NOAO DATA

Chapter 2
DECam Imager

Version 2.0.5 March 28 2014

In This Chapter…

The Dark Energy Camera (DECam) Imager began operation at NOAO-S on the Blanco 4-m telescope at Cerro Tololo in late 2012. It was built by the Dark Energy Survey (DES) Collaboration in order to carry out the Dark Energy Survey for which the collaboration has been awarded 525 nights over a period of five years. The DES began in September 2013, the DES observing season is September through February where the project will occupy approximately 60% of the observing time. DECam is also available for community use. The instrument design, operation, and performance is described in detail in *The Dark Energy Camera (DECam)* (Depoy et al. 2008). The material for this chapter has been drawn from a large number of sources, including DECam technical documents, the Dark Energy Survey (DES) website, data file headers, software design documents, and informal conversations with experts. NOAO and the DES Collaboration are continuously carrying out tests leading to ever more sophisticated realizations of the DECam data and the pipelines and infrastructure needed to optimize performance and image quality. This chapter describes the instrument and CCD characteristics and data products in enough detail that users who are not familiar with DECam can evaluate the scientific reliability, quality and suitability to support their science goals with DECam. The chapter also give some basics on the use and operattion of DECam. As NOAO-S grows in their familiarity with DECam, updates and additions to this chapter will be implemented.

2.1 INSTRUMENT OVERVIEW

DECam is a prime focus optical imager with a three square degree field of view (FoV) and a large focal plane array (FPA) consisting of a near-circular array of 62 2kx4k CCDs with a total of 520 million pixels. A schematic of the instrument is shown in Figure 2.1. Table 2.1 lists some basic characteristics of DECam.

The major components are a five-element optical corrector, four filter slides each holding two filters, a shutter, and a cryostat ("imager vessel") holding the focal plane of 62 science CCDs, 8 wavefront sensing CCDs, four guide CCDs and pre-amplifiers. Four electronics crates are mounted behind the Imager. The focal plane is cooled by a liquid nitrogen flow system with off-telescope regeneration and storage. The CCD vessel, shutter, filters and corrector are supported as a single unit by a hexapod that provides accurate adjustability in focus, lateral translations, tip, and tilt. This provides a real-time focus and alignment system to maintain high image quality.

2.1.1 Instrument Capabilities & Design

Optical Corrector

The corrector is a five-element, all fused silica design where the final element (C5) is the cryostat window. The large and steeply curved front element (C1) is not coated, the remaining elements have multi-layer anti-reflection coatings. These coatings contribute to the short-wavelength cutoff of the system throughput at around 340 nm. The optical corrector does not include an atmospheric dispersion compensator, therefore images in the bluer filters (u,g) at moderate to high airmass will show psf distortions in the direction of the parallactic angle.

Filters

The seven available filters are similar to those for the SDSS (u,g,r,i,z) with the addition of a Y filter and a very broad (500-760 nm) VR filter. Traces and data for the filter profiles can be found at http://www.ctio.noao.edu/noao/content/Dark-Energy-Camera-DECam. The filters are all multi-layer interference coatings on both sides of a 62 cm diameter fused silica substrate. All filters were supplied by Asahi Spectra Co. and exhibit steep transmission edges and flat tops, and no significant out-of-band response.

There are small differences in transmission and wavelength of the transmission edges as a function of radial distance from the center of the filter. DECam has an auxiliary system (called DECal) that illuminates the flat field screen with near monochromatic light, and thus can scan the system response (telescope primary, optical corrector, filters, CCDs) through each filter, as a function of position on the focal plane – in principle for every pixel. At time of writing (ver 2.1) final versions of these scans are being prepared and when available will be posted on the CTIO DECam WWW pages.

Shutter

The shutter is a "Bonn shutter", see http://www.bonn-shutter.de. Two blades sweep across the focal plane in very accurate synchronization, the elapsed time between the passing of the two blades over a position in the focal plane defines the exposure time. The blade-pair sweep in alternate directions each exposure. The shutter timing parameters substantially exceeded specifications. The timing accuracy is better than 1 ms at any position across its 600 mm diameter circular apertures (*DES Document 4398-v1*). The shutter exposure time repeatability is better than 5 ms, and the shutter allows a continuous range of exposures from 100 milliseconds upward. The absolute timing of an exposure is measured to a precision of 10 ms, and the accuracy of the shutter timing is < 50 ms (*DES Document 2071-v6*).

Focal Plane

The CCDs are mounted on an aluminium plate in a hexagon-pattern (see Fig 2.2) and are coplanar to approximately 15 microns (rms). Note that the gaps between CCDs are real and that the center of the field is inside a gap. The focus and alignment (active optics) CCDs are in four pairs with each component 1.5mm above and below the focal plane respectively. The detectors reach peak quantum efficiency (QE) above 85% at ~6500 Å, but have useful sensitivity from the atmospheric cut-off near 3200 Å to ~1 µm.

The delivered point spread function (PSF) is very well sampled by the detectors; image quality is seeing-limited at all wavelengths. The image quality at the Blanco is good, with little focus gradient or PSF variation across the field of view. The pixel scale is slightly variable (0.3% per radial degree) from the center to the edge of the field of view due to pincushion distortions.

Table 2.1: DECam Characteristics

Effective Area of CCD Focal Plane	3.0 square degrees
Optical Corrector Field Diameter	2.2 degrees
Pixel scale @center/edge of FoV (arcsec/unbinned pixel)	0.2637 / 0.2626
Image CCD pixel format/total # pixels	2K x 4K/520 Mpix
Telescope focal ratio	F3.0

The CCD detectors are 250 μm thick, fully-depleted devices. This is about 10 times thicker than conventional thinned CCDs. The thickness was chosen to improve the quantum efficiency in the near infrared (*Estrada et al. 2010, SPIE Vol 7735*). A substrate voltage maintains the field through the depleted region so that photoelectrons are efficiently collected. However charge diffusion is one of the major effects that goes into making up the image quality budget.

Each of the CCD detectors has two amplifiers with which to read the pixel arrays, and pixel binning is not supported. The detector properties, or ranges of properties, are given in Table 2.2. As of January 2014,two CCDs, devices N30 and S30, do not work properly.

Full well ranges from 130K to 210K electrons but is typically near 180Ke^-. Thus the CCDs all saturate before the 16-bit digital electronics saturate at 65K counts. Saturated stars bleed along columns, but not excessively. An effect where extremely saturated stars cause bleeding and overflow in the serial register is due to be fixed (early 2013).

Charge transfer for all the CCDs is excellent, 0.999995 or better when tested in the laboratory.

Linearity is good in general. However, there are some devices (listed in Table 2.3) that display a non-linearity at low light levels (below ~1000 electrons, ~200 adu). Most devices seem to become slightly non-linear at levels greater than (~0.6 fullwell). There is one CCD that has one amplifier unstable in its gain properties (amplifier B of S7) at light levels below 1000 adu and should be used with caution for precision photometry.

Finally, the QE is stable and except at the very ends of the range is very similar from device to device. Nevertheless, photometric transformations from instrumental magnitudes to standard systems should be calculated per detector.

Table 2.2: CCD Array Characteristics

Array Dimensions	
Axis 1:	2048 pixels
Axis 2:	4096 pixels
Pixel Size	15 µm square
Typical Gain	5 e–/ADU
Read noise	7-9 e–
Max. linear count	160,000 to 230,000 e–
CCD Gaps	
in rows (long edge)	3.0 mm, or 201 pixels
in columns (short edge)	2.3 mm, or 153 pixels
Exposure overheads (hardware)	
Readout + clear	17 sec + 3 sec

Figure 2.2 shows the arrangement of the FPA on the sky, which includes the 12 2k x 2k CCDs for guiding and focus controls. *Note that the raw image array coordinates are remapped from the detector coordinates, such that the orientation is as in the figure. For reduced data, the images are transposed so that North is up and East is to the left.*

