Southern African Large Telescope

PFIS Distortion and Alignment Model

Kenneth Nordsieck
University of Wisconsin

Document Number: SALT-3120AS0023

Revision 1.0
2 Mar 2005

Change History

Rev	Date	Description
1.0	2 Mar, 2005	Original

Table of Contents

1 Scope

This document describes the mathematical model that is used to correct for the PFIS CCD mosaic alignment, detector dewar alignment, and optics distortion as a function of wavelength and temperature. The SALT IRAF package maintains two files, PFISgeom.dat and PFISdistortion.dat, containing the relevant parameters.

2 Alignment

The following alignment parameters were determined in PFIS imaging mode using a Cartesian grid slitmask with pinholes every 5 mm. Alignment parameter entries in the IRAF data files are dated, since they may change as the result of detector alignment or dewar servicing.

2.1 CCD Mosaicing

The PFIS detector consists of three EEV 2048x4096 CCD's, mosaiced with a gap of 90 - 100 unbinned pixels. The alignment of chips 1 and 3 were defined relative to chip 2 as follows: $\Delta\phi$ is the rotation, and Δx and Δy is the offset of the center of the chip from where it would be if the rotation were zero with zero gap.

Chip	$\Delta\phi$ (deg)	Δx (pix)	Δy (pix)
1	0.0735	-104.56	3.24
3	-0.0380	91.87	1.31

These parameters are kept in PFISgeom.dat, and are used to mosaic the multi-extension file into a single FITS file. These were determined from a distortion calibration taken at 630 nm on 1 Dec 2004. A comparison with the subsequent calibration on 24 Feb, 2005, reveals an error of roughly 0.5 pixels in Δx and Δy, and 0.04 deg in $\Delta\phi$. Since these were determined using different masks, and the mask error is about 0.3 pixels, this error may be mostly in the mask. A better calibration awaits a sky image.

2.2 Detector Alignment

The detector alignment is defined by three parameters, ϕ, x_0, and y_0, which are the rotation of the central chip with respect to the instrument coordinate system, and the unbinned pixel coordinates of the optical axis (defined by the Cartesian pinhole mask). Relative to the "central" pixel of the center CCD ($x_c = 1024$, $y_c = 2048$), the current alignment is,

$$\phi = -0.1226 \text{ deg}$$

$$x_0 - x_c = -0.749 \text{ pixels}$$

$$y_0 - y_c = 13.776 \text{ pixels}$$

These were determined from the mean of distortion calibrations in five interference filters on 24 Feb, 2005. The RMS error among the five determinations was ±0.23 pixels for x and y, and 0.0006 deg (2.2 arcsec) in rotation. There is a systematic shift in y of about 0.5 pixel from 400 to 800 nm.

3 Distortion

A model of the optical distortion between the slitmask plane and the detector plane was constructed using the PFIS ZEMAX raytracing model. In imaging mode, it is a function of field angle, wavelength, and temperature (in order of decreasing sensitivity). In spectroscopic mode, there is an additional distortion due to spectral line curvature and due to the change in anamorphic magnification in the direction of dispersion. The distortion model has so far been verified in imaging mode at five wavelengths and one temperature.

3.1 Imaging Mode

Imaging mode distortion is defined by a function of three parameters, R_{max}, A , and B , where A and B are cubic and fifth order distortion coefficients, and R_{max} gives the undistorted "normalized pixel scale" in mm/ 4 arcmin. All are normalized at ρ_{max} = 4 arcmin, the maximum field angle. The distance R in mm from the optical axis at the detector is then given by:

$$R/R_{max} = (r/r_{max}) + A\,(r/r_{max})^3 + B\,(r/r_{max})^5$$

where r is the distance from the optical axis and r_{max} is the normalized pixel scale at the slitmask plane. (We currently assume zero telescope distortion, and with r_{max} = (240 arcsec/1000)×223.8 microns/arcsec = 53.712 mm).

The PFIS chromatic lateral aberration makes R_{max}, and to a lesser extent, A and B, a function of wavelength. This dependence has been modeled empirically as follows

$$R_{max}(\lambda) = R_0 + R_1\,\lambda + R_2 / \lambda^2 + R_3 / \lambda^3$$

$$A(\lambda) = A_0 + A_1 / \lambda + A_2 / \lambda^2$$

$$B(\lambda) = B_0 + B_1 / \lambda + B_2 / \lambda^2$$

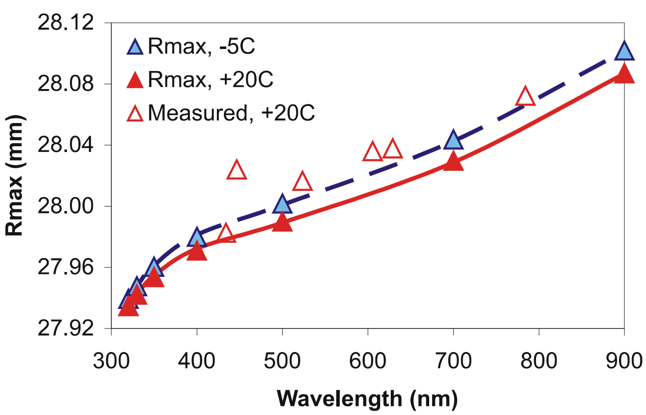
Finally, R_{max}, A, and B are weak functions of temperature, which may be modeled empirically by treating their wavelength coefficients $f_{0,1,2,3}$ as functions f(T)

