Modeling the PFADC Corrector on the Blanco Telescope

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ABSTRACT

New corrector optics incorporating atmospheric dispersion compensation are now in routine use at the prime focus of the 4m Victor M. Blanco telescope at CTIO[1]. The corrector is described and direct photographic measurements of the optical field angle distortion (OFAD) coefficients are compared with the values predicted from the optical design. The results are used to provide a better quantification of the baseline behavior of this corrector than could have been done with either theory or experiment alone. The model is then extended to predict the behavior of the corrector using instrument configurations which have not been directly measured.

1. Introduction

When the 4m Blanco telescope at CTIO was designed in the late 1960's, no provision was made for it to be used at prime focus with any detector other than photographic plates. Wide field imaging was to be done with a camera using a pair of non-achromatic triplet correctors, optimized for use in red and blue light.

The telescope has changed greatly since then, as have other large telescopes constructed during the same era. Imaging is now done almost exclusively with CCDs. Image quality has been significantly improved by careful control of environmental variables and upgrading the optics where feasible (Baldwin *et al.* (1996)).

A new corrector, the Prime Focus Atmospheric Dispersion Compensator (PFADC) has been installed to take better advantage of the telescope's improved imaging capability. The PFADC provides high-quality, wide-field achromatic imaging at prime focus and

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incorporates atmospheric dispersion compensation (ADC). It has been used primarily with a CCD imager and a fiber-fed, multi-object spectrograph known as Argus, now decommissioned. Direct photography is still supported, though this option is now little used.

In principle, everything there is to know about a system like this can be computed directly from the optical design. However, there are at least 70 independent variables involved in the design and fabrication of this set of optics; spacings, curvatures, tilts, decenterings, refractive indices, etc. Each of these parameters can be measured, though always with some uncertainty.

The corrector can only be tested as a unit on the telescope where the variables which can be measured are the optical field angle distortion (OFAD) and the image size. Photographic plates are the classical method of directly determining the OFAD. The large detector area, flatness, continuous nature of the detecting medium and high dimensional stability of plates makes them ideal for the job. Monolithic CCDs of the requisite size, flatness and number of pixels still lie in the future.

OFAD coefficients for the old CTIO prime focus UBK-7 triplets were determined photographically by Cudworth & Rees (1991) and Guo *et al.* (1993). A similar determination of the OFAD for the PFADC has been made recently by Guo *et al.* (1998).

Several instruments with differing configurations are used at prime focus and some of the elements of the PFADC are movable. It is impractical to directly measure the OFAD with all possible permutations. What we have done is to carefully compare the empirically determined OFAD under a single known set of conditions to the predicted performance under the same conditions and use this information to quantify a baseline behavior.

Monte Carlo simulations show that the observed performance of the optics is within the range of variation from the predicted performance that would be expected as a result of normal manufacturing tolerances, giving us confidence that the corrector was built properly. We are then able to use a combination of theory and experiment to provide a better characterization of the corrector's behavior than would have been possible using the information provided by either computer modeling or direct measurement alone.

We believe the results presented here are not necessarily only interesting to potential users of this corrector. The exercise has demonstrated to us the importance of performing a similar quantitative analysis on any corrector of this type. Even the answer to such an apparently mundane question as "What happens when a filter is changed?" can be more interesting and important than one might think. In our case, we now understand the corrector well enough to determine the proper model to use with Argus, which was our original goal. Similar techniques will be used to characterize another ADC corrector now being installed at the R/C focus of the Blanco telescope. It will be used with "Hydra-CTIO", a new multiple object fiber-fed spectrograph now being constructed by NOAO. Hydra-CTIO is an improved descendent of Hydra-WIYN, in use at KPNO (Bardeen et al, 1993).

In this paper, our extrapolations of the PFADC's behavior involve changes of the optical parameters which deal with the effect of changing filters and the corrector back focal distance. We do not yet have enough information to allow us to do precise comparisons of direct measurement with theoretical models of the ADC function. This is a different and complex problem which we plan to study further as time permits.

