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Design of an f/1 Camera for the HET Low-Resolution Spectrograph IR Extension*

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ABSTRACT

We present the optical design of the f/1 camera for the Hobby-Eberly Telescope Low Resolution Spectrograph Infrared Extension (LRS-J). This instrument extends the coverage of the LRS to 1300 nm by adding a fast cryogenic camera and volume holographic grisms (VPHG) to the LRS. This approach enables new science without the expense of building a complete new instrument. The camera is a catadioptric Maksutov type design, based on that of the optical LRS, that uses a HAWAII-1 1024x1024 detector. The design succeeds in imaging virtually all the light into one pixel over the HET field of view (FOV) and the wavelength range 900-1300 nm. We discuss the challenges of designing and manufacturing a fast camera for cryogenic use, and give details of the tolerance analysis.

Keywords: Telescopes: Hobby-Eberly Telescope, Astronomical instrumentation: Spectrographs, Infrared Spectrographs

1. INTRODUCTION AND PROPERTIES OF THE INSTRUMENT

From the start, the Hobby-Eberly Telescope (HET) Marcario Low Resolution Spectrograph (LRS)[1] has been designed with an extension to 1.3 microns in mind. This extension involves the substitution of the camera and detector system and grisms, but otherwise uses the rest of the LRS components, including the multi-object spectroscopy (MOS) unit. The J-band extension to the LRS (LRS-J)[2] will replace the optical camera and CCD system by a f/1.0 catadioptric camera with a HAWAII-1 array at its focus. The McDonald Observatory CCD controller is being adapted to run the HAWAII-1 array[3]. The aim of this enhancement is to provide multi-object capability at wavelengths up to 1.3 μm, in order to follow rest-frame optical features in galaxies out to redshifts z~2. The design of this camera is well advanced, and we hope to commission it in early 2003.

The design requirements are for a fast (f/1) camera capable of good image quality for both imaging and spectroscopy, that can mate with the existing LRS and fit in the very tight space envelope available on the tracker of the HET. The HET will produce images around 1.0 arcsec FWHM under the best conditions[4]. In order to optimally sample the images and still provide the largest possible wavelength coverage, the pixel scale must be quite coarse (0.4 to 0.5 arcsec per pixel), dictating a camera focal ratio of f/1, for the 9.2 m HET, and the 18.5 micron pixel size of Rockwell HAWAII-1 HgCdTe detector arrays. It is difficult to design such a fast refractive camera, but our experience with the f/1.4 catadioptric optical camera for the LRS[5], suggested a similar design for LRS-J. Initial design studies showed the image

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quality to be excellent in spite of the very fast focal ratio, and the resulting camera is very compact, so we embarked on a design study, which we report here.

In order to realize sufficient resolving power (R~2000) to work between the OH^- sky emission lines in the J band, we split the wavelength coverage of 0.9 to 1.3 microns into two sections around 1.1 microns. Holographic grisms will provide this resolving power at high efficiency[6], and we expect LRS-J to have a peak throughput approaching 25% on the sky. We expect to reach J~21 in one hour with 1 arcsec seeing. In this paper we describe the properties of the LRS-J camera optical design.

2. SPECIFICATIONS

The LRS-J Camera will be attached to the same base plate as the optical LRS camera. It will be possible to interchange the cameras with the instrument in position on the HET tracker. LRS-J will probably be allocated 1-2 week runs in bright time, several times per year. The main specifications are:

- Wavelength range: 0.9 to 1.3 μm without refocus.
- Entrance pupil: 142 mm
- Pupil relief: 100 mm
- Focal ratio: F/1.0
- Plate scale: 45.025 μm/arc-sec
- Pixel size: 18.5 μm
- Pixel Scale: 2.43 Pixels/arc-sec
- 80% Encircled energy diameter 18.5 μm or less
- Imaging FOV: 4.0 x 4.0 arcmin, limited by HET vignetting
- MOS FOV 4 x 3 arc-min in the spatial and spectral directions respectively.
- Imaging of the slit should not degrade the resolution by more than 10%
- Compact format, less than 400 mm length.

