Orientation of C4 Lens, Barrel, Focal Plane, DS9, Fits Files, SESO figures, Zemax, WaveFront Error Maps, CCDs, and all that.

Stephen Kent, Feb 7, 2011
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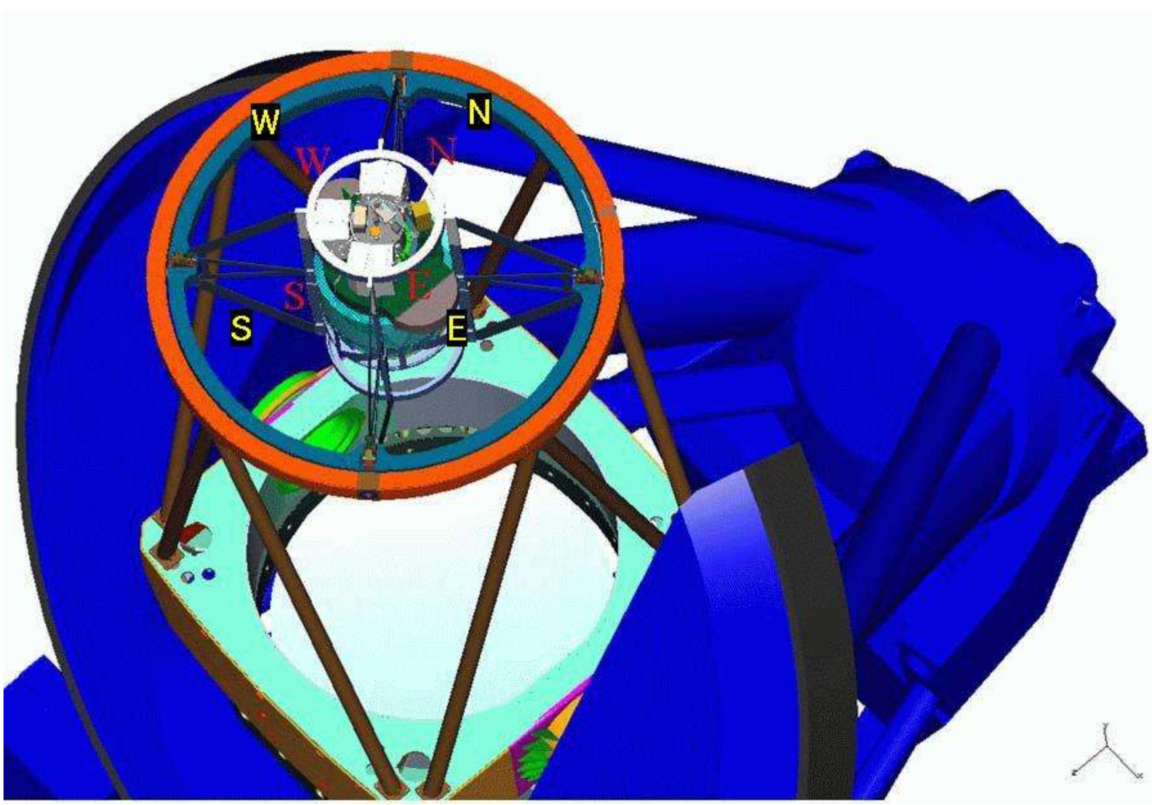
The motivation for this article is to document how surface height errors in the C4 lens impact images seen by the Focus/Guiding sensors in the focal plane. In order to do this, we need to understand the conventions used by various systems for defining the orientation and parity of different components in DECam. Fortunately all systems are sufficiently well defined that there is no ambiguity - we simply need to tie all the pieces together. No new conventions are defined here for the telescope or lens or CCDs. [The hexapod system documentation is a bit ambiguous, but the ambiguity is resolved by following markings on the hexapod itself.]

