Optical Design of the Discovery Channel Telescope

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ABSTRACT

The Discovery Channel Telescope (DCT) is a joint venture between Discovery Communications and Lowell Observatory\textsuperscript{1}. The telescope will have a 4.2-meter clear aperture, active primary mirror working at F/1.9. Two observing stations are presently planned; a Ritchey-Chretien focus some two meters behind the vertex of the primary mirror and a prime focus featuring a wide-field optical corrector (WFOC) with a two-degree field of view. The Ritchey-Chretien focus will be used for a variety of optical and near infrared imaging and spectroscopic instrumentation while the prime focus will be largely used as a survey tool to search for near-earth and Kuiper belt objects, for example.

In order to take advantage of sub-arc second seeing at the DCT site, a stringent set of requirements has been placed on the two foci. The requirements are for the full-width, half-maximum (FWHM) image of a point source to be less than 0.20 arc second at the Ritchey-Chretien focus over a 21 arc minute field and less than 0.27 arc second at prime focus in each of six filter bands including a very broad band for survey purposes.

This paper describes the optical design of the field correctors at the two foci. Particular attention is paid to the WFOC. This state of the art device poses a number of optical challenges which are discussed here, as well as mechanical challenges which are discussed elsewhere\textsuperscript{2}.

Keywords: DCT, Ritchey-Chretien, prime focus, wide-field.

1. INTRODUCTION

Lowell Observatory, in partnership with the Discovery Channel is planning to build a 4.2 meter telescope which is intended, in part, to communicate the excitement of astronomical discovery to the public. The telescope will be used for a wide range of observing projects including searches for near-earth asteroids and Kuiper belt objects as well as research in a variety of astrophysical and planetary science areas. The search projects will benefit greatly from both a large aperture and a wide field of view. With this in mind, Lowell commissioned Goodrich Corporation to conduct a study to define the prime focus optics for a telescope with a two-degree field of view working from 330 to 1000 nm.

The wide-field prime focus observations are best conducted during the dark of the moon. A Ritchey-Chretien focus is provided for projects that can be done during bright time, or for those requiring deep UV or near-IR wavelength coverage, or spectroscopy. This focus will allow the mounting of instruments massing several tons and will feature a 15 arc minute square field of view.

When the study contract was originally let, the assumed diameter of the primary mirror was 4.0 meters. It soon became evident that a blank could be made with a 4.3-meter diameter which allow a finished clear aperture of 4.2 meters. It was decided that, rather than scaling the focal lengths with the aperture, that the finished focal lengths of the primary and the Ritchey-Chretien foci would be held constant thereby

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decreasing the focal ratios by about 5%. This complicates the optical design somewhat but a number of other factors such as matching the physical size of the detector to the two-degree field and allowing a shorter tube and smaller enclosure more than offset this difficulty.

The optical design study concentrated on the WFOC; however, before it could be designed, the primary mirror had to be specified and this required some knowledge of the Ritchey-Chretien focus. Therefore, this focus will be discussed first.

2. THE RITCHEY-CHRETIEN FOCUS

While the assumed aperture of the primary mirror was still 4.0 meters, it was decided that the system focal ratio should be F/6.4 and the focal point should be exactly two meters behind the vertex of the primary. Increasing the aperture decreased the focal ratio to F/6.1. The primary mirror is to have a vertex radius of 8 meters, making it F/1.9. The science field of view is 15 arc minutes square but it is desirable to have a field for guiding which is a full 30 minutes in diameter.

Solving the first and third order equations for the above conditions gives us the data in Table 1. Notice the large (negative) value of the primary mirror’s conic constant. This value proved to be helpful in designing the WFOC as will be seen below. Being a Ritchey-Chretien, the telescope is, of course, free of spherical aberration and coma but is afflicted with field curvature and astigmatism. The transverse astigmatism is about one-half arc second at the corner of the science field. However, the radius of curvature of the medial focal surface is about 2.5 meters concave to the secondary mirror and this causes the image to be about two arc seconds in diameter at the corners. This necessitates the use of a field corrector/flattener at the Ritchey-Chretien focus for critical applications.

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<th>Parameter</th>
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<tr>
<td>Plate Scale (arc sec / mm)</td>
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Table 1. Ritchey Chretien Focus Parameters.

