A Curvature-compensated Corrector for Drift-Scan Observations

PAUL HICKSON
Department of Physics and Astronomy, University of British Columbia, 2219 Main Mall, Vancouver, BC V6T 1Z4, Canada; paul@astro.ubc.ca

AND
E. HARVEY RICHARDSON
Department of Mechanical Engineering, University of Victoria, Victoria, BC V8W 3P6, Canada; harveyr@me.uvic.ca

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ABSTRACT. Images obtained by drift-scanning with a stationary telescope are affected by the declination-dependent curvature of star trails. The image displacement due to curvature and drift-rate variation increases with the angular field of view and can lead to significant loss of resolution with modern large-format CCD arrays. We show that these effects can be essentially eliminated by means of an optical corrector design in which individual lenses are tilted and decentered. A specific example is presented of a four-element corrector designed for the Large-Zenith Telescope. The design reduces curvature errors to less than 0.074″ over a field of view centered at 49° declination. By changing the positions and tilts of the lenses, the same design can also be used for any field centers between 0° and ±49°.

1. INTRODUCTION

In recent years, the technique of time delay integration (TDI, also known as drift-scanning) has become well established in astronomy (McGraw, Angel, & Sargent 1980; Hall & Mackay 1984). For this technique, the telescope remains stationary or tracks at a nonsidereal rate, resulting in a steady drift of images across a CCD detector (which is aligned so that the drift direction coincides with the orientation of the CCD columns). The CCD is scanned continuously at a rate that moves the photon-produced charge along the columns at the same speed as the optical image. This prevents charge spread and results in sharp images with an integration time equal to the drift time of the image across the CCD.

TDI offers several benefits compared with conventional imaging. A chief advantage is that variations in pixel-to-pixel sensitivity are greatly reduced because the response is averaged over all CCD pixels in each column. The required flat-field correction is essentially one-dimensional. This results in as much as a factor of 45 reduction in background variations, after flat-field correction, for a 2048 × 2048 pixel CCD. Because background variations are often a limiting factor in photometry of faint or low surface brightness objects, even conventional telescopes are sometimes operated in drift-scan mode in order to take advantage of this and other benefits (Shectman et al. 1992; Schneider, Schmidt, & Gunn 1994).

The TDI technique is particularly important for telescopes that have no tracking capability. Liquid-mirror telescopes (LMTs) employ rotating primary mirrors that are surfaced with a liquid metal such as mercury. Because the rotation axis must be vertical, these telescopes are best suited for observations near the zenith, although it is possible in principle to observe at large-zenith angles using specially designed correctors (Richardson & Morbey 1987; Borra, Moretto, & Wang 1995). By operating their CCD cameras in TDI mode, such zenith-pointing telescopes can survey large areas of sky as the Earth rotates. For example, the UBC-NASA Multiband Survey (Hickson & Mulrooney 1998) employs a 2048 × 2048 pixel CCD camera at the prime focus of the 3 m LMT of the NASA Orbital Debris Observatory (NODO) (Potter & Mulrooney 1997). This survey covers 20 deg² and reaches m\textsubscript{ab} = 20.4 in a single TDI scan through medium-band filters.

For TDI observations, it is essential that the images of all objects drift at the same rate, on parallel linear tracks, or image spread will result. For this reason, it is important that the telescopes used for TDI observations be equipped with correctors that reduce the pincushion or barrel distortion that is usually present. For a prime-focus configuration, this normally requires a corrector having at least four optical elements.

After the removal of telescope distortion, however, there remains a more fundamental difficulty. With the exception of objects on the celestial equator, the image tracks are not straight but concave, in the direction of the nearest celestial pole. Furthermore, the linear rate of image motion is a function of declination, so there is no universal CCD scan rate that will prevent image spread. These effects can lead to significant image degradation for telescopes at moderate latitudes employing large-format CCD cameras (Gibson & Hickson 1992).

An elegant solution to this problem has been realized with the great-circle camera (Zaritsky, Shectman, & Breithauer 1996), which uses a combination of rotation and motion in
declination to trace a great circle on the sky. As a result, the nonlinear effects are minimized. While the great-circle camera does reduce the curvature effects, it has a fundamental limitation. Because of the physical motion required of the camera, the length of the great-circle track is limited. This restriction is particularly severe for zenith-pointing telescopes that cannot move to follow a great-circle track. TDI observations would need to be interrupted frequently while the camera position is reset to follow different great-circle arcs.