3. OPTICAL DESIGN OF THE F/1 CAMERA

The LRS-J camera was designed in the Zemax optical design package. The basic layout (figure 1) follows that of the optical camera of the LRS, but the entire camera is housed in an evacuated cryostat with a fused silica window before the first corrector lens. In the LRS camera, the two fused silica corrector lenses have little net power, but in LRS-J the corrector lenses proved to need some power to produce good enough images. Following a glass substitution search, we arrived at an F2 plus SFL57 doublet. This combination was found to have excellent chromatic behavior for the wavelength range. These lenses are followed by the blocking filter, which will pass the wavelength range 0.9 to 1.3 microns, but block longer wavelengths out to 2.5 microns. After investigation of designs with the blocking fil ter close to the detector, in the converging beam it was deemed too difficult to manufacture a filter with tight enough physical properties (thickness, wedge, refractive index etc.) to not degrade the imaging performance, significantly. The large blocking filter in the (close to) collimated beam is much more forgiving. As a result of this design decision, the cavity between the filter and the mirror must be carefully shielded from thermal "light" leaks and must be maintained below T=-100 Celsius to ensure negligible background counts from the detection of thermal photons with wavelengths out to 2.5 microns. The field flattener of PK50 provides further blocking of long-wavelengh photons as it cuts off quite sharply at $\lambda > 1.35$ microns. Table 1. presents final design details

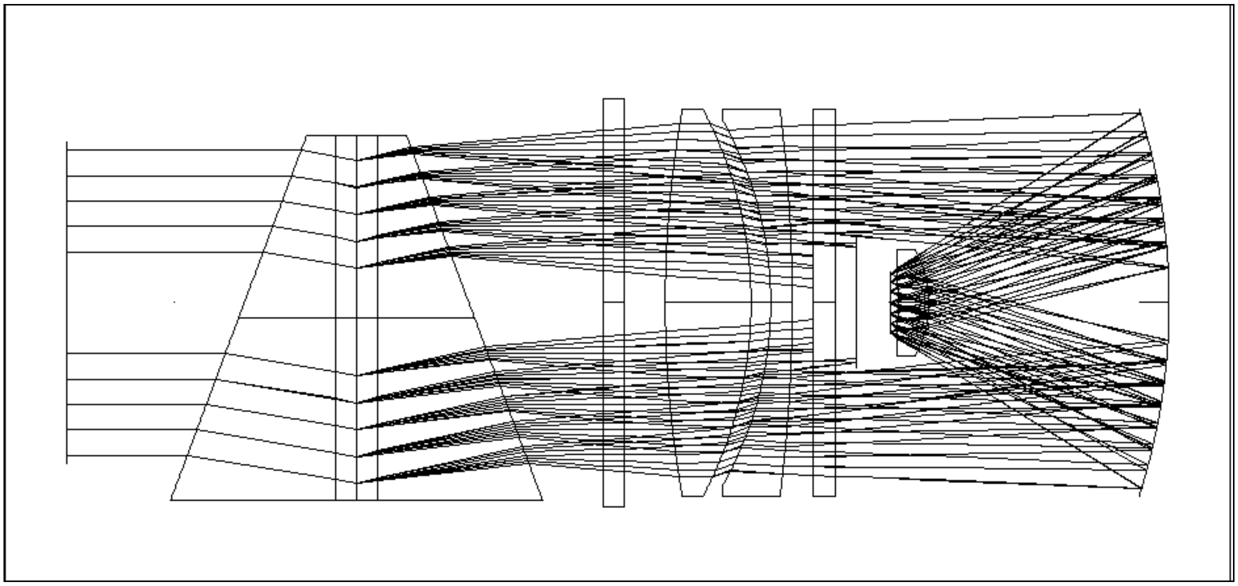

Fig.1: LRS-J layout showing VPHG, window, F2 plus SFL57 corrector doublet, filter, mirror, and after reflection, field flattener and detector. Only rays that hit the detector are shown. Incoming parallel rays are refracted towards the volume phase holographic grating at the Bragg angle, and then diffracted symmetrically. Note the offset of the grism by 7 mm which causes the diffracted light to enter the camera symmetrically, reducing the clear aperture needed for the camera[6].

