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Simplifying the Prime Focus Corrector of the Discovery Channel Telescope

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ABSTRACT

The Discovery Channel Telescope (DCT) is planned to have a state-of-the-art prime focus corrector which was described previously[1]. The initial design contained I-line glasses which had long procurement times. Goodrich Corp. undertook a study funded by Lowell Observatory to determine whether significant savings in cost and schedule would be possible with an acceptable reduction in the performance of the telescope.

This paper reports on changes in the optical design of the wide-field optical corrector (WFOC) with a view to eliminating the long-lead materials. The consequent changes in performance are also discussed. The required FWHM of the telescope was relaxed somewhat and the imaging requirements of the ultraviolet (U) band were eliminated. The new design meets the two-degree field of view requirement and recovers most of the performance in the ultraviolet.

Keywords: DCT, prime focus, wide-field, optical design.

1. INTRODUCTION

A preliminary design for the prime focus corrector of the DCT was discussed in some detail recently[1]. The design had to meet a stringent set of requirements regarding field of view, spectral range and image quality. Additionally, an atmospheric dispersion corrector (ADC) was specified to work over a large range of zenith distances. In the preliminary design, cost was not a major constraint; rather, meeting all of the scientific and engineering requirements was given the highest priority. With the preliminary design in hand, Lowell Observatory was able to identify the real cost drivers and began the process of minimizing costs while, simultaneously, maximizing the scientific return expected from the telescope. Consequently, we undertook a study to investigate ways of economizing on the optical and mechanical aspects of the telescope. This paper documents the major changes made to the optical design of the WFOC. Changes in the mechanical design will be documented elsewhere.

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2. RECONSIDERING THE REQUIREMENTS

Table 1 is a summary of the original operational requirements for the WFOC. The value of the FWHM is to guarantee that the top quartile seeing at the site will be degraded by no more than 10%.

Table 1. Original WFOC Imaging Requirements.

Field of View	2.0 Degrees
Focal Ratio	F/2.3
Spectral Range	345 – 1000 nm
Filters	U, B, V, R, I, (B+V+R)
FWHM	< 0.27 arc sec
Atmospheric Dispersion Compensation	< 0.27 * (cos Z) $^{-0.6}$ arc sec (to 65°)

Early on, it became clear that maintaining a high-quality imaging capability in the ultraviolet would be very expensive. The reasons for this are discussed below. Also, significant savings could be realized by relaxing the FWHM requirements somewhat by considering normal seeing conditions rather than the relatively rare "best" seeing conditions.

The decision made at Lowell was to sacrifice the U band, changing the required spectral range to 390 – 1000 nm. Also, the FWHM requirement was relaxed to 0.38 arc sec. This value will degrade the *median* seeing by no more than 10% rather than the upper quartile. The field of view and focal ratio were not allowed to change. No requirements on the ADC were changed since, at the time, there were reasons to believe that there would be no performance degradation in it.

As originally envisioned, the WFOC and the Ritchey-Chretien secondary mirror were to be mounted "back-to-back" in the same prime focus pod. The switch from one observing station to the other would be accomplished by rotating the entire pod assembly while still on the telescope. This concept has since been abandoned in favor of demounting the WFOC completely and replacing it with a separate secondary mirror mounting. It was thought that this might give some additional freedom in the optical design but this turned out not to be the case. The additional length that became available to the WFOC could not be used effectively.

The two simple changes in requirements, sacrificing the UV and relaxing the image quality slightly, have lead to a substantial reduction in the cost of the WFOC.

3. EVOLUTION OF THE ADC

At the direction of Lowell, the original WFOC design had a Subaru-type ADC[2]. In short, this is a plano-convex, plano-concave pair of lenses with similar refractive indices but differing dispersions. The curved surfaces have equal radii and face each other in near contact. The effect is simply a plane parallel plate for light where the two indices of refraction are equal. For other wavelengths the light is bent either toward or away from the optical axis. The former requirement for good imagery and high transmission in the ultraviolet severely restricted the selection of materials. It was decided that the glasses would have to be I-line glasses for their high UV transmissivity. The glasses selected were BAL15Y and PBL1Y. Their refractive indices were not a particularly good match but they were the best that could be found in that restricted set. Also, it was necessary that one other lens in the corrector be made of a flint-like glass and that was also designated to be PBL1Y.

