Dark Energy Camera Specifications and Technical Requirements

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Introduction

The specific objectives of the DES and implied science requirements of the Dark Energy Camera (DECam) are given in http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=812. These define the science-based motivations for the technical requirements for DECam. In general, this document describes the high-level technical requirements that DECam must meet in order to produce data acceptable to meet Survey goals. Details of the requirements, including additional detail and testing procedures, can be found in additional documentation, which is referred to as appropriate.

There are, of course, practical considerations that constrain the characteristics of DECam. Most obviously, the DES will be conducted on the CTIO Blanco 4m telescope. The project has been assigned 525 nights on the telescope and must be designed to complete both survey parts (the Imaging Survey and the Supernova Survey) within that allotment of time over five years. The characteristics of the CTIO site (weather, seeing, telescope reliability, etc.) are described below as appropriate for the DECam requirements. In particular, environmental conditions at the site are given in http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=763; all parts of DECam must function as described below over these range of conditions.

General Requirements

The Dark Energy Survey requires an instrument with three key performance parameters. These are very wide field-of-view, excellent responsivity at red wavelengths, and detectors with relatively rapid readout rates at adequately quiet noise. Specifically, these parameters correspond to

1. An individual exposure that must cover a field-of-view of at least 3 square degrees.
2. Detectors with an average quantum efficiency in the wavelength range from 800-1000 nanometers of at least 65%.
3. An imager with less than or equal to 15 electrons of noise when read out in 17 seconds or less.

Field of View, Tiling, and Exposure Times

We have been allocated 525 nights on the CTIO Blanco 4m telescope over five years. The DES supernova program will take 10% of the time, leaving 473 nights for the imaging survey of ~5000 deg^2. This requires an acquisition rate of 10.6 deg^2 $night^{-1}$. Nights are ~8 hours long, giving a 10.6 deg^2 per 8 hour rate. However, survey operations cannot be 100% efficient. We expect to lose ~50% of time due to bad weather at CTIO and other factors as observer errors, equipment malfunctions, etc. Note that this excludes the possibility of anomalously bad weather years (such as consecutive El Nino years). Assuming 50% of nights are unusable, DECam needs to survey 10.6 deg^2 per 4 hours in routine operation. Our total exposure time on a given field is expected to be roughly one hour (see below), so DECam must cover at least 2.7 deg^2 in an individual exposure. We include a further 10% contingency in the single-exposure sky coverage to allow for gaps in detector coverage, time lost to calibration activities, telescope slew time, etc.

Multiple exposures around each survey pointing are needed to fill in the inter-CCD gaps, remove cosmic rays, and accumulate sufficient exposure to meet the required photometric precision. We estimate that four exposures will be needed at each survey pointing. This number of exposures leads to the g and r bands having deeper limiting magnitudes than is needed by the science requirements.

To achieve our science goals we require a signal-to-noise of 10 at the limiting magnitudes. The integration time is the total of all individual exposures. The calculation of the exposure time depends on the mirror area, the throughput of the system, the read noise of the instrument, the sky background, and the area over which the object is spread.

The sky brightness contributes to the noise in galaxy magnitudes and colors in proportion to the area of the aperture one uses to measure the magnitudes. We assume the seeing at the Blanco 4-m is roughly 0.9 arcsec and use an aperture of 1.6 arcsec in diameter, which is ~20% larger than the optimal aperture size for a point source and appropriate for the measurement of the colors and magnitudes of faint galaxies. Table 1 shows our assumptions for the sensitivity estimates and consequent exposure times. More detail on the estimated throughput of DECam can be found in http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=1423.

Table 1: Limiting Galaxy Magnitudes

Filter	g	r	i	z
Required limiting magnitude (10σ)	23.1	23.7	24.3	23.6
Estimated throughput	0.32	0.43	0.42	0.38
Sky brightness (mag arcsec^{-2})	21.7	20.7	20.1	18.7
Adopted total integration times (sec)	400	400	1200	2000
Estimated Limiting magnitude (10 σ)	24.6	24.2	24.4	23.8

Row four of table 1 gives the adopted integration times for the reference survey strategy. The increased exposure times in the g and r filters reflect our photometric calibration strategy, which will use multiple survey tilings and a minimum exposure time of 100 sec.

TG.1: The DECam field of view should be at least 3 degree^2

TG.2: Assume observing time contingency of ~50%

TG.3: There will be 4 slightly offset exposures at each survey position in each filter

TG.4: Total integration times for DES operations at [g, r, i, z] = [400, 400, 1200, 2000] sec.

TG.5: The single exposure time for DES operations will be 100 sec

Radioactivity and Charged Particle Events

Radioactivity generates spurious charge events in many detectors and must be minimized. The radioactive isotopes possibly present include K-40 and Th-232. Inside the vacuum, beta rays from radioactive decay on the surface of the dewar window can strike the detector; such particles will be absorbed and produce complex tracks (unlike cosmic ray muons, which pass through the CCD on straight-line trajectories). Upper limits represent the amount of material of each type that will produce an event rate about equal to that of cosmic rays at sea level.

The basis for this requirement is that charged particle tracks will deposit more charge and affect more pixels onto detectors under consideration for DECam (thick LBL CCDs) compared with their impact on traditional, back-illuminated CCDs. For a charged particle entering at an angle of 45 degrees, the trail will be about 17 pixels long. Data processing software must identify these trails as non-astronomical objects and remove them from the image. Long exposures will need to be broken into shorter ones in order to aid in distinguishing charged particle trails from astronomical objects, decreasing the efficiency with which data are collected.

The main purpose of this requirement is to ensure that care is taken with choice of materials to avoid inadvertent introduction of radioactive materials, particularly in the dewar or window. For example, the Potassium content of any glass should be less than 1% and trace thorium no more than 10 ppm by weight. This requirement excludes BK7, which has 10 percent potassium, as a choice for the dewar window, for example.

TG.6: Charged particle events from radioactive material in the instrument shall cause a background no worse than that due to the measured cosmic ray rate on Cerro Tololo (~5 events cm^{-2} $minute^{-1}$).