1. Telescope & Focal Plane

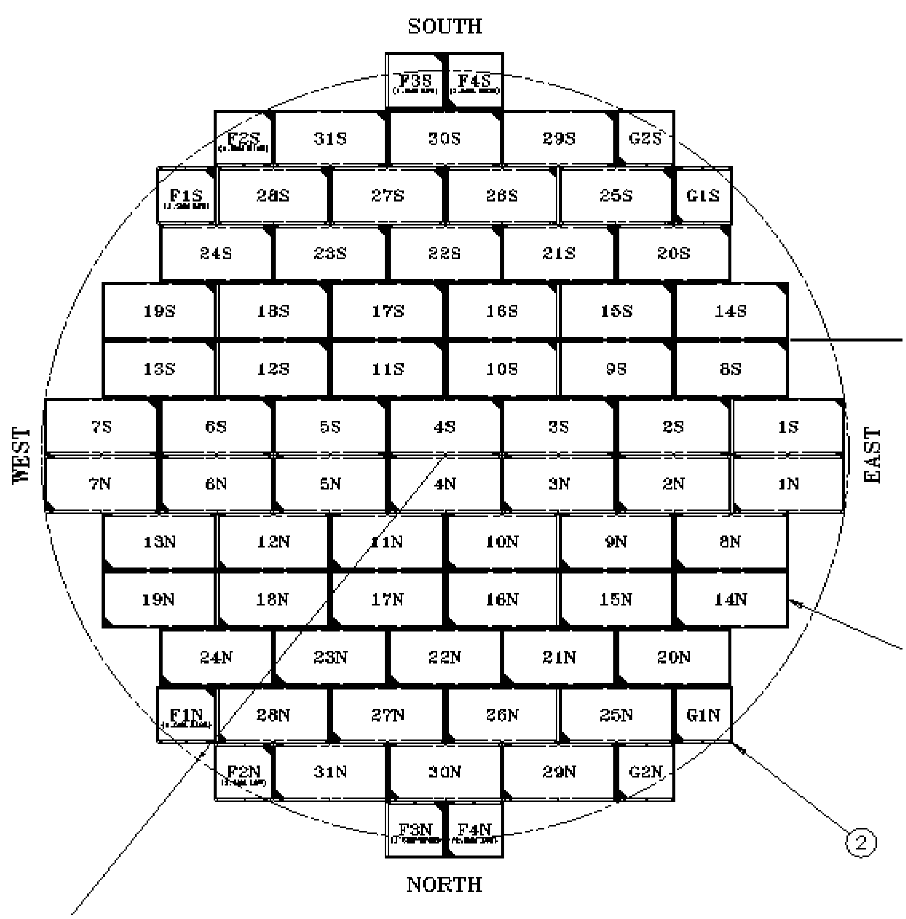
Orientations are defined with the camera and corrector mounted on the telescope with the telescope pointed to zenith. This geometry is shown in cd-docdb #994-V7, "436446 Basis of orientation assumptions", page 5. A copy (with better lettering than in the original) is shown here:



The Blanco telescope is in the Southern hemisphere. The large, horseshoe bearing is on the S side of the telescope. The CCD focal plane is labeled NESW as shown in the figure - the directions refer to the geographic orientation of the camera as it sits on the telescope.

[NOTE: the orientation of the sky image projected onto the focal plane is inverted - i.e., the North side of a field on the sky is oriented to the South side of the focal plane. To avoid confusion, we will not use the orientation of the sky image anywhere in this document. Rather, North refers to the direction of the Atacama desert, East refers to the direction of the Andes, South refers to the direction of the Antarctica, and West refers to the direction of the Pacific ocean.]

The layout of CCDs in the focal plane is shown in des-docdb #994-V7 "436446 Front of Focal plane array". This figure show the focal plane as viewed from the primary mirror. [The shaded corner on each CCD is supposed to mark the side with the serail register, but I believe that this particular drawing is wrong - CAUTION!!!) A copy of the figure is shown here:



The focus and alignment sensors are on the N, W, and S sides of the focal plane. The guide sensors are on the E side.

2. Barrel

Here is a description of the barrel coordinate system from Gaston Gutierrez (Jan 6, 2011 email):

```
1- The axis of the barrel go thought the middle of the C5 cell,
and positive is in the direction from C5 to C1.

2- The focal plane forms the x-y plane (in reality right now we
are using the Barrel's C5 flange to define the x-y plane, but as
far as we can tell both are parallel to within specs)

3- Z= O is at the focal plane (in reality we are again defining
the Z origin using the nominal value of Z=117.650 mm for the
barrel's C5 flange Z position)

4- The y-axis point south (physically it goes through a sphere
in the C5 cell labeled south)

5- The coordinate system is right handed.
```

In short, the x,y,z coordinate system is a right-handed system with the z axis oriented from the sky into the ground, the x-axis points East, and the system is a right-handed system (thus the y-axis points South).

A position angle "phi" is defined such that phi=0 along the x-axis and phi increases as one rotates to the +y-axis.

The following file shows the runout on the mirror cell rings. According to Any Stefanik (email from Jan 13, 2011), the lenses contact the cell from "below the plotted data" (i.e., from the negative z side.)
http://www-clued0.fnal.gov/~gaston/barrel/frame/studies/C4_BodyCS_5files.pdf

3. C4 Surface Height Map

Peter Doel has circulated several versions of the surface height error map produced by SESO. Here, I will describe the final version sent around by Peter Jan 13, 2011, titled Img-PDF859504. (This version includes some handwritten notes using what apppears to be blue ink; the phrase "convex surface is written in the top left.) This map gives the surface height errors as viewed from the convex side of the lens - i.e., as viewed from the primary mirror. This view direction is the same as that of the focal plane described above. [The lens can be rotated, so a definitive orientation w.r.t. the focal plane is not yet possible.] A copy of this figure is included here:

4. C4 Surface Height Files

Peter Doel has sent around two sets of files with surface height errors for the convex side of C4 (the aspheric surface). The first set is labeled as follows:

```
C4cxfullarea.asc
C4cxterpolandundistorted.asc
```

These contain the surface height errors in units of "waves" and scaled up by 32000. These data files are in the format outputed by the interferometer (Wyko format).