The I-line blanks had to be of very substantial sizes; about 700 mm in diameter and 100 mm thick. Discussions with the manufacturer revealed that this would require a special pour for each of the glass types and a minimum order of five blanks of each type needed to be ordered. The total order would be approximately one million dollars. Since only three blanks were needed, the cost of raw materials for the ADC and lens L4 would be about $300,000 per blank!

Relaxation of the ultraviolet imaging requirement substantially reduced the raw material costs. Normal glasses could be used and this gave nearly an order of magnitude cost reduction for the blanks. Furthermore, since normal glass types could be used, the refractive index match was much better than with the I-line glasses and the redesigned ADC working from 390 – 1000 nm had much improved performance over the previous model.

The redesigned ADC was comprised of N-BAK2 and LLF6HT. The lens L4 also became LLF6HT and all of the other elements in the corrector were fused silica. In the course of reoptimizing the corrector for the new glass types, the lens L4 became quite weak. Noticing this, one of us (EWD) suggested that it could become the ADC itself if it were tilted and decentered according to the air mass. This was originally suggested by Blanco, *et. al*.[3] during a preliminary investigation into this telescope.

In subsequent optimization runs, care was taken to force L4 (see Figure 1) to have very low power and to try correcting atmospheric dispersion by decentering it alone. This did not work well; however, when tilted and decentered, as if the lens were rotated about an axis perpendicular to the optical axis and about one meter from the lens, an excellent dispersion correction was obtained. The ADC now gives excellent imagery to at least 75 degrees zenith distance. Thus, in two steps we were able to eliminate two very expensive lenses from the corrector and replace another with a much less expensive and more commonly available glass at a substantial cost saving to the program.

With only one, relatively thin lens of LLF6HT and everything else being made of fused silica, the ultraviolet transmission of the WFOC was restored so the U band was included, with low weight in the final optimization. The results were remarkably good. Even at a zenith distance of 75°, 80% of the computed encircled energy falls within three-quarters of an arc second.

One other advantage to the changes in the ADC is that the ghost reflection[1] due to the two parallel, curved surfaces in the ADC was eliminated.

4. REDUCING THE ASPHERIC COUNT

The original version of the WFOC[1] had three aspheric surfaces, two of which had 10th-order polynomial terms. The third was a concave ellipsoid. When the FWHM requirements were relaxed, we investigated the possibility of reducing the number of aspherics. After some preliminary numerical experiments, the aspheric curve on the concave surface of L1 (see Figure 1) was eliminated completely. This will result in decreased cost and risk since this lens is thin for its aperture. The ellipsoidal curve which was on the concave surface of L2 is now on the concave surface of L3. This is a somewhat smaller lens which should ease the fabrication process somewhat. The surface is still an ellipsoid with a conic constant of about -0.4. This surface could, if desired, be tested with a simple conjugate test.

The third aspheric surface was on the strongly curved side of the lens L5. At the time we published the first study[1], the rear surface of that lens was mildly concave. Therefore, we decided to try putting the aspheric curve on the rear of the lens in hopes that it could be tested in reflection. This hope did not pan out as the surface became mildly convex during optimization. However, somewhat to our surprise, adequate performance was obtained with only a 6th-order polynomial rather than the 10th-order curve which was there previously. Since this aspheric is on a gently curved surface rather than the strongly curved front side, it should be significantly easier to fabricate and test yielding additional cost savings.

5. IMAGE QUALITY

The ultimate criterion of image quality is the full-width at half maximum (FWHM) of the stellar image. This value was computed and is summarized in Figure 2. Here the polychromatic FWHM in each of the spectral bands is plotted against zenith distance from 0 to 75 degrees.

Although the WFOC has been simplified, in the sense that it has fewer elements and fewer aspheric surfaces, the computed performance of the corrector still meets the requirement. Figure 3 is a set of spot diagrams computed at four field angles and eight zenith distances from 0 to 75 degrees. Rays were traced at nine wavelengths from 390 to 810 nanometers. Performance is similar in the I band (760 – 1000 nm) and also, as mentioned above, in the U band (345 – 400 nm).

Although spot diagrams show the excellent quality of the ADC, a more meaningful criterion is the smallest diameter that encloses 80% of the energy from a single star -- D(80). At the zenith (Figure 4), D(80) < 0.3 arc-second. Even at 75 degrees' zenith distance (Figure 5), D(80) < 0.5 arc-second over the entire field.

6. SUMMARY

By making very modest adjustments to the specification for the WFOC, major simplifications in the design have been possible. By relaxing the FWHM requirements from a less than 10% degradation of the upper quartile seeing to a less than 10% degradation of the median seeing, the number and complexity of the aspheric surfaces have been reduced. A different concept for the atmospheric dispersion compensator resulted in the elimination of two very expensive components with almost no loss of performance. Although the requirements on the U band image quality were abandoned, the modified corrector gives quite good performance in that band (Figure 6).