Table 1: Partial listing of LRS-J Camera design (HET and VPHG are not included for simplicity). Notice the HAWAII-1 HgCdTe detector has a 330 micron thick structural layer of Sapphire on it (surface 48).

Surface	Radius	Thickness	Glass	Diameter	Comments
37	Infinity	10	SILICA	190	Window
38	Infinity				
39	518.62	58	F2	190	Corrector
40	-193.14				1st Lens
41	-173.2	10	SFL57	190	Corrector
42	-713.33				2nd Lens
43	Infinity	10	Custom	190	Blocking
44	Infinity				Filter
45	-297.16	--	MIRROR	196	Mirror
46	-50.57	15	PK50JN	50	Field
47	-455.78				Flattener
48	Infinity	-0.33	SAPPHIRE		Detector
IMAGE					Cover

Two Volume phase holographic grisms will cover the wavelength range. The first has 590 l/mm and covers 900 to 1100 nm at R=2100 (for 1 arcsec-wide slit). The second has 575 l/mm and covers 1100 to 1300 nm at R=2500. The higher resolving power of the second grism is chosen to give better sky subtraction as the OH^- emission lines get stronger into the J band than they are below 1100 nm. With the MOS unit, which has 1.3 arcsec-wide slitlets, the grisms give R=1600 and 1900 respectively. Studies have shown this to be adequate resolution for sky subtraction in the J band[3]. VPH grisms have two major advantages over grisms based on replicated physical diffraction gratings. The first is the higher throughput at higher resolution achievable with VPH gratings[7]. The second is the customization that comes with exposing each grating, rather than relying on the existence of existing ruled masters that are rarely a perfect match to requirements (either as far as blaze or physical size goes)[6]. For the LRS, with its 142 mm pupil size, there are no suitable ruled masters for far-red wavelength region grisms, and physical diffraction transmission gratings would be very inefficient at these dispersions.

4. DESIGN PERFORMANCE

The LRS-J f/1.0 camera design provides superb images, even better than the optical camera due to the smaller physical size of the detector, and the smaller wavelength interval utilized. It delivers about 85% of polychromatic light into one pixel, which corresponds to 0.41arc-sec. (Fig. 2.) The HET is expected to deliver 1 arc-sec images[8], so the LRS-J image quality is telescope-limited. As with the LRS optical camera, we require good mage quality because the telescope pupil has a time-variable illumination, and this would translate into a variable point spread function if the images were poor.

Spectroscopic behavior is analyzed first by means of centered long slit imaging (fig. 3), and then with long slits displaced +/-1.5 arc-min in the dispersion direction (figs. 4 and 5). The figures show the results with the 590 line/mm volume phase holographic grism. The behavior with the 575 line/mm grism is similar.