The field at the Ritchey-Chretien focus is quite modest; even the guide field is only 30 arc minutes in diameter. The design decided upon is modeled on the two-element corrector that Wynne designed for the KPNO four-meter telescope. The material is fused silica because high transmission is required from 300-1100 nm to accommodate various instruments and detectors. A layout of the corrector is shown in Figure 1. The large lens on the left has a clear aperture of 300 mm and is 23.2 mm thick. The large block of glass just in front of the focal plane is a surrogate for the dewar window, filter and atmospheric dispersion corrector (ADC) which have not been specified yet. Once they have been, the field corrector will be modified slightly to account for the actual thicknesses and materials of the components.

Figure 2 is a set of spot diagrams showing images from 300 to 1100 nm and on axis to 15 arc minutes off axis. The size of the boxes is 0.20 second. Calculation of the white light FWHM yields values of less than 0.04 second.

At this point it was clear that achieving the required image quality at the secondary focus of the telescope presented no problems. The preliminary design outlined here was considered sufficient and further work on the secondary focus was suspended.
2. The Wide Field Optical Corrector

The specifications for the WFOC call for a two-degree field of view with 0.27 second FWHM images. The wavelength region to be covered is 330 – 1000 nm although not all at one time. There are five separate bands to be selected by filters: U(mod), B, V, R and I as defined by Epps and di Vittorio\(^5\). A sixth filter position is to be essentially the sum of B + V + R and is used as a “white light” band. This band runs from 390 – 810 nm and is the one used in the evaluations presented here. An atmospheric dispersion corrector (ADC) is to be included in the design such that the image size as a function of zenith distance grows no faster than \((\cos Z)^{-0.6}\).

2.1 Design Philosophy

The problem with designing a prime focus corrector has been well summarized in several places\(^6,7,8\). In essence: the level of correction obtainable is lower for a mirror of higher numerical aperture. To maintain a given level of correction with a faster mirror it is necessary to restrict the field size or the spectral region, increase the overall size of the corrector or add aspheric surfaces to the correction. In the case of DCT, this has resulted in a physically very large corrector with a number of aspheric surfaces.

Preliminary design studies for a telescope of this type were carried out by Blanco, et. al.\(^9\) and Epps and di Vittorio\(^5\). Subsequent rewriting of the specifications made it necessary to revisit the design. Since transmission in the ultraviolet is important for this telescope, it was decided early on that the bulk of the refractive power would be provided by fused silica elements. Of course, something will be needed which acts like a flint glass in the ADC and to partially compensate the chromatic aberration of the silica. The Ohara I-line glass PBL1Y was chosen although problems with availability may force an alternate choice.

Knowing at the outset that this would be a difficult design problem, the starting point was taken to be a four-element corrector with all spherical elements\(^10\). The first (nearest the primary mirror) and fourth were
positive and the second and third were negative so that the lenses formed a pair of nearly afocal doublets. Afocal doublets in contact have no primary or secondary chromatic aberration. The lenses are of fairly low power and that keeps the primary chromatic aberration under control when the lenses are no longer in contact. One can then “bend” the two afocal doublets to correct the coma and astigmatism of the primary mirror. The positive lens nearest the focus serves as a field flattener so what we have is an optical system with essentially no chromatic aberration, coma, astigmatism or field curvature. The major remaining aberration is spherical which is large in these afocal doublets and cannot be eliminated by further bending of elements so far from the stop. However, reference to Table 1 shows that the primary mirror is a strongly overcorrected hyperboloid whose spherical aberration is of equal magnitude and opposite sign to that of the corrector elements. This is one of the reasons that the telescope was designed with a low secondary magnification. The “aparabolic” term of the primary mirror’s conic constant varies inversely as the cube of the secondary magnification. The large departure of the primary mirror from a parabola allows greater correction in this type of field corrector.

The large value of the conic constant allows the corrector to move away from the final focus and become larger. This was discussed by Richardson, et. al. This procedure was stopped when the front element grew to just over a meter in diameter. This was considered to be a practical limit. The performance of the corrector was still not acceptable so recourse was taken to aspheric surfaces. This is a subject that was studied in detail by Cao and Wilson. They concluded, as did Wynne, that using two aspheres did not give much improvement and that three were necessary.