In this paper, we propose a new solution to the problems of star-trail curvature. By offsetting and tilting the lenses of a suitably designed corrector, one can introduce an asymmetric field distortion that compensates for the nonlinear motion of the images. As a result, the images track in parallel straight lines at a common constant rate with high accuracy. This effect can be achieved without introducing any additional optics in the light path. Moreover, the same corrector can serve telescopes at different latitudes just by repositioning the optical elements.

The paper is organized as follows. In § 2, we analyze the geometry of the star-trail curvature and derive formulae for the resulting image displacements. In § 3, we describe an example of a prime-focus corrector that compensates for these effects. The performance of the corrector is examined in § 4, followed by our conclusions.

2. ANALYSIS OF STAR-TRAIL CURVATURE

Star-trail curvature effects have been discussed previously by Gibson & Hickson (1992), Stone et al. (1996), and Cabanac (1998), who give approximate formulae for the distortions. Our aim here is to present a simple, exact derivation or the relevant relations as well as useful approximate formulae. The geometrical picture is illustrated in Figure 1. The circle represents the celestial sphere, which, for convenience, we take to have unit radius. Its center is the origin of a three-dimensional Cartesian coordinate system \((x, y, z)\). The \(z\)-axis is aligned with the North Celestial Pole (NCP); hence, the \(x-y\) plane intersects the sphere at the celestial equator. For clarity, the \(y\)-axis, which is perpendicular to the page, is not shown in the figure. Now let us consider a telescope whose axis lies in the \(x-z\) plane at an angle \(\delta_0\) to the celestial equator. Therefore, \(\delta_0\) is the declination of the center of the telescope field of view. For a zenith-pointing telescope, \(\delta_0\) is equal to the latitude of the observatory. In the telescope’s focal plane, perpendicular to the optical axis, we set up a two-dimensional Cartesian coordinate system \((X, Y)\), oriented so that the \(Y\)-axis is parallel to the \(y\)-axis. The optical axis passes through the origin of the \(X-Y\) coordinate system, so that \(X\) and \(Y\) give the north and east position of the image with respect to the field center. It is convenient to work with the projection of the focal plane through the telescope optics and back onto the celestial sphere. Figure 1 shows the projected focal plane that is tangent to the celestial sphere at the point where it is intersected by the optical axis. Since the sphere has unit radius, the values of \(X\) and \(Y\) can be converted to physical distances in the focal plane by multiplying by the telescope’s effective focal length \(F\).

Now let us consider the sidereal motion of a star at arbitrary declination \(\delta\). As the Earth rotates, the line of sight to the star sweeps out a cone, which is indicated in Figure 1 by the asterisks. The intersection of this cone with the tangent plane defines the track of the star’s image on the focal plane. This track is by definition a conic section, which is an ellipse, parabola, or hyperbola depending on whether the declination \(\delta\) is greater than, equal to, or less than the co-angle \(\pi - \delta_0\) (for a zenith telescope, the colatitude).

The equation of this track is easily derived. The equation of the cone is

\[
X^2 + Y^2 = z^2 \cot^2 \delta_0, \tag{1}
\]

while the plane is defined by

\[
x = -X \sin \delta_0 + \cos \delta_0, \\
z = X \cos \delta_0 + \sin \delta_0. \tag{2}
\]

Eliminating \(x\) and \(z\), and setting \(y = Y\), we obtain

\[
(sin^2 \delta - \cos^2 \delta_0)X^2 - 2 \sin \delta_0 \cos \delta_0 X
+ (Y^2 + 1) \sin^2 \delta - \sin^2 \delta_0 = 0. \tag{3}
\]

The northerly displacement \(X\) of the image as a function of
east-west position $Y$ is given by the solution

$$X = \frac{\sin \delta \cos \delta}{\sin^2 \delta - \cos^2 \delta}$$

$$\times \left(1 - \left(1 - \frac{(\sin^2 \delta - \cos^2 \delta)(1 + Y^2) \sin^2 \delta - \sin^2 \delta_0}{\sin^2 \delta_0 \cos^2 \delta_0}\right)\right)^{1/2}.$$