<u>Heat dissipation</u>

The heat released into the local environment by DECam should be sufficiently small so as to have no significant impact on the image quality of survey operations. In practice this suggests that all external parts of the instrument will be no more than ~3°C warmer than the ambient temperature.

TG.7: External surfaces of DECam will be <3°C warmer than ambient temperature

<u>Orientation changes</u>

During assembly, test, shipping, and use DECam will experience all possible orientations. For example, even when DECam is not in use on the telescope, it will be necessary to run any and all instrument components for diagnostic and test procedures in laboratory conditions that may include horizon, zenith, or nadir pointing positions.

The angular change specification corresponds to a 20-minute exposure time at the most unfavorable orientations.

TG.8: All instrument components shall perform to specification at all possible orientations.

TG.9: The maximum change in telescope zenith angle during one exposure will be 5°

Environmental conditions

TG.10: DECam should function in all conditions expected to be encountered during survey operations (see http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=763)

Absolute time of individual exposures

TG.11: Absolute timing of an exposure should be measured to a precision of 10ms and recorded in the resulting image FITS header.

Flat field accuracy

DES data is required to be photometrically accurate and precise. In particular, the brightnesses of stars observed on any part of the focal plane must be measured with a precision better than 2% in order to meet the science requirements. This puts constraints on the degree to which the instrumentally induced variations in effective throughput must be removed. We estimate that this flat fielding procedure should be accurate to 0.5% to meet the objective.

TG.12: The rms variation in photometric calibration of any star measured in different positions of the focal plane shall be no worse than 0.5%.

Telescope beam vignetting

The light from astronomical sources should not be significantly blocked by any piece of DECam, so as to preserve the maximum possible throughput and survey efficiency. The current configuration of the Blanco telescope blocks approximately 2.41 m^2 or 19.5% of the light from reaching the bare mirror clear aperture (3.9654 m in diameter). This is due to the presence of an outer "seal" (see CH2922-A001) that blocks 1.6%, existing fins and cage rails that block 0.6%, the central hole in the primary that "blocks" 11.0%, and the PF cage baffle for the *f*/8 secondary that vignettes an additional 6.3% (see http://www.ctio.noao.edu/telescopes/4m/4m.html). We adopt an increase in this total obscuration of the incoming beam of less than 20% as a minor difference. Thus, DECam can block no more than an additional 0.5 m^2 of the primary mirror and the total area blocked must be less than 2.91 m^2.

TG.13: DECam and associated structures will not decrease the light that would otherwise hit the bare primary mirror by more than 20%, which implies that the total area of DECam as seen from above the telescope must be less than 2.91 m^2.

Optics Requirements

Pixel scale

The science requirement on pixel scale is that images be properly sampled under conditions of good seeing. We define properly sampled as 2.5 pixels per FWHM of the seeing disk. Since we expect that the best conditions will be have FWHM ≈ 0.7 arcsec, this requirements implies a DECam pixel scale of ~0.27 arcsec. Coincidentally, this requirement is close to the natural scale at the Blanco prime focus (0.27 arcsec for 15 μm pixels).

TO.1: The DECam scale should correspond to ~2.5 pixels per best expected image FWHM, which translates to ~0.27 arcsec $pixel^{-1}$

Point spread function (PSF)

The requirement on image quality, exclusive of atmospheric seeing, is that it be no worse than that delivered by the current telescope and mosaic imager system. This corresponds to a total system image quality of 0.55 arcsec. Table 2 gives a budget for contributions to the image quality, along with the basis for each contribution. CCD diffusion, the largest contribution, is the value currently achieved by LBNL with CCDs matching the DES CCD design (see the next section for more description of DES detector requirements). The optical corrector itself is required to produce images comparable to the existing as-designed corrector.

The delivered PSF is a combination of atmospheric and dome-induced seeing, CCD diffusion, the optical design, mechanical alignment and stability, as well as the telescope tracking (guiding and focus). Table 2 shows that the combined contribution is 0.49 arcsec, smaller than the requirement of 0.55 arcsec. The remaining 0.25 arcsec is carried as a contingency for any remaining contributions that are not yet identified or that are difficult to quantify. The primary mirror figure contributes about 0.16 arcsec and CCD diffusion contributes about 0.37 arcsec FWHM (1-D sigma of 9 μm for a scale of 17.7 arcsec mm^{-1}) to the image size. The best quartile of seeing delivered by the site is about 0.6 arcsec. The combination produces images with a PSF width of 0.73 arcsec. We require the corrector degrade this by no more than 10% or about 0.33 arcsec.

Stars in the science images will be used to measure the PSF. In a single 100 sec exposure we can reach ~21 mag at S/N ≈ 100. At this brightness there are about 2000 stars deg^{-2}. Based on experience with SDSS, roughly a quarter of these 2000 stars will be away from frame edges, cosmic rays, and other stars and galaxies. This corresponds to a little more than 1 useful star per cm^2 on the focal plane (= 9 $arcmin^2$). With this information, a map of the average PSF and linear variations over the focal plane will be generated.

There are approximately 100,000 galaxies in a single 3 deg^2 FOV image (10 galaxies $arcmin^{-2}$ to the limiting sensitivity). The correlated shear signal on the scale of 1 degree is $\sim 10^{-6}$. The combined error from both "shape noise" and "cosmic variance" in measuring this signal is expected to be 2% of the signal itself. We require that systematic errors in the PSF calibration increase this error by no more than 10%. For galaxies 0.9 arcsec in size, the corresponding allowed error in the rms "whisker" length, after calibration, is 0.045 arcsec. (A whisker is: (a2 - b2)1/2 where a2 and b2 are the major and minor axis second moments of an image.) More discussion of weak lensing requirements is in http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=353).