7. ACKNOWLEDGEMENT

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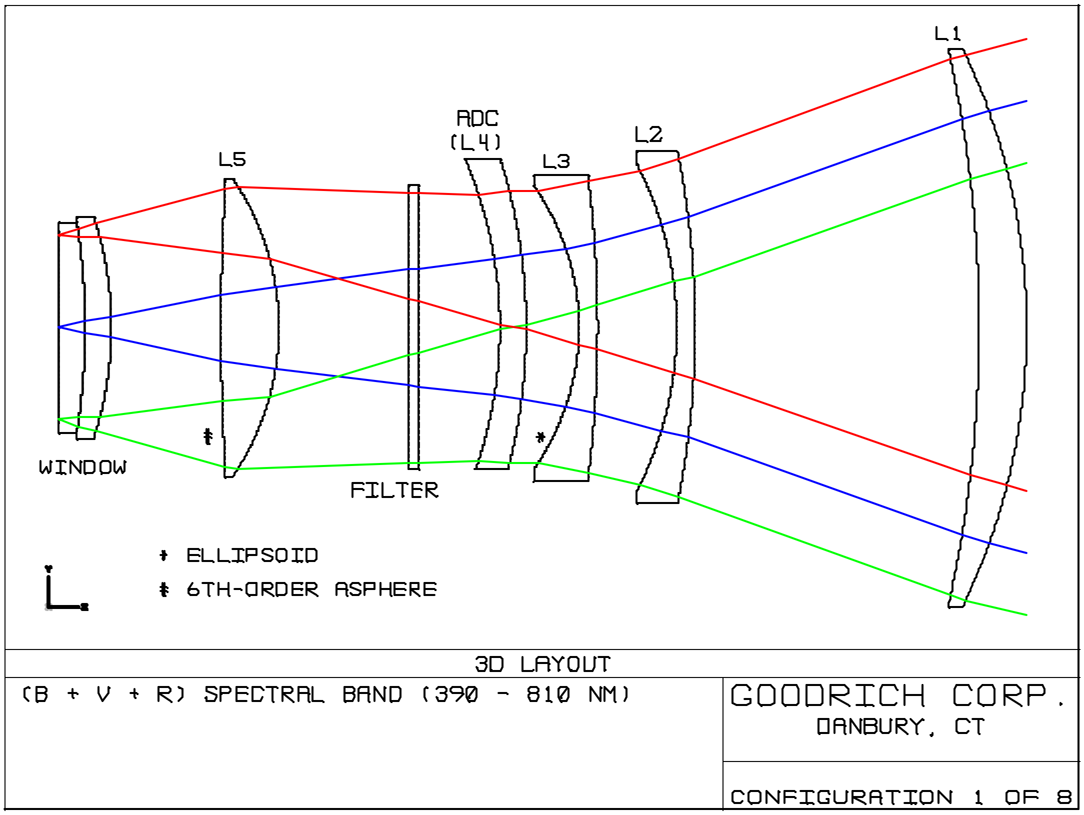

Figure 1. Layout of the WFOC.