2. The PFADC

2.1. Optical Design

The PFADC was designed by Richard Bingham at University College London under contract to CTIO. The values shown in Table 1 are not those of the nominal design, but of the measured system as it was actually built. The theoretical performance of the "as built" configuration is virtually identical to that expected from the original design.

This corrector is a descendant of the triplets originally provided with the Blanco telescope (Wynne, 1968). Addition of a fourth element provides broadband color correction and significantly improves image quality. The basic optical configuration is similar to a 4-element design first described by Wynne (1967) for the Hale 5m. Though the 1967 design is for a Cassegrain optical system, Wynne (1987) later showed that it could be adapted for use on a Ritchey-Chretièn telescope.

Wynne and Worswick (1988) demonstrated that an ADC version of this corrector could be built by putting a pair of rotating, curved, zero-deviation, Risley-like prisms with an oiled mating surface in front of the basic 4-element configuration. Such a corrector was designed (Wynne, 1989) for the CTIO 4m. However, Bingham (1988) proposed a simpler configuration in which a pair of rotating ADC prisms with an oiled, flat, rotating contact surface served as the first element of a 4-element corrector. This reduced the number of elements from 8 to 7. Glass-air interfaces were decreased from 10 to 8.

While designing the PFADC for CTIO and a similar corrector for the WHT, Bingham was able to further improve the design by separating the two rotating ADC prisms and

Table 1: Optical Design of PFADC on 4M Blanco Telescope

Surface	Radius of Curvature	Axial Separation	Material	Clear Dia.
1	21311.60	9991.7	Air	3950
2	2920.60	25.0	LLF1T	391
3	1466.49	39.3	PSK3T	382
4	-12682.9	2.9	Air	375
5	303.97	25.0	PSK1T	348
6	289.60	31.3	LLF1T	331
7	298.62	122.9	Air	313
8	748.58	15.0	BK7T	265
9	244.89	328.2	Air	248
10	294.17	27.8	FK5T	202
11	1715.95	91.9	Air	198
12	∞	0	—	160

- All parameters as measured. All dimensions in mm.
- Hyperbolic primary: conic constant= -1.09763
- Surface 3 cemented with .1mm RTV; Inclined at 1.17°
- Surface 6 cemented with .1mm RTV; Inclined at 1.37°
- 91.9mm in space 11 includes 4mm filter and 6mm window
- "T" suffix glasses are adjusted for melt variations
- Both doublets are free to rotate over 360°

shaping the doublets similar to the corresponding elements of the basic 4-element corrector. This eliminated the need for an oiled rotating surface and reduced the number of elements from 7 to 6. Each doublet is made of glasses (LLF1 and PSK3) which have almost the same indices of refraction but different dispersions. The cemented surfaces of the doublets are slightly inclined, so both act like zero-deviation prisms with a small dispersive power. When the axes of the prisms are 180° out of phase, their dispersions cancel and the system has essentially the same image quality as the basic 4-element design. The final optical system contains 6 pieces of glass and 8 glass-air interfaces.

Both doublets can rotate independently over 360°, allowing an artificial dispersion of variable magnitude to be added in any direction. This permits the corrector to compensate for atmospheric distortion with very little image degradation at any azimuth and at zenith angles to 70°. The optical design provides excellent UN-vignetted images at all wavelengths within the design range from 3500$\mathring{A}$ to 10000$\mathring{A}$ over a 48 arcmin field. There is minimal image shift with ADC. Chromatic effects are small. The quality of imaging at all air masses is now mainly seeing-limited.

The four surfaces on the two singlets have been coated with broad-band anti-reflection coatings having high transmission from $3500 - 10000\mathring{A}$. The doublets were coated with MgF_2. Use of the new coatings on the doublets was felt to involve too much risk because their long-term characteristics were not well known at the time the elements were made and they would have been extremely difficult to remove had they deteriorated with time. Fortunately, experience has shown them to be stable and robust.