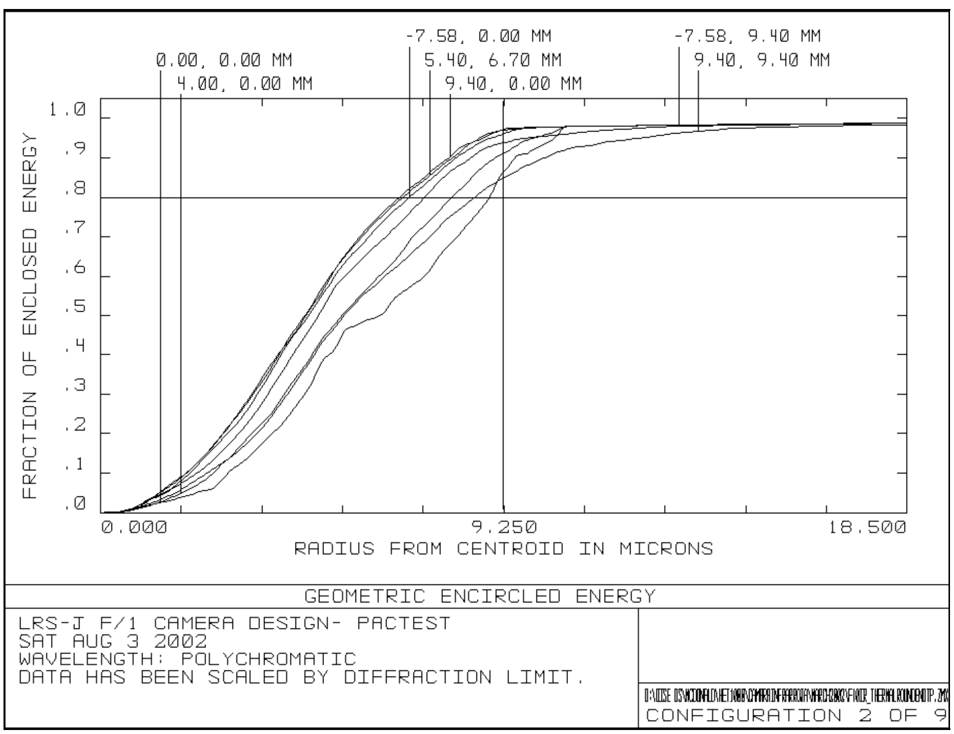

Figure 2. Polychromatic encircled energy diagram in imaging mode, showing the 80% encircled energy line (horizontal line), and the size of one pixel (vertical line).

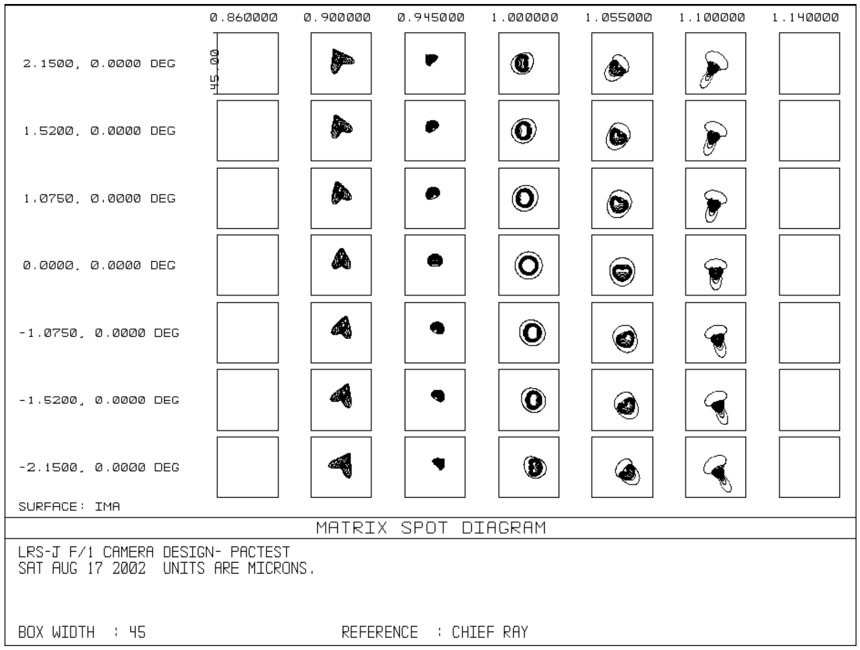

Figure 3. Centered Long slit images. The box size is 1 arc-sec square. Field angles are indicated vertically as physical position on the detector in mm, and wavelengths are in microns, horizontally.