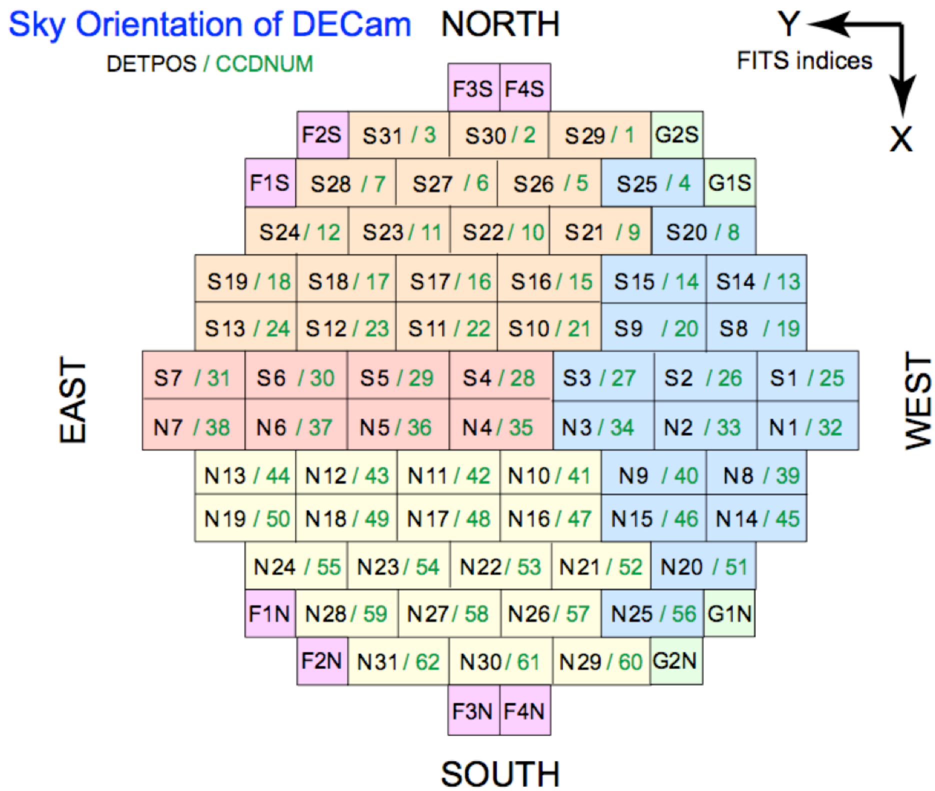

Figure 2.2: Orientations on the sky and spatial footprint of the FPA for DECam. 2k x 2k CCDs labeled as "F" will be used for focus and alignment control; those labeled as "G" will be used for guiding. Two amplifiers on each chip may be used for parallel read-out. The pixel coordinate origin is in the lower-left corner of each detector array.

Operations

DECam is controlled through the Survey Image System Process Integration (SISPI) software. Detailed information on SISPI is given below in section 2.2. Detailed instructions for logging in to DECam and configuring the instrument for operation are given on the CTIO DECam Cookbook webpages at: http://www.ctio.noao.edu/noao/content/DECam-Cookbook The CCD substrate voltages are controlled by the ***Vsub*** button and therfore must be turned on before DECam is operational.

It is possible to permanently damage the DECam CCDs with light due to over-illumination. Therefore, there are a number of protocols in place for observing with DECam. For the safety of the instrument, it is very important that the instructions below are followed and taken seriously.

1. Twilight sky flats (evening or dawn) are forbidden.

2. On-sky observing will start no earlier than 30 minutes after sunset and will finish no later than 30 minutes before sunrise. The telescope operator will advise the astronomer of these times.

3. Before the dome is opened, at any day time between the above limits, the person opening the dome will check on the DECam GUIs whether VSUB is OFF and the block is in the beam. This includes opening the dome to allow the telescope dome to ventilate prior to observing, and when extra light is needed in the dome for daytime work.

4. Before turning on the lights in the dome, check that no calibrations are underway and that the shutter is closed and VSUB is OFF.

5. Please use the "Calibrations warning signs" on the console and in the elevator. Any calibrations running in the morning after observing must finish before 08:00 a.m. unless arrangements have been made with the TelOps Manager the previous day.

Almost all observing programs will require calibration frames, such as bias (zero) frames and dome flats, in order to facilitate calibration. Normally, a set of calibration frames is taken in the afternoon, using a standard script that sequentially takes 10 zeros then 10 exposures of the flat field screen through all six filters. This script takes approximately 45 minutes to execute. The flats are very stable and it is not necessary to take a set after observing is completed in the morning. The flat field system produces u band dome flats of excellent quality.

The dark rate is very low, and dark frames are not necessary.

Many observers will want to obtain multiple exposures of their fields using the same filter in order to reject cosmic rays; often this is combined with a sequence of small spatial dithers in order to observe in the gaps between the CCDs in the FPA, and to enable the construction of continuous regions of sky free of gaps and detector artifacts. A few observing programs construct sequences of (slightly) overlapping images to map large regions of sky from the component tiles.

The CCDs fringe in the Y band (1% p-p) and z band (0.5% p-p) and have higher amplitude in the center of the focal plane compared to the edges. Producing a master fringe frame and an illumination correction from your data will be attempted by the pipeline operator, or alternatively library calibrations will be used.

A number of observing tools are available to support DECam in order to facilitate the planning, monitoring and reduction of observations. A list of these useful tools is given in section 2.3.

2.2 SURVEY IMAGE SYSTEM PROCESS INTEGRATION (SISPI)

The Survey Image System Process Integration (SISPI) is DECam's read-out and control system. Figure 2.2.1 shows a schematic overview of SISPI Components in a block diagram. (DES-doc-1965-v8) An exposure sequence starts when the observer sends a request to the Observation Control System or OCS (center of block diagram in Fig. 2.2.1). The OCS first queries the state of the instrument and sends commands to the telescope control system to slew the telescope to the given location, to adjust the hexapod controller, and to load the requested filter. Next the OCS preps the front end electronics to receive a new image. The OCS opens the shutter for the length of the exposure, and upon exposure completion, assigns an image builder process to assemble all pixel streams into the full image. The electronics are triggered to readout the CCDs. Image data flows from the DECam CCDs (Focal Plane) and the Monsoon front end electronics to the Image Acquisition and Image Builder systems before it is recorded on a storage device and handed over to the NOAO data transfer system (Data Management). At a rate of 250 kpix/s it takes about 17 seconds to transfer the data from the focal plane to the computers of the Image Acquisition system. During this time the telescope can slew to its next position. Further details on SISPI can be found on the DES SISPI overview page. At the telescope, SISPI is run, monitored and controlled through a series of Graphical User Interfaces (GUIs). The GUIs can be accessed from any browser once on the CTIO network at: http://system1.ctio.noao.edu:7001/apps [2], but full support for all the apps is currently provided only for specific browser versions. The GUIs of most interest to observers are highlighted below, and more details on all GUIs can be found on the DES SISPI Graphical User Interface page.

Logging In and Starting Up

Before you can begin to take data you must log in. When you click for the first time on any DECam Graphical User Interface (GUI), you will be required to login. The user name is DECamObserver and the password is the proposal ID of the observations taking place. This password is valid only during the days of the run. It expires automatically afterwards. By default, you will be logged in with authentication level user. At this level, you can watch the system, but you cannot control it. To control it, you will have to change your authentication level to 'observer'. This is done in the Observer Console GUI.

Observer Console

The observer console (Fig. 2.2.2) is the main GUI to operate DECam. This GUI is organized into a few sections for ease of control and monitoring of the system. The system status information, system control and exposure monitoring.

System Status: The status display in the upper left corner informs the observer about the status of the DECam system and if SISPI is ready to take an exposure. Monitor lights indicate that a system component is ready (green), in an intermediate state (yellow) or not ready (red) for operation. In addition, top panel status monitors show the state of readiness for the entire system, as well as the observer's user level.

System Control: The system control area has 3 tabs. Under The System Control tab, the observer can input information like Observer, Proposal Id, Program name and Program PI. The information in these sections is important as it is used in the headers for bookkeeping of the data taken. Errors in this section can slow post-observing data access. The Edit button must be used to change information in this section.

Exposure control: This button allows the observer to manually input information about the exposure to be taken. This includes target information for slewing, selection of filter, exposure time, etc. Once the information is entered, and the queue is unlocked, the exposure can be taken immediately (expose) or added to the queue (add). Alternatively, the observer's pre-written scripts can be uploaded to the queue and run by selecting the 'load exposure script' button that allows the user to browse directories.

Dither control: The dither control button gives the user an opportunity to setup multiple exposures that include a series of dithers. The available dither patterns are limited in step size and orientation. However more elaborate or random dithers can be done within an observing script.

Chat control: The *Chat Control* tab provides the observer with a simple tool to communicate with remote users and experts. The *RING* button is particularly useful to get someone's attention.