Transmission of the PFADC including coatings and glasses is above 85% at all wavelengths from 3700$\mathring{A}$ to 8700$\mathring{A}$, falling to 75% at 3650$\mathring{A}$ and 10000$\mathring{A}$ and 54% at 3500$\mathring{A}$. Transmission falls rapidly at wavelengths shortward of 3500$\mathring{A}$ because of attenuation in the glasses used. High quality photometry can be done using the PFADC though calibrations are more difficult in U than at longer wavelengths because of the short wavelength transmission limit.

The original design specification called for image quality of .25" full width half maximum (fwhm) in the center of the field and .5" fwhm at the edge for any wavelength within the design range. The corrector meets this specification. However, the images produced by ADC correctors have irregular profiles which often makes fwhm a misleading representation of image size. In the rest of this paper, we will refer to image quality by specifying the diameter of a circle in which 70% of the incident energy is contained (D_{70}). Requiring that D_{70} be less than a certain value is approximately as stringent a specification as insisting the fwhm be less than the same value. D_{70} as a measure of image quality provides a more meaningful quantification of the performance of the telescope in a single number and is easier to quantify than fwhm. For the purpose of theoretical OFAD modeling, the images are considered to lie at the centroid of the spot diagram.

2.2. Instrumental Configurations

The PFADC was planned with a CCD imager as the default instrument. The design assumed that a 4mm BK7 filter would be placed within the back focal space (distance 11 in Table 1) in front of a 6mm window of fused silica. With the corrector as built, theory predicts the best imaging with the focal plane of the nominal detector 91.9mm behind the rear face of the corrector. Under these conditions, the focal plane is very nearly flat and the system is achromatic. If the surfaces of the window and filter are flat, they can be put anywhere within the back focal distance without significantly affecting the optical behavior of the system.

Argus placed its fiber tips directly in the image plane. As a result, 10mm less refractive material is in the back focal distance with Argus than is called for in the nominal design. This causes a shift of the image plane and a small amount of chromatism. To maintain the same optical distance between corrector and detector as in the nominal CCD case, the Argus fibers must be placed closer (88.5mm at 4400$\mathring{A}$) to the last optical surface of the corrector. Everywhere in the field, more than 90% of the transmitted light at all wavelengths from 3500$\mathring{A}$ to 10000$\mathring{A}$ falls into a .7 arcsecond circle at zenith angles to 70°when the system is focused through a B filter and the rotating elements have been moved into the correct positions. This image quality allowed efficient broadband spectroscopy to be done through Argus' 1.86" diameter fibers.

The filters used in the Prime Focus Camera are nominally 2mm thick and made of BK7. For best overall imaging with these filters, the film surface should be 89.1mm from the nominal corrector. The filters normally used for photography actually have slightly different thicknesses and compositions. The effect of these differences is minimal.

In the three main configurations, the instruments have been mounted with back focal distances which are as close as possible to optimum for the respective configurations in the nominal design. The "as built" and measured distances (±.1mm) between the rear of the corrector and detector plane are 88.5mm and 89.2mm respectively for Argus and the PF Camera. The optimum distance to the focal plane is different for each CCD because of variations in the nominal filter and dewar window thicknesses and the need in some cases for a curved window to compensate for curvature of the CCD.

3. Determination of the OFAD

3.1. OFAD Modeling

In an astrograph, the spherical sky is presumed to be projected onto a flat plate perpendicular to the beam of the astrograph. In this ideal case, the distance r_o from the optical axis to a point on a plate is given by $r_o = fTan(A)$, where f is the focal length of the astrograph and A the angular distance from the optical axis to the same point.

Correctors such as the PFADC deviate from this model via radial pincushion distortion, called optical field angle distortion (OFAD), which varies as a function of the distance from the optical axis. We will represent distortion using the model in Chiu's 1976 paper

$$r = fTan(A)[1 + d_3Tan^2(A) + d_5Tan^4(A)]. \tag{1}$$

Here, r is the measured distance from the center of the field to the image in the detector plane. Distortion is modeled via the third and fifth order dimensionless distortion coefficients d_3 and d_5.