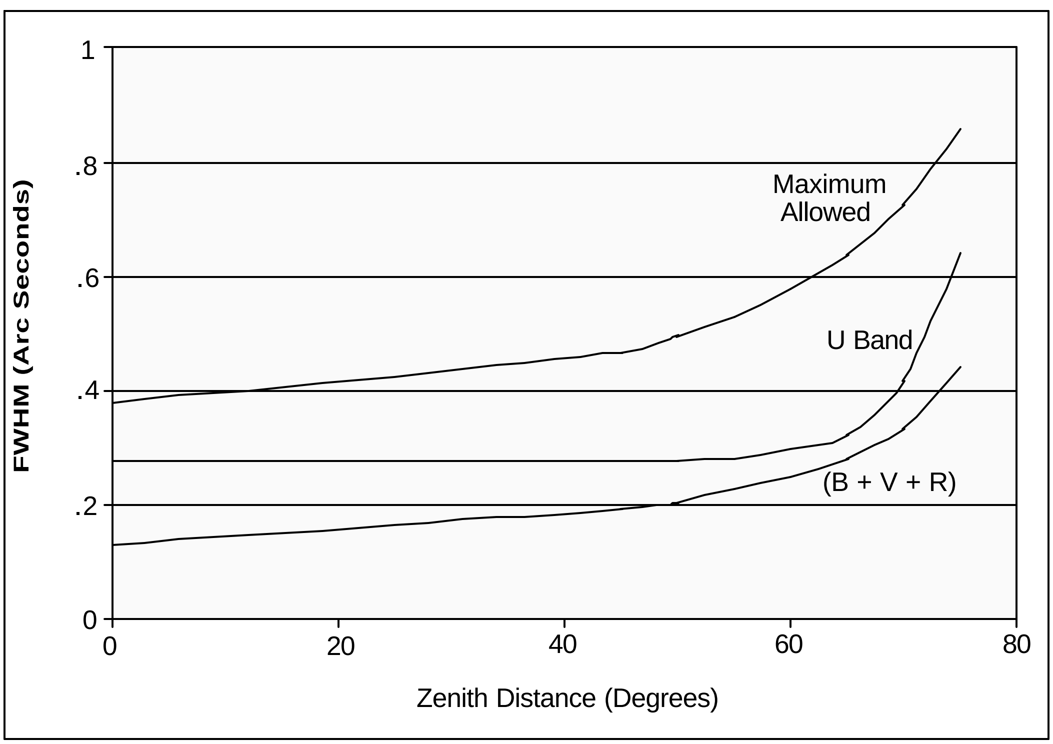

Figure 2. FWHM vs. Zenith Distance.

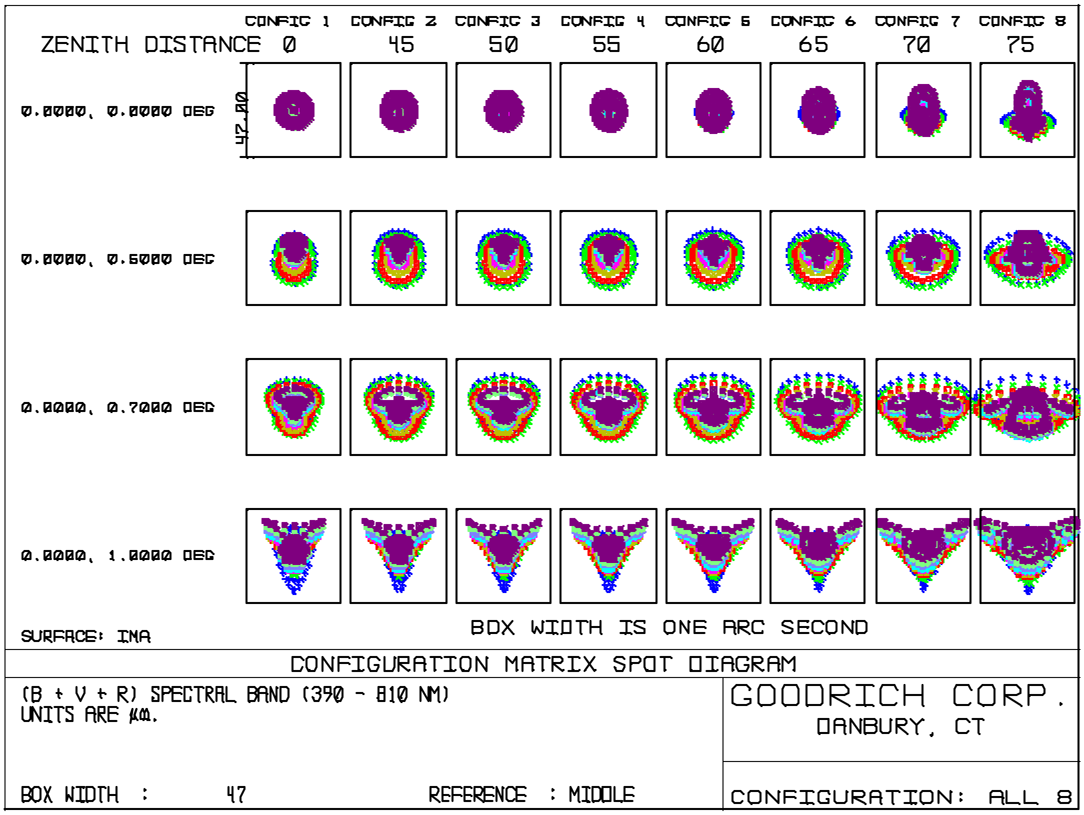

Figure 3. Spot Diagrams Showing Performance of the ADC.