No atmospheric dispersion corrector (ADC) will be incorporated into DECam. This decision is driven by weak lensing image quality stability requirements. Although, weak lensing will be done primarily in the i and z bands, where differential refraction is minimal, an ADC introduces zenith angle-dependent systematic effects that mimic a weak lensing signal and are comparable in magnitude to differential refraction and thus the ADC effects would need to be calibrated on top of all other effects. The strategy in existing CTIO and KPNO weak lensing surveys has been to keep the ADC turned off. The tradeoff is that images obtained in good seeing and at high zenith angles, particularly in the g band, would be somewhat elongated. We estimate that the elongation will be 10% (for 1 arcsec seeing) in the g band at the highest airmass used in the survey (sec z = 1.5). Since the effect is very predictable and stable across the DECam field-of-view, no science goals are compromised by the absence of an ADC.

The procedure for calibrating the PSF shape for weak lensing will likely be developed as an iterative process. It is likely that data from multiple images will be combined in order to increase the density of stars sampling the focal plane. There are several possible sources of systematic error that are comparable in amplitude to the target systematic error of 0.045 arcsec whisker length.

TO.2 The delivered PSF from the telescope, instrument, and other factors exclusive of the site seeing will be no greater than 0.55 arcsec FWHM (separate components should be taken from Table 2)

TO.3 No ADC will be included in the design

TO.4 For each dynamic source of systematic error (e.g., focus variations), the peak amplitude induced in the PSF whisker length will be no larger than 0.045 arcsec.

Table 2: Image quality budget

Source	FWHM (arcsec)	RMS Radius (microns)	Reference
Dome Seeing	0.1	3	Not known with certainty
Telescope Guiding	0.03	1	Guess - take same as focus errors
Wind Shake	0	0	Assume "calm" night
Corrector			
Design	0.27	9.3	Current performance Blanco-2605
Manufacturing	0.11	3.6	Radii, index, thickness, homogeneity, polishing, etc
Silica Inhomogeneity	0.04	1.4	Grade C
Assembly Errors	0.08	2.6	Decenter, tilt, etc.
Flexure	0.04	1.5	Gravity loading, etc.
Focal plan location	0.05	1.7	30 micron p-p
Lens Deformation	0.03	2.0	Gravity Loading
Thermal	0.05	1.6	-5 to +25 C, Steel
CCD Diffusion	0.31	10	Assumes 7.5 microns rms 1-D, LBNL papers
Depth-of-focus	0.03	1.0	Kubik and Estrada report (i band)
Prim. mir. Figure	0.16	5.3	CTIO mirror testing report
Prim. mir. support (static)	0	0	
Prim. mir. support (flexure)	0	0	Assume small with active control of optics/camera position
Tel. collim. (static)	0	0	Combine with flexure
Tel. collim. (flexure)	0.05	1.7	200 micron offset
Focus	0.03	1	Scaled from SDSS 2.5 m focus loop performance
TOTAL	0.49	16.5	Telescope + Instrument

System Requirements for the DES optical corrector

Here we summarize additional technical specifications for the DES corrector. We recognize that the general astronomical community will use the camera for a variety of purposes and the corrector has been designed with this in mind. Any changes in requirements beyond those required for DES that have a significant cost impact will require that those costs be borne by an organization other than the DES Collaboration.

The DECam corrector should be designed to work optimally over the g, r, i, and z passbands. Furthermore, ultraviolet performance should be preserved as possible. Since we anticipate that DECam will ride on a precise and accurate platform capable of rapid adjustment, small changes in focus and consequent scale are allowed; we define small as <2% scale change between filters.

Ghost images in the optical design should be minimized. In particular, two classes of ghosting need to be considered: re-imaging of the exit pupil and ghost halos around bright stars. The former is endemic to prime focus wide field correctors and causes problems with flatfielding and photometric calibration. The requirements are to have exit pupil ghosts that introduce no more than a 3% gradient over a 0.3° region of the focal plane. This will ensure the DECam can achieve the top-level photometric accuracy of 2% (systematic error only). This requirement depends in detail on the photometric calibration plan. As a baseline, we assume that flatfielding is done using the sky background from median-averaged images, and that a single zero-point (derived from standard stars) is used to convert ADU to AB magnitudes. Ghosting introduced non-uniformities into the sky background, creating artificial gradients that mimic sensitivity variations. A gradient across the focal plane introduces a photometric offset error relative to the average of all stars on the device (depending on where the standard star is positioned). The requirement is intended to allot 25% of the total systematic variance to flatfielding.

We also require that ghost images of bright stars do not contaminate survey images and compromise sensitivity. Ghost images are irregularly distributed across the focal plane and introduce local jumps in sky brightness, causing error in measuring the local sky for photometry of faint galaxies. (To second order, they affect the construction of the median flat; we do not consider this here). We expect one V = 6 star per DES field at latitude b = -50. The natural sky brightness is about 21.5 mag arcsec^{-2}. A ghost image of about 4% of this brightness is comparable to what we expect in the exit pupil ghost. An r = 23.4 mag galaxy of radius 100 has a surface brightness of 24.6 mag/arcsec square. The local sky background should be measured accurately for all except galaxies at the boundary of the ghost image. In the worst case, a locally determined sky will be in error by 50%, causing a photometric error of 20%. This error is statistical in form, since, when averaged over many DES fields, it is random in nature.

The corrector should deliver a flat focal plane with a curvature less than the specification for the co-planarity across the detector surface (see below). We believe it will be easier and more precise to design and construct a mosaic array with a flat vs. curved focal plane and our studies show that no significant gains are to be had by allowing the focal plane to be curved.

The physical size of the corrector is limited by space constraints at the prime focus of the CTIO Blanco 4m telescope. In particular, the largest lens must be less than 1300 mm in diameter and no lens should be more than 2300 mm from the focal plane. Note that these constraints do not include any consideration of availability or associated risk for the size or cost of any particular optical component.

The type of glasses used in the corrector should be selected according to availability, cost, and performance given other requirements (low radioactive element content, durability, etc.). We note that fused silica meets these requirements.

The detector dewar window must be part of the optical design and will comply with all appropriate safety standards to ensure the integrity of the instrument. The window may have power, if appropriate, as long as the sag can be mechanically accommodated. The curvature of the window induced by the air-vacuum pressure differential must be computed and its impact included in the optical design analysis.