This equation has a simple Taylor series expansion:

$$X = \tan(\delta - \delta_0) + \frac{Y^2}{2 \cot \delta} + \cdots.$$  

From this, we see that the local radius of curvature $R$, measured at the center of the track, is

$$R \equiv \left|\frac{d^2X}{dY^2}\right|^{-1} = \cot \delta,$$  

which, in physical units, is $F \cot \delta$. Note that this curvature depends only on the declination of the object and is independent of the pointing direction or location of the telescope. Equation (5) may be written

$$X = X_0 + \Delta X,$$  

where $X_0 = \tan(\delta - \delta_0)$ denotes the $X$-coordinate of the center of the track ($Y = 0$) and $\Delta X$ measures the departure of the track from linearity, in the north-south direction. Except at very large declinations, the radius of curvature of the trails is nearly constant across the field, and we may use the value at the field center:

$$\Delta X = \frac{1}{2} Y^2 \tan \delta_0.$$  

Now let us consider the rate at which the images move. Let $\phi$ be the azimuth angle of the object in the $(x, y, z)$ coordinate system, referenced to the $x$-axis. As the Earth rotates, $\phi$ increases at a constant rate. From the definition of $\phi$,

$$Y = y = x \tan \phi.$$  

Substituting this in equation (1) and using equation (2) to eliminate $z$, we obtain

$$Y = \frac{\sin \phi}{\sin \delta_0 \tan \delta + \cos \delta_0 \cos \phi}.$$  

From this, we see that the rate of image motion is a function of both the declination of the object and the declination of the field center. For a given azimuth angle $\phi$, objects that cross the field north of the field center ($X_0 > 0$) will have smaller $Y$-values than those passing south of the field center (in the Northern Hemisphere; the opposite is true in the Southern Hemisphere).

Let $Y = Y_0 + \Delta Y$, where $Y_0$ denotes the $Y$-coordinate of a star, having the same azimuth angle, whose track passes through the field center ($X_0 = 0$). From equations (5), (7), and (10), we obtain

$$\Delta Y = -X_0 Y_0 \left(\frac{1 + \tan \delta \tan \delta_0}{\tan \delta + \cot \delta_0 \cos \phi}\right).$$  

The factor in parentheses typically varies very slowly across the field and may be replaced by its value at the field center. This gives

$$\Delta Y \approx -X_0 Y_0 \tan \delta_0.$$  

### 3. Correcting Curvature Effects

In the previous section, exact and approximate formulae were developed to describe the distortions produced by the star-trail curvature. For most practical situations, the approximate formula of equations (8) and (12) give more than enough accuracy. The maximum distortion can be found by setting $X_0$ and $Y_0$ equal to half the north-south and east-west extent of the detector, respectively. The two distortions are closely related. For a square detector, the east-west image smear, which is due to rate variations, is 4 times as large as the north-south smear, which is due to curvature. (Because the distortion changes sign as the star crosses the field, the east-west image smear is twice $\Delta Y$.)

As an example, let us consider observations of a star at $\delta = 45^\circ$ using a CCD camera with a square field of view of 20' ($X_0 = Y_0 = 0.002909$ rad). Equations (8) and (12) give maximum distortions of 0.000004231 and 0.000008462 rad (0.873 and 1.745), respectively, for $\Delta X$ and $\Delta Y$. These are significant distortions that would cause unacceptable image degradation for TDI observations.