The inverted model

$$r_o = r + b_3r^3 + b_5r^5 \tag{2}$$

is usually preferred for analyzing plates, along with the image scale S, usually expressed in arcsec/mm. The two models are equivalent for our purpose and easily interchangeable via the simple relations

$$f = 206265/S,\ \ d_3 = -b_3f^2 \ \ and\ \ d_5 = (3b_3^2 - b_5)f^4. \tag{3}$$

3.2. Measured and Predicted OFAD

In Table 2, results of theoretical analysis of the OFAD for the "as built" PF camera using Zemax^{tm} are presented along with the values photographically determined by Guo *et al.*(1998) using plates taken in 1995. In both cases, the two ADC doublets were set in a "neutral" position with their dispersive axes opposed in the north-south direction. UBVRI bands are approximated in Zemax by the conventional wavelengths of 3600Å, 4400Å, 5500Å, 7000Å and 9000Å.

The photographic exposures were made through UG-5, GG385 and GG485 filters with thicknesses of 2.73mm, 1.96mm and 1.84mm respectively. All focal lengths in Table 2 have been adjusted to the values they would have had if the filters had been 2mm thick and made of BK7.

The OFAD coefficients produced by the computer differ significantly from the values obtained by measuring the plates. Once the focus has been adjusted in the theoretical model to account for fabrication variations, the rms distance between the positions predicted by the two models is approximately .1 arcsec, which is roughly the same as the rms plate-to-plate variations in the empirically determined image positions. Nowhere does the position of a star image predicted by the two models differ by more than .2 arcsec.

The differences in the two sets of OFAD coefficients come partly from the fact that the empirical modeling process treats all three OFAD parameters as variables, while the computer assumes f to be the paraxial focal length. There are also slight systematic

Table 2: Theoretical and Experimental OFAD Coefficients for the PF Camera

Source	Band	f.l. (mm)	d_3	d_5	Comments
Guo	U	11465.4	360.0	775000	Measured
Guo	B	11467.3	360.2	695000	Measured
Guo	V	11467.8	357.6	687000	Measured
Zemax	U	11462.9	364.4	805000	Predicted
Zemax	B	11465.2	359.2	800000	Predicted
Zemax	V	11466.5	355.8	795000	Predicted
Zemax	R	11467.2	352.6	800000	Predicted
Zemax	I	11467.9	350.3	800000	Predicted

• d_3 and d_5 are dimensionless
• Images have been refocused for each passband
• All values are for 2mm BK7 filters

differences between the position of an irregularly image determined by measuring its location on a seeing-limited photographic plate versus calculating it with a computer.

Theory and experiment agree that there is a gradual increase in f with increasing wavelength while d_3 and d_5 decrease although there is no longitudinal chromatism in the design system. Chromatic variation in the OFAD coefficients causes the blue images near the optical axis to fall slightly closer to the center than those in the red, making the paraxial focal length slightly shorter in the blue. Farther out in the field, the shorter wavelength images begin to move out more rapidly with increasing field angle, passing the longer wavelength images near the edge. This effect is manifested in both models by larger values of d_5 and longer focal lengths at shorter wavelengths. The relative shift between the images in different colors can be as much as .36". This shift makes the broad band images which may be required by Argus significantly larger than the narrower band images generally used for CCD exposures. With Argus, the PF Camera and the PFCCD there are small additional shifts of image position with color resulting from chromatism caused by the incorrect filter and window thicknesses.

3.3. Details of the Photographic Measurements

The photographic calibrations used here are based on eight plates of two fields, all taken on the night of February 23/24, 1995. These fields are called LP543 and M68 by Guo *et al.* The measured OFAD coefficients in Table 2 are averages in which equal weight is given to all plates.