The DECam corrector lenses must be coated to achieve the maximum possible throughput. The coatings must not degrade in the environmental conditions each lens will encounter or over the expected lifetime of the instrument. The coatings must also be mechanically robust and survive the expected handling. The selection of coatings must also take into account cost/performance and risk considerations. We currently anticipate that a committee will be formed to study coating options once potential vendor responses are collected.

TO.5 The design shall be optimized for performance within individual passbands of 400-540, 560-680, 690-820, and 820-1000 nm

TO.6 Focus and/or scale changes between passbands of <2% are allowed

TO.7 The corrector shall permit imaging in the UV (~350 nm), although there are no formal specifications for throughput or image size.

TO.8 The intensity of ghost image of exit pupil, expressed as the fraction of incident sky brightness reflect back as a ghost image, shall have a gradient over 0.3 degrees of no more than 3%.

TO.9 Ghost images of an in-focus star of 6 mag shall create a ghost image with a surface brightness no greater than 25 mag arcsec^{-2}

TO.10 The optical design shall incorporate a flat focal plane. The peak-to-peak variation in matching CCDs to the focal plane shall be 30μm. The positioning of CCDs relative to a flat plane includes any CCD nonflatness.

TO.11 The maximum diameter of any optical element shall be less than 1300 mm.

TO.12 The leading optical element shall be no more than 2300 mm in front of the focal plane.

TO.13 Glass type(s) shall be chosen according to availability, its ability to meet the design requirements, durability, and low coefficient of thermal expansion, low radioactivity.

TO.14 A committee will select appropriate lens coatings after evaluation of vendor responses

Filters

DECam is required to work over a 400 to 1000 nm wavelength range and specifically to use the SDSS g, r, i, and z filters. Table 3 gives rough center wavelengths (CWL) and widths (FWHM) of the bandpasses. The filters should have characteristics that are consistent with DES sensitivity/throughput goals and adequately uniform to ensure photometric precision objectives are met. Further, the filters must be mechanically rigid and stable and of sufficient optical quality to have no meaningful impact on image quality (here defined as smaller than any entry in the image quality error budget) or stray/scattered light performance (here defined by the estimated pupil ghosting from a 6 mag star in the field). The filters must be large enough to not vignette the incoming light as well. The filters should also last the expected lifetime of the DES project without significant performance degradation.

TO.15 Average filter transmission will be >85% in over the g, r, i, and z bandpasses

TO.16 Transmission shall be uniform in wavelength (≤10% peak-peak variation) over the full wavelength ranges

TO.17 All filters shall have the same optical thickness to within 0.03 mm air equivalent.

TO.18 The transmitted wavefront error over any 125 mm sub-aperture of every filter will be < $\lambda/4$, where λ is the central wavelength of each filter

TO.19 The filters will work at angles of incidence appropriate for their expected location in the optical beam: 0 – 4 degrees for f/2.9 beams (maximum range 0-12 deg)

TO.20 The average filter transmission shall fall within the transmission envelopes given in http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=775

TO.21 At any wavelength, the transmission uniformity shall be such that the transmission at all filter locations divided by the average measured transmission at this wavelength shall lie within the renormalized transmission envelopes provided in http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=775

TO.22 The parallelism of the sides of each filter will be <30 arcseconds

TO.23 The filter substrates should be bubble class 0 with <0.1 mm^2 per 100 cm^3 and with no bubble > 0.5 mm in diameter

TO.24 The filters will have a minimum clear aperture of 570 mm

TO.25 Filter striae will be < 30 nm

TO.26 The filters will have no pinholes with diameter > 60 µm, no more than one with diameter of 30-60 µm, and a combined pinhole equivalent area of < 900 μm^2 per 100 mm^2 surface

TO.27 The filter surface quality should be 80/50 scratch/dig or better

TO.28 The filter should have Mil-C-48479 or better durability to abrasion

Table 3: Filter Transmission Requirements

filter	CWL (nm)	FWHM(nm)	Average Transmission
g	475	150	85%
r	635	150	85%
i	775	150	85%
z	925	150	85%

Science Detector Specifications

The focal plane detectors in DECam must meet many specifications to ensure compliance with the DES science objectives. These derive from the required photometric and sensitivity requirements. Further, all detectors in the focal plane should meet uniformity specifications to ensure that the DES data quality is uniform and without meaningful biases over the entire survey area. We define performance non-uniformity of greater than 10% as unacceptable. The detectors should also contribute no meaningful noise to survey images and be capable of being read out quickly enough to have no substantial impact on survey efficiency. The detectors should not introduce any irremovable artifacts (residual images, residual dark current, charge transfer smearing, etc.) that could compromise survey data. Many requirements mimic the known characteristics of detectors working in similar instruments and are generic to any modern astronomical detector.

TD.1 nonlinearity: 1% or better

TD.2 full well: >130,000 electrons

TD.3 The residual image for an object with a signal of 1×10^6 electrons in a given pixel will produce <100 electrons pixel^{-1} hour^{-1} of additional dark current, which is <10 electrons in a single 400 second exposure

TD.4 focal plane readout rate: <17 seconds for all science pixels

TD.5 dark current: $\leq$ 25 electrons pixel^{-1} hour^{-1}

TD.6 CTE: > 0.99999

The minimum required QE averaged over a device and bandpass is given in table 4. The maximum on-chip variation in QE (the flat field) should be ≤ 5%. The maximum chip-to-chip variation in QE should be ≤ 10%.

Table 4: Detector QE Requirements

filter	wavelength (nm)	Required QE
g	400-550	60%
r	560-710	75%
i	700-850	75%
z	850-1000	65%

These came from the signal to noise calculations that support the 4 key science projects. Filter transmission is also considered.

TD.7 Average detector quantum efficiency – [g, r, i, z]: [60%, 75%, 75%, 65%]

A related issue is the QE stability, which should be adequately stable over a night of observing so as not to compromise calibrations. Also, the entire focal plane should have ≤ 5% variation in QE to ensure uniform data quality. These imply requirements on the temperature stability of the selected detectors and focal plane, as detector temperature typically affects the red sensitivity of the devices. For convenience of testing, we write these stability requirements as a dependence of QE on temperature, which is relatively rapid to test in the lab, and as a specification on the temperature stability of the detectors during a night (see TOM.2 below as well).