Fortunately, it is possible to eliminate to a large extent these effects for zenith telescopes, located even at moderately high latitudes, by means of an asymmetric corrector. The idea is to use a combination of decenters and tilts of the optical elements in order to introduce distortion that closely matches that described by equations (8) and (12), but with an opposite sign. Such a design has been recently developed for the Large-Zenith Telescope (LZT), which employs a 6 m f/1.5 liquid-mercury primary mirror (Hickson et al. 1998). The corrector was de-
signed by E. H. Richardson to specifications provided by P. Hickson. The required image quality was a 50% encircled energy diameter (EED) of 0.4 or less over a 10.5 × 21′ field of view (in order to match a 2048 × 4096 pixel CCD). The procedure was to aim first for a corrector with zero distortion. Global optimizations were employed to keep the maximum clear aperture relatively small, in order to reduce cost, while meeting image-quality specifications over the required field of view. The corrector was then reoptimized to introduce the required sidereal distortion. In this process, curvatures, tilts, decenterers, and spacings were all allowed to change. At first, a wedge was allowed for one element, but it was found that this could be eliminated, allowing the same lenses to be used at different latitudes. After optimization for the +49°17′ latitude of the LZT, the lens curvatures and thicknesses were frozen.

In order to illustrate the flexibility of the corrector, the design was then reoptimized for the +32°59′ latitude of the NODOLMT and the equator (0°), allowing only the tilts, decenterers, and locations of the lenses to change.

The optical configurations, for latitudes +49°17′ and +32°59′, are illustrated in Figures 2 and 3. The corrector employs four lenses that are all fabricated from the same optical material. The details of the corrector design are provided in Table 1, which gives parameters for the two asymmetric configurations and for the symmetric case. Each row of Table 1 describes an optical surface, in the order in which light reaches it. Light enters parallel to the z-axis of a Cartesian coordinate system aligned with surface 1 (the parabolic reflector). Columns (7), (8), (10), and (11) describe translations and rotations of the coordinate system in which subsequent surfaces are defined.

![Fig. 2.—The LZT corrector configured for observations at +49°17′ declination.](image)

![Fig. 3.—The LZT corrector configured for observations at +32°59′ declination.](image)

### Table 1

| Surface | Type | R (mm) | A (mm) | 0° | t (mm) | +32°59′ | +49°17′ |
|---------|------|--------|--------|----|--------|---------|---------|
|         |      |        |        |    |        |         |         |
| 0       | Object | ∞      | ...    | ...| 0.000  | ...     | ...     |
| 1       | Mirror | -18000.000 | K = -1.000 | -853.542 | 0.870 | ...     | ...     |
| 2       | BK7   | -201.785 | ...    | -30.000 | 0.000  | -8.193  | 3.584   |
| 3       | Air   | -200.549 | ...    | -253.805 | -0.660 | ...     | ...     |
| 4       | BK7   | -799.735 | ...    | -12.000 | 0.000  | -11.002 | -5.250  |
| 5       | Air   | -105.956 | 0.686E-08 | -56.097 | -1.083 | ...     | 0.646   |
| 6       | BK7   | 594.610  | ...    | -20.000 | 0.000  | 11.817  | 2.839   |
| 7       | Air   | 236.851  | -0.212E-07 | -40.216 | 0.782  | ...     | 0.980   |
| 8       | BK7   | -131.008 | ...    | -50.000 | 0.000  | -11.998 | 0.822   |
| 9       | Air   | -540.262 | 0.227E-06 | -15.193 | 0.260  | ...     | 0.358   |
| 10      | BK7   | ∞       | ...    | -7.000  | 0.000  | 0.169   | -1.023  |
| 11      | Air   | ∞       | ...    | -6.000  | 0.000  | ...     | 0.000   |
| 12      | Quartz| ∞       | ...    | -5.000  | 0.000  | ...     | 0.000   |
| 13      | Air   | ∞       | ...    | -11.000 | 0.000  | ...     | 0.000   |
| 14      | Image | ∞       | ...    | ...     | ...    | ...     | ...     |
Surfaces following such a transformation are aligned on the local mechanical axis (z-axis) of the new coordinate system. The new mechanical axis remains in use until changed by another transformation. In these transformations, the translation applied before the rotation.

