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Optical Design of the LSST Camera

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ABSTRACT

The Large Synoptic Survey Telescope (LSST) uses a novel, three-mirror, modified Paul-Baker design, with an 8.4-meter primary mirror, a 3.4-m secondary, and a 5.0-m tertiary feeding a camera system that includes a set of broad-band filters and refractive corrector lenses to produce a flat focal plane with a field of view of 9.6 square degrees. Optical design of the camera lenses and filters is integrated with optical design of telescope mirrors to optimize performance, resulting in excellent image quality over the entire field from ultra-violet to near infra-red wavelengths. The LSST camera optics design consists of three refractive lenses with clear aperture diameters of 1.55 m, 1.10 m and 0.69 m and six interchangeable, broad-band, filters with clear aperture diameters of 0.75 m. We describe the methodology for fabricating, coating, mounting and testing these lenses and filters, and we present the results of detailed tolerance analyses, demonstrating that the camera optics will perform to the specifications required to meet their performance goals.

Keywords: Large optics, optics fabrication, optics metrology, optics coating, optics mounting

1. INTRODUCTION

1.1. LSST Optical Design

The current baseline optical design[2] for the LSST is a modified Paul-Baker three-mirror telescope that includes an 8.4-meter primary mirror (M1) coplanar with a 5.0-m tertiary mirror (M3) [1, 2]. After a first reflection on M1, the optical beam converges on the 3.4-m convex secondary mirror (M2). From M2, the reflected beam diverges toward M3, and is then focused toward the camera located in front of M2 on the optical axis (Figure 1). The current design employs three aspheric mirrors. The three-mirror telescope system delivers, without the camera corrector optics, a spherical wavefront on axis that will greatly help in initial assembly and alignment.

The baseline LSST camera optics design[2] consists of three refractive lenses with clear aperture diameters of 1.55 m (L1), 1.10 m (L2) and 0.69 m (L3) and six interchangeable, broad-band, filters with clear aperture diameters of 0.75 m, which provide spectral coverage from the UV to near IR [3, 4]. Two of the refractive elements in the camera have aspheric surfaces.

The necessity for the refractive optics in the camera comes from two sources. First, L3 is required as a window and vacuum barrier for the dewar containing the detector array. Second, the filters are required for the science program. L1 and L2 are then required to minimize chromatic effect of L3 and filters. Integrated design of mirrors and lenses improves design. For example, adding asphericity to L2 helps to reduce asphericity on secondary mirror.

This optical design delivers a flat focal plane with a circular field of view (FOV) of 3.5-degree in diameter and an image spot size about 0.2 arcsec FWHM for 6 spectral bands covering a wide wavelength range (from 350 to 1060nm). In addition, the LSST is a very fast telescope (f/1.234) with a plate scale of 50microns/arcsec and a detector diameter of 0.64m. The 10-micron pixel size detectors match the superb performance in image quality.

The wide range of wavelengths specified for the LSST requires some adjustments for operating at different spectral bands in order to preserve the high image quality. First, filters with different pass bands need to be inserted to change

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[2] Baseline design as of the LSST Conceptual Design Review, held in September 2007.

the spectral range. Each filter has a unique central thickness to compensate for chromatic difference in aberrations. Thicknesses range from 26.2 mm in the u band to 13.5 mm in the y band. Furthermore, some filters have a slightly different second radius of curvature to further correct for chromatic aberration. The y-band filter and the z-band filter are equi-meniscus, with radii of curvature of 5624 mm convex and concave. The second concave radius of other filters varies from 5513 mm in the u band to 5612 in the i band. Second, the entire camera assembly is axially refocused with each filter change.