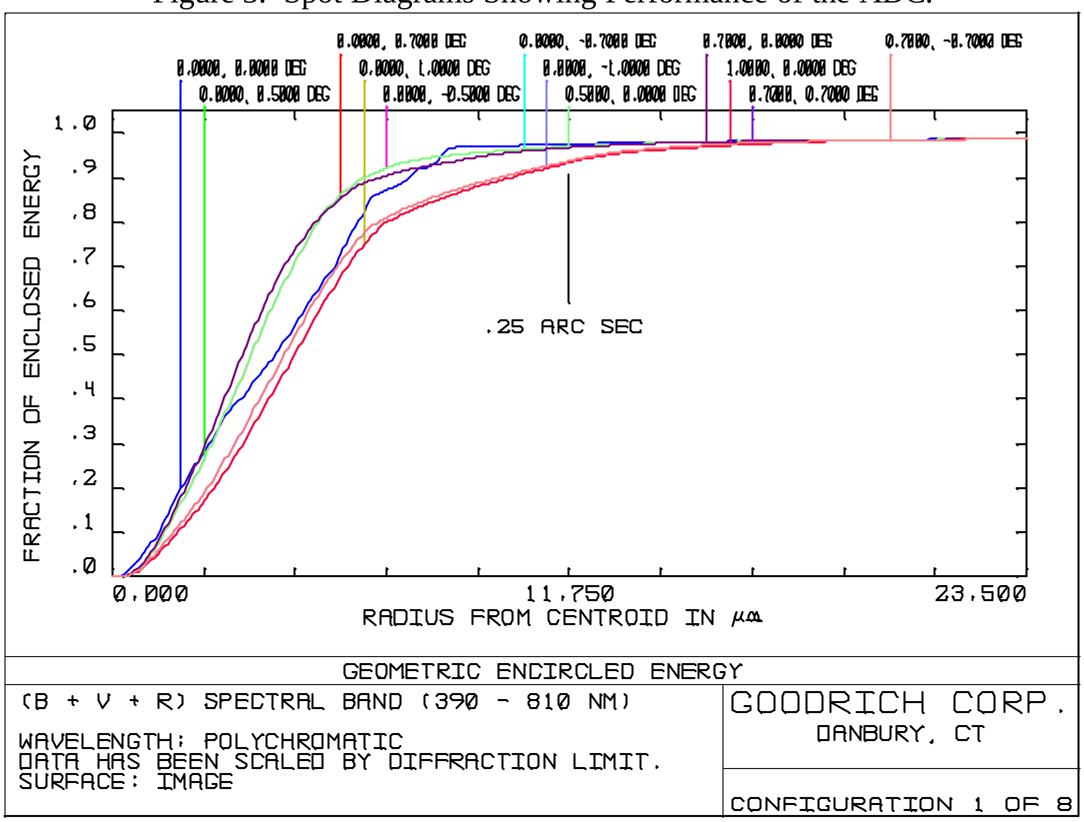

Figure 4. Encircled Energy Curves at the Zenith.