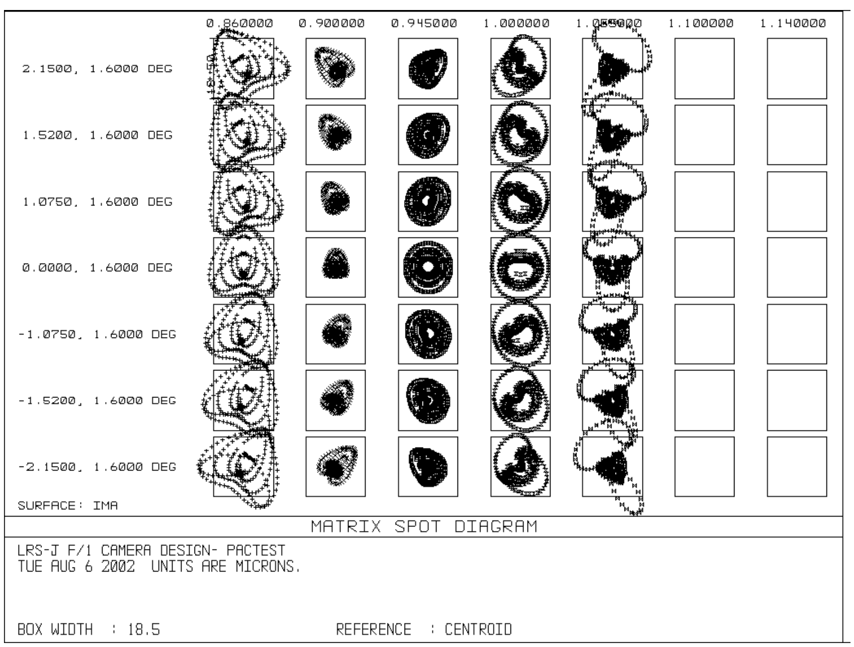

Figure 4. Displaced long slit images. This is one extreme of the MOS slitlet range (+1.5 arc-min from the axis). Box size is now one pixel; 0.41 arc-sec width. Wavelengths between 0.86 and 1.055 microns fall on the detector.

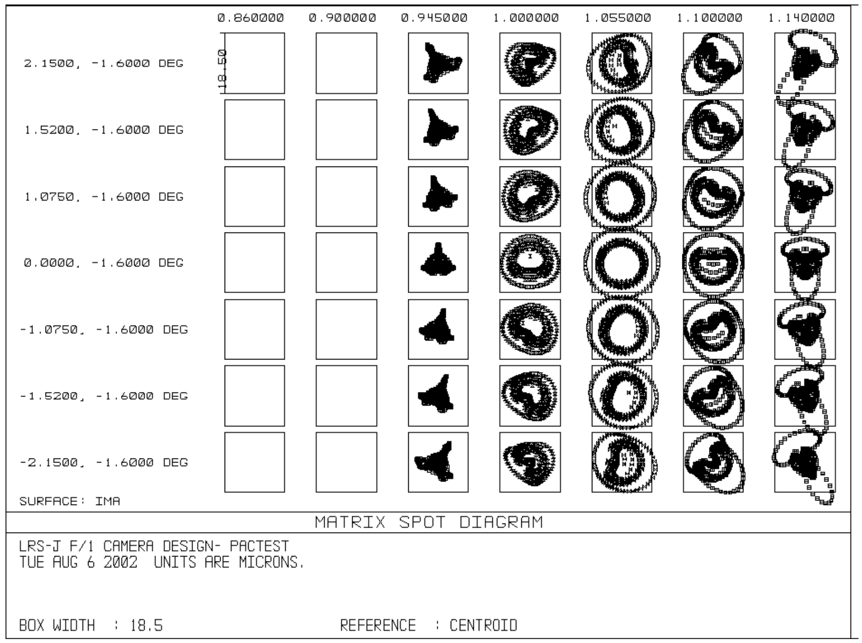

Figure 5. Displaced long slit images. This is the other extreme of the MOS slitlet range (-1.5 arc-min from axis). Box size is one pixel; 0.41 arc-sec width. Wavelengths between 0.945 and 1.14 microns fall on the detector.

5. THERMAL DESIGN

This camera presents challenges due to the tightness of some of the tolerances and the fact that it will be used in a cryogenic environment. The cryogenic properties of the Schott glasses in the design are not published. In order to reduce the unknowns, we obtained samples of the glasses and measured their coefficients of thermal expansion (CTEs) in a simple test-fixture made of invar-36. The inferred mean CTEs for the room-temperature to T~80K were obtained by immersing the samples in liquid nitrogen and repeatedly measuring the length difference relative to ambient temperature. These values are shown in Table 2, along with values given in the Schott catalog for higher temperature ranges. CTE tends to zero as temperature approaches T=0 Kelvin, so we added this constraint into a polynomial fit to the CTE values given in Table 2, and interpolated the mean CTE between room temperature (20 C) and the adopted element temperature noted in the same Table.