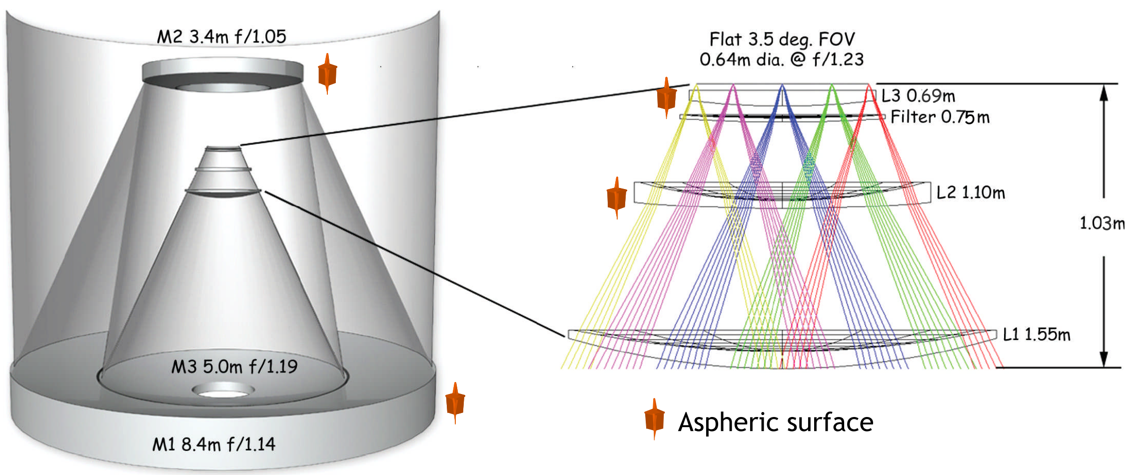

Figure 1. LSST optical design includes 3 large mirrors, 3 large lenses and a set of 6 large transmission filters.

Table 1. LSST camera optical element design parameters.

	Lenses			Filters					
Clear Aperture Dims	**L1**	**L2**	**L3**	**u**	**g**	**r**	**i**	**z**	**y**
Surface 1 vertex to FPA	1031.950	537.080	88.500	149.500	149.500	149.500	149.500	149.500	149.500
Surface 2 vertex to FPA	949.720	507.080	28.500	123.300	128.360	131.700	133.800	135.300	136.000
Center thick.	82.230	30.000	60.000	26.200	21.140	17.800	15.700	14.200	13.500
Clear aperture rad.	775.000	551.000	346.000	375.000	375.000	375.000	375.000	375.000	375.000
Surface 1 spherical rad.	2824.000	1.000E+15	3169.000	5624.000	5624.000	5624.000	5624.000	5624.000	5624.000
Surface 2 spherical rad.	-5021.000	-2529.000	-13360.000	-5513.000	-5564.000	-5594.000	-5612.000	-5624.000	-5624.000
Sagitta of Surface 1	108.424	0.000	18.945	12.516	12.516	12.516	12.516	12.516	12.516
Sagitta of Surface 2	-60.172	-60.754	-4.481	-12.769	-12.651	-12.583	-12.543	-12.516	-12.516
Thick. at Clr Aperture	33.977	90.754	45.536	26.453	21.275	17.867	15.727	14.200	13.500

*All dimensions in mm except as noted "Approx Physical Dims" are for reference only

A schematic of the LSST camera optics, including the rays bounding the light distribution incident on the central and peripheral field points, is also shown in Figure 1. The current design for the largest lens, L1, with a clear aperture of 1.55 m, calls for an edge thickness of ~3.4 cm and a center thickness of ~8.2 cm. The middle sized lens, L2, with a clear aperture of 1.10 m, has an edge thickness of ~9.1 and a central thickness of 3.0 cm. The space between L2 and the filters is 36 cm, which provides adequate space to accommodate the filter interchange. The smallest lens, L3, with a clear aperture of 0.69 m, is also the vacuum barrier for the cryostat containing the detector array. There is 2.85 cm between the inner surface of L3 and the focal plane. The central thickness is specified in order to provide a significant safety margin for potential fracture of L3 due to the pressure differential. Empirical data shows that a thickness ratio of ~12 is adequate to provide this safety margin, which yields a thickness of ~6 cm for this lens. The filters are designed to be fabricated using multi-layer dielectric interference coatings deposited on glass substrates. The baseline design has the first surface of the filters concentric about the chief ray in order to keep the angles of the light rays passing through the filters as uniform as possible over the entire range of field positions. The central thickness and the curvature of the second surface are optimized for image quality. The minimum center thickness is 1.35 cm, for the y-band filter. Detailed parameters for the camera optics are given in Table 1.

