Design of a high speed UV-transmitting camera for the Keck LRIS

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ABSTRACT

Preliminary optical designs have been developed for the blue channel of the Low Resolution Imaging Spectrograph (LRIS) for the Keck Ten Meter Telescope. This paper discusses the configuration-driving factors and performance of the designs, as well as coating and fabrication issues.

1. BACKGROUND

The Low Resolution Imaging Spectrograph (LRIS) for the Keck Ten Meter Telescope was from the beginning intended to be a two-channel instrument (Miller, 1987; Oke, et al., 1994a, 1994b), with both "red band" and "blue band" dispersing elements (and/or filters), camera optics, and CCD detectors operating simultaneously. A dichroic beamsplitter positioned in the parallel beam following the collimating mirror would separate "red" from "blue" wavelengths. The red channel has been built and deployed, and operates over the wavelength range from 380 nm to over 1000 nm. Funds and time available initially were sufficient only for an LRIS instrument containing the red channel. The blue band camera, yet to be built, must operate over the wavelength range from 310 nm to 550 nm. In practice the choice of transition wavelength will determine the long wavelength extreme sent to the blue side, and the short wavelength extreme on the red side.

This paper describes the results of our re-investigation of optical design alternatives for the blue band camera for LRIS. After considering reflective, catadioptric, and refractive configurations, we ruled out the reflective and catadioptric designs due to their large obscuration-induced light loss. We identified several all-refractive lens designs combining high throughput (being antireflection coated and cemented, and free from obscuration), low aberrations, and low distortion. The 8 inch element diameters make materials selection a critical issue for this design task.

The specifications for these designs are summarized in Table 1. We have established the feasibility of meeting these performance specifications.

2. MODES OF OPERATION

The LRIS instrument concept requires that both the red and blue channels operate in two modes, the imaging mode and the spectrograph mode. In the imaging mode, a 6 by 8 arcminute object field is re-imaged by the LRIS collimator and cameras onto the CCD detectors, with no dispersion of the wavelengths. In the spectrograph mode, a slit mask is introduced in the telescope focal plane; a red channel reflection grating and a blue-channel "grism" (prism with attached grating) are inserted into the respective collimated

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TABLE 1
SPECIFICATIONS VERSUS PREDICTED PERFORMANCE
LRIS BLUE BAND CAMERA PRELIMINARY DESIGNS

Parameter	Specification	Predicted Performance: 11 elements (CaF2, Silica, Ultran30)	Predicted Performance: 9 elements (CaF2, NaCl, Fused silica)
1. Spectral band (nm)	310-550	S (same as spec)	S
2. Entrance pupil diameter (mm)	129.54	S	S
3. Image size (mm)	49.15 square	S	S
4. Lens focal length (mm)	254	S	S
5. Distance, pupil to first lens surface (mm)	254	S	S
6. Diameter of circle enclosing 80% of PSF (micron)			
i. Imaging Mode	<30	22	26
ii. Spectograph mode	<30	28	27
7. Line bowing in imaging mode	2.4 micron at detector (0.025 arcsec in object space) deviation from straight line	0.8 micron 0.008 arcsec	1.5 micron 0.016 arcsec
8. Transmission (%) at individual wavelengths across band	Maximize	69-88	69-89

beams, following the dichroic, and the dispersed light is imaged by the cameras onto the CCD detectors. For optical design purposes in the spectrograph mode, the prism wedge angle of the blue-channel grism, and its grating frequency, were chosen to meet the two criteria of i) rays at 310 nm and 550 nm separated by the full width of the CCD, and ii) the diffracted angles of the 310 nm ray and 550 nm ray are equal and opposite, relative to the optical axis of the camera lens, so that the extremes of the spectral band fall on the edges of the CCD.

3. MATERIALS SELECTION

A refractive design in the 310-550 nm spectral band, used under the required operating conditions, is challenging due to the relative scarcity of materials that will transmit over the band, and the difficulty of controlling chromatic aberration using the few available materials. Primary and secondary chromatic aberration, and variation of the monochromatic aberrations with wavelength, all tend to be high over this band.

