be covered in detail.

2.1 Engineering Unit Camera Design

The engineering camera unit design evolved from two main principals:

- Incorporation of an aspheric surface to improve the performance. This was an enormous improvement to the design, since it overcame the difficulty of correcting the spherical aberration of different orders in a fast compact design.
- Use of a long wavelength passes coating on a surface within the camera to replace an external filter. The optical design requires a long wavelength pass filter, transmitting the wavelengths 530 to 1000 nm. In the preliminary designs this had been a separate filter element ahead of the first lens. For weight considerations, this was replaced by a filter coating on one of the lenses.

For the starting design a Petzval design form was chosen, which has the speed but lacks the field of view compared with the requirements. Experimentation with variations, adding negative elements, moving the stop and adding an asphere resulted in the final design. Even with the advances in optical design programs and the use of global optimization features, a fast wide angle lens covering a broad spectral range still requires a considerable amount of time and experimentation. Global optimizations can't move the stop position, change the number elements, or decide which surfaces the aspherics should be on. Fictitious glass approaches can also end up with designs that can't be realized with real glasses. Iterative cycles for developing understanding from the previous design failures are necessary to get to a design which can actually be made.

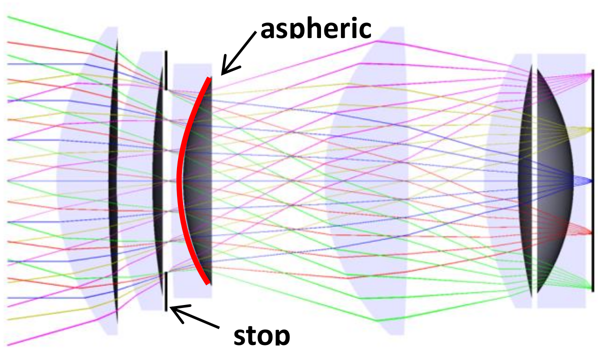


Figure 1 Engineering Unit Lens

The resulting design, shown in Figure 1, was a hybrid Petzval lens, with the negative elements helping with achromatization and broadening the field of view. It should be noted, that compared with a standard optical design, where the aspheric typically provides an improvement of 20%, in this design the aspheric on lens 3 improves the spot sizes by 50%.

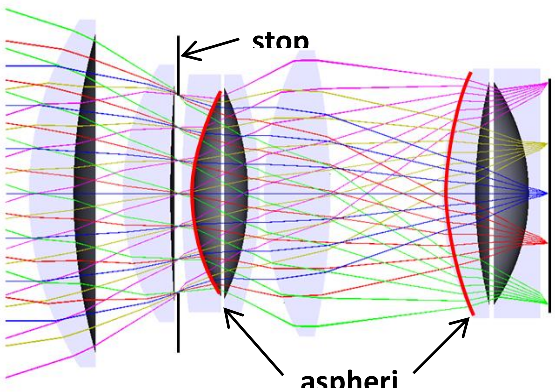
The refractive index of the materials at -70°C was generated by extrapolating the data from the Ohara's standard glass tables, which only go down to -40°C.

This engineering design was built, and testing showed that it met the cryogenic performance predictions. One of the glasses, Ohara SFPL51, proved difficult to fabricate without breaking, resulting in it being eliminated from the follow on flight design.

2.2 Flight Camera Design

The specifications for the flight camera design are shown in the table in Figure 2. The entrance pupil diameter and speed of the lens were increased from the engineering unit, so another lens element and an additional aspheric surface were added to the optical design to maintain the image performance.

In approaching the new design a number of constraints were incorporated to improve fabrication. The front lens was near to the maximum slab thickness that Ohara supplies SLAH55V in. Therefore a constraint coupling the radii and thickness were was used during the design to fit the lens in the slap. From the structural analysis, guidelines for the lens the edge thicknesses ensured sufficient bonding area, and the air spaces were controlled to provide for sway space during vibration. The resulting design with the two aspheric surfaces is shown in Figure 2.



