Impact of distortions on fiber position location in the Dark Energy Spectroscopic Instrument

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ABSTRACT

The Dark Energy Spectroscopic Instrument, to be located at the prime focus of the Mayall telescope, includes a wide field corrector, a 5000 fiber positioner system, and a fiber view camera. The mapping of the sky to the focal plane, needed to position the fibers accurately, is described in detail. A major challenge is dealing with the large amount of distortion introduced by the optics (of order 10% scale change), including time-dependent non-axisymmetric distortions introduced by the atmospheric dispersion compensator. Solutions are presented to measure or mitigate these effects.

Keywords: Optical Distortion, Fiber View Camera, Wide Field Corrector, Dark Energy, Focal Plane Mapping, Baryon Acoustic Oscillations

1. INTRODUCTION

The Dark Energy Spectroscopic Instrument (DESI\textsuperscript{1}), currently under construction, will measure the expansion history of the Universe using the Baryon Acoustic Oscillation technique. The spectra of 40 million galaxies over 14000 sq deg will be measured during the life of the experiment. A new prime focus corrector for the KPNO Mayall telescope will deliver light to 5000 fiber optic positioners. The fibers in turn feed ten broad-band spectrographs. A six-element corrector\textsuperscript{2} gives a useful field-of-view of 3.2 degrees diameter.

Wide field fiber-fed spectroscopic instruments often present challenges in the accurate positioning of fibers, with the degree of difficulty depending on the method of fiber positioning, the accuracy with which the as-built optics are known, and other factors such as the telescope focal ratio and fiber diameter. Systems employing fiber positioners (e.g., FMOS at Subaru\textsuperscript{3}) are not able to position fibers sufficiently accurately open-loop, so some external feedback mechanism is needed. For example, FMOS use a focal plane camera mounted on an X/Y stage to image portions of the back-illuminated fiber system. The solution chosen for DESI, is to use a large format CCD camera near the primary mirror vertex (the Fiber View Camera; FVC) and image the entire back-illuminated focal plane at once; this system is similar to that being implemented by the Subaru Prime Focus Spectrograph.\textsuperscript{4} Because the camera is outside the corrector, its focal plane should map nearly linearly to the sky. Absolute positioning on the sky is achieved with six acquisition/guide CCDs.

Because the acquisition CCD views the sky through the corrector, distortion introduced by the corrector optics must be accounted for. Additionally, one needs to be able to accurately map sky coordinates to the focal plane.
plane for target assignment. The DESI design presents several challenges to calibrating the distortion pattern. There is no wide-field imaging camera at the focal plane other than the acquisition/guide CCDs, which are located at the periphery of the focal plane. The DESI fiber size is small - 107 microns (1.5 arcsec). Finally, the DESI corrector employs a novel atmospheric dispersion compensator system, consisting of two counter-rotating lenses, each with one wedged surface, which causes the distortion pattern to be a function of the settings of the two lenses.

2. LAYOUT

The overall layout of the telescope and instrument is shown in Fig. 1. Key parameters for the instrument and optics are given in Table 1.

The corrector and focal plane layout is shown in Figure 2. The corrector contains six lenses overall. Two surfaces are aspheric. Four of the lenses are made of fused silica. The two lenses forming the ADC are made of S-BSL7. The two facing surfaces of the ADC lenses have a wedge of 0.25 degrees each. This wedge induces a differential chromatic aberration of the type introduced by Amici prisms, and the two lenses can be counter-rotated to operate like a classical ADC. The image quality is lower than that of the current Mayall corrector, but is satisfactory for fiber-fed spectroscopy. The corrector has overall (negative) power, increasing the focal ratio from 2.9 to 3.8 (average).
### Table 1. DESI Key Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final focal ratio</td>
<td>$f/3.8$</td>
</tr>
<tr>
<td>Mean plate scale</td>
<td>14.19 arcsec mm$^{-1}$</td>
</tr>
<tr>
<td>Wavelength range</td>
<td>360 - 980 nm</td>
</tr>
<tr>
<td>Target fiber positioneers</td>
<td>5000</td>
</tr>
<tr>
<td>Fiducial fibers</td>
<td>123</td>
</tr>
<tr>
<td>Acquisition CCD dimension</td>
<td>$1024 \times 2048$ pixels</td>
</tr>
<tr>
<td>Acquisition CCD pixel size</td>
<td>15µ per pixel</td>
</tr>
<tr>
<td>Fiber View Camera Demagnification</td>
<td>24.06</td>
</tr>
<tr>
<td>GFA central wavelength</td>
<td>640 nm</td>
</tr>
<tr>
<td>Fiducial central wavelength</td>
<td>470 nm</td>
</tr>
</tbody>
</table>