Current Exposure and Exposure Queue: The middle part of the observer console page is reserved for information on monitoring and control of the exposure queue (on the left) and current and past exposures (on the right). When the exposure queue is unlocked, exposures that have been set up with the exposure or dither controls can be run immediately or added to the end of the queue and then run sequentially, automatically or stepped through one at a time. Alternatively, the observer can select their own pre-made script, by filename, to load observation sequences into the exposure queue. The left side of this section shows the observations that are presently waiting in the queue. While the right side shows the file number and count down of the current exposure as well as the history of earlier exposures. The green lights in this section indicate at what stage an exposure is in the readout and control system.

The GUI elements on the bottom of the page can be collapsed to have more space for the exposure information. When visible the section in the bottom left corner shows an animated view of the image data flow through SISPI. Messages from the OCS are displayed in the text field at the bottom right corner.

More detailed information about the Observer Console and its use can be found at https://cdcvs.fnal.gov/redmine/projects/sispi/wiki/ObsGUI

Comfort Display

The Comfort Display web GUI (Figure 2.2.3) is a ds9 window on the comfort display monitor and shows the last image taken. This lower resolution png file (scaled down images of 1 graphic per crate) image is updated automatically as new images are completed. The display shows all science CCDs and focus CCDs. All of the images taken will be automatically transferred to the observer2 work station and can be more closely examined (i.e., with IRAF) from there.

Image Health

This GUI displays detailed statistics on each CCD for each image. Depending on which of the three image health views are selected in the bottom left corner, a color code indicates each CCDs (1) noise level, (2) sky level or (3) seeing. The mean, variance per amps for the overscan and data regions are also displayed. Clicking on a CCD will pop up the image of that particular CCD and the values for that ccd will display on the right panel.

Other GUIs of Note

There are a number of other GUIs that are usually opened during observations for monitoring the DECam system. A few of the most usefull ones are listed below. More detailed information on other useful GUIs can be found at https://cdcvs.fnal.gov/redmine/projects/sispi/wiki/GUI ,under the Components section.

Electronic Logbook: DECam has an electronic logbook, in which exposures automatically are recorded. Certain alarms will be automatically added to the logbook. The logbook can be accessed either through SISPI, or independently, by pointing your browser to the url: http://system1.ctio.noao.edu:8080/ECL/decam [6] . A login is required to post (but not to view) logbook entries. Observers are encouraged to make comments. An observer can ask their assigned user support staff member for information on posting comments.

Guider shows the region of interest for the guider CCDs,

Architect Console shows all the SISPI nodes and the status of their components,

Variable Viewer allows the user to monitor shared variables,

Exposure Table shows the list of exposures taken recently,

Exposure Browser allows the user to query the exposure table,

Alarm History lists the alarms generated by the system,

Interlock Viewer shows the status of the various SISPI interlocks,

Instrument Control System (ICS) shows the status of various instrument control system components (i.e., shutter, filter changer, hexapod, etc.)

Telemetry Viewer displays time series of variable relevant to the operating status of the system (i.e., the LN2 tank level and pressure, the CCDs temperatures and voltages, etc.)

2.3 DECAM OBSERVING SUPPORT TOOLS

There are a number of additional tools that are provided for supporting, planning, and executing DECam observations. Explanations and web based locations for these tools are listed below.

Exposure Time Calculator

An Exposure Time Calculator (ETC) has been written by Darren DePoy (TAMU) and Alistair Walker (NOAO). This excel spreadsheet includes as-built optics transmissions, filter transmissions, CCD QE as a function of wavelength, and sky brightness at various lunar phases. It should give reasonable estimates for *stellar* photometry with DECam. The ETC can be found at http://www.ctio.noao.edu/noao/sites/default/files/DECam_ETC-ARW2.xls

ScriptsEditor

The ScriptsEditor tool is a stand alone code that can easily be installed on any workstation. Python (with Tkinter support) is the only requirement. This software can be used to write exposure scripts for DECam allowing the creation of an observing queue, including multiple exposures and dithering. The output script are .json files. They are merely text files but have special formatting to allow them to be read by SISPI The source code and additional documentation can be downloaded from the website
https://cdcvs.fnal.gov/redmine/projects/sispi/wiki/ScriptsEditor

RASICAM

RASICAM is a radiometric all-sky infrared camera which monitors night sky conditions in support of DECam observations (i.e. detect and quantify the optical depth of clouds, and determine photometricity). Information about RASICAM and a link to view live sky images can be found at http://rasicam.ctio.noao.edu/RASICAMWebService/static/RASICAMwebService.html

Quick Reduce

Kentools

These are a number of command line tools written by Steve Kent that allow the observer to quickly assess data. The are run outside the iraf environment, but mimic some of the iraf functions. More on the KentTools and how to run them can be found at http://www.ctio.noao.edu/noao/content/DECam-Tools

2.4 DATA PRODUCTS

This section describes the content and format of the various data products that are produced for the DECam. Most of the products are generated during the course of calibration processing, the details of which are discussed in the next subsection. The data products of the Community Pipeline (CP) are categorized by processing type (PROCTYPE) and product type (PRODTYPE). Processing types are different classes or stages of calibration while product types are various associated data from a particular class. The processing types are master calibrations, instrumentally calibrated exposures, distortion corrected exposures, and field stacks/coadds. The product types are flux images, data quality maps, weight maps, and exposure/coverage maps. There are also raw data products classified as observing type (OBSTYPE). Classifications of the data types can be found in the primary header; the possible values are summarized in *Table 2.3*. The processing level (see Table 1.2, "Levels of Data Processing," on page 1-4) at which the product is generated is listed in column 5 (Proc. Level). The Community Pipeline will ignore any image for which neither appropriate standard calibrations nor appropriate library calibrations are available.

Table 2.3: Data Product Content Type

PROCTYPE	PRODTYPE	OBSTYPE	FILENAME KEYWORD extention	Extensions	Proc. Level
Raw	image	object| zero|dark| dome flat		IMAGE * N_{ext}	1
InstCal	image	object	_oi	IMAGE * N_{ext}	2
InstCal	dqmask	object	_od	BINTABLE * N_{ext}	2
InstCal	wtmap	object	_ow	BINTABLE * N_{ext}	2
Resampled	image	object	_ri	IMAGE * N_{ext}	2
Resampled	dqmask	object	_rd	BINTABLE * N_{ext}	2
Resampled	wtmap	object	_rw	BINTABLE * N_{ext}	2
Stack	*image*	*object*	*_si*	*IMAGE * $N_{ext,tile}$*	*3*
Stack	*image*	*object*	*_sil*	*IMAGE * $N_{ext,tile}$*	*3*
Stack	dqmask	object	_sd	BINTABLE	3
Stack	expmap	object	_se	BINTABLE	3
Stack	wtmap	object	_sw	BINTABLE	3
MasterCal	image	zero		IMAGE * N_{ext}	2
MasterCal	wtmap	zero		IMAGE * N_{ext}	2
MasterCal	image	dome flat		IMAGE * N_{ext}	2
MasterCal	wtmap	dome flat		IMAGE * N_{ext}	2

2.4.1 Image Formats

The image data from DECam is stored in FITS multi-extension files (MEFs), the general structure of which was described in section 1. The detailed arrangement of the image portions among the extensions differs depending upon whether the data are raw (unprocessed) or reduced.

Raw Data

Raw data from DECam consists of 16-bit unsigned integers, and includes virtual overscan along each row at the beginning (pre-scan: 6 pixels) and end (over-scan: 50 pixels) of the CCD readouts, which is stored with the image pixels as shown in Figure 2.4. Note that the coordinate origin for all images is in the lower-left corner of the read-out section (for the convenience of image display), rather than at the location of the read-out amplifier. The output from each amplifier (including the overscan regions) is stored in a separate image extension in the FITS MEF file (see Chapter 1); thus, there are as many image extensions in the raw science file as the total number of amplifiers used to read out all detectors in the focal plane. The size and location of the photo-active regions and the overscan are given in Table 2.4.