The first incarnation of the WFOC was very similar to what has just been described. There was a four-element Wynne corrector with three aspheric surfaces, a curved dewar window, an interference filter on a 18 mm thick fused silica substrate and an ADC. The ADC will be discussed below. It is important that there always be a filter in the beam since the spherical aberration it induces is removed by the corrector. The filters are located in a space where the focal ratio is F/3.6 rather than in the final space before the dewar where the focal ratio is F/2.3. The smaller beam vergence there will have a smaller impact on the edge characteristics of the filters.

When the sensitivities of the corrector to perturbations were calculated, it was found that the second element in the train, the first negative element, was incredibly sensitive to alignment errors. The concave surface of this element was working at about F/0.6 and was a 10th order aspheric surface with a maximum departure from the best fit sphere of over a millimeter! It was rapidly decided that this lens could not be built. Therefore the lens was split into two negative menisci, but only one was initially allowed to have an aspheric surface. It was hoped that the two lenses, with the reduced incidence angles on their strongly curved surfaces would relax the solution enough that the corrector could be fabricated. In subsequent optimization, the 10th order asphere began to resemble an ellipsoid. Consequently, that surface was forced to be an ellipsoid because of its obvious testing advantages. In addition, the maximum aspheric departure of this surface was reduced to about 350 microns, which is a good deal more tractable than it had been previously.

The concave surface of the front element is also aspheric with a maximum departure of 300 microns from the best fit sphere. It has not proved possible to reduce this surface to a conic section. The final aspheric surface is convex and has a maximum departure of 50 microns. Each of the lenses in the corrector has a notional transmission test which can be used to figure the aspheric surface once the spherical surface on the lens is finished. Testing will be discussed in 2.4 below.

Finally, the window of the dewar was allowed to change shape as long as its final shape is commensurate with its primary job of holding a vacuum.

Figure 3 is a layout of the WFOC. Its overall length is 1.95 meters and the largest element is 1.1 meters in diameter. The mass of glass, with six filters in place (only one is shown) is almost 400 kg. Figure 4 is a set of spot diagrams. The size of the boxes is one-half arc second. The calculated FWHM varies from 0.03 arc second on axis to 0.085 arc second at the edge of the two-degree field.
Figure 3. Layout of the WFOC.

Figure 4. Spot Diagrams. Box size is 0.50 second. Wavelengths are 390, 442.5, 475, 547.5, 600, 652.5, 7050, 757.5, 810 nm, left to right. Field angles are 0, 0.3535, 0.5, 0.7071, 0.866, 1.0 degrees.
2.2 Atmospheric Dispersion Corrector

The ADC is modeled on that of the Subaru telescope\textsuperscript{12}. It consists of a plano-convex lens with its curved surface in close proximity to that of a plano-concave lens of the same curvature. The lenses have the same refractive index for some chosen wavelength but different dispersions. As the telescope moves to larger zenith angles, the ADC is shifted laterally to cancel atmospheric dispersion.

This simple device has much to recommend it. The motion is a simple lateral translation whose maximum amplitude is about 90 mm. The cancellation of atmospheric dispersion is good allowing total image spreads of one second or less at a zenith distance of 70 degrees and 1.4 second at 75 degrees.

As originally envisioned, the ADC was to have an index-matching fluid in the space between the two curved surfaces. This would decrease by two the number of air-glass surfaces in the optical train and eliminate a ghost reflection. However, the lenses will have a somewhat unusual shape, being larger in the dimension in which they are translated and it was thought that the seal containing the liquid might not be secure enough to guarantee no leakage. A leak at the prime focus could be disastrous and so the fluid was abandoned in favor of AR coatings on the curved surfaces.

The glasses chosen for the ADC were the Ohara Hine glasses PBL1Y and BSL15Y. They were chosen for their high ultraviolet transparency and the fact that they have similar refractive indices and a relatively large dispersion difference. They are however, very expensive in the sizes required and the lead time for ordering is very long. It may prove necessary to find alternate materials for the ADC.