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% (with filter)
Mass	9.3 kg
Dimensions	17.0 cm diameter 21.1 cm long

Figure 2 Flight Camera Design and Parameters

Forbes aspheres were used for the initial design, since it is relatively easy to constrain them with regard to maximum fringe density that will be viewed in the interferometer. The conversion routines in CODEV to switch from Forbes aspheres to regular aspheres caused the performance to degrade too much, so extra regular coefficients were added in

The trade on which surfaces to place the two aspheres for optimum performance proved challenging. In the end a routine was written which optimized the lens for every possible combination of two aspheric surfaces, with some constraints on the maximum fringe density, so that the aspheres could be manufactured. The results are shown in Table 1, including the choice made by CODEV[3] Asphere Expert. Asphere Expert gave r.ms. spot sizes 25 percent larger than the search solution and the aspherics are difficult to fabricate with surface slopes up to 5 times higher than the sear results. These results and the lens and sequence files were sent to SYNOPSYS for analysis but they could not provide an explanation. Tools like Asphere Expert are convenient to use and probably provide an optimum solution for most designs; however, for a design like this where the aspheric correction is large it seems necessary to do a manual search.

For this design, fortunately Godard Space Flight Center provided us with measurement data for our glasses at the cryogenic temperatures from their CHARMS[4] facility.

Table 1 Asphere Improvements to Error Function

Aspheric Surfaces	RMS Error Value	QSL1 fringe density	QSL2 fringe density
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

In the flight design, the two negative lenses provide a correction of one third of the field curvature, with the field flattening lens taking care of the rest. The positive aspheric lens in front of the final lens helps with the correction of the transverse chromatic aberrations.

2.3 Tolerances

The fabrication and assembly tolerances are given Table 2. Tighter tolerances are used for refractive index and Abbe number, because the lens is recalculated based on the actual glass melt indices. These tolerances have proven reasonable for fabrication and the lens that has been assembled. The compensators used are decentration and spacing of the first lens together with refocus of the detector.

Table 2 Lens Tolerance Table

Lens	Sur.	Fringes (power)	Fringes (irregularity)	dN	dV (Abbe)	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

2.4 Ghost Images

A paraxial ghost image search was performed to check for ghost images created by the by any two reflections within the lens including the back reflection from the detector. The two paths that were of most concern are shown in Figure 3.

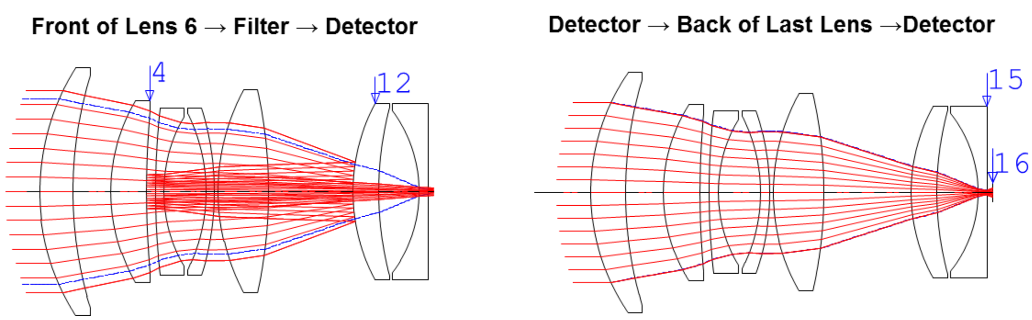


Figure 3 Principal Ghost Image Paths

The first path was the reflection from the CCD onto the final plano surface of the field lens and then back onto the CCD. Fortunately due to the defocus of this image, its intensity is less than 10^{-8} of the primary image. The second path was less predictable. This was a bounce of the first surface of the sixth lens, which is back reflected from the filter coating to form a defocused image on the detector. Again due to transmittance path losses and the focus at the image the intensity is less than 10^{-8} of the primary image, which meets the requirements.

3. LENS BARREL ASSEMBLY

The lens assembly in the barrel is shown in Figure 4, with the detector assembly mounted at the end of the lens. The lens barrel is from aluminum 6061, with the lens elements mounted using silicone RTV pads to internal aluminum bezels. These bezels have shims beneath them for adjustment of the lens positions during the assembly and alignment.