Figure 2 shows a schematic view of the assembled camera. Five filters are resident in the camera; the active filter can be changed in less than 90 seconds. One of the six filters will be stored at off-camera at any given time and can be exchanged with any of the five on-camera filters during a daytime servicing operation.

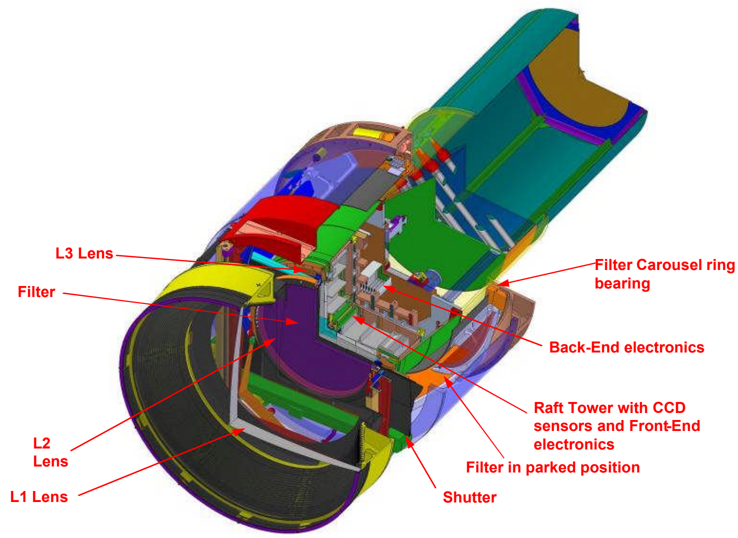

Figure 2. Baseline LSST camera design schematic.

2. CAMERA OPTICS DESIGN CONSIDERATIONS

The following issues have been considered in the design of the LSST camera optics.

1. What type(s) of glass are needed for the camera optics?
2. Can the required glass be obtained?
3. Can these large, thin, transmissive optics be fabricated?
   • L1 will be one of the largest lenses ever made
4. How will the optics be mounted?
5. How will we know if the optics, as fabricated, meet the required performance specifications?
6. What coatings are required for the optics, especially the filters?
7. Can the required coatings be fabricated?
8. What is the plan for future work on camera optics?

These issues are addressed in the subsequent sections.

2.1. Camera optics glass

The current camera optics design can meet all design requirements using fused silica substrates. We have identified a qualified vendor, Corning, for the required fused silica glass. The Corning manufacturing process for fused silica can produce glass of the required size and quality. Corning estimates of cost and schedule to produce the required fused silica glass have been used as input for LSST camera optics schedule and budget

2.2. Camera optics fabrication

The main challenge in the production of the LSST camera optics is the fabrication of large, thin lenses and filter substrates. In order to assess this risk, a team of LSST representatives has visited multiple commercial vendors, supplied these vendors with documentation on the baseline optics designs as described above, and initiated discussions with the vendors concerning the specifications, cost, schedule and technical risk of fabricating these optics. The preliminary feedback from all vendors indicates that commercial costs and schedules are consistent with LSST budgetary and program planning estimates. Furthermore, the responses from multiple commercial vendors demonstrate that a substantial industrial base exists for fabricating large, thin optics.

2.3. Camera optics mounts

The optic mounts provide the interface between L1, L2, L3 and filter optics and the structures that support them. These interfaces may include adjustment capability for alignment purposes. In some cases, the vendors may be asked to supply the optics already installed and qualified in the mounts. Details of the optical mounts are found in a companion paper [5].