TD.8 The QE dependence on temperature will be <0.5% per degree K

TD.9 Detector temperature stability will be ±0.25 degree K stability over 12 hours.

TD.10 Spatial temperature variation across the focal plane will produce ≤ 5% variation in QE

TD.11 The detector focal plane spatial temperature variation will be ≤ 10 degrees K across the focal plane.

To meet our science sensitivity goals we require that the read noise be a factor of 2 smaller than the sky noise so that in the quadrature sum, the effect of read noise is less than a 10% increase above pure sky noise. The g band has the darkest sky (thus smallest sky noise) and with 100 sec exposures, a read noise of 15 electrons will be less than one-half the sky noise. This readout noise should be achieved at readout rates of ~17 seconds, which corresponds to the anticipated survey rate.

TD.12 Detector read noise must be ≤ 15 electrons pixel^{-1} at the anticipated survey readout rate

Charge diffusion in the science detector should not seriously compromise the image quality. In practice, this means that the diffusion should not broaden images by more than ~0.5 pixel (see previous section, where this effect is included in the image quality error budget). This is the current performance of LBNL CCDs, and it is comparable with the performance in other state-of-the-art CCDs (e.g., SITe, E2V).

TD.13 Charge diffusion should have an rms 1-D width σ no greater than 7.5μm.

The point spread function sets a requirement on the flatness of the CCDs. The PSF should change by no more than 2% in second moment semi-major axis and by no more than 2% in ellipticity, defined as b/a, when convolved with a 0.6 arcsec circular Gaussian and measured over 1 cm spans. The requirement derives from the ability of the weak lensing analysis to track PSF variations and from the optical error budget.

TD.14 Detector flatness on < 1 cm^2 scales should be ≤ 3μm.

TD.15 Detector flatness between adjacent ≤ 1cm^2 areas on a given CCD should be ≤ 10μm.

The detector must also not contain a large number of unusable pixels. In effect, unusable pixels decrease the survey area per exposure, so additional observations are required to obtain complete coverage and survey efficiency is compromised. Unusable pixels also interfere with psf calibration needed for weak lensing measurements. We define an unacceptable loss to be 0.5% of the focal plane. See document http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=1012 for more details.

TD.16 Cosmetic defects should account for no more than 0.5% loss in detector area from non-usable pixels.

Signals from one amplifier, detector, or electronic component/group can induce spurious signals on other parts of the focal plane. This "cross talk" can then affect photometric measurements of many objects and must be minimized. Although data reduction software can in principle remove most of the systematic error induced by cross talk, the detector hardware should also minimize the effect so as to not force frequent (re)calibration. We require that a single saturated pixel not cause a cross talk signal great than 0.1% of the saturated level on any other pixel on the same CCD. Specifically, since we expect saturation to correspond to ~135,000 electrons, cross talk should be <135 electrons. Assuming that data reduction software can reduce this effect by at least a factor of 10 and read noise of less than 15 electrons per pixel, then the signal-to-noise ratio in a single pixel of the cross talk signal would be less than one. We further require that cross talk between other components of the signal chain be smaller than between amplifiers on a CCD and that the cross talk be stable, both to mediate the need to perform frequent calibration of the cross talk effect.

TD.17 Cross talk between the two amplifiers on the same CCD should be < 0.001. Crosstalk between channels of a video board should be < 0.0005. Crosstalk between cards in a crate or between crates should be < 0.0002. With a given set of hardware, individual crosstalk coefficients should remain stable to < 0.0001 over at least 2 weeks.

Guide and Focus/Alignment System Requirements

The delivered PSF can be strongly affected by the telescope tracking and focus. The TCS incorporates an interpolated lookup table model (pointing model) to compensate for flexure, hysteresis, and irregularities in open-loop telescope tracking. Guide cameras follow stars near the object being observed, sending tracking corrections to the TCS roughly every second and closing the tracking servo loop thus guaranteeing good quality images. Guide detectors must be closely coupled to the science focal plane, so as to ensure that there is negligible differential flexure between the guide system and the science detectors. The guiders should also observe through the same filter as the science detectors, again to ensure negligible differential motion of the guide stars and the science targets.

The observer currently corrects focus changes at the Blanco telescope resulting from changes in ambient temperature manually. The existing prime focus camera delivers image FWHM typically between 0.8 arcsec and 1.1 arcsec. Unguided focus sequences, that are designed to locate current best focus, show a median FWHM of 0.7 arcsec to 0.8 arcsec. We conclude that the telescope performs well on the 10-second timescale of a focus exposure sequence, but less well in the several hundred second exposures of a typical observing run. This might be erroneous, however, as many observers will happily and appropriately refocus the telescope should the seeing improve, but not when it degrades when it would be a waste of observing time. The existing guiding algorithms are not perfect and effort will be put into refining them where possible.

We will devote space on the focal plane to both guide and Focus & Alignment (F&A) sensors. F&A detectors will be mounted on the same plate as the science focal plane array, but displaced vertically from that plane by a distance sufficient to produce the classic “donut” image of an out-of-focus star. With a known displacement, the measured size of the donut allows a precise determination of the best focus position. Analysis of changes in the shape of the donuts allow us to measure misalignments between the DECam corrector and the primary mirror and also provide an indication of low order aberrations derived from errors in the primary mirror’s figure and can be used to close the active optics loop. More discussion and analysis of the F&A sensor capabilities can be found at http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=97.