**Figure 2. Layout of the corrector and focal plane.**

The surface of best focus is not flat, but rather is aspheric in shape, convex to the corrector. The corrector and focal plane have been optimized to ensure that the incoming beam is telecentric (perpendicular to the focal plane) to within a degree at most wavelengths. The focal plane is equipped with both motorized fiber positioners, for spectroscopy of target objects, and a set of fiducial fibers, which are fixed in position and are measured in advance to provide reference locations for metrology. The target and fiducial fibers can be back illuminated with LEDs at a wavelength of 470 nm.

Around the periphery of the focal plane are located ten “guide/focus/alignment” (GFA) CCDs (3). Four of these are used as wavefront sensors for focus and alignment adjustment; they are not used for field acquisition. The remain six are equipped with FLI ML230 1024x2048 (active area) CCDs and are used for field acquisition and guiding. Each CCD is mounted on a custom fixture and is equipped with a filter with central wavelength 640 nm. Additionally, two fiducials are attached to each fixture, and the locations of the fiducials relative to the CCD is measured to high precision. These fiducials tie the on-sky astrometric solutions obtained by the
acquisition CCDs to the rest of the focal plane.

A fiber view camera (FVC) is located just below the vertex of the primary mirror. This camera has a 600 mm telephoto lens and a Kodak 50100 CCD with a $6132 \times 8165$ array of 6 micron pixels. The entrance aperture is adjustable; the nominal diameter is 38 mm. The camera is used to image the back-illuminated fiducials and measure any mis-centering of the target fibers relative to their desired location.

3. DISTORTION

The nominal linear scale factor, 14.19 arcsec mm$^{-2}$, is the mean scale between the center and the edge of the field-of-view at 406.17 mm radius. The main distortion relative to this linear approximate is a radial fifth-order pattern with a peak amplitude of 6.6 mm. This pattern is shown in the left side of Figure 4. Subtracting this pattern leaves a residual dipole distortion pattern as shown on the right side of Figure 4. The exact amplitude of the radial and dipole distortions depends on the orientation of the ADC lenses, and in particular, is a function of both the zenith distance $z_d$ and the parallactic angle $\psi$ (which is the angle between the direction of apparent North on the focal plane and the direction of the zenith.) Figure 5 shows the orientation of these lenses needed to achieve the optimal image quality as a function of zenith distance for an instrument at the elevation of the Blanco telescope. The distortion pattern changes by 100 microns peak as the lenses are adjusted through their full range of travel.
Figure 4. Left: Radial distortion pattern. Right: Residual dipole distortion pattern.

The distortion pattern can be modeled as follows. Since the pattern is mainly radial, at any location in the focal plane the distortion pattern can be decomposed into components in the radial ($\Delta r$) and tangential ($\Delta t$) directions. The location itself is expressed in polar coordinates ($r$ and $\theta$). The distortion patterns are expressed in the following form:

$$
\Delta r = \sum_{n=0}^{5} [A_{nz} + A_{nc} \cos m\theta + A_{ns} \sin m\theta] r^n \tag{1}
$$

$$
\Delta t = \sum_{n=0}^{5} [B_{nz} + B_{nc} \cos m\theta + B_{ns} \sin m\theta] r^n,
$$

where $m = 1$ for $n$ even and $m = 2$ for $n$ odd, $\Delta r = r - r_0$, $r$ is the actual position of an image, and $r_0$ is the predicted position in the absence of distortion.