The second set is labeled as follows:

```
C4cxfullarea.dat
C4cxfullareacropped.dat
C4Cxinter.dat
```

These files contain the surface height errors in units of mm. They are in a format that can be input to Zemax.

The data in the .asc files are the same as in the 1st and 3rd .dat files - just formatted and scaled differently. The scaling factor is 632.8e-6/32000. (convert from waves to nm to mm; divide by 32000).

The last file in each set (size 201x201) is thought to be the best for analysis - the original maps are cleaned up and corrected for distortion.

The files "interp ..." are rotated 180 degrees with respect to the "full" files. Here, I will describe the orientation of the "full" files. BEWARE!

The "full" .asc files contains 248 lines of data, each with 248 values. The first value on the first line refers to the upper left corner of Peter's figure. The first line of values go left to right across the figure; success lines go top to bottom.

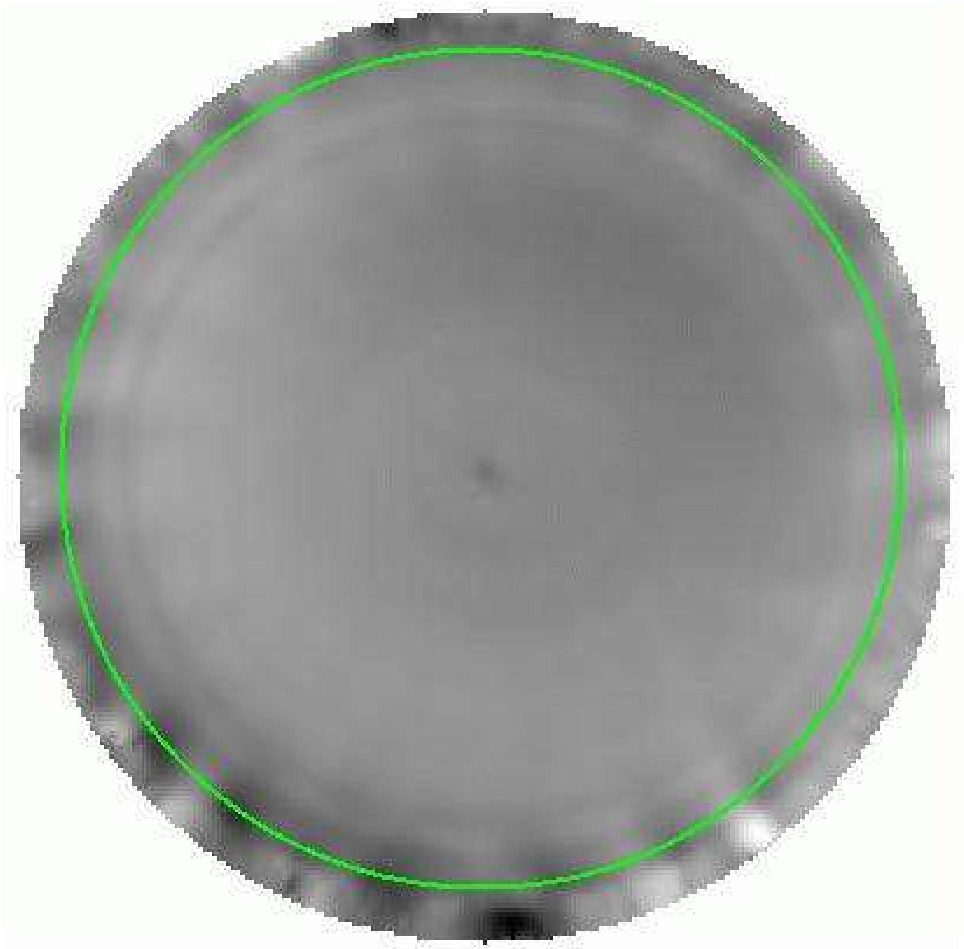
The "full" .dat file is 247x247 (apparently the last row & column are cropped). It simply expands the values on a line in the .asc file into multiple lines (one value per line) in the . dat file.

The "interp" files are both 201x201. They contain essentially the same data as the "full" files but with a distortion correction applied and bad areas interpolated. For some reason, the data are also rotated 180 deg. relative to the the "full" files - thus, the first pixel value is in the lower, right edge of Peter's figure.