2.4. Null testing

A key aspect of the corrective camera optics that enables fabrication using industry standard techniques is that they have relatively simple null tests that are designed simultaneously with the full LSST. An eleven-configuration telescope design file incorporates these three null tests along with configurations for each of the six filters and two additional alignment null tests. The lens null tests, using spherical mirrors for L1 (radius ~ 5.0 m) and L2 (radius ~ 3.1 m) and a plano mirror for L3, are described below. All null tests use a retroreflecting mirror to test the lens in double pass transmission. A perfect point source is reimaged onto itself with a wavefront error less than 1/20 wave at 633 nm. The null test design influences the final optics prescription. L1 is a spherical lens. Adding an asphere to L2 simplifies testing and helps to reduce asphericity on the secondary mirror Adding a weak asphere on L3 provides an easy test for L3. Null tests are performed with optics mounted in the same manner as during operation in the camera. These null tests also serve as the quality assurance that the optics meet their specifications as fabricated. Tight control, on the order of 0.1%, on the fabricated focal lengths of these lenses is required to maintain a sufficiently flat focal plane.

2.4.1 L_1 fabrication and testing

The baseline parameters for L_1 are given in the following table.

R_2	Axial thickness	R_1	Test wavelength	Comments
-5021 mm (cc)	82.23 mm	-2824 mm (cx)	632.8 nm	Surfaces are spherical

The fabrication procedure, employing the null test, for L_1 is as follows. The null test for L_1 is summarized schematically in Figure 3.

1. The second spherical radius (R2 = 5021 mm concave) is generated and tested in an interferometer.
2. The interferometer is placed at the center of a spherical reference mirror, R ~ 5000 mm with a diameter of 1.7 m. The actual radius of curvature is unimportant.
3. Lens L_1 is placed 4769.26 mm from the interferometer focus. The interferometer and the reference mirror are not moved during this process.
4. The interferometer is shifted 1257.26 mm towards the lens. The two positions of interferometer focus define the optical axis. The convex surface of L_1 is figured to generate a perfect null test in double-pass. The wedge angle has been reduced to zero, either by figuring or by laterally centering the lens in the optical test setup. In practice, a slight aspheric surface will be generated on the convex surface to overcome effects of index variations, asymmetries on the concave surface and gravity effects.

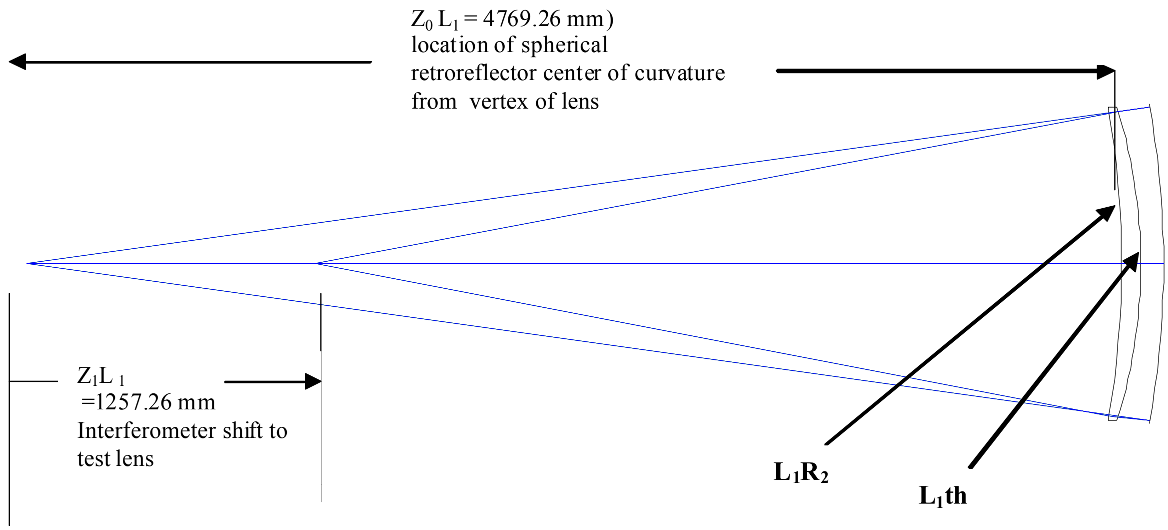

Figure 3. Schematic of null test for L_1.