The equations introduce 36 coefficients total. In practice, some are negligible (e.g., all $n = 5$ sin and cos terms) or redundant (e.g., $B_{0c}$ and $B_{0s}$) so in practice only 25 coefficients are actually used. These coefficients are valid only for a single setting of the ADC lenses; thus each coefficient is further fit with a third-order polynomial as a function of $\tan z_d$ to account for the variation with ADC angles.

Raytracing shows that the use of 123 fiducials to solve for the coefficients is satisfactory, with rms residuals of 2 microns at the most extreme zenith distances.

In the focal plane in the vicinity of the GFAs, the full distortion equation is awkward to use; for these, a third-order approximation is used:

$$
\Delta x = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^2 + a_6 x^3 + a_7 x^2 y + a_8 xy^2 + a_9 y^3, \tag{2}
$$

where $x, y$ are coordinates aligned with and centered on a CCD and $\Delta x = x - x_0$ is the difference between the distorted position on the CCD and $x_0$, the predicted position in the absence of distortion. A similar equation is used for computing $\Delta y$. These equations are valid for both the GFA CCD and the two comounted fiducials.
The coefficients $a_0$, etc. depend on the position angle of the GFA in the focal plane and on the parallactic angle. To a good approximation, each coefficient can be expressed in the form

$$a_0 = a_{z0} + a_{c0} \cos \theta + a_{s0} \sin \theta,$$

where $\theta$ is the position angle relative to the zenith direction.

Finally, each of the coefficients in Eq. 3 can be expressed as a cubic function of $\tan z_d$.

These equations express the distortion in coordinates centered on the CCD. Additionally, we need to express the center of the CCD $x_c, y_c$ relative to the field center. For a GFA at position angle $\theta$, the following equation is used:

$$x_c = a + b \cos \theta + c \sin \theta + d \cos 2\theta + e \sin 2\theta,$$

with a similar equation for $y_c$. The coefficients $a, b, c$ etc. are again expressed as a cubic function of $\tan z_d$.

4. CHROMATIC EFFECTS

The ADC action is not perfect, so monochromatic centroids as measured by the fiducials and the GFA will be offset slightly from the polychromatic centroid which are desired for positioning the target fibers. The amplitude is of order $10^{-20}$ microns, depending on wavelength. The deviation between the monochromatic and polychromatic centroids can be broken down into two components: 1) a radial dependence that can be approximated with a fifth order polynomial, and 2) a constant offset primarily in the zenith direction. The radial dependence does not depend on the ADC setting as a function of zenith distance; the constant offsets do and are fit with third-order polynomials in $\tan z_d$.

The chromatic effects for wavelength 640 nm and $z_d = 45^\circ$ are show in Fig 6.
5. CHIEF RAY

The Fiber View Camera samples only a small portion of the outgoing beam from the back-illuminated fibers, around the chief ray. Certain aberrations, such as coma, introduce an offset between the chief ray and the centroid of the full beam. The offset can be as large as 13 microns. The form of the offset has the same behavior as that of the chromatic effects described in the previous section and are handled in the same way. Figure 7 shows a typical pattern. The offset is only evaluated at a wavelength of 470 nm, that used by the fiber back-illumination system.

6. POLISHING ERRORS

Because the beam of the FVC is so much smaller than the full beam of the telescope, polishing errors have a much bigger impact on spot positions at the FVC focal plane than they do for the telescope itself. For the metrology camera\textsuperscript{4} designed for the Subaru Prime Focus Spectrograph, such errors are large enough that the camera aperture has been made deliberately large (necessitating a Schmidt design for the camera) to ameliorate these effects. Here, where the correctors lenses are still being fabricated, the impact of polishing errors has been calculated by assuming that the lenses just meet the polishing specifications.