Common materials appropriate for this spectral band include Fused Silica, Calcium Fluoride (CaF2), and Sodium Chloride (NaCl). Within the last several years Schott Glass Technologies has introduced the Ultran series of glasses, with good UV transmission. Of these materials, Fused Silica and CaF2 are the most useful because of their availability in the required diameters (up to 8 inches) and their relatively good environmental stability. NaCl has higher dispersion which aids color correction when used with the other materials, but is water soluble. Thus NaCl is most safely used in a cemented triplet, sandwiched between materials with higher stability. Schott Ultran30 also has good optical properties (especially its refractive index which is higher than CaF2 and Fused Silica), but it has limited applicability in this design due to the current maximum available blank thickness of about 1.5 inch. Since most elements in our preliminary designs exceeded 1.5 inches at their thickest point, Ultran30 could be used only in the smaller elements near the focal plane.

4. PRELIMINARY DESIGNS

During this study, major effort was directed toward minimizing the number of elements and air-glass interfaces in order to maximize the transmission. Two of the simplest designs, consistent with specification-compliant performance, are discussed below; their performance is summarized in Table 1. In both designs, a powered Fused Silica element was used as the detector window. To minimize aberrations and element count, aspheric surfaces were used on two elements. To minimize fabrication difficulty, the aspheric profiles were allowed to have no inflection points (1st derivative changing sign). We avoided using aspheric surfaces on CaF2 elements, also for ease of fabrication.

4.1 Design with 11 elements (Fused Silica, CaF2, Ultran30)

The first preliminary design consists of 11 elements in four components. Figure 1 shows a layout of this design. It uses 10 elements of the common UV materials Fused Silica and Calcium Fluoride, plus one element made of Schott Ultran30. The performance could have been better if more Ultran30 elements were used, since Ultran30 has favorable dispersion properties that reduce chromatic aberrations. But as discussed above, size limitations restricted its use to one of the smallest elements, nearest to the focal plane, as shown in Figure 1.

Figure 2 shows a plot of 80% encircled energy diameter of the geometric point spread function (PSF) versus field, in the imaging mode. All wavelengths are included in the PSF. The maximum diameter is 22 microns, versus the 30 micron goal. Figure 3 is a plot of distortion versus vertical field, in terms of deviation from a straight line by the image of a straight horizontal line field in object space. Distortion is within ± 0.8 microns, versus a goal of 2.4 microns (0.02 arcsec, nominally 0.1 pixel).