According to Peter, the “red/orange” areas of his figure are bumps (which make the lens thicker). These are marked as positive deviations in the color bar-code. These points on the map have negative values in the file (which is a consequence of the fact that the surface height errors in the file are actually measured while viewing from the concave side). Conversely, the green areas in the figure have negative values and, according to Peter, are “dips”. These points on the map have positive values in the files.

The data files include areas of the lens that are outside the clear aperture. The surface error maps in Peter's figure have been cropped to just the clear aperture. I do not know how to crop the data file values precisely to match Peter's figure; a “chi-by-eye” approach seems needed. The amount of trimming needed appears to be about 10 pixels in radius.

A grey-scale version of the “interp” plot is show in the following figure. I have inverted the values from the file, so that dark areas match the green and light areas match the red on Peter's figure (and thus, light areas are where the lens is thicker). The green circle show the approximate boundary of the map on Peter's figure. [UPDATE v2 - changed the orientation of this figure by 90 deg from v1.] The orientation matches that of Peter's figure.



H position

5. Creating a FITS file for DS9

In a FITS file, the NAXIS1 keyword defines the number of columns (left to right, X axis in a DS9 image). The NAXIS2 keyword defines the number of rows (bottom to top, Y axis in a DS9 image). Note that in DS9, the origin is in the lower left corner. [CAUTION: I have been told that different versions of DS9 have different defaults for where pixel 0,0 is located on the screen. The above description matches what I see in Version 6.]

[UPDATE v2 - The mapping to a FITS file was described differently in v1 of this document.] There is a bit of arbitrariness in storing the surface height error map data in a FITS file. I have chosen the convention that the FITS file as displayed in DS9 should match the same orientation as Peter's figure. This choice turns out to also match the Zemax convention as well. This choice means that pixels in the .dat file are mapped first into *increasing* column (X) number, then into *decreasing* row (Y) number in the FITS file and in the DS9 image respectively. In this way, the map `C4cxfullarea.dat` is displayed in DS9 with the correct "parity" - i.e., DS9 displays the map with the same orientation as Peter's figure. Also, in this manner, DS9 X and Y coordinates and Zemax X and Y coordinates also have the same "handedness" as Gaston's barrel system (but the absolute rotation angle is not defined.)

6. Raytrace program CRAY.

The following is specific to my raytrace program. I map the data in the FITS file to my internal X,Y,X coordinate system. I take increasing column number (NAXIS1) as the increasing X direction and increasing row number (NAXIS2) as the increasing Y direction. My XY handedness matches that of DS9 and that of Gaston's barrel system. (The absolute rotation is undefined.) My Z axis matches that of Gaston's system as well.

7. Sky

DECam does not have any intermediate focus. Thus, the image of the sky projected onto the focal plane is inverted - i.e., the South edge of a field on the sky is imaged such that it is along the "North" edge of the camera (similar to how the "North" magnetic pole of the earth would labeled "S" on a bar magnet). At present the Data Challenge simulations do not account for this inversion.

