DECam Focus And Alignment Procedure

Steve Kent, May 29, 2012

I. Introduction

This document descri bes the procedure for determining focus/alignment corrections of the hexapod (and primary mirror active support system) using donut images from the science CCDs on DECam. This procedure draws heavily from the document "DECam Focus and Alignment Systems" (des-docdb #5452). It also relies on the document "DECam Orientation Conventions" (des-docdb #5282).

NOTE: While this document was being prepared, Aaron Roodman wrote "Alignment with Donut" (des-docdb #6536), which presents essential the same alignment procedure. The present document focuses on different details and gives the results of some tests on SDSS data, so I think it still has some value.

There are four main adjustments that need to be made to the alignment systems, and these must be deduced from the pattern of donut images across the science CCDs. The four adjustments are:

1. Hexapod tilt (2 axes)
2. Hexapod translation (2 axes)
3. Hexapod piston (focus) (1 axis)
4. Primary mirror support system astigmatism (2 axes)

Note: the primary mirror astigmatism adjustment system was not discussed in the previous document (and is currently not included in Roodman's document), but since it is a part of the alignment analysis it is included here. The higher order corrections in the primary mirror system (trefoil and quadrafoil) are not included here.

2. Observing procedure

I assume that the following procedure has been performed:

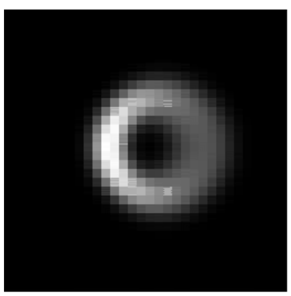
1. Telescope defocused by 1500 microns
2. Exposure taken
3. Donuts on each science CCD have been analyzed. I assume that all measurements are combined to give the equivalent measurement of a single donut at the center of the CCD.

3. Raytrace program CRAY and ZEMAX conventions

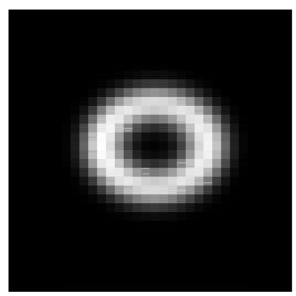
The sign and orientation conventions for coma and astigmatism are explained more fully as follows. [NOTE: The following analysis is done using my raytrace program CRAY and thus uses its conventions. It will be important to repeat these analyses using ZEMAX to determine its conventions. Note also that my Zernike polynomials use a different normalization scheme than ZEMAX - my coma terms are bigger by sqrt(8) and my astigmatism terms are bigger by sqrt(8); however, in what follows I have not relied on any specific normalization as of yet.]

CRAY and ZEMAX both utilize right-handed coordinate systems such that X and Y define a plane such as the focal plane and Z increases in the direction from the camera to the primary mirror (i.e., into the Earth). One can orient the X and Y axes such that they match Gaston Guttierez' "barrel coordinate system" - in this case X points to the geographic East, and Y to the geographic South directions. A fuller discussion of orientation conventions and how these map to the Hexapod system is given in my orientation guide, des-docdb #5282.

I impose aberrations on the primary mirror and examine images in the focal plane. A +1µ aberration of the "cosine" term (either coma or astigmatism) causes the primary mirror shape to deviate in the +Z direction at each point along the +X axis. A Zernike analysis of the wavefront error at the focal plane gives a Zernike term that is +2µ (since the WFE is doubled by a reflective surface). To generate donuts, I move the primary mirror closer to the focal plane by 300µ. The following shows the geometry of the resulting donuts:


+X

Coma


+X

Astigmatism

If the primary mirror had been move away from the focal plane, the coma image would be unchanged, but the astigmatism image would be rotated by 90 degrees.

3. Zernike Parameters

For each donut, the following parameters are measured:
c1 Zernike coma "cosine" term
s1 Zernike coma "sine" term
c2 Astigmatism "cosine" term (along X/Y axes)
s2 Astigmatism "sine" term (45 degrees to X/Y axes)
rad Donut radius

rad is the average radius of the donut. It corresponds to the coefficient of the Zernike focus term. [NOTE: the radius is actually a combination of the focus and spherical aberration Zernike terms. The latter is usually constant as the hexapod piston varies; thus the "best focus" often corresponds to a Zernike focus term that is non-zero but best balances the spherical aberration. This fine point will be ignored below.]