2.4.2 L_2 fabrication and testing:

The fabrication procedure, employing the null test, for L_2 is as follows. The null test for L_2 is summarized schematically in Figure 4.

1. The first step in the fabrication of L_2 is to make the flat first surface.
2. The interferometer is placed at the center of a spherical reference mirror, radius of curvature ~ 2500 mm with a diameter of 1150 mm.
3. Lens L_2 is positioned 2264.80 mm from the focal point of the interferometer. The interferometer and the reference mirror are fixed.
4. The interferometer is moved 1596.20 mm away from its original position. This setup will generate a perfect null test for the required L_2 lens.

The null test setup is shown below for the nominal L_2 prescription for a 30 mm thick lens with a plano second surface. The location of the interferometer point source and the center of curvature for the spherical retroreflecting mirror with respect to the lens vertex is shown below. The concave surface is figured to produce a perfect wavefront.

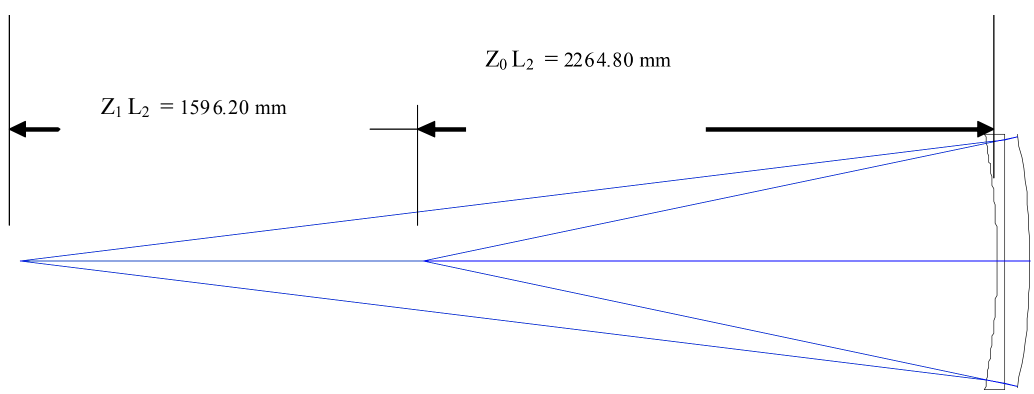

Figure 4. Schematic of null test for L_2.

2.4.3 L_3 fabrication and testing:

The fabrication procedure, employing the null test, for L_3 is as follows. The null test for L_3 is summarized schematically in Figure 5.

1. The second spherical radius (R2 = 13360 mm concave) is generated and tested in an interferometer.
2. The interferometer is placed ~ 6000 mm from a flat mirror with a diameter of 740 mm.
3. Lens L_3 is positioned 5577.74 mm from the focal point of the interferometer. The interferometer and the reference mirror are fixed. This setup will generate a perfect null test for the required L_3 lens.

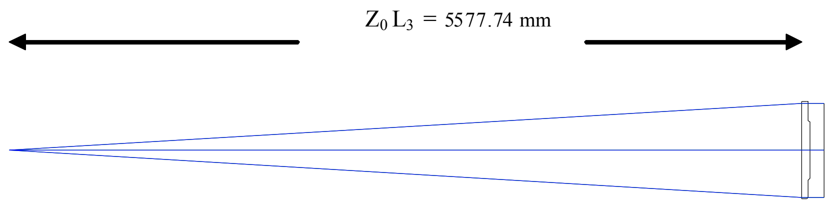

Figure 5. Schematic of null test for L_3.

2.4.4 Filter fabrication and testing:

The fabrication procedure for the filters is similar to the fabrication procedure for L_1, using a similar null test methodology.