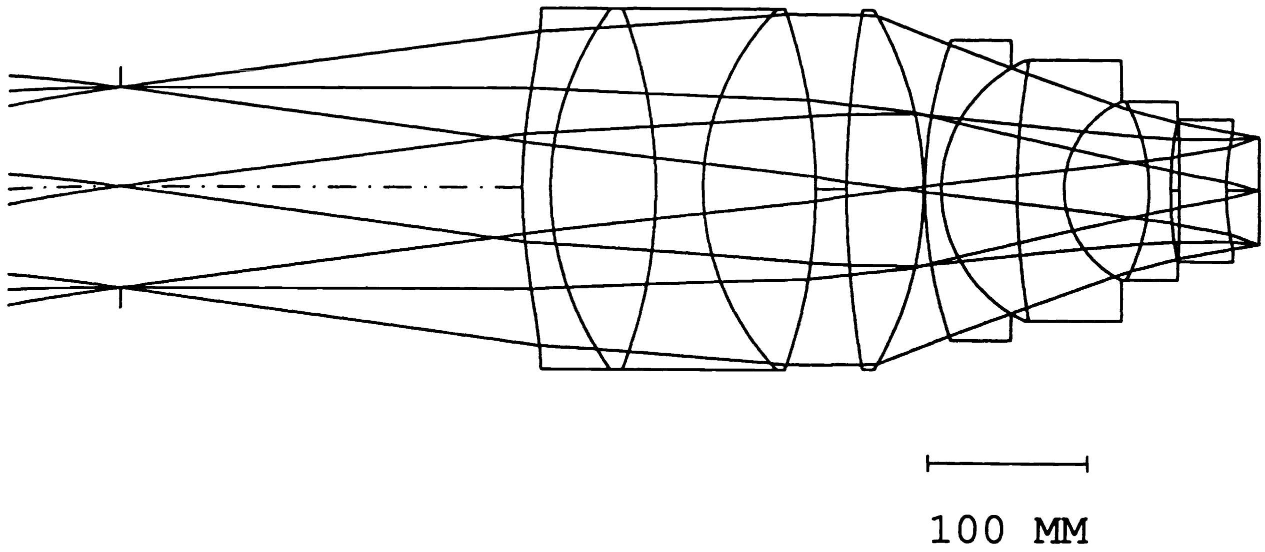

Figure 1. 11-element design, imaging mode

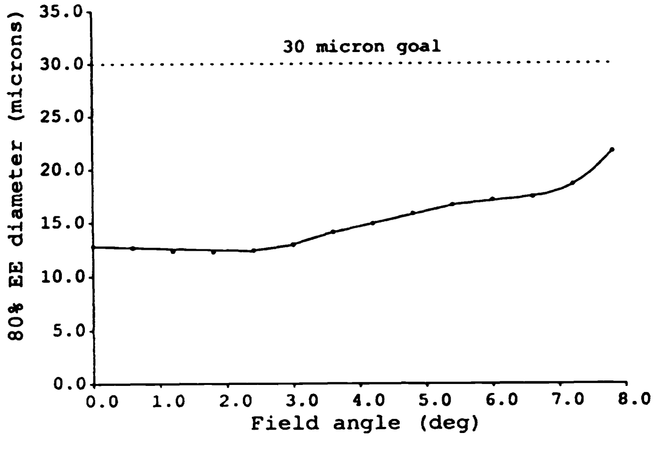

Figure 2. Encircled energy diameter vs. field, 11-element design in imaging mode.

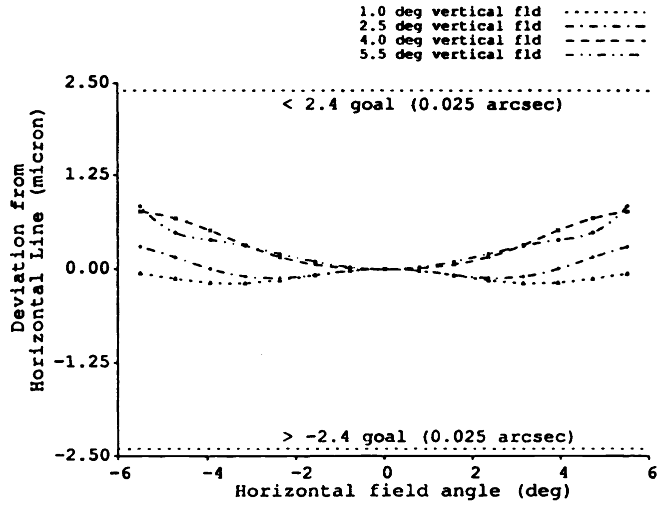

Figure 3. Line bow, 11-element design in imaging mode.

Figure 4 shows a layout of this preliminary design in its spectrograph mode, with the grism in front. Figure 5 plots the encircled energy diameter across the spectral band, at three fields of view. Diameters are under 28 microns across the field and band.