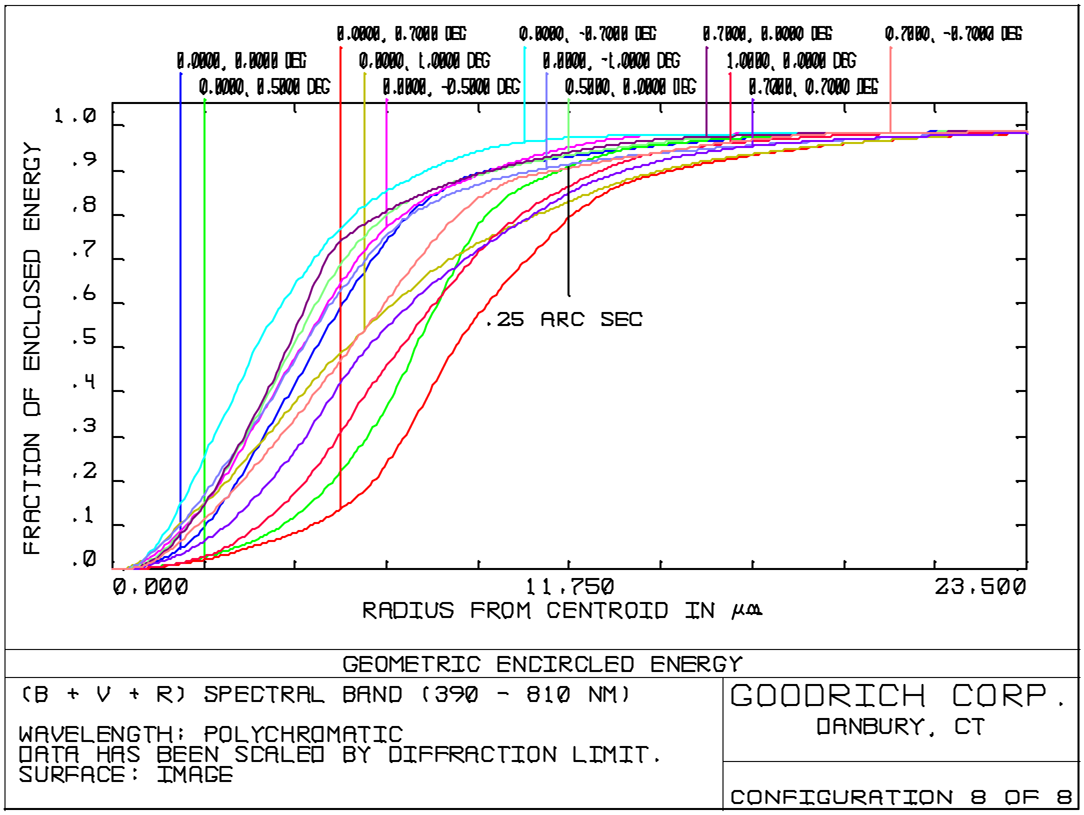

Figure 5. Encircled Energy Curves at 75° Zenith Distance.

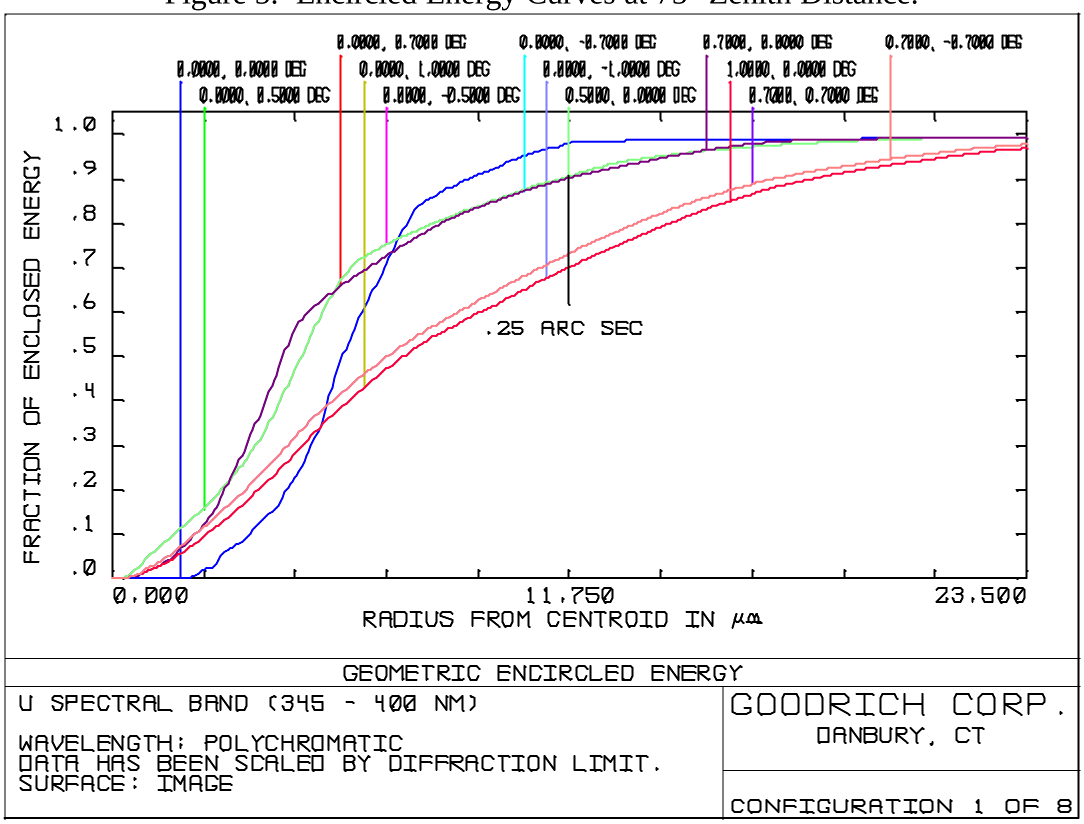

Figure 6. U-Band Encircled Energy Curves at Zenith.