Once the above parameters have been measured, they need to be turned into hexapod and primary mirror corrections. The process for doing so is as follows.

As an intermediate step, it should be noted that there exist TWO neutral points along the optical axis of the Blanco/DECam system. At each neutral point, if one pins the optical axis of the primary mirror and the optical axis of the DECam corrector at this point but allows the two axes to otherwise pivot relative to one another, then one of the optical aberrations remains 0 for modest amounts of pivot.

One of the neutral points is located near the filter position; pivoting about this point changes the astigmatism due to misalignment while coma remains 0. Let us call this the "comatic pivot" (since it means that coma is constant).

The other neutral point is located about 10 meters above the focal plane; pivoting about this point changes the coma due to misalignment while astigmatism remains 0. Let us call this the "astigmatic pivot" (since it means that astigmatism is constant).

A combination of pivots about each neutral point is equivalent to a translation and tilt of the corrector using the heaxpod. The advantage of using the neutral points is that it allows us to conceptually decompose the motion of the hexapod into two motions, each of which controls one of the Zernike terms independent of the others.

The optical design has considerable intrinsic coma and astigmatism. Because the pattern is axially symmetric, the value of any Zernike term averaged over the whole focal plane is zero.

Raytracing shows that coma induced by optical misalignment is approximately constant across the focal plane. Thus, one simply averages the c1 and s1 terms across all science detectors in order to determine the mean coma. As a side note, any coma induced by the primary mirror is likewise constant across the focal plane; one is correcting both together.

Likewise, astigmatism induced by the primary mirror is also approximately constant across the focal plane. Thus, one simply averages the c2 and s2 terms across all science detectors in order to determine the mean astigmatism. Note that this astigmatism must be removed via the primary mirror support control system; the hexapod is of no use.

Finally, raytracing shows that astigmatism induced by optical misalignment depends on position in the focal plane as follows. The absolute amplitude (c2 plus s2 combined in quadrature) depends linearly on distance of the detector from the optical axis. The individual amplitude of c2 and s2 vary azimuthally as $\cos([2(\varphi-\varphi_0)]$ and $\sin([2(\varphi-\varphi_0)]$, where φ is the azimuthal position angle of a detector and φ_0 is a rotation angle that defines the major axis of the pattern. If the detectors are distributed symmetrically across the focal plane, the average value of c2 and s2 due to misalignment is 0, and thus this pattern is orthogonal to and decoupled from the pattern of constant astigmatism induced by the primary mirror.

The process proceeds as follows. The average values of c1 and s1 are computed - these determine the coma correction and are mapped to a motion about the "astigmatic pivot".

The average values of c2 and s2 are computed - these determine the primary mirror astigmatism correction. The average value of the donut radius is computed - this determines hexapod piston. Finally, a least-squares fit is made to the radial and azimuthal dependences of c2 and s2 on focal plane location, resulting in an amplitude of the slope and postion angle of the astigmatic pattern from misalignment. These values determine the astigmatism correction and are mapped to a motion about the “comatic pivot”.

The two pivot motions are finally combined to produce the equivalent translation and tilt of the hexapod.