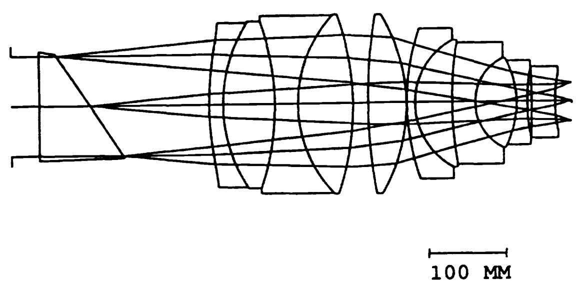

Figure 4. 11-element design in spectrograph mode

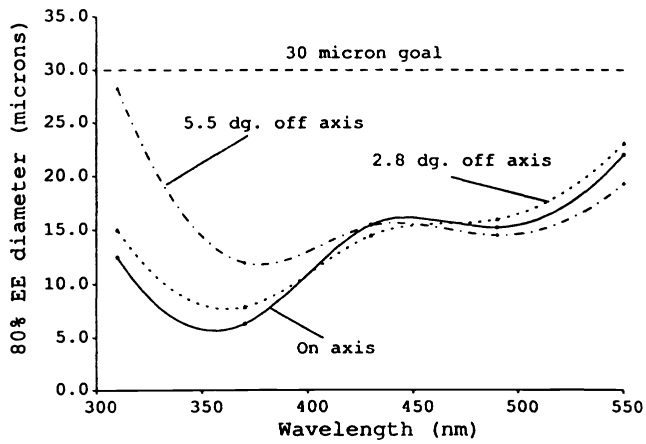

Figure 5. Encircled energy vs. wavelength, 11-element design in spectrograph mode.

<u>4.2 Design with 9 elements (Fused Silica, CaF2, NaCl)</u>

The second preliminary design consists of 9 elements in four components. See Figure 6 for a layout. The design uses 8 elements of Fused Silica and Calcium Fluoride, plus one element made of NaCl. NaCl has a dispersion roughly twice that of CaF2, Silica, and Ultran30, and hence allows much better control of chromatic aberration than a design using the same number of elements of the other three materials. The greater aberration control offered by NaCl allows the design to have two fewer elements than the Silica/CaF2/Ultran30 design, while achieving similar (and specification-compliant) performance. The disadvantage of this design is that NaCl is water soluble and easily damaged. We have minimized the damage risk by sandwiching the NaCl element between two CaF2 elements. Before the final design is completed, we will decide whether the reduced complexity of the design is worth the higher risk of damage.

Figure 7 shows a plot of 80% encircled energy diameter of the PSF, versus field, in the imaging mode. The maximum diameter is 26 microns, versus 30 micron goal. Figure 8 is a plot of line bow versus vertical field. Distortion is within ± 1.5 microns, versus a goal of 2.4 microns. Figure 9 plots the encircled energy diameter across the spectral band in the spectrograph mode, at three points along the 5.5 degree slit length.

5. CEMENTS AND ANTIREFLECTION COATINGS

One of the most important performance goals in this design is to maximize transmission. One key factor in improving transmission is minimizing reflection losses by reducing the number of air-glass interfaces. This is done by cementing elements with an appropriate bonding material. The other factor in maximizing transmission is to apply high-efficiency anti-reflection coatings to the remaining air-glass interfaces.

Both preliminary designs use several (5-7) cemented interfaces. The elements must be bonded at the interface by optical cements or flexible couplants. Most cements and couplants, usually used in the visible wavelength band, are highly absorbing in the ultraviolet. During this study, we accumulated information on several cements and couplants. We have identified candidate materials that show promise of providing high transmission; they will be reviewed and tested before the final design phase is initiated.