Table 2.35: Extensions

Extension	Description	Resource
Foreign	FITS extension that provides a mechanism for storing an arbitrary file or tree of files in FITS, allowing it to be restored to disk at a later time	http://arxiv.org/abs/1201.1829
Bintable	Binary table (organized into rows and columns) that comes after the primary data "file" in a FITS file	Cotton, Tody & Pence, A&AS, 113, 159 (1995)

Table 2.4: Raw Data and Over-scan Regions

Detectors	Amp	Photo-Active Data Section	y-Overscan	x-Overscan	Prescan
1N–31N	A	[57:1080, 1:4096]	[1:1080, 4097:4146]	[7:56, 1:4146]	[1:6, 1:4146]
	B	[1081:2104, 1:4096]	[1081:2160, 4097:4146]	[2105:2154, 1:4146]	[2155:2160, 1:4146]
1S-31S	A	[1081:2104, 1:4096]	[1081:2160, 4097:4146]	[2105:2154, 1:4146]	[2155:2160, 1:4146]
	B	[57:1080, 1:4096]	[1:1080, 4097:4146]	[7:56, 1:4146]	[1:6, 1:4146]

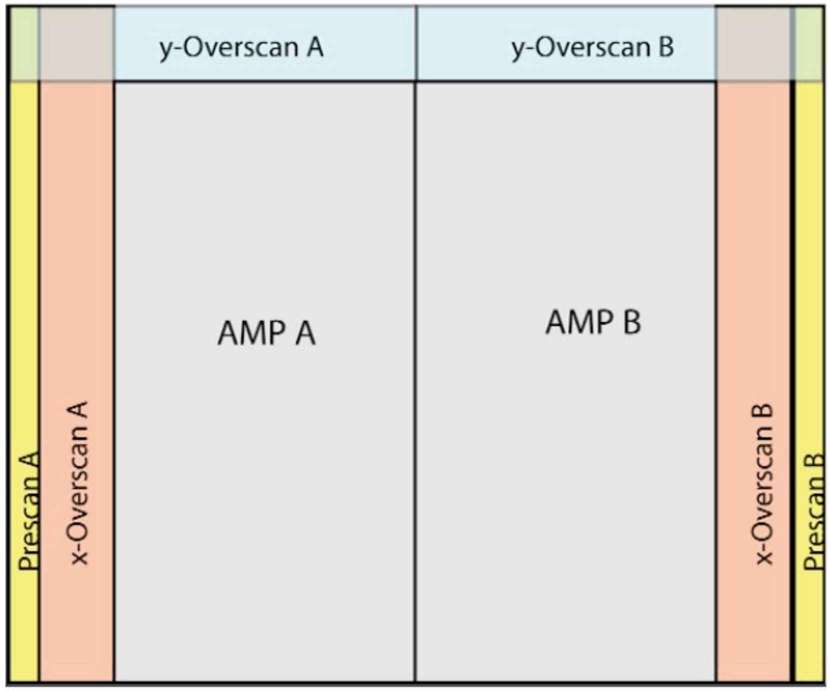

Figure 2.3: Schematic of the image array just after read-out of DECam. Note that there is some overlap in the pre-scan and overscan regions. (DES 4809-v3)

Calibrated Data

The NOAO Science Archive contains data products that are produced with the DECam community calibration pipeline (CP). The specific calibrated science data products are listed in Table 2.3 on page 2-12 and are described in more detail below. Each image has an associated data quality mask (DQM).
The science images are compressed by the FITS tile compression, which provides an acceptable level of lossy compression[2]. See the DECam E2E ICD by Science Data Management for more details.

InstCal. Instrumentally calibrated images are MEF files consisting of CCD extensions where the pixel data have not been interpolated and have been processed to remove instrumental signature. Note that the CP has chosen to eliminate one CCD that is of problematic utility. The CCD images are trimmed of bad edge pixels and the header metadata attempt to capture the scientifically useful information from the telescope and processing. The associated data

[2] More details on the FITS tile compression can be found here: http://arxiv.org/abs/1007.1179

products, each in its own MEF file with matching extensions, are the basic flux images, data quality maps, and weight maps.

Reprojected. Resampled/remapped exposures are MEF files where each extension is an image of a single CCD that has been resampled/ remapped/ interpolated/ warped (take your pick of terms) to a standard orientation and pixel scale at a standard tangent point. The point of this is to make different exposures congruent in pixel sampling. While this data product doesn't provide new information relative to the instrumentally calibrated version, it is provided to allow investigators to apply their own sky and/or gain adjustments and make coadds with a different subset of exposures without needing to remap. If the tangent points are the same then images only need to be registered by an integer offset before combining. The associated data products are the flux images, data quality maps, and weight maps where all are MEF files.

Stacked/Coadded. If two or more observations of a given target are obtained on the same night using the same filter and have spatial overlap by 75% or more, these images are combined using an average with outlier rejection to remove detector blemishes, gaps between the detectors, and artifacts such as image persistence and cosmic rays. The result is a union of the spatial footprints of the stack, with nearly the same pixel scale as the raw images. In general, these images will be larger—sometimes very much larger—than the resampled images because the area of the sky that is mapped can be significantly larger than the instrument FoV. Stacked/Coadded fields are MEF files where each extension is a piece of the field. The full overlapping stacked field is divided into abutting *tiles* whose size is less than 16K on a size. The investigator can work with individual tiles or recreate a single large image by pasting the tiles together. The associated data products are the flux files, data quality maps, weight maps, and exposure or coverage maps.

There are two versions of the stacked flux images provided to investigators; one with only a planar background removed and one with a low order spline fit to a grid of mode values in each CCD. These 2 stacked products reflect the different calibrations needed for different target fields. For fields with only stars and small galaxies, better matching across CCDs, and hence better stacks, is achieved by fitting a low order background surface to each CCD. However in fields with large galaxies (arc minutes or more) or large nebulosity, individual CCD fitting produces gross effects. In that case only a global sky gradient can be subtracted. Determining sky subtraction to use in an automatic pipeline is beyond the ability of the CP. Instead data products using both methods are applied leaving the best choice to the investigator.

The exposure duration for stacked images, as recorded in the `EXPTIME` keyword, refers to the sum of all exposure durations of all images used to create the stack. The exposure depth and noise properties of a stack of dithered images is a discontinuous and possibly complicated function of position in the image. Use the exposure map to track the detailed expo-

sure depth at the pixel level

Master Calibration. Reference files are created during the course of pipeline processing (as opossed to extrenally produced calibrations), such as bias structure, dome flat stacks, etc., for each night. These files are used in pipeline processing to remove instrumental signatures from the science data. These reference files are 32-bit floating-point images, stored as MEF files with as many extensions as the corresponding raw images, where each extension is data from a single CCD. The product types are the flux data and weight maps. There are currently no data quality maps.

Concomitant Data. All reduced images are accompanied by data quality masks (DQM); These maps provide integer-value codes for pixels which are not scientifically useful or suspect. Table 2.5 lists mask values that are applicable to nonstacked images.

Table 2.5: Data Quality Bit Definitions in DQM

Bit	DQ Type	PROCTYPE
1	detector bad pixel	InstCal
1	detector bad pixel/no data	Resampled
1	No data	Stacked
2	saturated	InstCal/Resampled
4	interpolated	InstCal/Resampled
16	single exposure cosmic ray	InstCal/Resampled
64	bleed trail	InstCal/Resampled
128	multi-exposure transient	InstCal/Resampled

2.4.2 **Header Keywords** *(3427-v10, Dec 2011)*

A wide variety of metadata are recorded in the headers of the science frames. Users should review these headers (and the extension headers) to familiarize themselves with the content. The more critical metadata are described in this subsection. Table 2.6 lists metadata by the keyword name, the header unit in which the keyword will be found (Primary or Extension), the point in the data processing where the keyword is introduced (or where the value is updated), and the meaning of the keyword (or group of keywords, if they are related). Some of the keywords are indexed by image axis, meaning they come in pairs, as indicated by the suffixes ***i*** and ***j***. Here, P, E and R designate that the keyword is located in the Primary, Extension and Raw Header, respectively. U means the keyword is updated in the data products during pipeline processing, and L2/L3 refer to whether the keyword is in Level 2 data products (single reduced exposures)/Level 3 data products (stacks and/or catalogs).