The column headings for Table 1 are as follows: (1) surface number, (2) material that the light enters when crossing the surface, (3) radius of curvature of the surface, (4) the aspheric constant A (except for surface 1, which is a pure conic section), defined by the equation

\[ \Delta z = \frac{r^2}{1 + \left[1 - (1 + K)\frac{r^2}{R^2}\right]^{1/2}} + Ar^4. \]

\[ (13) \]

where \( r \) is the distance from the z-axis to a point on the surface and \( \Delta z \) is the z-displacement of the surface with respect to a plane, (5) distance along the z-axis from this surface to the next for the 0° configuration, (6) change in the z-axis distance required for the +32°59′ configuration, (7) displacement of the origin of the coordinate system at the surface, and (8) rotation angle of the coordinate system at the surface. Columns (9), (10), and (11) are the same as columns (6), (7), and (8), but for the +49°17′ configuration.

\[ \text{TABLE 2} \]

| 100% EED for +49°17′ |
|----------------------|
| 400 nm | 500 nm | 600–800 nm |
| X (deg) | Y (arcsec) | 50% (arcsec) | 80% (arcsec) | 100% (arcsec) | 50% (arcsec) | 80% (arcsec) | 100% (arcsec) | 50% (arcsec) | 80% (arcsec) | 100% (arcsec) |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
| -0.088 | 0.000 | 0.353 | 0.502 | 0.698 | 0.162 | 0.265 | 0.351 | 0.172 | 0.244 | 0.649 |
| 0.000 | 0.000 | 0.154 | 0.252 | 0.524 | 0.072 | 0.107 | 0.132 | 0.176 | 0.259 | 0.676 |
| -0.088 | 0.088 | 0.371 | 0.509 | 0.780 | 0.153 | 0.291 | 0.576 | 0.203 | 0.320 | 0.918 |
| 0.000 | 0.088 | 0.220 | 0.313 | 0.853 | 0.097 | 0.154 | 0.357 | 0.158 | 0.264 | 0.714 |
| -0.088 | 0.088 | 0.238 | 0.631 | 1.453 | 0.162 | 0.222 | 0.584 | 0.218 | 0.351 | 0.787 |
| -0.088 | 0.176 | 0.396 | 0.568 | 1.297 | 0.196 | 0.357 | 1.107 | 0.285 | 0.495 | 1.184 |
| -0.088 | 0.088 | 0.396 | 0.568 | 1.297 | 0.196 | 0.357 | 1.107 | 0.285 | 0.495 | 1.184 |
| -0.088 | 0.176 | 0.370 | 0.569 | 1.826 | 0.353 | 0.533 | 1.478 | 0.250 | 0.417 | 1.019 |
| -0.088 | 0.176 | 0.370 | 0.569 | 1.826 | 0.353 | 0.533 | 1.478 | 0.250 | 0.417 | 1.019 |

\[ \text{TABLE 3} \]

| Image Displacements for +49°17′ |
|------------------|
| X (deg) | Y (arcsec) | λ (nm) | ΔX | ΔY |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| -0.088 | 0.176 | 400 | 1.131 | 1.162 | 1.130 | 1.123 | 0.032 |
| -0.088 | 0.176 | 600 | 1.131 | 1.123 | 1.130 | 0.919 | 0.040 |
| -0.088 | 0.176 | 800 | 1.131 | 1.113 | 1.130 | 1.068 | 0.065 |
| -0.088 | 0.176 | 1000 | 1.131 | 1.113 | 1.130 | 1.068 | 0.065 |
| -0.088 | 0.132 | 400 | 0.636 | 0.614 | 0.000 | 0.035 | 0.041 |
| -0.088 | 0.132 | 600 | 0.636 | 0.575 | 0.000 | 0.025 | 0.066 |
| -0.088 | 0.132 | 800 | 0.636 | 0.611 | 0.000 | 0.022 | 0.033 |
| -0.044 | 0.088 | 400 | 0.283 | 0.264 | 0.056 | 0.554 | 0.023 |
| -0.044 | 0.088 | 600 | 0.283 | 0.283 | 0.565 | 0.526 | 0.039 |
| -0.044 | 0.088 | 800 | 0.283 | 0.240 | 0.565 | 0.513 | 0.066 |
| 0.044 | 0.088 | 400 | 0.283 | 0.259 | -0.565 | -0.605 | 0.047 |
| 0.044 | 0.088 | 600 | 0.283 | 0.259 | -0.565 | -0.569 | 0.024 |
| 0.044 | 0.088 | 800 | 0.283 | 0.259 | -0.565 | -0.553 | 0.027 |