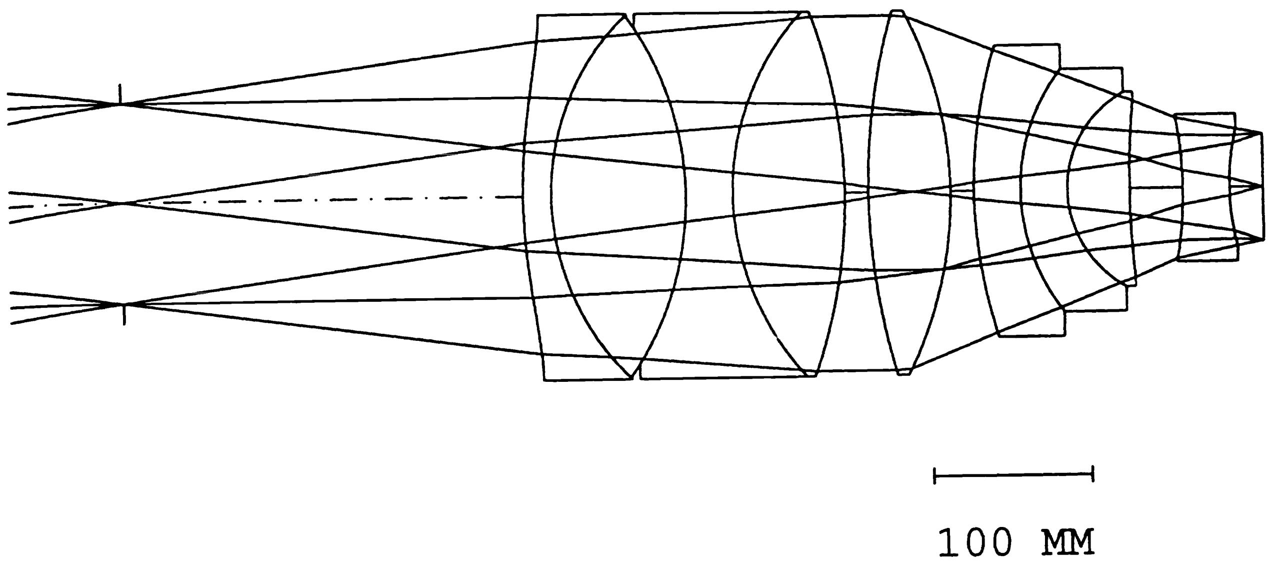

Figure 6. 9-element design, imaging mode

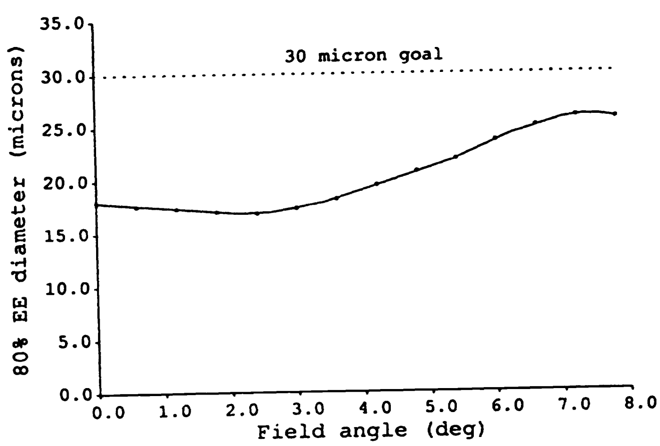

Figure 7. Encircled energy diameter vs. field, 9-element design in imaging mode.

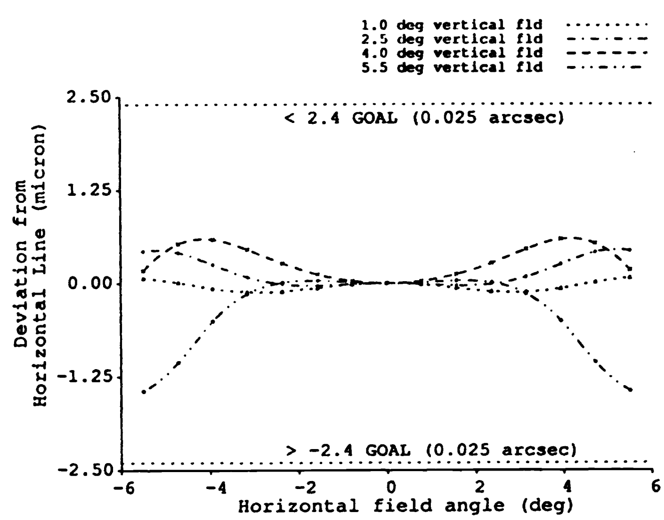

Figure 8. Line bow, 9 element design in imaging mode.