8. Zemax

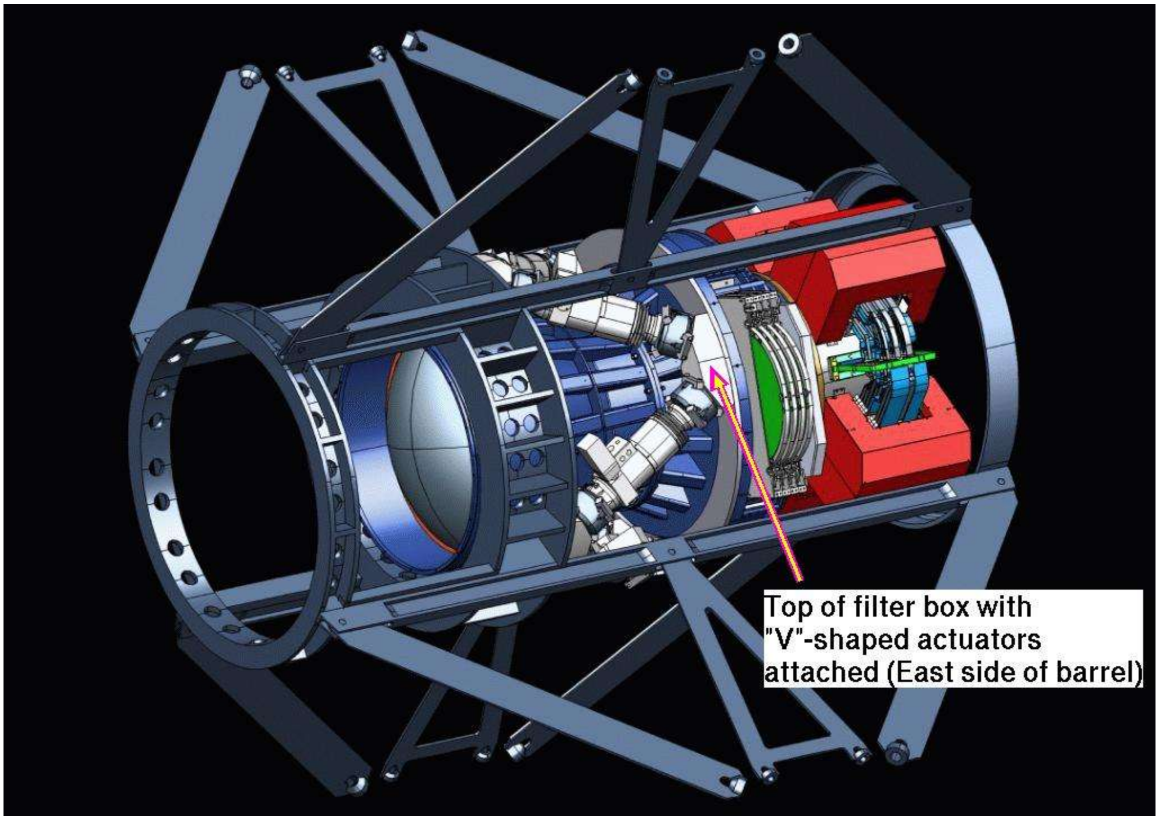
The .dat files are in a format that can be read by Zemax. According to the Zemax documentation, the first pixel in the file is at the -X, +Y limits of the Zemax coordinate system. Pixels are ordered in *increasing* X, then *decreasing* Y. If one matches this ordering to that of DS9, then X corresponds to column number, Y corresponds to row number, and the image will be displayed with the same orientation at Peter's figure. Additionally, the Zemax X, Y system matches my raytrace X,Y system and has the same handedness as Gaston's barrel system.

9. Hexapod System

The hexapod system is described in des-docdb #4604-v2, Software manual. The system description is somewhat ambiguous; what follows is a “reverse-engineered” description.

The hexapod system consists of a “fixed flange” that is mounted to the cage, a “mobile flange” that is mounted to the barrel, and six actuators that join the two. The fixed flange is closest to the primary mirror. The document describes a right-handed Cartesian system on p. 9, but the description is a bit ambiguous as to whether the system is fixed relative to the “fixed flange” or the “mobile flange”, whether the Z axis points to the Zenith or Nadir and the orientation of the X,Y system. The ambiguity was resolved by conducting tests using the telescope simulator.

The orientation of the actuator system relative to the barrel is uniquely defined by two actuators that form a “V” with the acute angle on the mobile flange at the location where the actuators attach to the filter box (i.e., the actuators are bolted to the filter box at this point). According to Andy Stefanik, this location is on the East side of the barrel. Because the actuator pattern has 3-fold symmetry, there is no corresponding acute angle on the opposite side of the filter box. The following image (from des-docdb #3358-v1, p. 4) shows the East side view of the barrel.



X,Y coordinates are marked on the mobile flange. +X is on the East side of the barrel, +Y is on the North side. For a right-handed system, this orientation means that +Z points away from the primary mirror and towards the Zenith when the telescope itself is in the Zenith position.

Tests were conducted using the telescope simulator. Commanding the actuators to increase the X, Y, and Z positions causes the camera and barrel to move East, North, and up (away from the primary mirror) respectively -- i.e., in just the way that the axes are marked on the barrel. (The precise alignment of X and Y with respect to the East and North directions was not established). Tip, tilt, and spin are defined in the manual; these motions were not tested on the telescope simulator. Additional tests were conducted at CTIO (Tighe May 30, 2012 report - CTIO docdb #490). The above motions in X, Y, and Z were verified. Moving positive in theta-x moved the barrel in the +Y (North) direction, measurements made mid-barrel. Moving positive in theta-y moves the barrel in the -X (West) direction. This motion thus follows the conventional rules for right-handed rotations. The pivot point is supposed to be at the nominal focal plane. The CTIO tests show some cross-talk in X, Y, and Z, which may have been due to the test setup.

The hexapod coordinate system is the one system that does not match the barrel coordinate system. The hexapod and barrel X axes are the same; the hexapod and barrel Y and Z axes have the opposite sense (but are otherwise aligned with one another).