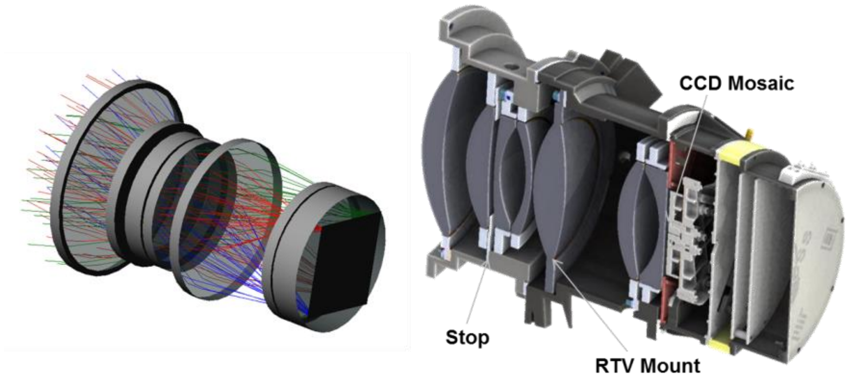


Figure 4 Lens Assembly

The silicone pad thicknesses are sized to ensure that the lens can operate at -75°C without lenses being over stressed by the aluminum barrel, and their bonding areas are determined by the shake loads. The engineering unit was tested and met the thermal and shake requirements.

4. STRAY LIGHT

Due to the nature of the TESS mission and the very high SNR required to detect transients, stray light was a major concern during the design phase of the optical assembly. Researchers at the MIT Kavli Institute performed a complete orbital analysis of the TESS mission in order to determine relative angles and distances between the spacecraft and the Earth and Moon. From this information, the total Earth- and Moon-shine incident on the CCD can be estimated. Combining this with the detection threshold of 100 counts/s/pixel, MIT derived the stray light suppression required to collect science data as 10^{-7}. The goal of the stray light design is to maximize the number of orbital cases where this condition is met.

The design space for the baffle was limited by both the optical design and the spacecraft geometry. While the lack of an intermediate image plane prevented the use of a field stop, an internal baffle in the large air gap between lenses 5 and 6 was originally considered. However, the size of the full field beam at that point was too large for a baffle to produce significant reduction in stray light without vignetting. In the end it was removed in favor of reduced SWaP. Secondly, the height of the thermal shield on the spacecraft served as a strict keep out zone for the baffles, limiting their length. Based on the available geometry, a sugar scoop baffle design with a rectangular aperture was selected.

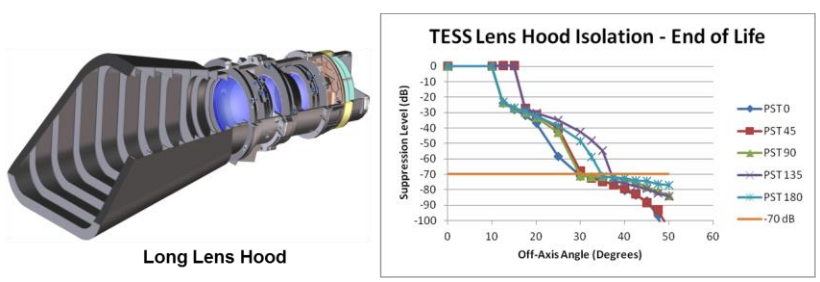


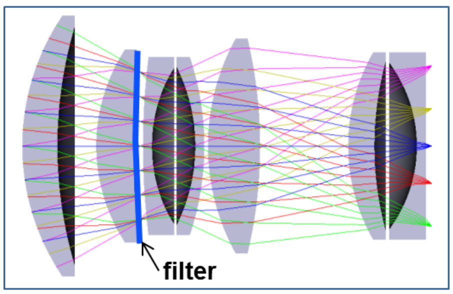
Figure 5 Stray Light

The point source transmittance (PST) of the camera was modeled in FRED to analyze system performance, using end of life on-orbit contamination estimates defined by the IEST-STD-CC-1246D standard. Exposed surfaces—the front of the first lens and the stray light baffle—were assumed to be 500B, while optics sealed within the lens barrel were assumed 250A. The TESS system contains four cameras, two of which are pointed at 36° to the spacecraft +Z direction and two at 12°. This results in two baffle designs, where the 12° short hood (SH) is a truncated version of the 36° long hood (LH). Both baffles have one-plane symmetry, so PST curves were generated at 5 azimuth angles to capture the entire space. The resulting curves are shown in figure 1.