2.5. Coatings

Once the lenses and filter substrates are fabricated, they must be coated. For the lenses, the coating is a relatively straightforward broad-band anti-reflection coating to minimize the optical loss through the system and the brightness of ghost images. The main challenge here is the size of the largest lenses. In the case of the filters, the coating is a relatively sophisticated multi-layer interference coating that is designed to transmit only light with wavelengths in a specified band, and to reject light at other wavelengths with a specified fidelity. The main challenge here is to deposit uniform coatings with the desired characteristics on the large, curved substrates.

In order to assess industrial capabilities for supplying the coatings required for the LSST optics, LSST project representatives have visited and/or initiated discussions with several commercial vendors. The preliminary feedback from vendors indicates that there are no unsolvable technical challenges, and at least two U.S. vendors have previously coated optics of similar size with similarly complex coatings. Other vendors are also interested in extending their current capabilities to enable coating of optics of the required sizes. In order to qualify vendors to produce these coatings with the desired characteristics, an RFP is being issued for a coating design study and witness sample fabrication demonstration.

The optical coating demonstrations will be performed using witness samples that are arranged in the coating chamber in such a way that they sample a representative portion of the area of the full-size LSST camera optics. A nominal example of such an arrangement is shown in Figure 6.

2.5.1. Filter characteristics

The current LSST filter complement (u, g, r, i, z, y) is modeled after the Sloan digital Sky Survey (SDSS) system because it has demonstrated success in a wide variety of applications such as photometric redshifts of galaxies, separation of stellar populations, and photometric selection of quasars.

The extension of the SDSS system to longer wavelengths (y-band) is mandated by the increased effective redshift range achievable with the LSST due to deeper imaging. The optimal wavelength range for the y-band is still under investigation. The addition of a u-band will improve the robustness of photometric redshifts of galaxies, stellar population separation, and quasar color selection, and will provide significant additional sensitivity to star formation histories of detected galaxies.

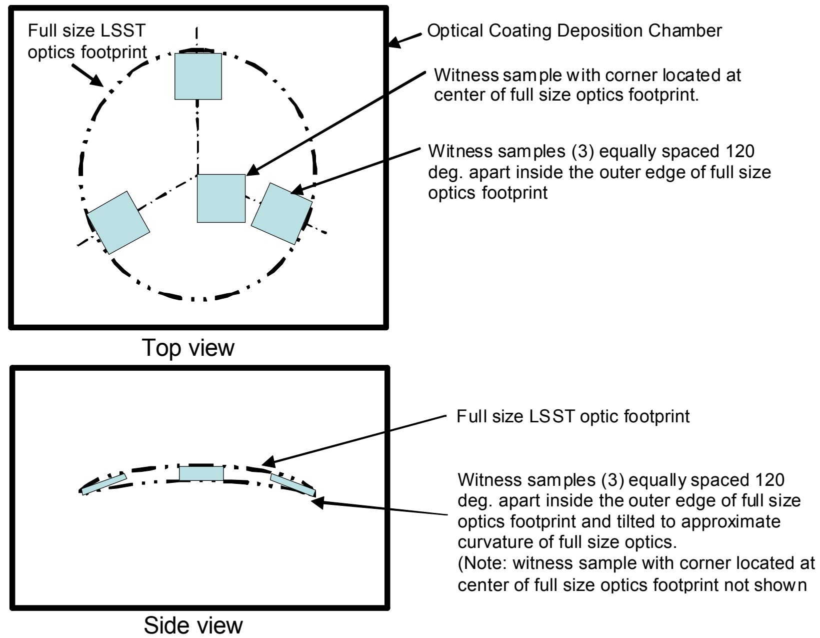

Figure 6. Schematic arrangement of LSST camera optics witness samples in coating chamber.