The mean CTE values in Table 2 were inserted into a modified glass catalog for use by Zemax, along with the melt data provided by Schott for the blanks. A multi-configuration file was set up with the first configuration being the design at room temperature and subsequent configurations reflecting a range of possible temperatures for the various optical elements in the design. In spite of the speed of the camera, it was found that the design is relatively insensitive to the temperature, and we are able to vary the temperature of the large corrector lenses by +/-50 Kelvin without degrading the images significantly. This is important because there is a significant thermal load on these lenses from the ambient surroundings (since the rest of the LRS is warm), and it is thus difficult to predict the exact operating temperature of each lens. The PK50 field flattener lens is part of the detector head, and will naturally have a temperature close to 77 Kelvin, since the instrument is cooled by liquid nitrogen.

Table 2: Mean Coefficient of Thermal Expansion (CTE) Values

Temperature Range	Mean CTE of Glass			Notes
Celsius	**F2**	**PK50**	**SFL57**	
-196 to 20	7.4	7.1	7.1	Measured
-30 to 70	8.2	8.8	8.7	Schott catalog
20 to 300	9.2	10.3	10.0	Schott catalog
Adopted Temperature	175 K	77 K	175 K	
Mean CTE	7.8	7.4	7.8	

6. TOLERANCE ANALYSIS

The Zemax design package was used for tolerance analysis. Table 3 shows the analyzed parameters, wedge was simulated by tilts on both surfaces of an element. For assembly, we considered five subsystems, the whole Camera including filter, Corrector doublet, Mirror, Field lens-detector head, and Detector itself. Thermal behavior and gravitational loading effects have been analyzed separately.

Table 3. Toleranced parameters.

Glass	Optical Fabrication	Lens Assembly	Subsystem Assembly
Refraction Index	Curvature Radii	Despace	Despace
Abbe Number	Wedge	Element Tilt	Subsystem Tilt
	Surface Irregularity	Element Decenter	Subsystem Decenter
	Thickness		

Initially, watching first order specifications, relatively loose parameter values where chosen to avoid over-restrictions and then the worst contributors to image degradation where each constrained in small steps, trying to balance fabrication difficulty between elements.

Soon we found it was necessary to impose tight tolerances in several surface curvatures, so we decided to tighten the tolerance by fitting the surfaces to known test plates to take advantage on their accurate measured radius. In this way we arrived at satisfactory solutions using test plates from a number of potential manufacturers. Once fabrication is contracted, a final test plate fitting is foreseen. Table 4 presents the final optical prescription for fabrication and table 5 the tolerances on assembly.

Table 4. Final optical prescription.

ELEMENT DESCRIPTIONS AND OPTICAL FABRICATION TOLERANCES												
Element	Material	Surface	Diameter (mm)	D. Tol. (mm)	C A (mm)	Centration (mm)	Radius (mm)	R. Tol. (mm)	Thickness (mm)	Th. Tol. (mm)	Figure Waves p-p	Polish scratch-dig
Window	Silica	1	190	+0/-0.1	170		Infinity		10	+/-0.1	1	40-20
		2					Infinity					
Corrector Lens 1	F2	3	180	+0/-0.1	170	0.05	518.62	+/-0.2	40	+/-0.2	1	60-40
		4					-193.14	+/-0.05				
Corrector Lens 2	SFL57	5	180	+0/-0.1	170	0.05	-173.20	+/-0.05	10	+/-0.2	1	60-40
		6					-713.34	+/-0.2				
Filter		7	180	+0/-0.1	170		Infinity		10	+/-0.2	1	60-40
		8					Infinity					
Mirror	F. Silica	9	196	+/-0.3	180	0.1	-297.16	+0.1/-0.2	25	+/-0.2	0.5	40-20
Field Flattener	PK50	10	90 x 90	+0/-0.1		0.1	-50.57	+0.1/-0.2	14.5	+0.1/-0.0	1	40-20
		11					-455.78	+/-0.2				

The alignment/mounting tolerances on some elements are quite tight. The tightest tolerances are associated with the alignment of the two large lenses in the corrector doublet. The separation and tilt/centering of these two elements can be held to the tolerance using accurate mounts with temperature compensated radial supports and lathe-assembly methods. We will describe the opto-mechanical design and performance in a future paper.