4. PERFORMANCE OF THE CORRECTOR

The corrector provides a 24′ diameter unvignetted field of view. The effective focal length is 10.000 m, which gives an image scale of 20.63 m. Table 2 gives the 50%, 80%, and 100% EEDs for various field angles and wavelengths. The median values of the 50% EED at 400, 500, and 600–800 nm are 0.353, 0.162, and 0.203, respectively. These values are well below typical ground-based seeing disk diameters at these wavelengths, which are typically 0.6 or more at the best astronomical sites, so the corrector will not appreciably degrade the image. There is a small, but nonnegligible, focus shift between the three wavelength regions. Since the corrector is intended to be used with common broadband (or narrower) filters, this is not an issue for image quality.

Table 3 summarizes the distortion characteristics of the corrector. For the field angles specified in columns (1) and (2), columns (4), (5), (6), and (7) give the target and achieved image displacements. The difference in position, which corresponds to the distortion error, is listed in column (8). It can be seen from Table 3 that the distortion errors are typically a few tens of milliarcseconds, with the maximum error being 0′74. Since these residuals are much less than the seeing diameter, the corrector effectively eliminates star-trail curvature and rate differentials as a source of image degradation.

Considering the 6 m diameter and fast focal ratio of the primary mirror, the corrector is very compact, having an overall length, from first element to focal plane, of 50.5 cm. The larg-
est lens, which has spherical surfaces, has a diameter of only 34 cm. This is quite small for a 6 m f/1.5 telescope, which helps reduce the cost of the corrector. The three smaller lenses have diameters less than 15 cm. The rear side of each is a low-order aspheric surface.

5. SUMMARY AND DISCUSSION

We have presented an analysis of star-trail curvature effects. If uncorrected, these effects can result in substantial image degradation in drift-scan images obtained with large-format CCDs. A new technique has been described in which the curvature effects are compensated by means of a corrector lens employing decentered and tilted elements. As an example, we have discussed a compensated prime-focus corrector designed for the 6 m LJT.

The corrector requires no additional optical components other than the four elements normally needed to remove telescope aberrations, including distortion. By varying the positions of the elements, the corrector can be used with a zenith-pointing telescope at any latitude up to at least ±50°. It provides a 24′ unvignetted field with a median 50% EED of 0′.2 and a maximum distortion error on the of order 0′.07.

An interesting question is how much image quality is sacrificed in order to achieve the distortion correction. The instantaneous image quality of the 49° configuration is slightly worse than that of a similar corrector optimized for zero distortion. However, the difference is much less than the improvement in integrated image quality provided by the distortion correction. For example, reoptimizing the corrector for zero distortion, thus allowing the lens shapes to change as well as the separations, results in only a 25% improvement in the worst case rms image spot diameters.

Can this design be extended to larger fields of view? How would the result compare with that of the great-circle camera? While we have not explicitly investigated this question, during the course of our work, an earlier design was made for a corrector that has a 30′ diameter field of view (in order to accommodate a 4096 × 4096 pixel CCD) and that assumes a 5 m f/1.8 primary mirror. The image quality at 49° is comparable to that of the present design. Because of the smaller primary mirror, a strict comparison with the present design is not possible, but it does show that wider field designs are possible.

In this context, it should be pointed out that even the great-circle camera is not entirely distortion free. The image displacements can be obtained from equations (5) and (11) by setting δ₀ = 0 and taking δ to be the field angle X. This gives ΔX = Y tan δ/2 = XY/2 and ΔY = 0. So while the great-circle camera is free from rate variation, there is a small amount of star-trail curvature. This results in an image smear that increases in proportion to the cube of the field diameter and that becomes substantial for field sizes on the order of 1° (the image displacement is 0′.548 for a 1° × 1° field).

While the corrector design presented here was specifically developed for a zenith-pointing telescope, the same optical design could also be used with a conventional telescope. Because the curvature effects depend only on declination, compensation could be introduced for any field center by means of mechanical actuators that would adjust the decenters and tilts of the individual elements in the corrector. The corrector would be reconfigured for each pointing of the telescope and then held fixed during the integration. This would be the case even if the scanning is done at a nonsidereal rate, so long as the declination of the field center remains constant during the exposure.

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