The focal lengths measured from the LP543 plates are approximately 3mm longer than those derived from the M68 series while the focal length determined from plates taken in the same color of the same field differed by less than a millimeter. The images were taken in uninterrupted sequence during the same night, which implies that an experimental error was made in the measurement of one series. The air mass at which the LP543 plates were exposed is somewhat higher than for those of M68 so an error may have been made in correcting for atmospheric refraction.

The models determined for each plate predict measured image positions on that particular plate with an rms precision of 1.5-2μ. However, the values of the positions predicted by the OFAD derived from plates within the same series differ by approximately 3-4μ rms from plate to plate.

The rms image position difference caused by the 3mm focal length discrepancy between the LP543 and M68 plates is 14μ. This is therefore the main source of error in the photographic measurement of the corrector's behavior. Since it is unlikely that the focal length changed between these two measurements, at least one of them must be incorrect. Since we don't know which one is wrong, the experimental focal lengths shown in Table 2 are averages of the two plate sets. This produces an rms uncertainty in the measured focal length of 2.2mm.

3.4. Predicted Behavior of the Corrector

The values for the paraxial focal lengths predicted by Zemax for each wavelength were assumed to be the "f" terms in the predicted OFAD.

The location of the principal ray of the central image was taken to be the center of a field. This ray was usually displaced slightly from the optical axis. Values for d_3 and d_5 were obtained by fitting the OFAD model to the positions given by Zemax for the centroids of a number of images distributed uniformly throughout the field. This procedure results in OFAD models which predict Zemax's theoretical image locations with an rms error of less than .5μ over the field in all colors.

As previously mentioned, the parameters given in Table 2 are not those of the corrector as it was designed, but reflect measurements made after construction. To estimate the effect of error in these measurements, Monte Carlo (MC) calculations were done during which the mechanical and optical parameters of the system were varied at random within the error bars which were estimated to have been maintained during manufacture, final assembly and measurement.

Every MC iteration creates a new, slightly different optical system which represents the way the corrector might have been put together. Each MC design was modeled in the same way as the nominal configuration, optimizing the image quality by refocusing after each iteration.

Image quality after a MC perturbation normally remained within the design specifications, i.e. with the monochromatic D_{70} not exceeding .25" in the center and .50" at the edge. In a small fraction of the MC iterations there was significant image degradation. The image center moved by as much as several hundred microns between iterations as a result of random tilts introduced by the Monte Carlo process.

New models were made after each iteration. First the field was centered and a model was made by the same process as in the un-perturbed case. Generally, the poorer the image quality, the poorer the rms fit of the new model. In some cases, the rms error of the new model was as much as 6μ over the field. The system focal lengths varied from the nominal values by an average of $\pm$5mm from after each Monte Carlo calculation. d_3 and d_5 also varied, but

3.5. Estimation of the Most Probable Values for the OFAD

The closest agreement between theory and measurement occurs with focal lengths .6mm less than the theoretical values. This is .9mm longer than the focal lengths of the M68 plates and 2.1mm shorter than the focal lengths of the LP543 series.

Either way, such small differences between theory and experiment give us confidence that the opto-mechanical parameters were maintained to better than expected precisions during fabrication. Since a focal length variation of up to 5mm could have been expected, the corrector's behavior clearly corresponds to its predicted performance well within the precision of this measurement of the OFAD.

Further evidence that the corrector was assembled properly comes from the fact that Guo et al were able to find an OFAD model which fit the experimental positions to a precision of 1.5-2μ, essentially the same as the precision with which we were able to fit a model to the theoretical image data. This implies that the corrector was assembled well and that manufacturing variations were minimal.

Having to choose between two slightly discrepant measured values for the focal length and a theoretical value in between them, we elected to use the theoretical OFAD coefficients "as is" with Argus. This model works well within the pointing precision of Argus, which should have allowed us to detect an imprecision of 3mm in the focal length. This gives us further confirmation that the system was assembled within specifications and that the theoretical model works well. It also implies that the focal lengths derived from the M68 plates are likely to be more correct than those from the LP543 measurements.