Table 5. Alignment tolerances.

Element Dimension	Value	Tolerance	Units	Comment
Field Flattener to detector	3.3	+0.1/-0.0	mm	
Field Flattener centration		0.1	mm	
Separation of corrector elements	9.233	+0.02/-0.05	mm	Set interactively at assembly with lathe adjustment
Tilt of mirror		+/-1.0	arc-min	Externally adjustable
Centration of mirror		0.1	mm	Compensated with mirror tilt
Corrector doublet assembly decenter		+/-0.05	mm	
Corrector doublet assembly tilt		+/-1.0	arc-min	
Tilt of detector with respect to FF		+/-1.0	arc-min	
Focus of mirror witt detector		-15/+20	Microns	Focus is very sensitive but adjustable

7. ANTI-REFLECTION COATINGS AND GHOSTS

It is important to minimize ghost images in this design since it will be used in a spectral region where the night sky emission is concentrated into discrete emission lines. Achievement of the sensitivity specification requires that ghosts from the sky emission lines be at a low enough level that they do not effect the dark spectral regions between the lines. Suppressing ghosts involves choosing effective anti-reflection (AR) coatings, and evaluating the design to identify elements that concentrate reflected light following multiple reflections. The relatively small wavelength range covered by this instrument (0.9 to 1.3 microns, a factor of 1.44, less than an octave) allows us to specify relatively simple AR coatings that perform very well. Modeling shows that, for the corrector lenses, a “W” AR coating (0.5 wave thick layer of Al_2O_3 and 0.25 wave thick layer of MgF_2), perform very well, with average reflectivity well below 0.5% per surface and maximum reflectivity of 0.7% per surface. This is particularly important for the interior surfaces of the doublet that have small separation and similar radii of curvature. These simple AR coatings keep any ghosts below the 1 part in 40,000 level. The largest reflectivities are associated with the blocking filter (<2% over the wavelength range) and the sapphire top coating of the HAWAII-1 detector (7.5 to 10% depending on the angle of incidence). The filter will cause ghosts if it is tilted or has significant wedge (at the 0.5 arcmin level). The detector is most problematic for reflections off the field flattener surfaces. We aim to have excellent AR coatings on the field flattener to alleviate this problem, and expect to have <0.20% per surface over the wavelength range, with 0.1% mean. This will give contrast of better than 1 part in 10,000, plus the defocus effect, which spreads the light over 100k pixels. The ghost off the detector to the filter and back is not a problem because the corrector doublet has enough power that the reflected light is significantly out of focus when it is reflected back and the detector lies within the central obstruction of the ghost image. This analysis is in line with the LRS optical camera performance, which does not show any detectable ghosts.

8. SUMMARY

We have presented the design of a very fast catadioptric camera for use in the astronomical z and J bands (0.9 to 1.3 microns). The design succeeds in meeting a difficult specification of >80% of light in 1 pixel (18.5 microns), which is 0.43 arcsec when mounted on the Low Resolution Spectrograph of the Hobby-Eberly Telescope. The optics will be used in an evacuated cryogenic environment, and care has been taken to evaluate the behavior of the design under a range of temperatures, since the exact temperatures of some of the elements are not yet known. We have made measurements of the CTE values for the glasses to ensure accurate design parameters and to facilitate temperature compensation of lens mounts. Tolerance analysis shows quite tight specifications on the corrector doublet lenses, and particularly on their alignment with respect to each other. All tolerances are however, within the current capabilities of manufacturers. We expect fabrication of the optics to be complete at the end of the year, and the first engineering observations with LRS-J will take place in early 2003.

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