We expect ~25 well measured stars (S/N = 100) per science CCD in a 100 sec. science exposure. If the focus chips were 10 times smaller than the science CCDs (i.e., focus chip area = 17 arcmin^2), 2 stars per CCD would be expected and we believe this to be sufficient. We assume the guide exposures will be 1 second, approximately the same rate as currently used on the telescope, although we plan to determine optimal rate during DECam commissioning. Note that we anticipate requiring sub-array readout of the guide detectors, so as to allow for the maximum allowable rate flexibility. S/N=20 for guide stars should allow determination of image centroids to ~0.05 pixel or ~0.01 arcsec, which will ensure that guiding errors will not contribute significantly to the image quality error budget. If we take the sky noise to be 16 electrons and the read noise over the star image to be 20 electrons, then a star producing 1000 electrons in 1 second should produce an adequate signal. This corresponds to ~19 mag in the r or i bandpasses, which have surface densities of $\Sigma = 0.2$ per arcmin^2 near the galactic pole. Assuming the stars are randomly distributed on the sky, the probability of finding no useable guide stars within a guide camera of solid angle Ω is $e^{-0.2}\times\Omega$. There are about 2000 fields in our survey. Guide CCDs covering 50 arcmin^2 yield a 10% chance of the survey encountering a field with no guide stars; we define this as the minimum acceptable guide field. Note that in DECam, one 2kx2k CCD with 15 μm pixels covers 85 arcmin^2.

TGFA.1 Guide error signal update rate will be ~1 Hz.

TGFA.2 Guide detectors will be sited within the dewar at the science focal plane array

TGFA.3 The guide detectors will observe the sky through the science survey filters

TGFA.4 Total guide detector area should be >50 $arcmin^2$

TGFA.5 Guide detectors should have 10 electrons read noise at 250 kpixel s^{-1}, 20 electrons at 500 kpixel s^{-1}, readout in 1sec in 4x4 binning

TGFA.6 Guide detectors require sub-array readout capability.

TGFA.7 The guide system must produce seeing measures suitable for use in the donut analysis as well as error signals suitable for guiding.

Considerations of seeing, overlap, and experience from other observatories yields an optimum size for donut images of around 30 pixels.

TGFA.8 F&A detectors shall be displaced by 1.24 mm perpendicularly to the focal plane

Donut size is affected by seeing, but this can be factored in by concurrent seeing measurements from the guide system. Sufficient stars must be available for the donut analysis. Our calculations and simulations of the star density we will encounter in the survey suggest that there should be adequate stars to use for focus adjustment and alignment monitoring in roughly the same area as required for guiding. Exposure times for the F&A detectors can be substantially longer than for guiding; we anticipate reading the F&A sensors at a rate comparable to the survey rate (i.e. 100 sec exposures).

TGFA.9 The F&A detectors should cover >50 $arcmin^2$

TGFA.10 F&A detectors can be read at the survey rate

All the required information can be derived from donut images taken on one side of focus, but a useful opportunity for consistency checking is provided by use of images from both sides of focus.

TGFA.11 F&A detectors should be arranged in pairs on opposing sides of the dewar on opposing sides of focus.

The F&A CCDs will be read out on the same cadence as the science FPA. Updates to the corrector position via the hexapod and to the primary mirror figure via the active optics system will be made at a cadence designed for maximum benefit which will be determined by experiment at the telescope.

TGFA.12 The F&A CCDs will acquire stellar images through the survey filters.

Opto-Mechanical Requirements

This section describes the requirements for the various opto-mechanical components of DECam. In general, the requirements exist to guide the detailed engineering design and testing of different parts of the instrument.

Camera vessel

The DECam detectors must be cooled to temperatures low enough to ensure detector dark current does not compromise the sensitivity or efficiency of survey observations and operations. Since detector performance depends on the exact temperature of the individual device, reasonable uniformity of temperature across the focal plane, both spatially and temporally, is also required. Given the expected characteristics of the CCDs, these requirements translate to the following specifications:

TOM.1 Expected range of mean focal plane temperature: -120°C to -80°C

TOM.2 Focal plane temperature stability will be ±0.25°C over 12 hours

TOM.3 Focal plane temperature stability: <10°C over entire focal plane

The relatively low temperatures required imply that a vacuum system will be required. The vacuum must be sufficiently low or the system designed so as to prohibit any chance of deposit of contaminates (water or other organic material) on the CCD surface. This suggests

TOM.4 Dewar vacuum must be $<2\times10^{-4}$ torr before cooling below ambient

TOM.5 Dewar vacuum should be $<10^{-5}$ torr in normal operation

The dewar should also require minimal attention during operations, so as to not negatively impact survey efficiency. We define manual attention more than once per day with a 25% contingency as an appropriate definition of minimal. We also require that the dewar not require frequent periodic attention to maintain performance. This should ensure that DECam is almost always ready to observe and not require frequent downtime for routine maintenance.

TOM.6 Temperature/vacuum requirements should be met with no manual input more frequently than once per ~30 hours

TOM.7 Vacuum and focal plane temperature should be maintained continuously over a period of >12 months without interruption

The system must also allow for reasonably fast cycling to ease testing of the CCDs and other camera components. This suggests that the focal plane cool down and warm up times cannot be long. Based on previous experience with similar instruments, we define reasonable here as a length of time that should allow for one dewar cycling per day.

TOM.8 The focal plane should come to operational temperature in <8 hours

TOM.9 The dewar should warm up and be ready to open to ambient environment in <12 hours

The strategy to maintain vacuum and temperature should not have an adverse affect on the focal plane. In particular, the focal plane should not move, vibrate, or otherwise deform enough to compromise the point-spread-function size, flatness, or other characteristics that would compromise the science quality of the images. We define unacceptable motions as those >10% as large as those expected to be induced by the camera optics in x,y and as <50% of the anticipated CCD co-planarity. The system should also not cause vibrations of the focal plane that will affect the image quality; here we require any vibration to be smaller than the typical entry in the image quality error budget. Note that all these specifications apply when DECam is in operation, with the focal plane cold. The change in position of the focal plane between warm and cold conditions is unimportant as long as when cold the focal plane is in the correct location and orientation relative to the corrector optics.