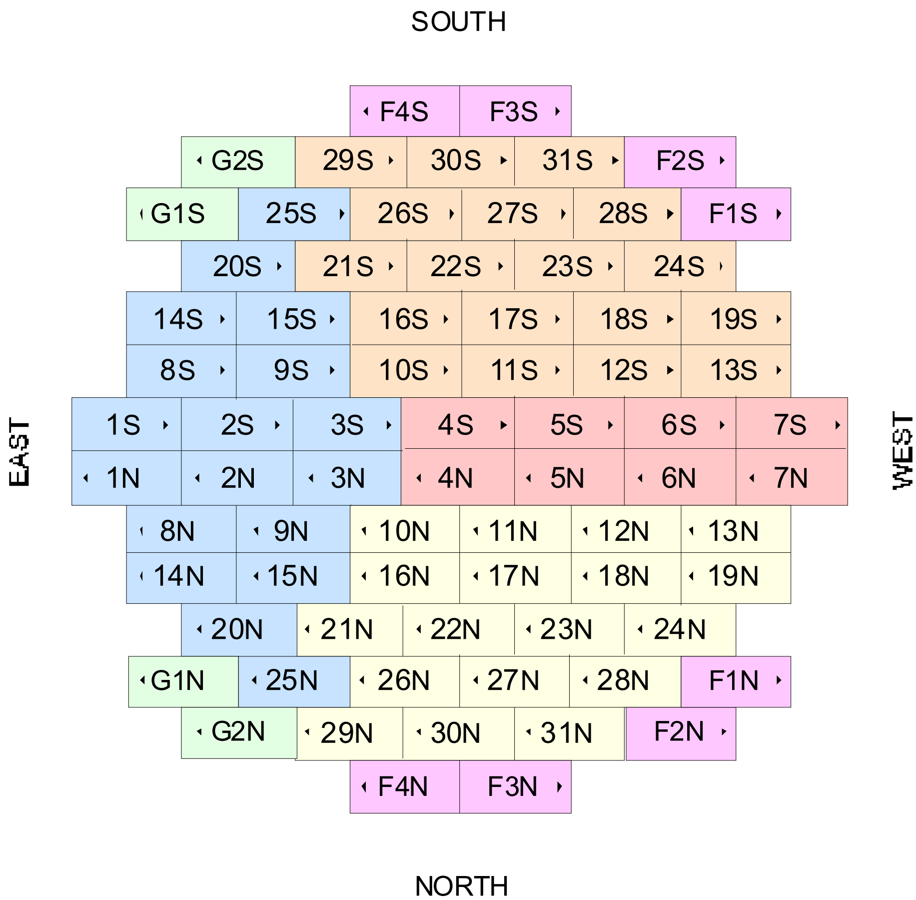
10. Telescope Simulator

[This section describes the DECam geometry during the Feb 2011 testing.] We learned that the camera is oriented properly on the TS, while the barrel/cage assembly is rotated by 180 degrees from where it ought to be on the telescope. Thus, when the TS is positioned at the Northwest platform with the cage flip oriented so the back of the camera is facing the platform, the camera South orientation is to the upper right as one stands on the platform and faces the camera; East is to the upper left. Because the barrel is rotated 180 degrees from its proper orientation, the barrel East side is to the lower right - this side is where the hexapod actuators attach to the filter box and the hexapod +X axis is marked on the mobile flange.

11. CCD Orientation

[I THINK this description is now correct.]

The details of how each CCD is read out are given in des-docdb #768. Figure 11, reproduced below, shows the direction in which charge moves for each CCD in the focal plane. [Note that the guider and focs/alignment sensors are drawn as 2k x 4k - that is the size of the “foot”, but the actual sensors are 2k x 2k.] The viewpoint for this figure is the opposite of the one above - i.e., one is looking down (in the direction of the primary mirror) at the electronics side of the mosaic array.



This document also defines an X, Y system on p. 22 that is different from the other systems used up to now. In the "VIB" system, the X axis points West, while the Y axis point South. Thus, this system is rotated 180 degrees from the Hexapod system. The Y axis is aligned with the barrel system while the X axis is inverted. Sigh.

Each CCD has two amplifiers, one at each corner of the readout direction. On readout, the two halves of a CCD are written to a FITS file extension. The process for doing this is called Panview. Part of the Panview process involves flipping the pixel ordering so that FIT images are all uniformly as they are viewed relative to the camera. All FITS files are then combined into one large file by a process called the image builder.

The VIB document #768 labels the two video channels as "U" and "L".