Table 2.6: Important Image Keywords (*still subject to change—origin should be confirmed*)

Keyword Name	HDU	Origin	Meaning
			Telescope
AIRMASS	P	R	Atmospheric pathlength for target at observation start
OBSERVAT	P	R	Observatory that operates this telescope
TELESCOP	P	R	Telescope used to obtain these data
TELDEC	P	R	Declination for the telescope position on the sky in degrees
TELRA	P	R	Right ascension for the telescope position on the sky in hours
			Instrument/Detector Configuration
CCDSUM	*E*	*R*	*CCD binning factors along Axis1 and Axis2*
CCDNUM	E	L2	Detector designation
FILTER	P	R	Filter name/designation
CCDBIN1	E	E, U	Pixel binning, axis 1
INSTRUME	P	L2	Instrument used to obtain data
GAINA	E	L2	Gain for amp A [electrons/adu]
			Time
DATE-OBS	P	R	Date and time of observation start
EXPTIME	P	R	Effective exposure duration in seconds
MJD-OBS	P	R	Time of observation start in MJD
TIME-OBS	P	R	Time of observation start
TIMESYS	P	R	The principal time system for all time-related keywords. Always UTC.
			Environmental
WINDSPD	P	R	Wind speed [m/s]
WINDDIR	P	R	Wind direction (from North) [deg]
HUMIDITY	P	R	Ambient relative humidity (outside) [%]
PRESSURE	P	R	Barometric pressure (outside) [hPA]
DIMMSEE	P	R	DIMM seeing [arcsec]
			World Coordinates
CD***i_j***	E	R, U	Transformation matrix from pixel to intermediate world coordinates; CD*i_i* is the pixel scale for axis *i*
CRPIX***i***	E	R, U	Location of the reference point along axis *i* in units of pixels
CRVAL***i***	E	R, U	Value of the world coordinate at the reference point for axis *i* in degrees
CTYPE***i***	E	R	Name of the coordinate represented in axis *i*
DEC	P	R, U	Declination for the center of the detector FoV in degrees

Keyword Name	HDU	Origin	Meaning
EQUINOX	E	R	Equinox in years for the celestial coordinate system in which the positions are expressed
NAXIS***i***	E	R	Number of pixels along axis *i*
PIXSCAL***i***	E	R	Pixel scale along axis *i* in arcsec/pixel
RA	P	R, U	Right ascension for the center of the detector FoV in hours
RADESYS	E	R, U	Name of the reference system in which the world coordinates are expressed
WAT***i_nnn***	E	R, U	IRAF-specific description of the nonlinear portion of the transformation from detector to world coordinates for axis *i*. This character string contains coefficients for a polynomial; the length of the string is such that it must continue for *nnn* FITS header records.
			Calibration
BLDPROC	*E*	*L2*	*Bleed trail processing parameters (bleed threshold & grow radius)*
BUNIT	E	L2, L3	Brightness units, normally "electron/s" for calibrated images
MAGZERO	*E*	*L2*	*Magnitude corresponding to one count in the image*
OBSTYPE	P	R, U	Type of target observed (see Table 2.3 on page 2-12)
PHOTBW	*P*	*L2*	*RMS width of bandpass (Å)*
PHOTCLAM	*P*	*L2*	*Central wavelength of bandpass (Å)*
PHOTDPTH	*P*	*L2*	*Photometric depth of the exposure. (See " " on page 2-28.)*
PHOTFWHM	*P*	*L2*	*FWHM of bandpass (Å), i.e., width measured at 50% of peak transmission*
PIPELINE	*P*	*L2, U*	*Pipeline name*
PLVER	*P*	*L2, U*	*Pipeline version identifier*
PROCTYPE	P	L2, U	Product type (see Table 2.3)
PRODTYPE	P	L2, U	Product data description (image | mask | expmap)
SATPROC	*E*	*L2*	*Saturation processing parameters (saturation threshold & grow radius)*
SEEING	*P*	*L2*	*Average FWHM of point sources in arcseconds*
SKYBG	*P*	*L2*	*Brightness level of background averaged over all CCDs in ADU*
SKYBG1	*E*	*L2*	*Brightness level of background in single CCD in ADU*
SKYNOISE	*P*	*L2*	*RMS noise in the background level in ADU*

2.4.3 Environmental Data

Environment data is merged into the FITS headers by the Survey Image System Process Integration (SISPI) from several different sources: the Tololo seeing monitor, the weather station and the Blanco set of sensors installed on the telescope and dome. In addition, data from the Radiometric All-Sky Infrared Camera (RASICAM)[4] is recorded in the headers. A terse summary of sky conditions at CTIO[5] are available on the Web.

2.4.4 NOAO Science Archive Portal

All DECam raw and CP processed data is available through the NOAO Science Archive[6]. The details of the science archive and its use are listed in chapter XXX . Listed here is some information for effectively searching the archive for DECam data, both proprietary and public. The PI should login to the archive on the home page before trying to search for proprietary data. Publically available data is available without login for all users.

In the archive, DECam data can be searched for using a number of identifiers. The archive portal allows the user to find data by defining a box search on an RA/Dec location, by the NOAO program number, PI name, observing dates, original (at the telescope) filename or archive filename. One can also refine the query with a variety of options including, exposure time limits, public release dates and raw and reduced data file types. In addition, for those familiar with SQL, there is an option of refining searches even further with the 'Advanced Query Form'.

Once the query results have been obtained, those can be sorted according to any of the displayed meta-data for each observation. Table XX includes the keywords for meta-data that is extracted for each observation in the results section of the archive portal. Sorting can be done by selecting the column header name of the column to be sorted. The small arrowhead (triange) that appears in the column header indicates in which column the sorting is being done. Selecting the column a second time will reverse the sense of the sort.

Any of the publically available data (Access = Retrieve) can then be marked if the fore-row square box for download. Data that is still proprietary (no selection box) can only be downloaded after logging in on the home page with the appropriate username and password.

When searching the archive, it is best to keep the query to the minimal search set for the most efficient return of accurate information. Queries that are too broad can often in advertently exclude data files that are actually intended as part of the request.

[4] http://rasicam.ctio.noao.edu/RASICAMWebService/static/RASICAMwebService.html
[5] http://www.ctio.noao.edu/site/phot/sky_conditions.php
[6] http://portal-nvo.noao.edu/

2.5 CALIBRATION

The Dark Energy Camera (DECam) Community Pipeline (CP) is an automatic, high performance processing system to apply the best instrumental calibrations as currently understood. During the first year of camera operation there were improvements being made as the scientists and engineers learned more about the characteristics of the instrument and explored calibration algorithms. This document describes the various calibrations for version 3 and its minor updates of the CP (V3.x.x). The version may be found under the PLVER keyword of the CP data products.

The current generation of pipeline processing produces Level-2 products, i.e., images where the instrumental signature has been removed and geometric and photometric calibrations have been applied; and Level-3 products, where spatially overlapping images in the same filter (and that have been obtained within the same observing run) have been stacked. The pipeline uses both calibration exposures, such as bias frames and dome flats, as well as portions of science exposures (i.e., areas free of defects, artifacts, and astrophysical objects) to construct the calibration reference files that are used as input to the processing. For simplicity, the subsections below will first describe the processing of the science images once the calibration reference files are available; then the processes for constructing the calibration reference files will be described with the overall flow as context. The actual sequence of processing in the pipeline software differs somewhat in detail, in part to optimize the performance of the parallel processing environment. Another challenge for presentation is the organization of the many calibrations. As a pipeline, the calibrations proceed in a relatively linear fashion. So, though some calibrations could be done in different orders with different advantages and disadvantages, this document follows the V3.x.x calibration flow.

The calibration pipeline for DECam reductions is tuned to maximize the use of exposures within the observing run in which they were obtained. As such, the quality of the data depends to a large degree on the quality of the calibration exposures that were obtained by the observer. However, under some circumstances, the pipeline will attempt to use calibration data from prior observing runs if the separation in time is not too great; the specific rules are described in the following sections.