TOM.10 The dewar and associated cooling and vacuum system will not distort or otherwise move the focal plane by more than 15 µm in x or y

TOM.11 The dewar and associated cooling and vacuum system will not distort the flatness of the focal plane by more than 30 µm peak-to-peak

TOM.12 The dewar and associated cooling and vacuum system will not vibrate the focal plane by more than 5 µm at any frequency

TOM.13 The separation of the focal plane from the last optical element of the corrector (which also forms the cryostat window) will conform to the specifications suggested in the analysis shown in doc-db #2975 by S. Worswick. This analysis implies that the axial spacing should be 30 ± 0.5 mm and the tilt should be within 0.00382 degrees (±15 µm) across the full diameter of the focal plane.

Instrument Mechanisms

Camera movement control and cage motion

DECam must be held within the CTIO Blanco 4m telescope prime focus cage with adjustment capability to remove expected changes in focus and lateral translation of the telescope top end and primary mirror cell. In the following, X and Y refer to motions of the corrector and camera in directions perpendicular to their optical axis. "Tilt" refers to rotations of the corrector and camera about the X or Y axes. "Focus" refers to motions of the corrector and camera in the direction parallel to their optical axis. "Rotation" refers to rotations of the corrector and camera about their optical axis. A mechanism that holds DECam within the prime focus cage should provide some control over all these degrees of freedom. In particular, recent measurements of the telescope primary mirror motions and flexure of the top end of the telescope structure indicate that the DECam support mechanism must be capable of adjusting the instrument position in focus (z), translation (x,y), and angle relative to the plane defined by the surface of the primary (tip/tilt). See http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=776 for additional information and measurements.

The total error budget for fabrication, assembly, etc is 0.1 arcsec FWHM (= 3.8 μm rms radius). It is assumed that this is contributed by 100 degrees of freedom (see http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=346). Thus, for any single degree of freedom, we assume an error budget of 0.01 arcsec FWHM or 0.38 μm rms radius, yielding the tolerances given on focus, X or Y or X-tilt or Y-tilt.

The total weak-lensing whisker error budget is 0.045 arcsec, after removal of linear gradients across a single detector. A sensitivity study shows that this entire amount is achieved by a translation of 500 microns. The degradation changes like the square root of the displacement. Defocus does not make an appreciable contribution to whisker length after removal of linear gradients across a detector.

The total PSF error budget is 0.55 arcsec FWHM. A sensitivity study shows that this degradation is achieved by either a defocus of 120 microns or a decenter of 1200 microns (assuming that this degradation is added in quadrature with other contributions to the image size). The degradation changes linearly with displacement.

The flatness of the FPA is specified as 30 μm (see Table 2), which corresponds to 0.05 arcsec contribution to the PSF FWHM. We require that the commanded focus position be capable of sampling this level of flatness, so as to ensure we can obtain the best possible global focus of the entire focal plane.

A change in ambient temperature of 30 °C corresponds to 3.6 mm focus change by expansion/contraction of the telescope structure, an adequate safety factor must be built into the end-to-end throw of the focus mechanism but the larger effect is the distance to which the camera must be driven out of focus to make observations with the Hartman screen (an independent method of measuring primary mirror aberrations). With the current camera, Hartman screen defocus is ~13mm. The current Blanco prime focus has a focus range of 30mm. We will preserve this capability, since it is important in understanding telescope collimation and control of the proper positioning of the primary mirror. All motions should be rapid enough to not significantly impact DES survey efficiency; this suggests that all typical movements of the instrument should be complete within ~7.5 seconds (roughly half the focal plane readout time).

TOM.13 The required precision for setting the focus with respect to an arbitrarily commanded position is ±7.5 μm peak-peak error. This requirement is to be achieved over the normal operating range of 3 mm.

TOM.14 Range of focus motion should be at least 30 mm to accommodate the needs of Hartman screen testing. For normal observing, the operating range is 3 mm.

TOM.15 The DECam focus mechanism shall be able to move 150 microns in 7.5 seconds (including ramp and settling times).

Translation and tilt of the corrector relative to the mirror optical axis both introduce coma into images. Within the expected range of travel for both, the degradation of images is identical. Furthermore, one motion can compensate for the other. A translation of 1 mm is compensated by a tilt of 20 arcsec. Correction of a translation of the primary mirror by a tilt of the corrector yields a residual tilt in the focal plane of ±1 micron at the field edges, which is insignificant. See http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=591 for additional information.

TOM.16 The range of lateral translation of the corrector shall be ±1.5 mm in X and Y directions (to allow initial centering). The normal operating range shall be ±500 microns.

The alignment sensors are expected to be able to measure misalignments to an accuracy of 50 to 100 microns, depending on the stellar density and brightness; see http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=97 for additional details. This level of de-collimation relative to the telescope primary mirror introduces <0.05 arcsec to the PSF FWHM and is also less than the "whisker" requirement for weak lensing measurements.

TOM.17 The precision in setting the corrector lateral translation will be ±25 microns relative to an arbitrarily commanded position over the normal operating range.

The requirements for tip/tilt are similar to those for translation, using the sensitivity analysis to convert from mm translation to arcsec tilt. The tip/tilt should also have the capability to correct for the measured tip/tilt introduced by the flexure of the telescope structure. The precision of the tip/tilt should be adequate to not introduce significant image degradation relative to the other components listed in Table 2.

TOM.18 The range of corrector tilt will be ±30 arcsec in X and Y. The operating range shall be ±20 arcsec in each axis

TOM.19 The tolerance on setting the tilt of the corrector shall be ±3 arcsec peak-peak relative to an arbitrarily commanded position.

We do not want the corrector to flop around if we translate, even though some flop can be compensated by more (or less) translation.

TOM.20 The tilt angle shall be maintained to an accuracy of ±3 arcsec over the normal operating range of translation.

TOM.21 Horizontal translation shall be maintained to an accuracy of ±25 microns over the full operating range of focus and tilt.

TOM.22 Focus (z position) shall be maintained to ±7.5 microns over the operating range of tilt and/or translation.

There is no top-level science driver on maintaining rotation (twist), other than convenience in reducing data. The only basis for a technical requirement is that, if one refocuses during an exposure, that rotation not contribute to the PSF size at the field edge. If I move in z by 100 microns, a rotation of 1.4 arcsec causes a motion of 0.1 pixels at the field edge, which we will consider negligible.