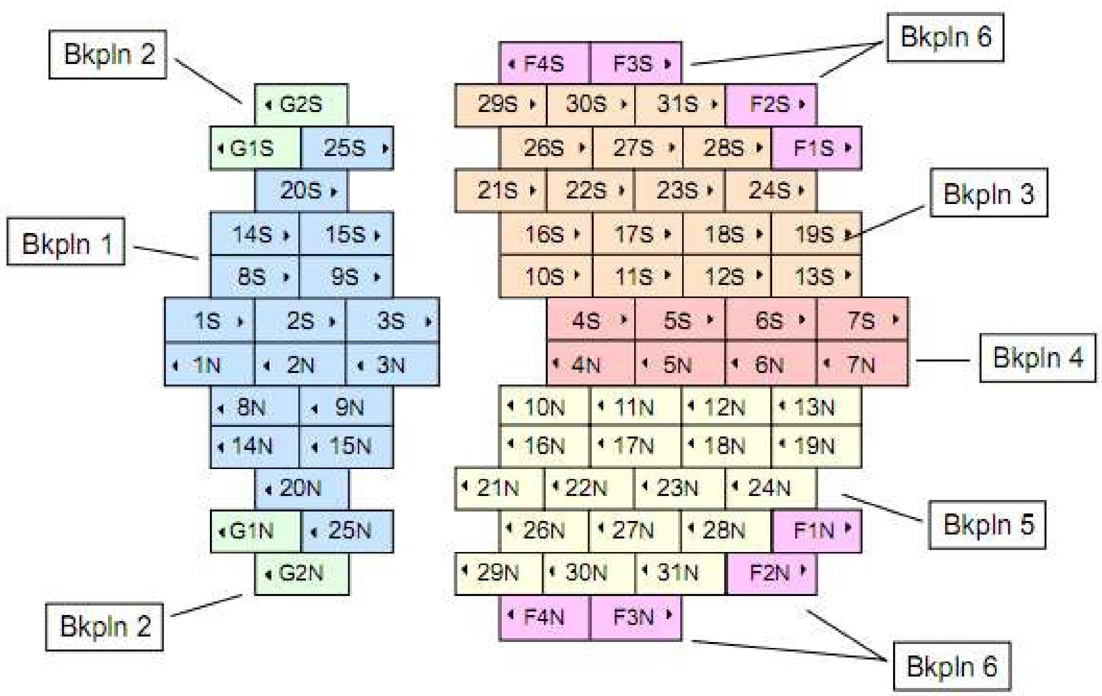
According to Jiangang Hao, "U" and "L" map to the physical CCD as follows. If one views the imaging side of a CCD (i.e., the side on which light from the telescope is focused) and orients the CCD such that the serial register and readout amplifiers are along the bottom edge, then amplifier "U" is on the left and amplifier "L" is on the right. [CAUTION: Jiangang also calls the two sides "L" and "R", such that his "L" is the opposite of the VIB document.] Each row from the CCD readout includes both "prescan" and "overscan" pixels. Each column from the CCD readout includes "postscan" pixels. SISPI (and the simulations) use "A" and "B" to describe the two sides. At the moment, I believe that "U" maps to "B" and "L" maps to "A" in all cases. (This is true even for the

F/A CCDs - I have not checked the guider CCDs.)

Panview combines pixel data from both the A and B sides of the a particular CCD into a single FITS image (or technically, the IMAGE section of a large FITS file). The pixels are reordered in both row and column as necessary such that the combined image has its first pixel in the South-East corner of a CCD (upper left as viewed in the colored figure above.) The sense in which pixels are actually read out from the array is documented in the "AMPSEC" keyword in the FITS header.