2.5.1 Processing Steps

This section provides descriptions for the various calibrations of the CP applied to science exposures in the order in which they are performed. *As explained below, some steps are not performed for data where the correction in question is not needed. Inputs to the processing include the raw science frames, calibration reference files (see "Calibration Reference File" on page 2-29), and photometric and astrometric catalogs. Outputs include the various reduced science images, plus their associated mask files (see "*Image Formats*" on page 2-13). Intermediate products that are produced during the course of pipeline processing, but that are not archived, are not shown. The processing is segregated by night, filter, and further by overlapping observing sequences when deriving stacked frames.* The challenge for a document of this kind is providing a useful amount of detail without becoming a dense system manual, thus *only summary descriptions are given here. More details can be found online at http:/www/?????????????????????????.*

List of Calibration Steps

- Electronic Bias Calibration
- Crosstalk Correction
- Saturation Masking
- Bad Pixel Masking and Interpolation
- Bias Calibration
- Dark Count Calibration (not in V3.x.x)
- Linearity Correction
- Flat Field Gain Calibration
- Fringe Pattern Subtraction
- Bleed Trail and Edge Bleed Masking and Interpolation
- Astrometric Calibration
- Single Exposure Cosmic Ray Masking
- Photometric Characterization
- Sky Pattern Removal
- Illumination Correction
- Pixel Area Correction (not in V3.x.x)
- Remapping
- Multi-Exposure Transient Masking
- Coadding/Stacking

Electronic Bias Calibration: A correction for electronic amplifier bias, generally known as "overscan subtraction", is made using overscan readout values. There are two amplifers per CCD, each with their own overscan values, and they are handled independently. A single bias value is subtracted from the part of the image line corresponding to a particular amplifier. Each line is treated independently; i.e. there is no smoothing of the overscan values across lines.

Crosstalk Correction: Crosstalk is an effect where the signal level in a pixel being read by one amplifier affects the signal level in another amplifier. The effect can either increase or decrease the measured/recorded value from the other amplifier. The CP computes a correction for every pixel in an amplifier caused by every other amplifier; though it is implemented so that if there is no effect between a pair of amplifiers no corrections is computed. The correction is essentially an empirical model that has been determined by the instrument scientists and engineers. The model provides a linear correction up to a threshold and then a non-linear correction up to the limit of the digital converter. Crosstalk subtraction is performed by the **DECam_crosstalk** executable.

Saturation Masking: Saturation is essentially the point where the accumulated charge in the CCDs can no longer be properly calibration. In the CP this is defined to be pixels which exceed a threshold determined by the instrument scientists. The threshold is different for each amplifier. The CP sets the most current values in the image headers and then adds a saturation bit (bit 2) in the data quality maps for those pixels exceeding that value. Saturation masking is performed by the **DECam_crosstalk** executable.

Bad Pixel Masking and Interpolation: A bad pixel calibration map is defined external to the CP. The identified bad pixels are added to the pre-identified exposure bad pixel maps. Bad pixels are replaced by linear interpolation from neighboring columns when only a single bad pixel is spanned. The weight of the interpolated pixel is reduced by a factor of 2.

Bias calibration: This consists of subtracting a master bias calibration. Master biases are created by the pipeline. The pipeline selects the nearest in time which is usually from the same night as the science exposures were taken. Bias subtraction is performed by **imcorrect** command which takes bias calibration file as an argument.

Dark Count Calibration: The CP does not do a dark count calibration and dark count exposures are ignored on input.

Linearity Correction: The DECam CCDs exhibit varying amounts of non-linearity at both low and high count levels. The instrument team provides a look up table for each amplifier to correct this. The linearity correction is performed by the **imcorrect** executable when a linearity look table (LUT) is provided.

Flat Field Gain Calibration: The principle, pixel level, gain calibration consists of dividing by a master dome flat field. Master dome flat fields are created by the pipeline from dome flat exposures (usually) taken during the same night. These master dome flat fields are, themselves, corrected for large scale effects; namely, camera reflections and differences in response between the dome lamp illumination and a typical dark sky. The corrections are derived from stellar photometry of a calibration field obtain during special calibration programs. These calibrations are called star flat fields or "starflats". Dome and star flat field gain calibration are performed by the **imcorrect** command which takes dome flat calibration image as an argument.

Fringe Pattern Subtraction: A couple of filters (z and Y) show an interference pattern, generally call a "fringe pattern", caused by narrow night sky lines. (See figure 2.5 for an example.) This is removed by subtracting a fringe pattern calibration. This calibration is produced externally from data taken during special calibration programs. The pattern has been determined to be sufficiently stable over time to use such a calibration. The calibration pattern is scaled by the median of the exposure and then subtracted. *The fringe correction is only applied to exposures taken through broadband filters with central wavelengths greater than 6290 Å.*

Bleed Trail and Edge Bleed Masking and Interpolation: Saturation in bright stars and galaxies produce trails along columns due to an effect called "bleeding" or "blooming". (A related effect is edge bleeding from the serial register which affects lines near the serial register side of the image when there is a very bright star near the serial register. An algorithm is used to identify pixels affected by these effects and add them to the data quality maps. In addition the pixels are replaced by linear interpolation across the bad data.

Astrometric Calibration: This consists of refining the world coordinate system (WCS) function based on matching sources in an exposure to a astrometric reference catalog (V3.x.x: 2MASS). The sources in each CCD are cataloged and then all the catalogs are combined and matched to the astrometric reference catalog. The matched sources are then used to refine the terms of the TPV WCS function. This astrometric solution is stored in the CCD image headers of the instrumentally calibrated data products. Note that there are also data products where the images have been remapped to a simple tangent plane world coordinate system.

Single Exposure Cosmic Ray Masking: Cosmic ray events are identified and the affected pixels are added to the data quality and weight maps. The single exposure identification is based on finding pixels that are significantly brighter than nearest neighbor pixels; i.e. have "sharp" edges. This algorithm has been tuned to avoid identify the cores of unresolved sources. Part of this is that exposures with very good image quality (FWHM < 3.3 pixels) are not searched. Note that cosmic rays are also identified at a later stage when multiple exposures of the same field are part of the dataset.

Photometric Characterization: A characterization of the magnitude zero point is derived by comparison to common sources in a photometric reference catalog (V3.0: USNO-B1 *see Monet, et al. 2003)*. This is obtained by creating a source catalog of instrumental magnitudes and matching it against a reference catalog. The mean magnitude difference in the matches yields the zero point. This zero point is useful both for users and for stacking multiple exposures. *Note that the result of the photometric calibration is to populate the science header with keywords—the pixel values remain unchanged, and have units of detected photons s^{-1}.*

In physical terms, the photometric depth of the exposure (zero) is the faintest point-source that can result in an 5-σ detection above the sky background, in units of magnitudes. The magnitudes for the USNO-B1.0 catalog were for the most part derived from photographic source material and have high uncertainties. In addition, the mapping from filters used with the Mosaic cameras to USNO-B bandpasses, and then the color transformation from USNO-B to the SDSS filter set, introduces substantial (but uncharacterized) additional uncertainties. The resulting magnitude zero-point and photometric depth given in the headers of DECam science data are uncertain by an unknown amount that may *approach 0.5 mag. At present the photometric calibration is not adequate to support science.*

Sky Pattern Removal: This correction attempts to make the sky background across an exposure be uniform on large scales. This applies to the non-remapped exposures from which remapped images and stacks are subsequently produced. The first pattern to remove is a camera reflection which appears as a large image of the pupil; hence often termed a "pupil ghost". The second pattern is a gradient across the field where, By gradient we don't mean just a plane but a structure that might be like a vignetting based on the orientations of the dome slit, strong light like the moon, or differential atmospheric transmission. It is realized that some of these are actually response variations rather than additive background but in V3.x.x all sources of low spatial frequency variation are treated as additive background.

Illumination Correction: This correction makes the ensemble response to sky light, after removing sky patterns due to camera reflections and illumination gradients, uniform across the field of view. This is done by combining all exposures of 60 seconds or more, in the same filter and over a small set of nights (usually a run), using source masks and medians to eliminate source light. This "dark sky illumination" calibration is divided into each individual exposure.

Pixel Area Correction (not in V3.x.x) : A photometric point to be aware of is that the various gain calibrations on the unremapped individual exposures assume the areas of the pixels projected on the sky are the same. This is a small effect in DECam (< 1% at the extreme edge) but, depending on how one performs the photometry, this may be a factor one should consider. The remapping and subsequent coadded stacks explicitly make the pixel areas the same (apart from the very small tangent plane projection) and so fixed aperture photometry would be as accurate as the gain calibration allows.

Remapping: The astrometric calibration allows remapping the data to any desired projection and sampling. Note that if the astrometric calibration failed (keyword WCSCAL) then remapping and coadding are not done on the exposure though a data product will still be available without an accurate astrometric calibration. The two reasons for remapping are 1) to provide data where instrument distortions have been removed, particularly pixel size variations on the sky which can affect photometry programs, and 2) to register images for stacking. The CP resamples (which means interpolates) each exposure to a standard tangent plane project with north up, east to the left, and each pixel being 0.27 arc seconds square. The interpolation method is reflected in the image headers (keyword REDAMPT1) and is an Lancozos interpolator in V3.x.x and earlier.