The polishing specifications are divided into four spatial frequency ranges: ultra-high, high, midscale, and low. Numerical values are given in 2. The exact choice of frequency limits for each range varies by surface. The form of the specification is different for each range and can be expressed as an rms height error, slope error, or peak-valley limit. To put all of these on a common footing, the power spectral density function (the absolute square of the Fourier transform of the 2-dimensional surface height error) is assumed to have a power law on frequency with slope $-3$. The beam size varies from 1.3 mm at back surface of C4 to 7.9 mm at the front surface of C1. It is assumed that power on wavelengths smaller than the beam size does not contribute to the centroid error (just to the overall image size). For wavelengths larger than 500 mm, the distortion function will measure and remove any errors on those scales, and thus power on those scales will not contribute either. By placing sinusoidal surface height errors of different frequencies on each surface, it was found that the rms centroid error $\Delta r_{rms}$, expressed in microns, at the focal plane is given by

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{monochromatic_v_polychromatic_centroid}
\caption{Offset between monochromatic centroid at 640 nm and a polychromatic centroid covering 360-1000 nm.}
\end{figure}
\[ \Delta r_{\text{rms}} \approx 0.33 \Delta s_{\text{rms}} z_s, \]

where \( \Delta s_{\text{rms}} \) is the rms slope error in radians and \( z_s \) is the distance of the surface from the focal plane in mm. Table 2 gives the detailed breakout of error budget and contributions to centroid errors for each surface. It is seen that errors are more or less uniformly distributed across all surfaces and frequency intervals. The combined rms is about 6.4 microns (1–d.)

Table 2. Polishing Error Impact On FVC Centroids (rms radius)

<table>
<thead>
<tr>
<th>Lens</th>
<th>Side</th>
<th>LSF (microns)</th>
<th>MSF (microns)</th>
<th>HSF (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Front</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Rear</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>C2</td>
<td>Front</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rear</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ADC1</td>
<td>Front</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rear</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ADC2</td>
<td>Front</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rear</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>C3</td>
<td>Front</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rear</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>C4</td>
<td>Front</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rear</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

7. ALIGNMENT ERRORS

The corrector assembly will not be perfect, and small decenter and tilt errors will be present for all lenses. These errors will modify the distortion pattern relative to that of a perfectly assembled corrector. The allocated error
Figure 8. Example distortion pattern introduced by alignment errors. RMS errors are 12 \( \mu \).

varies by lens but is typically 200 microns in decenter and 180 microradians in tilt; the complete list of allocations is given in 2. The impact was tested by running simulations in which each optical element was displaced by the full error allocation in tilt and decenter but at randomly oriented angles. Figure 8 shows a typical example of how centroids move as a consequence of these displacements. The pattern is complex, with an rms motion of 12 microns. The pattern can be removed by modifying the coefficients in the distortion equation (Eq. 1).

8. FIELD CENTER

Beside distortion, the optics introduce a translation in the image of the sky on the focal plane; this shift can reach 1 arcminute for extreme zenith distances. The shift in coordinates is modeled as a third order polynomial in \( \tan z_d \). It is applied as a correction to the telescope pointing in order that a particular sky position be centered on the focal plane.

9. THERMAL EFFECTS

The focal plane is fabricated from aluminum, so thermal effects can be modeled as simply a change in scale. The GFA assembly is more complex, so thermal effects are modeled as a) motion of the CCD/fiducial assembly with respect to the mounting base, and b) motion of the GFA fiducials with respect to the CCDs. These thermal effects are all linear in temperature and are determined from FEA models.

Aside from the above, thermal effects on telescope dimensions and lens properties have only a minimal impact on distortion.

10. ADDITIONAL ISSUES - APPARENT COORDINATES

For completeness, other factors that must be accounted for by the fiber positioning software are listed here, although they are external to the corrector. The Mayall telescope is an equatorial mount design, which means that the DESI focal plane will always have one axis aligned with apparent North. Precession and other effects cause the field to rotate relative to the center; rather than go through the full equations for precession, etc., it
is simpler to implement the equations as a rotation (plus a small change in obliquity if nutation is included). This approach has the advantage that it is straightforward to include the impact of polar axis misalignment, since this effect simply introduces additional rotations. Aberration causes a small change in scale factor but is otherwise conformal. Differential refraction is computed in the standard way. Polar motion is not included.

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REFERENCES