TOM.23 Rotation shall be maintained to ±40 arcsec over the normal operating range of focus (z position). Rotation shall be maintained to ±10 arcsec over the normal operating range for translation and tilt.

Filter Changer

DECam will incorporate a mechanism capable of inserting different filters into the optical beam. The positioning of the filters must be adequately precise and reproducible that there are no significant errors induced in the photometric quality of the survey data (here defined as <0.002 mag addition to survey photometric precision) and have rapid exchange capability so as not to compromise survey efficiency (that is, filter exchanges must happen faster than the time required to read the focal plane detectors). The filter mechanism must also accommodate an adequate number of filters: although DES requires only five filters, we expand the requirement to include an additional three for the use of the community. The filter mechanism must obviously also be capable of holding filters large enough to not vignette the beam; preliminary investigations and potential vendor discussion suggests these filters will be no more than 15 mm thick.

TOM.24 The filter mechanism must place each filter into the optical beam with a precision and reproducibility of < 0.5 mm.

TOM.25 Filters of 580 mm in diameter and up to 15 mm thickness will be accommodated.

TOM.26 The filter changer mechanism will accommodate at least 8 filters.

TOM.27 The filter changer will require less than 10 seconds to change between any two filters.

Shutter

The DECam shutter controls the illumination of the science detectors by permitting light to reach the focal plane for a specific amount of time or by blocking light from reaching the detectors. The shutter timing must be sufficiently precise, accurate, and uniform to allow the DES photometric goals to be achieved. The shutter must also be light tight to allow for calibration frames to be obtained during the day and reliable so as not to impact survey efficiency and duration. The shutter must also be large enough to not vignette the incoming light.

TOM.28 The shutter exposure time uniformity should be better than 10 ms (i.e. the actual exposure time anywhere on the focal plane should not be more than 10 ms different from anywhere else)

TOM.29 The shutter exposure time repeatability should be better than 5 ms

TOM.30 The shutter exposure time accuracy should be <50 ms. That is, the difference between the actual shutter open time and what was requested should be <50 ms

TOM.31 The shutter shall be ready to begin a subsequent exposure no more than 10 seconds after completion of a previous exposure

TOM.32 The absolute timing of an exposure should be measured to a precision of 10 ms

TOM.33 The shutter should allow a continuous range of exposures from 1 second upwards

TOM.34 The clear aperture of the shutter shall be 600 mm

TOM.35 Closed the shutter shall admit $<2\times10^{7}$ photons sec^{-1} m^{-2} with an ambient illumination of 1 lux (at 550 nm). This is equivalent to 10% of the expected dark current when the shutter is in full moonlight illumination

TOM.36 The shutter mechanism shall have a MTBF larger than 1,250,000 cycles or equivalent

Corrector cell/barrel

The corrector cells and encompassing barrel will be as specified in http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=450. This document includes all pertinent mechanical and optical requirements to ensure that the optical elements will be mounted and held in proper positions independent of orientation or environment so as to be consistent with the requirements given in Table 2.

Instrument Software Requirements

Quick Look Data Reduction

There must be software tools available to rapidly and efficiently reduce and analyze DECam images. This software must allow scrutiny of the images during testing and commissioning so as to allow performance verification and should include provision for bias correction, flat fielding, a rough astrometric solution, and an approximate photometric solution for each image. We expect that the USNO-B1.0 catalogue will provide the basis for the initial astrometric and photometric calibration. This processing should be complete within <10 seconds of completion of an exposure so as to allow for operational flexibility and exposure planning.

A tool will also be need that will allow inspection of the images for more detailed evaluation. This tool should have the ability to measure a wide range of image characteristics: radial profile plots for selected targets, contour plots of sub-arrays within the image, statistical measures of image sub-arrays, etc. A good example of what is required is the functionality in the IRAF routine “imexam”.

DECam will provide images in a standard format that will allow individual detectors to be examined and reduced if desired.

TS.1 Quick look tools shall be available for observer use that allow for bias-correction, flat fielding, and rough astrometric and photometric calibration for complete images of the entire focal plane

TS.2 A reduced image will be available for inspection by the observer in <10 seconds after the completion of the focal plane read out

TS.3 An examination tool will be available to DECam observers that will allow inspection of the images. The tool will include provisions to scrutinize the characteristics of images such as image quality, sky background level and uniformity, contour plots, image statistics, etc.

TS.4 Science images will be in multi-extension FITS format with one extension per detector; sufficient metadata will be present in the headers to enable stand-alone processing of each detector’s image

User Interface

A simple user interface allowing access to all camera functions must be provided. This interface may be in the form of a CLI or GUI, but must provide a simple way to control the camera and allow single exposures, direct filter changer motion commands, direct communication with the DECam support system, etc. The control software will also provide alarms to alert the observer to conditions that could compromise data quality (these are not intended to provide hardware or personnel safety). Remote observing will also be possible, subject to capabilities appropriate to reduced bandwidth. Furthermore, a facility database of configuration parameters, telemetry log, and a record of all transactions between DECam subsystems will be created, which will be periodically synchronized with the DES Data Management system and NOAO off-site databases in FITS "foreign" format.

TS.5 An instrument interface that allows straightforward access to all camera functions will be provided

TS.6 Alarms will be provided to warn of conditions that would harm data quality

TS.7 Remote observing capability will be possible

TS.8 A database of information on DECam status and history will be available

Image Display Capability

DECam images will be displayed in a coordinated and complete manner. In particular, display of the entire focal plane as a unit will be available. Additionally, sub-sections of the images will also be available for closer scrutiny and application of the tools described above.

TS.9 DECam images will be displayed in their entirety with provision for straightforward and closer inspection of selectable sub-sections

Data delivery and format

DECam will put images on a disk in the format required by the DES data management system. The images will have an associated header that includes all pertinent key words and information needed to reduce, analyze, and catalogue the data. See http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=563 for more description of the DES data management system and associated links for descriptions of data requirements. These images will be cached for three days of DES operations, so as to protect against interruption of data flow to the final data storage location.

TS.10 Images will be stored for three days on-site to provide backup against data flow breakdown