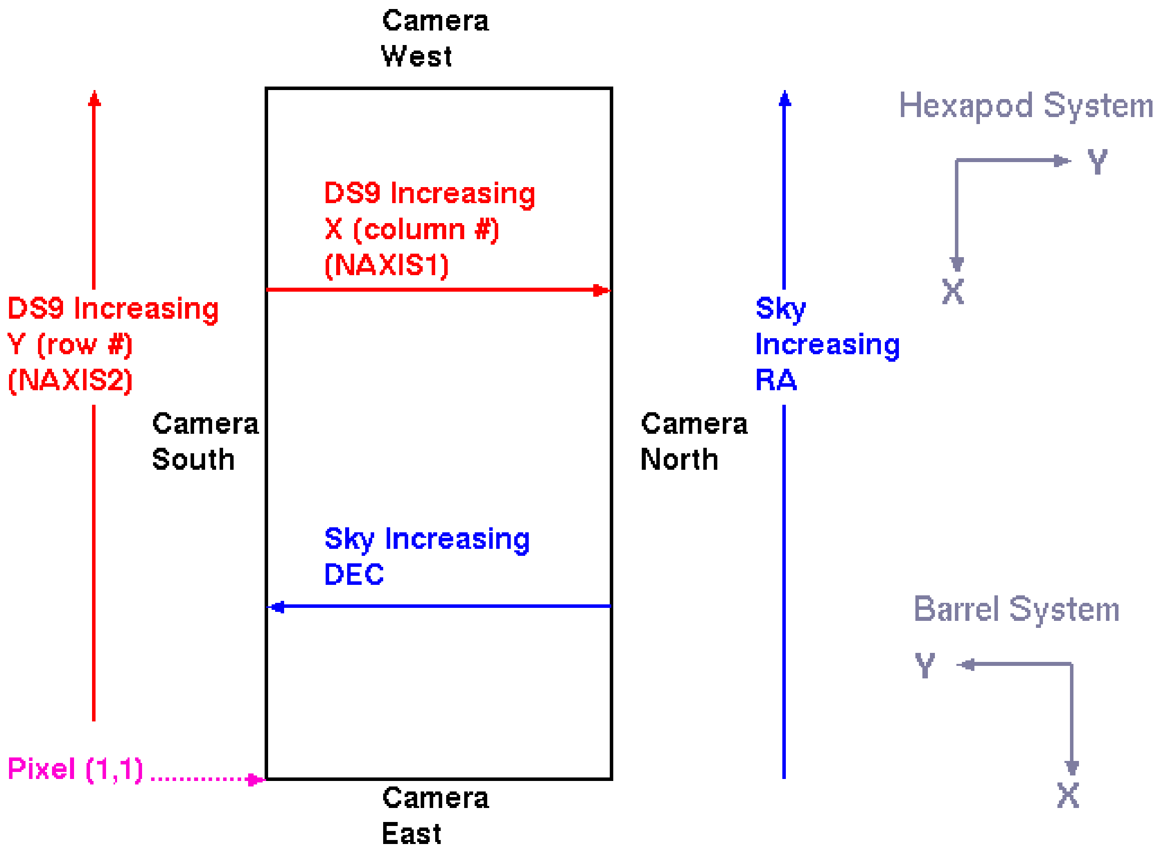
SISPI also lays out a global coordinate system for the mosaic array. This system is recorded with keywords "DETSIZE" and "DETSEC" in the FITS headers. The origin of this coordinate system is the SE corner of the camera (actually outside of the array). The first coordinate increases S to N while the second coordinate increases E to W. This sense of direction is the same as that for pixels in the file (such that NAXIS1 is increasing column number, NAXIS2 is increasing row number). [CAUTION: remember that all these cardinal directions refer to a terrestrial system - the projected sky image is rotated 180 degrees.] The gaps between CCDs are NOT counted in this coordinate system - i.e., it treats the CCDs as if they abutted seamlessly.

The following figure (also des-docdb #768) shows the backplane assignments. The science CCDs attached to backplane 5 are ones that show a bias jump at amplifier row 2048+50 due to early end of the F/A CCD readouts.



[CAUTION: Some care is needed in relying on older documentation - the orientation of the CCDs has sometimes been misconstrued - e.g., once due to an unanticipated change in the default orientation for DS9 to display images between two versions of that program. Se below regarding DS9 Version 6.2.]

The following figure shows how to orient a single CCD image as viewed in DS9. [Caution: the orientation of a CCD image in DS9 will not match that of the C4 surface height map described in Section 4. The conversion is given below.]



DS9 view of one CCD

The relation between the barrel system et al. and CCD images as displayed in DS9 is as follows. In the barrel system, X points E and Y points S. In the DS9 system, X points N and Y points W. Thus, the two systems are rotated and flipped relative to one another.

If one maps sky coordinates onto DS9, then Declination increases right to left and Right Ascension increases bottom to top. Images are flipped relative to how we view them on the sky. In other words, our view of a CCD in DS9 is from the perspective of the sky looking down towards the primary mirror (and thus at the back side of the CCD with all the electronics.)

CAUTION: If you use DS9 to display an image using "Mosaic WCS" mode, be aware that Version 6.2 (the current version as of this writing) has a bug. [UPDATE - we discovered an error in the WCS information as well, but there is still a bug.] The image from the first HDU is displayed rotated by 180 degrees from images in all subsequent HDUs. Single CCD images are still displayed correctly. Also, "Mosaic IRAF" mode seems to work OK.

12. Hexapod - TCS Interaction

Moving the hexapod in either X/Y translation or X/Y tilt will cause the apparent telescope pointing to change. To first order, a translation of the entire corrector by 1 mm has the same effect as moving the focal plane alone by 1.1 mm (i.e. 10% bigger). A tilt has almost no impact because the pivot point is at the focal plane. In more detail, here is the impact of each hexapod motion. (The boresight is position on the sky that falls at the center of the CCD array).

ΔX (hexapod) = +1 mm	ΔRA(Boresight) = –19" (sky West)
	(Equivalently, a star appears to move East by this amount)
ΔY (hexapod) = +1 mm	ΔDec(Boresight) = –19" (sky South)
	(Equivalently, a star appears to move North by this amount)
ΔTilt-X (hexapod) = +20 arcsec	ΔDec(Boresight) = –0.25" (sky South)
	(Equivalently, a star appears to move North by this amount)
ΔTilt-Y (hexapod) = +20 arcsec	ΔRA(Boresight) = +0.25" (sky East)
	(Equivalently, a star appears to move West by this amount)