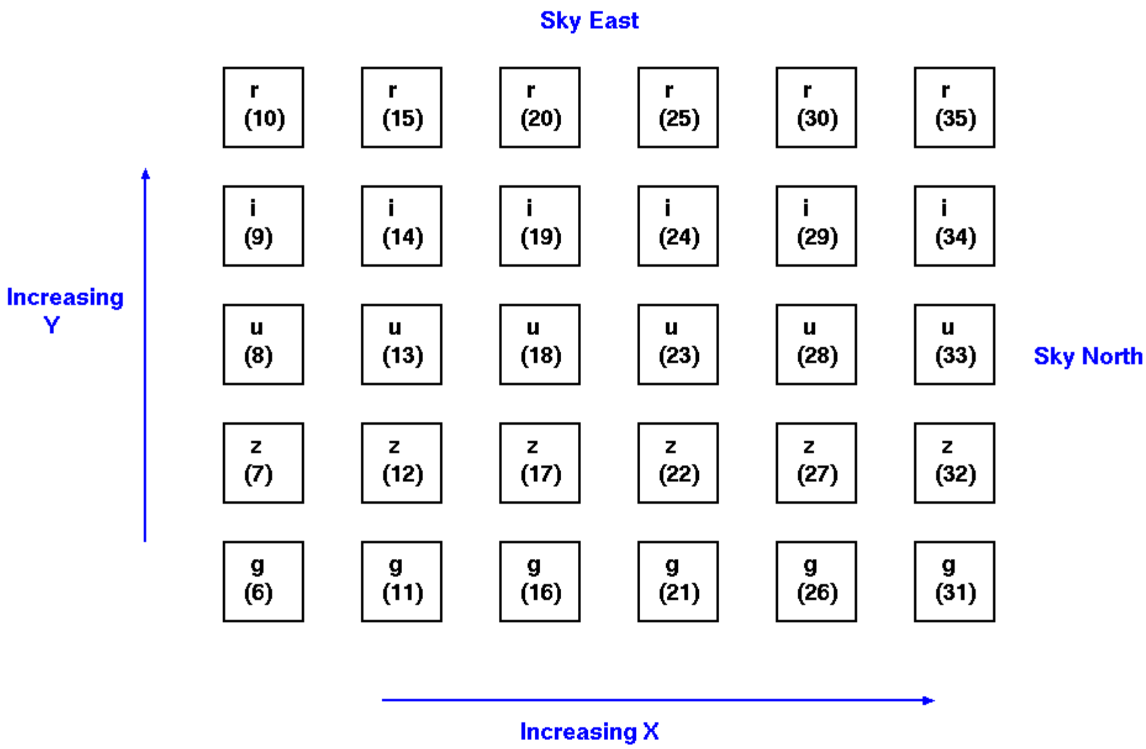
4. Tests on SDSS Data

The above procedures have been tested using SDSS engineering data. Run 6405 contains donut images obtained with the secondary moved to both sides of focus by +/- 300 microns. The images at +300 microns are the ones analyzed here.

The SDSS analysis is modified slightly from that for DECam because the SDSS telescope is a Cassegrain system with a pair of correctors close to the focal plane. The correctors are fixed relative to the focal plane; the primary and secondary can be adjusted independently, and motions of one or the other are not entirely equivalent. I adjust coma by pivoting the primary mirror about the “astigmatic pivot” point, which is located at ΔZ = -11000 mm from the primary mirror vertex. I adjust astigmatism by pivoting the secondary mirror about the “comatic pivot” point, which is located at ΔZ = -1073 mm from the secondary mirror vertex.