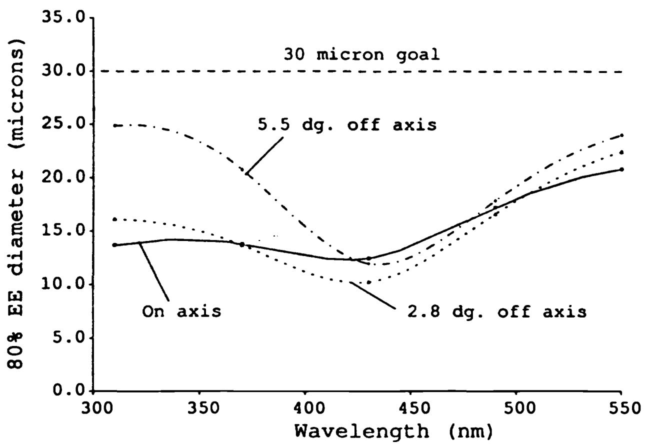

Figure 9. Encircled energy diameter vs wavelength, 9-element design in spectrograph mode.

An antireflection coating of the most common type, a single quarter-wave layer of Magnesium Fluoride, provides about 98% surface transmission over the band. When modeled on all air-glass interfaces of the preliminary designs, these coatings resulted in overall transmission ranging from 62% at 310 nm to 78-79% at longer wavelengths, with an average transmission of about 75% over the spectral band. This does not include absorption by the still-unselected and untested cement or couplant.

More complex coatings can reduce the reflection loss and improve transmission. We made a brief study of a 2-layer antireflective coating, using coating materials Magnesium Fluoride and Hafnium Dioxide, which transmit above 310 nm and above. This coating provides single surface transmission between 98% and 99.7% over most of the band. When the 2-layer coating is applied to the air-glass interfaces of the preliminary designs, the transmission ranges from 69% at 310 nm to 88% at 490 nm, with an average of 80% across the band. Figures 10 and 11 plot transmission versus wavelength for the two preliminary designs for this coating. Again, this does not include the absorption effects of the cements or couplants.

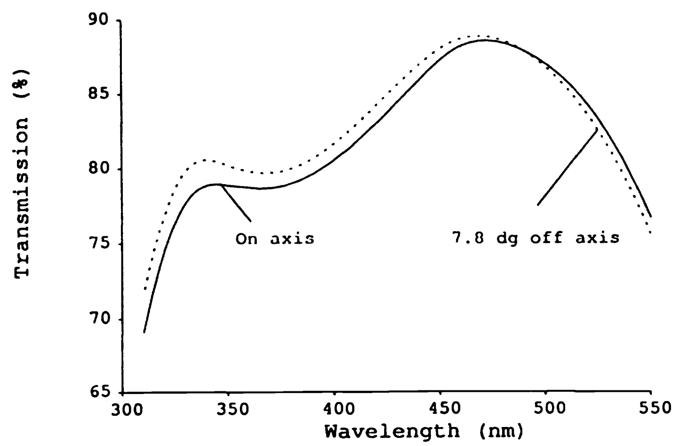

Figure 10. Spectral transmission, 11-element design with 2-layer coating.

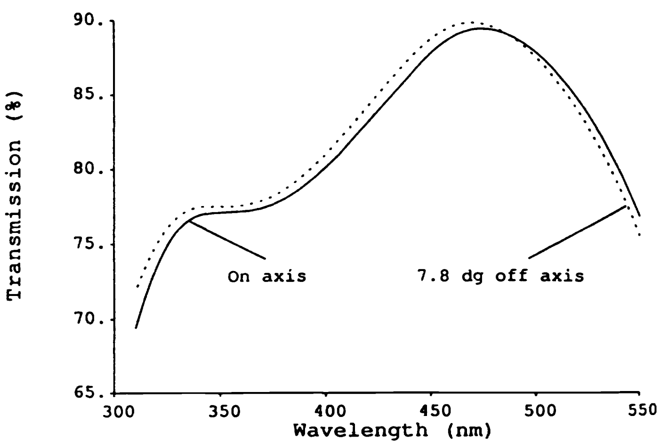

Figure 11: Spectral transmission, 9-element design with 2-layer coating.