With the baffle length and size determined by the keep out zone and field of view, vanes were added to prevent single bounce reflection from illuminating the first lens. However, this geometry means the first lens is still directly illuminated out to angles of incidence of 30-40°, depending on camera orientation. The stray light analysis shows that beyond this angle, the 10-7 suppression requirement is reached. Because the payload in its orbit tends to point away from both the Earth and Sun, this is sufficient to satisfy >90% of all orbital cases.

5. COATINGS

All 14 of the optical surfaces are coated to increase transmittance in the 600nm to 1000nm wavelength region. There is a desire to block energy below 600nm from entering the system to enhance the signal to noise ratio of the camera system. Generally speaking, the seven elements are coated with AR coatings optimized over that wavelength range and over the angles of incidence associated with each surface.



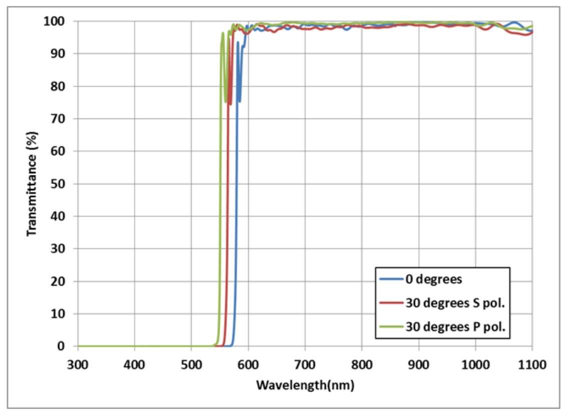


Figure 6 Filter Transmittance

However, in order to block energy at wavelengths below 600 nm, there would traditionally be a window element out in front of the lens assembly, and that window would be coated with a wavelength filter coating such as a long pass filter. The TESS design team's approach was to place the filter coating on one of the lenses already within the optical design, thereby having one less element and decreasing the size and weight of the camera system. Placing this coating on a relatively flat surface with minimal curvature was desirable to reduce challenges associated with coating thickness non-uniformity. The second surface of Lens 2 was chosen as the best location for the filter coating. Over a fairly broad angular range (0 to > 30°) the coated optic must provide high blocking via reflectance at wavelengths less than 530 nm and high transmittance between 600 nm and 1 micron. Reflectance is the preferred method of blocking in order to help reduce thermal gradients caused by solar absorbance. The desired coating would have low intrinsic stress and would ideally be deposited at low temperatures to reduce the stresses caused by mismatches in thermal expansion coefficients of the substrate and the coating materials. It was also desirable to keep the total thickness of the coating low, as bending (sag) goes as the stress of the coating times the coating thickness. The coating materials must also be resistant to low levels of radiation. Figure 1 should the spectral response of the TESS Lens 2 side two coating for normal incidence and for a 30° angle of incidence for both horizontal and vertical polarization states.

6. CONCLUSION

The hybrid Petzval design presented here, with no vignetting, proved to have the best light gathering for the given volume and weight constraints. The two aspheric surfaces provided a large amount of correction, improving the r.m.s. spot sizes by 60% compared with the non-aspheric design. An internal long wavelength pass filter coating successfully replaced an external filter and has been fabricated to meet the requirements. Stray light rejection specifications were met through the design of the lens hood baffle design. Currently, the risk reduction unit of the flight camera lens has been fabricated and assembled, with initial results at room temperature matching performance predictions.

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REFERENCES

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[2] http://tess.gsfc.nasa.gov/

[3] CODEV is an optical design program from SYNOPSYS

[4] http://itpo.gsfc.nasa.gov/wp-content/uploads/goddard-CHARMS.pdf