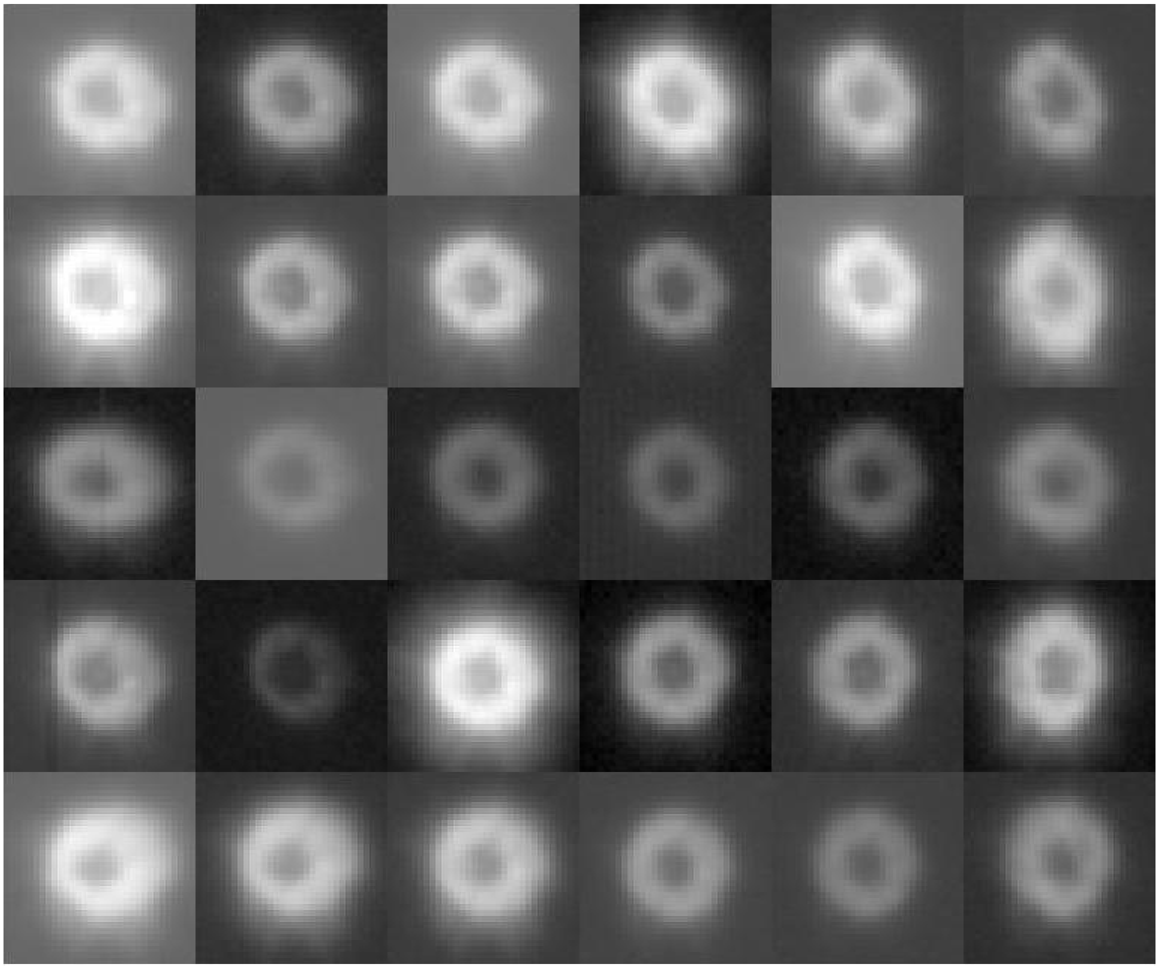
One needs to account for sign conventions for focus motions along the Z axis. According to the TCC Operator's Manual, the TCC convention matches the CRAY and ZEMAX conventions. (A +300 micron motion moves the secondary closer to the primary.)

The geometry of the SDSS focal plane is shown in the following figure, along with a mapping to CRAY coordinates and DS9 coordinates (which coincide):



SDSS Imager Focal Plane

The following figure shows a mosaic of actual data donut images, one per CCD, that matches the layout shown above:



Because I do not have a proper Zernike code working, I wrote some code to create approximate versions of Zernikes as follows.

I find the center of a donut, then compute the intensity along a set of rays sent out at different position angles φ. I compute the peak intensity and a characteristic radius along each ray. The radius is fit by the function

$$r = r_{avg} [1 + f_a \cos 2(\varphi - \varphi_a)]$$

The intensity is fit by the function

$$I = I_{avg} [1 + f_c \cos (\varphi - \varphi_c)]$$

$\varphi = 0$ along the +X axis. The Zernike coefficients are proportional to the following terms:

$c1 = f_a \cos 2\varphi_a$
$s1 = f_a \sin 2\varphi_a$
$c2 = f_c \cos \varphi_c$
$s2 = f_c \sin \varphi_c$

One could also use use the cos(2φ) dependence of the intensity to derive an alternate measure of astigmatism, but it seems to be less reliable, possibly because the algorithm to find the center of a donut is too simplistic and can miss it rather noticeably (in particular, there is often a bright peak at the center of a donut image, whereas I assume it is an intensity minimum.)

I use a few test cases to determine the conversion from donut coefficients to tilt amplitudes for the primary and secondary. Here are the conversions, all for an increment in secondary position of +300 microns.

Primary mirror astigmatism

1 micron (peak) => 2 microns WFE => 0.2 f_a

Coma (primary mirror tilt)

50 arcsec tilt => -1.5 microns WFE => 0.42 f_c

Astigmatism (secondary mirror tilt)