The worst-case transmission, at 310nm, is limited not by the AR-coatings but by the internal transmission of the optical materials (71% at 310 nm), dominated by the CaF2 elements. The limitation on transmission due to bulk absorption can be clearly seen in Figure 12, which plots total transmission and bulk transmission, on axis, for the 11-element design. Higher efficiency multi-layer coatings would improve the overall throughput somewhat, although not substantially at 310 nm since internal absorption is dominant.

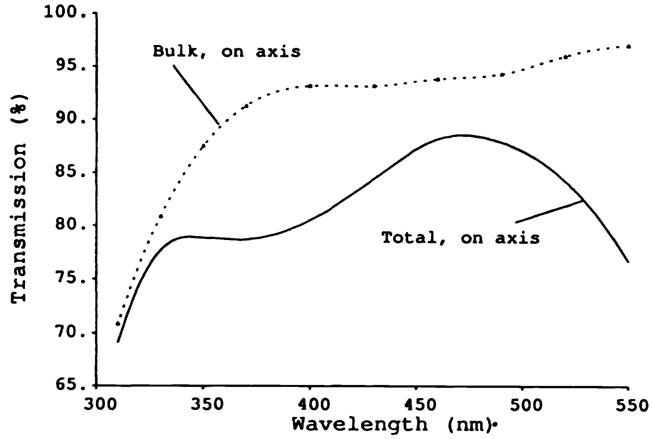

Figure 12. Bulk and total transmission of 11-element design with 2-layer coating.

6. FACTORS INFLUENCING COMPLEXITY OF THE DESIGNS

The complexity of the preliminary designs, in terms of element number and size, asphericity, and materials, is high. It is worthwhile to discuss the operating conditions that caused this complexity.

A key driver was the 310-550 nm spectral band. This restricted the feasible materials, as explained above, to those that have relatively low index (1.5 or less). A lens with exclusively low index elements can correct aberrations less efficiently than a design with higher index materials. An element with a given power has steeper surfaces with a low index material than a high index, and the steeper curvature produces higher order aberrations. This is corrected only by using aspheric surfaces, additional elements, or both.

The entrance pupil distance, one full focal length in front of the lens, increased the difficulty of controlling field aberrations. Lenses having significant fields of view typically have an entrance pupil inside the lens. In systems having an external entrance pupil, aberration control becomes increasingly difficult as the pupil-lens distance increases. In this system, the large distance required increased complexity to control aberrations.

The entrance pupil distance, in combination with the 130 mm entrance pupil diameter and 15.6 degree total field of view diameter, also resulted in large element diameters of up to 8 inches. To maintain a reasonable diameter-to-thickness ratio, the element thicknesses needed to be correspondingly large (up to 2.5 inches), increasing the glass path and reducing transmission.

In the final design phase, we will explore further tradeoffs in performance (e.g. taking advantage of the margin in the nominal spot size below the as-built goal) in order to further reduce the complexity (number of elements and/or aspheric amplitude).

7. CONCLUSION

We have developed preliminary optical designs of the blue band spectrograph camera to be used with the Keck telescope. Two of these designs are documented in this paper. They have similar performance, but differ in complexity and materials. We will next consider the relative advantages of each design, and choose the one that is the best tradeoff between performance, complexity, and fabrication difficulty. The selected design then will be completed in the final design phase.

We have investigated antireflection coatings and UV-transmitting lens cements and couplants. A 2-layer coating can provide significantly higher transmission than can a single layer coating, especially at 310 nm. Several candidate couplants have been identified. We plan to make transmission tests of the available couplant materials to see which would allow the highest transmission. The main factor limiting transmission in all preliminary designs is the use of CaF2, which was needed for good aberration correction, but which increasingly absorbs light at wavelengths below 350 nm.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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