Figure 5 shows the performance of the ADC from zenith to 75 degrees zenith distance. For reference, at 75 degrees, the uncorrected atmospheric dispersion in (B + V + R) is 5.3 arc seconds.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Spot Diagrams at Zenith Distances of 0, 45, 50, 55, 60, 65, 70, 75 Degrees (left to right). Nine Wavelengths are traced in the (B + V + R) Band. Boxes are one arc second.}
\end{figure}
2.3 Testing

Several tests have been devised to guide the manufacturing of these large lenses. Two of the lenses have concave aspheric surfaces. Null tests at the centers of curvature of these two surfaces have been devised using diffractive null correctors (DNC’s). Of course, the ellipsoid could be tested at its two conjugates but we do not presently plan to do this.

Each of the lenses, including the ADC and the dewar window has a transmission test of the kind shown schematically in Figure 6. Each of the lenses will have a different DNC but only two retro spheres are necessary for all of the lenses. Preliminary designs of all of the DNC’s have been completed to make sure that fabrication of all of them is within the state of the art. There do not appear to be any fundamental problems in testing the components of the WFOC.

There are plans to use a similar approach to a subsystem test to verify that the WFOC has been assembled correctly. The focused beam from an interferometer will be injected at the center of the image plane. An appropriate nulling aberrations introduced by means of a DNC.

Once again, this beam will have the focused beam propagate backward through the WFOC until it emerges from the large aspheric element L1 (See Figure 7). The emergent beam then encounters a reference sphere whose center of curvature is at the focal point of the primary mirror. This sphere can be the larger of the two test spheres mentioned above for testing the individual components. The combination of the retro sphere and the DNC will mimic the presence of the primary mirror which, of course, will not be available for the WFOC assembly procedure.

This test will allow the lenses to be centered and squared on with great accuracy. Any trace of decenter or tilt coma will show up readily. The presence of spherical aberration provides evidence that one or more of the elements is despaced longitudinally.

While the test, as outlined here, is quite sensitive to misalignment of the front elements of the WFOC, it is less so for the last elements in the optical train. This is because the beam at the convex aspheric lens and at the dewar window is quite small. It is possible, by tilting the retro sphere and moving the interferometer to an off-axis position, to increase the sensitivity of the test for the rear elements of the WFOC.
2.4 Ghost Reflections

The WFOC has been studied to determine if there are any ghost images present. Several were found but none are expected to compromise the performance of the device. The most severe ghost found was, as might be expected, a reflection off of the two curved, internal faces of the ADC. We can judge the effect of a ghost image by using Seppala’s\textsuperscript{13} simple formula,

\[ I_G = \frac{R_1 R_2}{(1 - \varepsilon^2)} \frac{S^2}{G^2}, \]

where

- \( R_1, R_2 \) = Reflectivity of the surfaces,
- \( \varepsilon \) = Relative obscuration due to secondary.
- \( S \) = Image diameter,
- \( G \) = Ghost image diameter.

Assuming the reflectivities to be 1% per surface, \( S = 20 \, \mu m \) and \( \varepsilon = 0.3 \), the double reflection off the interior of the ADC has an intensity 19 magnitudes less than the image. A second ghost was found which was a reflection off of one face of the filter and then off of the meniscus lens L4 (Figure 8). This has a similar intensity but here, the intensity is very sensitive to the longitudinal position of the filter. Since there are six filters, each of which will have a different longitudinal position, only one of the filters is expected to be a problem. After these two reflections, no other ghost was found which had an intensity greater than 21 magnitudes below the star image.

The effects of reflections off of the filters can be minimized by spacing them carefully.

The internal reflection in the ADC could be eliminated by using an index-matching fluid as mentioned above. If it turns out to be a problem, then we may want to revisit this issue. Alternatively, changing the internal radii would eliminate this ghost although it would slightly change the required amplitude of motion of the ADC.

Figure 8. Ghost Reflection off back of filter.

3. SUMMARY

The discovery channel telescope will be a 4.2 meter telescope with a F/6.1 Ritchey-Chretien focus meant for UV, optical and near-IR spectroscopic, photometric and imaging work. Additionally, a state of the art prime focus corrector will offer a two-degree field of view with seeing-limited images for projects such as surveys to discover near-earth objects and Kuiper belt objects. The design philosophy of the WFOC has been presented here. The opto-mechanical design of the prime focus pod assembly (PFPA) is presented elsewhere\textsuperscript{2}.
REFERENCES