The current LSST baseline design has a goal of 1% relative photometry. One implication of this is that it is desirable for the filter characteristics to maintain ~<1% variation in transmission over independent ~10 cm diameter areas (the size of the beam corresponding to a given field point at the filters). In addition, the filter should not transmit more than 0.01% of the flux in any 10 nm interval at any wavelength beyond one FWHM of the central wavelength, and the integrated transmission at all wavelengths beyond one FWHM from the central wavelength (and between 300 nm and 1200 nm) should be below 0.1%. The filter set wavelength design parameters are shown below, and the approximate FWHM transmission points for each filter are shown in Table 2.

g – aligned with the Balmer break @400nm
r – matches SDSS
i – red side short of sky emission @826
z – red side stop before H_2O bands-starts ~930nm
y – red cutoff before detector cutoff

Table 2. Baseline LSST filter band-pass FWHM points in nm

Filter	Λ_1	λ_2
u	330	400
g	402	552
r	552	691
i	691	818
z	818	922
y	970	1060

2.5.2. Filter models

Filter coating designs have been studied in sufficient detail to verify feasibility of meeting requirements. A plot of nominal filter bandpass characteristics is shown in Figure 7. These filter curves were generated using detailed thin film coating design software for the purpose of verifying feasibility of the coatings. However, the actual coating designs are expected to be produced by the coating vendor, and an RFP for a detailed coating design study is being issued by the LSST project.

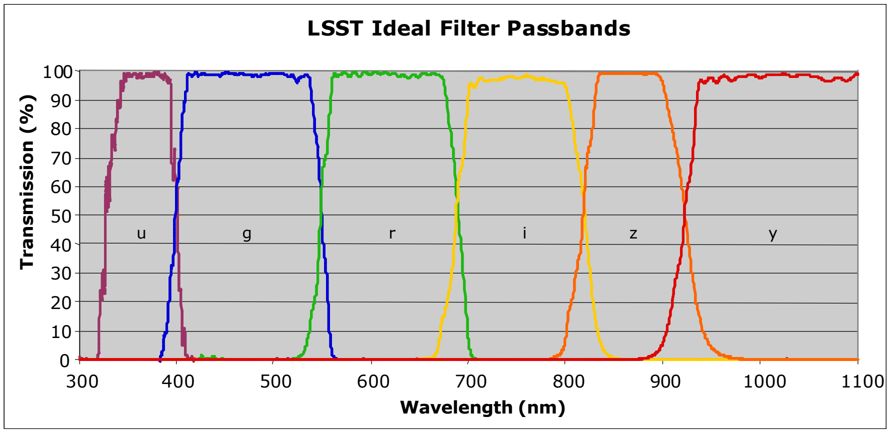

Figure 7. Plot of nominal LSST filter transmission curves.

2.6. Error budgets and tolerances

As part of the system engineering process for the LSST [6], detailed error budgets allocations have been developed for the camera optics. These error budget allocations are expressed in terms of the increase in diffraction image full-width at half maximum (FWHM). The error budget allocations for the camera optics are as follows:

Fabrication – 0.05 arcsec FWHM
Assembly – 0.03 arcsec FWHM
Flexure – 0.03 arcsec FWHM

In order to assess whether the error budget allocation are met by the baseline camera optics design, extensive tolerance analyses have been performed. These analyses include:

1. Optical effect of rigid body motions
2. Rigid body motions due flexure
3. Optics surface deformations due to flexure
4. Optical effect of optics surface deformations
5. Optical effect of inhomogeneity in glass index of refraction
6. Optical effect of fabrication errors
7. Optical effect of assembly errors

The tolerance analyses all indicate that error budget allocations for the camera optics are achievable.

2.7. Future Work

A complete set of tolerance specifications is being compiled based on the tolerance analyses

3. CONCUSION

We have developed a baseline design of the LSST camera optics. We have discussed optics fabrication issues with vendors and found that a substantial industrial base exists for the optics fabrication. We have also discussed the optics coating issues with vendors and found that an adequate industrial base exists for optics coating. We have developed a project execution plan, including budget and schedule for completion of the LSST camera optics. The next steps in this plan call for the completion of the tolerance specifications for the camera optics, and the completion of the filter coating design and demonstration by the coating vendor(s).

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