Multi-Exposure Transient Masking: The pipeline masks "transient" sources in overlapping exposures. These masked sources are then excluded from coadds of the exposures. Transient sources include cosmic rays, satellite trails, and asteroids. In summary, anything which is significantly different in one exposure compared to a median of the exposures. However, the algorithm purposely is insensitive to differences within galaxies and stars. It also becomes statistically insensitive when there are very few exposures in regions of overlap. The key tools for this algorithm are the IRAF tasks **imcombine** and **acediff**.

Coadding/Stacking: The CP combines exposures which overlap significantly. The exposures which overlap are determined during the remapping step in the more detailed description. Exposures are considered overlapping when they have the same tangent point. As noted there, exposure patterns that move fields by roughly a DECam field of view will generally produce separate coadds and not one very large coadd.

The overlapping exposures are divided up into multiple stacks by the following criteria. Exposures are grouped by exposure time with groups for very short ($t < 10s$), short ($10s <= t < 60s$), medium ($60s <= t < 300s$), and long ($t > 300s$) exposures. If a group has more than 50 exposures it is divided in the smallest number of subgroups which all have less than 50 exposures.

Of the exposures that are identified for a stack another set of criteria are used to exclude outlier exposures that can degrade the image quality. These critera are based on outlier statistics, meaning exposures that depart significantly from the typical values. The quantities considered are unusually large relative flux scaling (e.g. low magnitude zero points due to bad transparency or short exposure time), poor seeing, and high sky brightness. In addition, only less than half of the exposures are allowed to be rejected, otherwise all exposures are used.

There are two stacks produced for each set of exposures satisfying the critera above. One has no background adjustments beyond those applied to the non-remapped data as described previously. The other subtracts an additional background from each CCD. This is a higher spatial frequency filtering which can produce a better matching of overlapping CCDs but can also subtract light from sources with extended light of 10% or more of a CCD. Because it is difficult for the pipeline to decide which is appropriate for a dataset, the two versions are produced from which the investigator can chose.

A common question is why a coadd does not include data over a long run or multiple runs. This is because the pipeline works on blocks of consecutive or nearly consecutive nights. Only data within a block of nights are available for defining a field. Long runs are sometimes broken up into multiple blocks due to disk space limitations. Programs that have assigned nights that are disjoint by many days (normally considered as different runs) are processed separately.

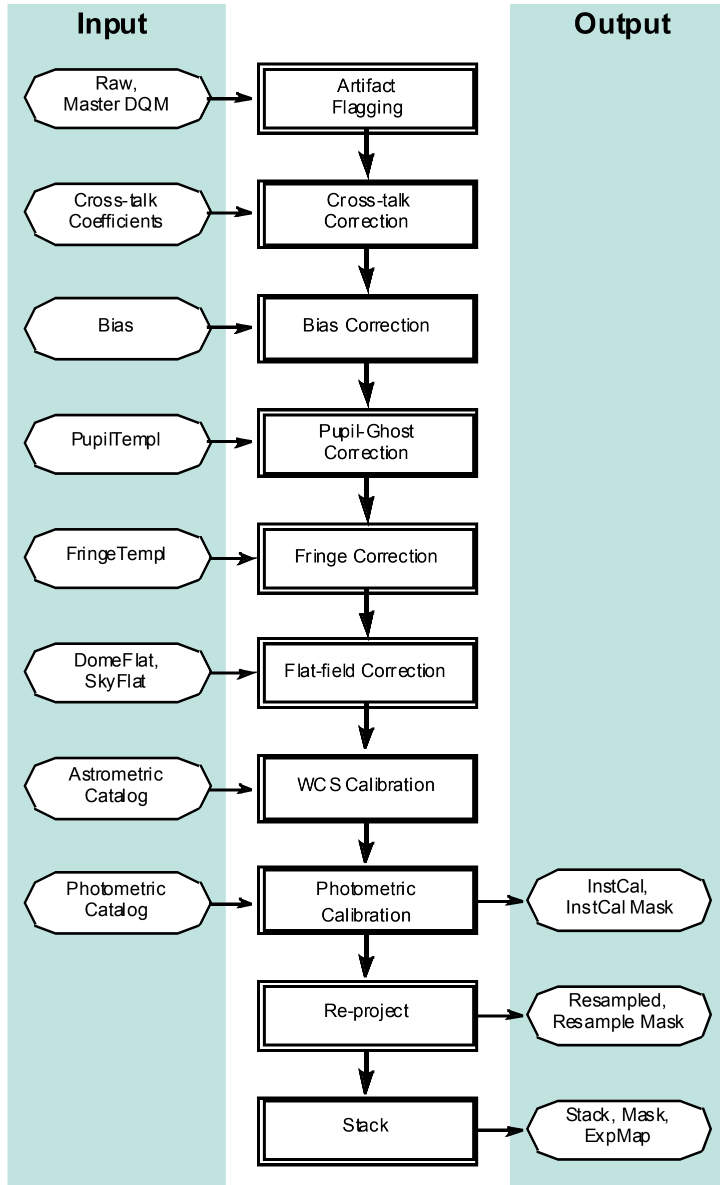

Figure 2.4: Flow of data taken with a common filter through pipeline processing and calibration to produce Level-2 and Level-3 data products. External catalogs, and data products defined in *Table 2.3*, are shown as inputs or outputs of the processing.

Artifact Flagging

Various image artifacts, including detector defects marked in the Master DQM reference file, are flagged in the Data Quality Maps (DQM) for each science *image. In addition, pixels with values above the saturation threshold for the parent CCD are flagged at the beginning of the processing. Further artifact flagging occurs later in the processing (see sections above), including transients (e.g., moving objects and cosmic rays) which are detected during the final image stack. Note that the regions flagged using the saturation and bleed trail thresholds are grown by up to a few adjacent pixels to minimize the risk of compromised data near artifacts. The final data quality mask for each InstCal image indicates all detected artifacts noted above; these values are propagated to the Resampled images, which generally increases the number of affected pixels to include areas adjacent to the pixels in the original geometry. All flagged pixels are excluded from contributing to the final, stacked image; if this process results in areas with no data, such pixels are so flagged (see "Concomitant Data" on page 2-17 for details).*

Note that all pixels in calibrated science frames (InstCal, Resampled, and Stacked) that are flagged in the DQM with a value other than zero will be interpolated over. The 1-dimensional linear interpolation is performed along the shortest dimension of the region over which to interpolate. This process is intended to avoid introducing "ringing" artifacts during the down-stream resampling of the images, as well as to mitigate scaling problems when using image display software. The affected pixels retain their flags in the DQM, however.

NEED DECAM FRING EXAMPLE HERE!

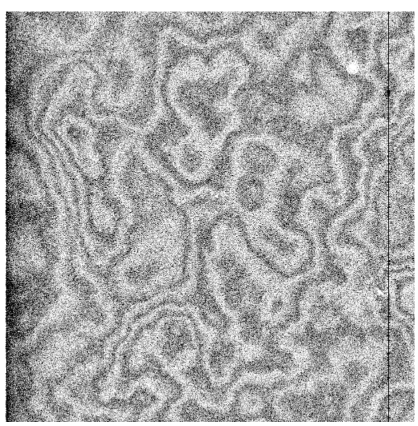

Figure 2.5: Example of the Mosaic-1 **fringe** pattern in a 512 x 512 pixel region. *This image needs to be updated for DECam data.*

2.5.2 Calibration Reference File

The calibration reference files that are used in the pipeline processing are constructed for each observing run where a sufficient number of appropriate exposures exist. For all but the bias structure file, the exposures that are used for calibration are affected by multiple instrumental signatures. It is important to distinguish between the additive backgrounds and the multiplicative sensitivity variations in order to avoid biasing the photometric accuracy of the processed science frames. Thus, the path to creating the reference files is an iterative one, and involves isolating the various effects, storing a characterization of the effect in a template image, and using these templates to construct down-stream reference files.

The CP maintains a Calibration Library of files which are applied during processing. The selection of a calibration file is based on the date of the exposure being calibrated. Some calibration files change infrequently and some are derived frequently from calibration or on-sky exposures taken by the observers. The processing metadata added to the data products provides the names of the calibration files used and, in principle, all calibrations files may be obtained from the archive.