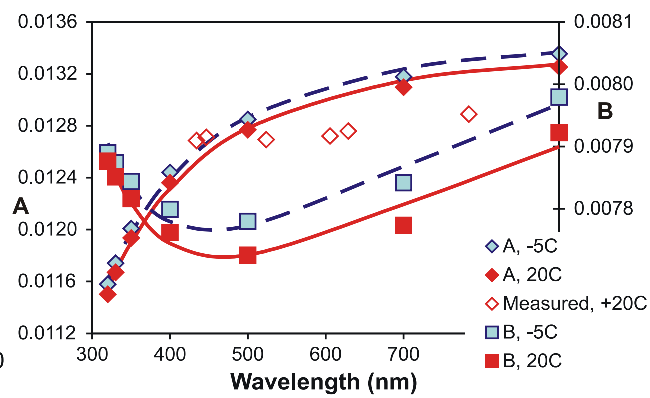
$$f(T) = f + f_t\,(T_h - T) / (T_h - T_c)$$

where T_c = -5° C and T_h = 20° C, the operational temperature limits of the spectrograph. This is formulated so that the coefficients with *0 - 3* subscripts all apply at T = T_h = 20°C, and the coefficients with additional *t* subscripts give the corrections to these. These coefficients have been evaluated by fitting the distortion coefficients from raytraces at 7 wavelengths and the two extreme temperatures. In this table the coefficients are given assuming wavelengths in microns.

Subscript	R_{max} (mm)	$R_{max,\,t}$	A	A_t	B	B_t
0	27.6485	0.0165	0.013283	0.000104	0.008488	0.000095
1	0.4246		0.000296	-0.000010	-0.000716	-0.000024
2	0.0620	-0.0012	-0.000273		0.000167	
3	-0.0150					

Figures 1 and 2 illustrate the distortion coefficients derived from the raytracings (symbols), and their fits to wavelength and temperature (+20C: line; -5C: dashed). Open symbols represent coefficients derived from the 24 Feb, 2005 distortion calibrations. The latter assumes a B coefficient taken from the raytrace. The fit with B allowed to vary gives a B within about 5% of the raytrace, with errors at least that large. The wavelength and temperature coefficients will be adjusted as more data comes in.





3.2 Spectroscopic Mode

In grating spectroscopy, there are two further corrections to the imaging mode distortion, spectral line curvature, and differential anamorphic magnification. We first make the approximation that the imaging distortion occurs before the grating, which is a good approximation for PFIS, for which the collimator distortion is an order of magnitude large than the camera distortion. Next, we assume that the grating and camera articulation angles are near Littrow ($\beta \cong \alpha$, where α = incidence angle and β = diffraction angle). It can then be shown, by expanding the grating equation for small out-of-plane angles and small off-Littrow angles, the curvature correction $\delta x'_c$ at the detector in the dispersion direction as a function of the cross-dispersion position y is

$$\delta x'_c\,(x',y) \cong (y^2/f) \tan\alpha \;\; (1 - x' \tan\alpha \;/ f)$$

where α is the grating incidence angle on-axis, f is the focal length of the camera (330 mm), and x' is the x-position relative to the on-axis Littrow wavelength position x_L . For operation near Littrow (central diffraction angle $\beta_0 \cong \alpha$), x_L may be approximated by

$$x_L \cong x_0 + (\beta_0 - \alpha)\, f$$

Finally, a correction must be made for the change in anamorphic magnification cos(α)/cos(β) in the direction of dispersion. Again expanding around the Littrow wavelength which falls at x_L, we should find for the anamorphic magnification correction $\delta x'_a$

$$\delta x'_a\,(x') \cong (x'^2 / f) \tan\alpha \,(\, 1 + x' \tan\alpha / f\,)$$

(Actually, all my attempted derivations give a 4/3 coefficient of the last tan α, oh well! The above seems to fit much better)

Applying the first term of the curvature correction to the magnification correction, and summing, we obtain for the total correction,

$$\delta x'(x',y) \cong (r'^{\,2} / f) \tan\alpha + (\, x' r'^{\,2} / f^2\,) \tan^2\alpha$$

where $r'^{\,2} = x'^{\,2} + y^{\,2}$.