The accuracy of the model would be improved by making a better measurement of the paraxial focal length alone, modeling the field using the theoretical values for d_3 and d_5, with f and the location of the field center as the only variables. This can be done with a CCD that does not cover the entire field but the pitch of the CCD pixels must be known to very high precision.

Thus we are led to the interesting conclusion that the primary benefit of our having done a direct experimental measurement of field distortion was to demonstrate that the system works as expected and was almost certainly assembled properly and theoretical OFAD model is at least as good as the measured one and that it is accurate enough to use with Argus.

Table 3: OFAD Coefficients for Nominal PFCCD

Band	f.l. (mm)	d_3	d_5
U	11461.8	361.8	845000
B	11463.5	358.8	805000
V	11464.5	356.1	785000
R	11465.1	352.9	790000
I	11465.7	350.7	790000

- With 4mm filter and 6mm window
- d_3 and d_5 are dimensionless
- Uncertainties are mainly in focal length

The OFAD given by Zemax for the nominal PFCCD with a 4mm BK7 filter and 6mm fused silica window are given in Table 3. For best broadband performance, Argus should be focused through a blue filter and the B band OFAD used. The predicted coefficients are f=11464.6mm, d_3=357.9 and d_5=835000.

As previously mentioned, chromatic aberration occurs when the thickness of refractive material between the corrector and the detector is different from that called for in the design. In Argus and the photographic camera there is too little material and in the PFCCD there is too much. In principle this means that both instruments should be refocused for changes in wavelength. This is a small effect and can generally be ignored.

3.6. Image Quality

Recent measurements indicate that .70" fwhm images have been observed with the PFADC under very good conditions of seeing. These images are undersampled because the CCD currently used has a scale of .43"/mm.

This observation implies that with perfect seeing the PFADC is almost certainly capable of producing images with D_{70} of less than .5". The images are clearly very good, though the atmosphere and pixel size currently prevent us from directly measuring how closely the central images approach the level of $D_{70} \leq .25''$ that theory predicts.

3.7. Effect of Changing the Back Focal Distance

Changing a filter is generally equivalent to moving the instrument with respect to the corrector because different filters will generally have different optical thicknesses. Obviously the system has to be adjusted to compensate. One naturally reaches for the "focus" control to perform this operation.

Unfortunately, focusing the Blanco telescope moves the prime focus pedestal and detector up and down as a unit. This is not the correct way to adjust for an error in back focal distance. The focal plane of the detector should be moved with the corrector left stationary.

Moving the corrector/detector assembly forces a change in the back focal distance by relocating the corrector assembly with respect to the primary mirror. This "focusses" the image, but does so by moving the corrector away from its optimum location, degrading image quality and making a significant change in the telescope's effective focal length.

This is not a serious problem with Argus nor with the Prime Focus camera. Argus is permanently mounted with its fiber tips in the correct plane. Observations with the prime focus camera are made with a set of filters which are nominally 2mm thick. Even though these filters actually vary in thickness from 1.8 to 3mm, the variation is small enough so there is no significant image degradation, though as expected there is a noticeable change in focal length with wavelength and filter thickness.

The Prime Focus CCD (PFCCD) is another matter. Originally, the detector was permanently mounted 91.6mm behind the corrector. This is close to the optimum distance which it should have had (91.9mm) assuming the system had the 4mm filter and 6mm window for which the corrector was designed.

However, the PFCCD as built uses a fused silica window 8.85mm thick. The window is a meniscus lens which compensates for curvature of the CCD. It acts as a Barlow, significantly increasing the system focal length. At its nominal location, this lens would be expected to increase the focal length by 66.5mm, to 11542.9mm in V with a 5.1mm filter.