List of CP Calibration Files

- Crosstalk Coefficient File
- Saturation Level File
- Linearity File
- World Coordinate System Coefficients File
- Bad Pixel Map
- Bias/Zero Calibrations
- Dome Flat Calibrations
- Star Flat Calibrations
- Fringe Calibrations
- Illumination Calibrations

Crosstalk Coefficient File : The crosstalk coefficient file is a text file provides the coefficients for the crosstalk correction described earlier. The is indexed by pairs of affected and source CCD amplifiers. This file is derived by a calibration team looking at potential affected pixels for bright sources in a variety of exposures. This may be updated periodically as needed.

Saturation Level File: A text file is provided by instrument scientists containing the saturation level for each amplifier. This is considered the best estimate and overrides values in the raw exposure headers.

Linearity File: The instrument scientist provide a linearity coefficient FITS file with tables of linearity coefficients for each CCD.

World Coordinate System Coefficients File: A text file is provided by instrument scientists containing the keywords required for the TPV world coordinate system (WCS). Besides the structural keywords this also provides the initial coefficients for each CCD. These keywords and coefficients override values in the raw exposure headers.

Bad Pixel Map: The instrument scientists provide a map of the known bad pixels for each CCD. This information is used to populate the initial data quality maps for each exposure. These files will be periodically updated as needed.

Bias/Zero Calibrations: All bias exposures from a night -- independent of proposal and excluding any subject to the voltage turn on transient -- are processed into a single master bias calibration. The first steps are the same as previously described for science exposures; namely, electronic bias, crosstalk, saturation masking, and bad pixel masking and interpolation. After these calibrations the exposures are combined, in CCD pixel space, by averaging the pixel values with lowest and highest values excluded. A weight map is also produced for error propagation.

Dome Flat Calibrations: All dome flat exposures from a night -- independent of proposal, excluding any subject to the voltage turn on transient, and grouped by filter -- are processed into a single master dome flat calibration. The first steps are the same as previously described for science exposures; namely, electronic bias, crosstalk, saturation masking, bad pixel masking and interpolation, master bias subtraction, and linearity. Each CCD is then scaled by the average of the central section ([500:1500,1500:2500]) with bad pixels identified by the current instrument bad pixel map excluded. The pixels are then combined, in CCD pixel space, by averaging the pixel values with lowest and highest values excluded. A weight map for error propagation is also produced.

Star Flat Calibrations: The star flat calibrations, one per filter, is a master calibration created outside of the CP. It is produced from many dithered exposures of a modestly dense stellar field taken as part of a separate calibration program. These exposures are processed through the normalized dome flat calibration. The logic is that the dithering produces many instances of the same star over the detector. Spatial variations from the average instrumental magnitude for that star provides a measure of the relative response differences between those sampled points. By combining a large number of stars a flat field map is produced which makes the instrumental magnitudes, and hence the response of the camera, uniform across the field of view.

Fringe Calibrations: Templates of the fringe pattern, one for z and one for Y, are quite stable. Therefore, these are derived periodically outside of the CP from many exposures of sparse fields. The exposures are combined to exclude sources. The the master stack is filtered to extract the fringe pattern with a mean of zero. During science exposure calibration the template is scaled and subtracted.

Illumination Calibrations: Illumination calibrations, grouped by filter, are derived from run datasets when the exposures are sufficiently numerous, dithered, and unaffected by large sources. This provides a gain correction to the more static star flat calibration. The calibration consists of images for each CCD with flat field pixel values. The values are generally spatially smoothed. When an illumination calibration is derived, and approved by the operator, it enters the CP calibration library. It may then be used for the individual exposures from the same dataset or by other datasets for which an illumination correction cannot be derived.

Table 2.7: Background Characteristics

Effect	*Contribution*	*Spatial Scale (pix)*	*Amplitude*	*Color Dependence*	*Notes*
Pupil Ghost	*Additive*	*2300*	*10%*	*High[7] @blue & red*	*Spatially stable per filter; amplitude depends on field brightness.*
Fringe Pattern	*Additive*	*10 s to 100 s*	*1–10% of sky*	*Strong*	*Spatially stable per filter; amplitude variable in minutes to hours.*
Flat-Field	*Multiplicative*	*2*	*~1–2%[8]*	*Moderate*	*Stable spatially & temporally, apart from shadows of dust particles.*

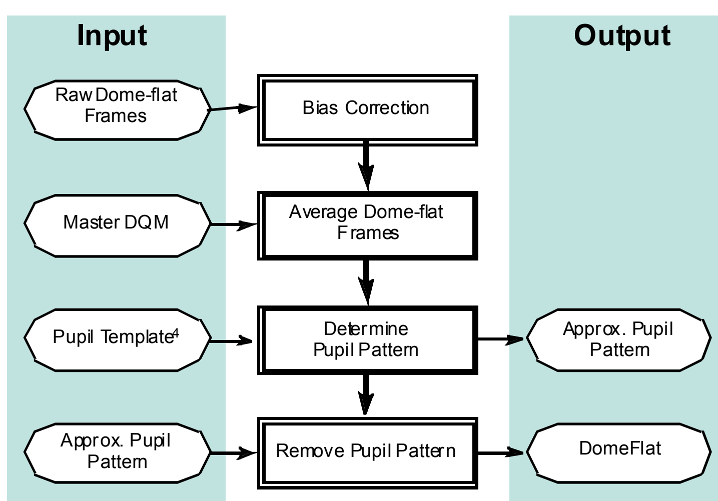

Figure 2.6: Process for characterizing the dome flat-field for each filter. Input dome-flat frames are uncalibrated. Pupil pattern characterization/removal applies to Mosaic-1 data obtained at the 4-m telescope only.

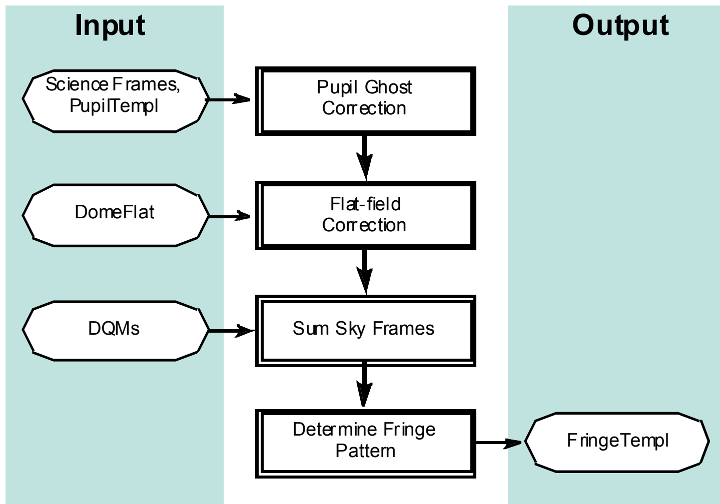

Figure 2.8: Process for characterizing the fringe pattern for each filter. Input science frames have had cross-talk and bias corrections applied.

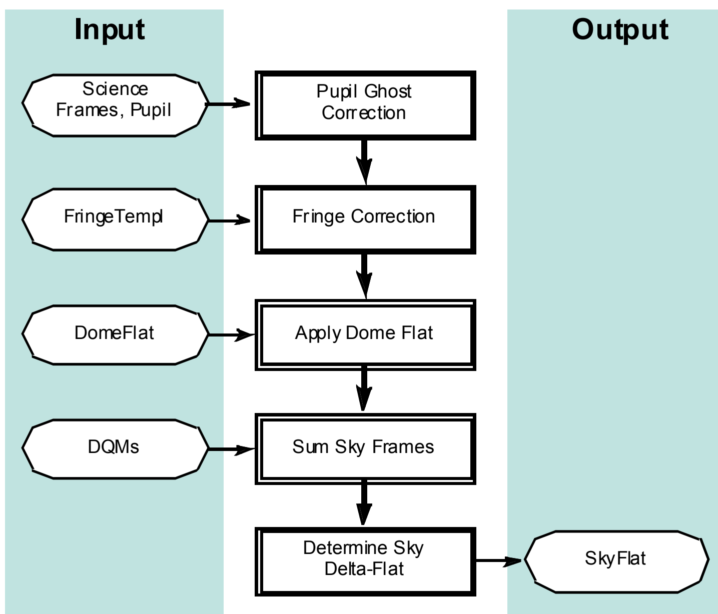

Figure 2.9: Process for characterizing the sky-flat for each filter. Input science frames have had cross-talk and bias corrections applied.

References

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For Further Reading