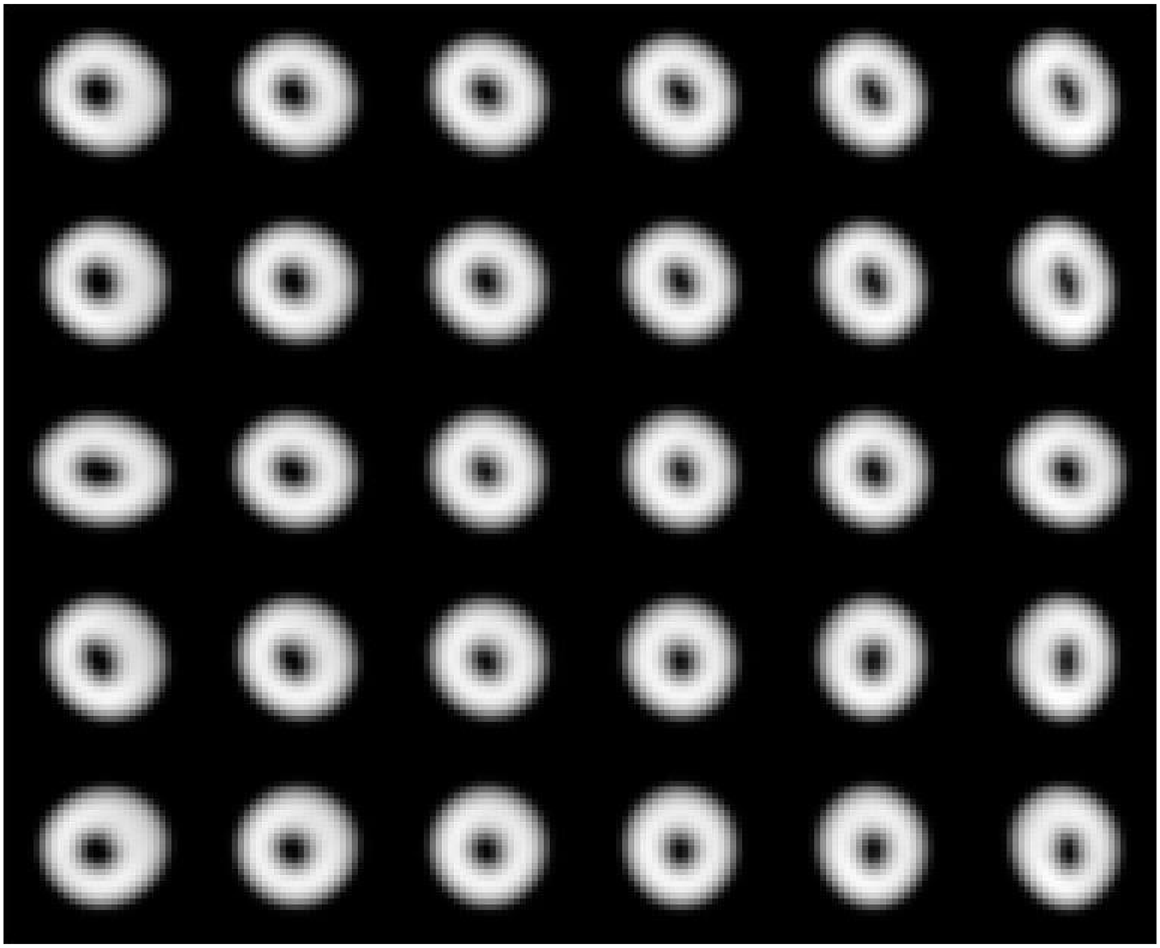
200 arcsec tilt => 3.6 microns WFE => 0.47 f_a at radius = 327 mm
(Caution - this calibration is probably not very accurate.)

The values I actually derive from the donut data are:

Primary mirror astigmatism (surface height error): -.2 (cosine) +0.2 (sine) microns
Primary mirror tilt: 9.2 arcsec @ position angle -135 deg
Secondary mirror tilt: 42.5 arcsec @ position angle -177 deg
Actual defocus: 316 microns

The tilts (since they are pivots about a fixed point) correspond to translations of the primary and secondary by 490 microns and 220 microns respectively.

Here is a mosaic image simulating the above:



[Note that the primary and secondary are not capable of actual pivot motions, since they only support pivoting about the vertex. A different combination of tilts would be needed to produce the actual corrections.]

As a second example, I analyzed donuts from run 5890. The defocus is -500 and +500. I can compare analyses from both sides of focus.

-500:

  No primary mirror astigmatism
  Coma: 8.9 arcsec @ 73 deg
  Astigmatism: 17.02 arcsec @ 163 deg

+500:

  No primary mirror astigmatism
  Coma: 6.5 arcsec @ 98 deg
  Astigmatism: 17.02 arcsec @ 163 deg

Thus, there is good consistency between the two sides.