The focal length increases as we expect it will, by roughly the predicted amount though there is considerable incertainty in the measurement caused by a lack of certain knowledge of the exact CCD pixel size at the working temperature. Assuming it to be exactly 24μ, the measured focal length is 11531.5mm.

For the rest of this paper we will consider the dewar window to be a plane quartz window 8.85mm thick with a flat detector. If the dimensions are accurately known, it is straightforward to predict the perturbing effect of windows which are not flat or which have other than nominal thickness.

The PFCCD normally uses filters which are between 5mm and 10mm thick, meaning considerable excess material is placed in the back focal space. This extra material moves the detector optically closer to the corrector. Compensating for these back focus errors by moving the pedestal causes image degradation and a substantial change in the effective focal length of the telescope.

In principle, the proper way to compensate for the problems introduced by changing filters would be to have two focusing mechanisms; one like the present pedestal height control to focus the telescope and a second adjustment which moves the detector with respect to the corrector to maintain the back focal distance at the optimum value as filters are changed. There is no mechanism like this currently on the PFCCD.

Table 4 shows what happens when there is an error in back focal distance which has been corrected by moving the pedestal. Image size and focal length as a function of Back Focus Error (BFE) are listed. The table shows that the PF camera and Argus are both mounted very near to the optimal locations while the original PFCCD with 5-10mm filters and an excessively thick window is not.

In the second part of the table, the theoretical behavior of the PFCCD is shown with

Table 4: Image Quality

Instrument	BFE mm	f.l.(B) mm	D_{70} (Center)	D_{70} (32' dia.)	D_{70} (48' dia.)
Photographic Camera	0.0	11465.2	0.21"	0.24"	0.31"
Argus (Broad Band)	0.1	11464.6	0.35"	0.40"	0.47"
PFCCD (Nom. +3mm)	3.0	11440.6	0.30"	0.50"	0.70"
PFCCD (Nom. +2mm)	2.0	11448.3	0.24"	0.43"	0.63"
PFCCD (Nom. +1mm)	1.0	11456.0	0.18"	0.34"	0.44"
PFCCD (Nominal)	0.0	11463.7	0.20"	0.34"	0.41"
PFCCD (Nom. -1mm)	-1.0	11471.4	0.22"	0.34"	0.49"
PFCCD (Nom. -2mm)	-2.0	11479.0	0.24"	0.48"	0.72"
PFCCD (Nom. -3mm)	-3.0	11486.7	0.31"	0.53"	0.75"

- Focal lengths and image quality are given for B band
- 5mm filter causes -1.3mm of BFE
- 10mm filter causes -3.0mm of BFE

the detector at incremental locations 1mm apart, beginning with the detector 3mm farther from the corrector than optimum and ending with it 3mm closer. This listing clearly shows that BFE greater than 1mm should be avoided and BFE of more than 3mm causes significant image degradation.

Table 4 shows that theory predicts a linear change in effective focal length as a function of BFE at a rate of -7.68 mm of focal length change per mm change in BFE. This change could either be produced directly by physical change in BFE or by the insertion or removal of refractive material within the back focal space. For a material of thickness T and refractive index n, this causes a back focal shift of T(1-1/n) and a change in focal length of 7.68 times this value. The variation in n with wavelength causes some chromatism. About .5mm of the 4.4mm focal shift with wavelength in Table 2 is due to this effect.

This -7.67mm difference in focal length per mm of back focus change should not be confused with the a shift in the focal plane of the telescope. The two are strictly proportional, but the pedestal only needs to move by -.86mm to back focus change to change by, which in turn changes the focal length of the telescope by 7.67mm. This is probably the reason no one seems to have paid attention to this problem in the past. It is not intuitively obvious that refocusing by moving the pedestal by less than 1mm will cause the focal length of the telescope to change by almost 8mm. This relationship was used to calculate the effect on focal length caused by differences in the thicknesses of the filters used to measure the values in Table 2.

Due to a fortuitous error, we have an empirical demonstration that these conclusions are accurate. Plates were first taken in 1993 to measure the OFAD. After our observations, we realized that the camera had been incorrectly mounted with a back focus of 91.5mm. The focal plane was lowered by 2.11mm before a second run in 1995. This increased the measured focal length by 15.9mm. This change is almost exactly the 16.2mm predicted by the BFE/focal length relationship, indicating that the focal length shift occurred as predicted. As expected, the change did not make a significant change in the measured distortion coefficients.

The quality of the images also varies with BFE. An estimate of the magnitude of this effect is also given in Table 4. These estimates are very approximate because image shape varies with color and BFE, but they are nonetheless interesting. The values shown are based on theoretical analysis of the spot diagrams combined with some subjective weighting of the effect of wavelength variations to attempt to make them reflect the real situation as well as possible in a single number.

In its nominal configuration the image plane of the PFCCD is achromatic even though there is a 3.7mm shift in focal length from U to I. This is a manifestation of chromatic difference in distortion, not change in focal plane. No focus change with color is required if the filters are all the standard thickness and composition. For example, in Table 2 the PF Camera actually can be seen to have a 4.4mm shift in focal length over the same range. Of this, .5mm is a real shift in the focal plane with color caused by the filter and the window being thinner than the design calls for. The rest is distortion chromaticity.

It is clear from Table 4 that the image plane of the PFCCD was not originally in the optimum location. A spacer 2.1mm thick has been installed to remedy the situation. It keeps the BFE to less than 1mm with any filter in current use and thus changing filters now causes insignificant image degradation, though the focal length will change slightly as filter thickness is varied. This solution to the back focus problem is reliable and was easy to implement. It improves image quality and will provide a new fixed focal plane location which can be used to make a more precise determination of the system's focal length.

Moving the detector farther from the corrector in this way changes the telescope's focal length to a value very near to the optimum for filters 7.5mm thick. There will be a very slight focal shift with color. This shift will have the opposite sign of the shift in the photographic camera because the PFCCD has too much refractive material in the beam rather than too little, as is the case for the PF camera.

4. Conclusions

In summary, our results indicate that the corrector was fabricated and assembled well within specifications. Image quality is as expected. In excellent seeing, mages of of $D_{70} \leq .5''$ should be achievable over the entire field.

When the corrector was built, it was taken for granted that we would have to make direct photographic measurements to determine the distortion parameters of the field to use with Argus. We now realize that if a corrector like this has been assembled properly, the OFAD can be determined more accurately from theory combined with a measurement of the paraxial focal length. Full field measurements are needed only to verify image quality over the field. This realization will greatly simplify the proces of determining the OFAD of the new R/C corrector now being implemented for Hydra-CTIO.

This analysis also emphasised the importance of knowing the precise mechanical parameters of a system before attempting to do absolute astrometry. As an example, consider Chiu's classic 1976 paper where he measured the OFAD of the Mayall, Hale and Lick telescopes. Accurate values for the OFAD parameters are given, but there is no mention of the thickness of the filters used nor any way to determine this information.

The OFAD coefficients Chiu determined are almost certainly accurate for the system he measured. Unfortunately, it does not appear that these results could be usefully employed to do astrometry to the precision with which the OFAD coefficients were determined. Chiu gives an uncertainty of $\pm$.4mm the of the focal length of the Mayall telescope. This is equivalent to a 160μ uncertainty in filter thickness.

The observation that in more than twenty years no one seems to have noticed this problem probably comes from the fact that until the advent of multi-object spectroscopy few people tried to do absolute astrometry except with astrographs. Astrometry is more commonly done by an observer comparing a target field with an astrometric field measured with the same instrument.

Finally, Table 3 gives the final OFAD to use for the PFCCD in the default location with the correct window and filter thicknesses. It is straightforward to extrapolate these results to determine the focal length and estimate image quality for other configurations by using the offsets from the focal lengths in Table 4 and the -7.68 mm/mm relationship between e.f.l. and BFE. These changes should not have a significant effect on d_3 and d_5.

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