THE FUTURE OF PHOTOMETRIC, SPECTROPHOTOMETRIC AND POLARIMETRIC STANDARDIZATION
ASP Conference Series, Vol. 364, 2007
C. Sterken

The Photometric Calibration of the Dark Energy Survey

Douglas L. Tucker, James T. Annis, Huan Lin, Stephen Kent, Chris Stoughton, John Peoples, Sahar S. Allam

Fermilab, MS 127, P.O. Box 500, Batavia, IL 60510-0500, USA

Joseph J. Mohr, Wayne A. Barkhouse, Choong Ngeow

Dept. of Astronomy, University of Illinois, Urbana, IL 61801, USA

Tanweer Alam, Cristina Beldica, Dora Cai, Greg Daues, Ray Plante

National Center for Supercomputing Applications, Urbana, IL 61801, USA

Chris Miller, Chris Smith

Cerro Tololo Inter-American Observatory/NOAO, 950 N. Cherry Ave., AZ 85719 USA

Nicholas B. Suntzeff

Physics Department, Texas A&M University, College Station, TX 77843-4242 USA

For the Dark Energy Survey Collaboration

Abstract. The Dark Energy Survey (DES) is a 5000 deg^2 $griz$ imaging survey to be conducted using a proposed 3 deg^2 (2$^\circ\!\!.$2-diameter) wide-field mosaic camera on the CTIO Blanco 4-m telescope. The primary scientific goal of the DES is to constrain dark energy cosmological parameters via four complementary methods: galaxy cluster counting, weak lensing, galaxy angular correlations, and Type Ia supernovae, supported by precision photometric redshifts. Here we present the photometric calibration plans for the DES, including a discussion of standard stars and field-to-field calibrations.

1. Introduction

The goal of the Dark Energy Survey (DES) is to perform a 5000 deg^2 $griz$ imaging survey of the southern Galactic Cap in order to constrain the Dark Energy equation-of-state parameter $w \equiv P/\rho$ to $\sim 5\%$ (statistical errors) in each of four complementary techniques and to begin to constrain the derivative of w with respect to redshift (dw/dz). By meeting this goal, DES will serve as a stepping stone to next-generation large-scale dark energy projects like Large Synoptic Survey Telescope (LSST; Sweeney 2006), the Joint Dark Energy Mission (JDEM)[1], and the Square Kilometer Array (SKA; Beck 2005).

[1] http://spacescience.nasa.gov/admin/divisions/sz/SEUS0310/Hertz_JDEM.pdf

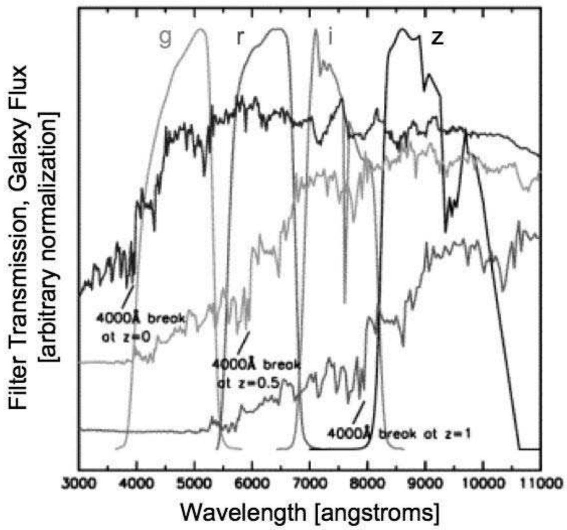

Figure 1. The response functions of the DES *griz* filters overplotted on the spectral energy distributions of a typical elliptical galaxy at $z = 0$, $z = 0.5$, and $z = 1.0$. Note that the passage of the 4000 Å break through the different filters with increasing redshift and the relative uniformity of the shapes of elliptical galaxy spectra permit accurate photometric redshifts ($\sigma_z = 0.02$–0.03) to be measured for individual cluster galaxies (credit: Huan Lin).

The survey will utilize the Blanco 4-m telescope at Cerro Tololo Interamerican Observatory (CTIO). In order to achieve the goal of surveying half of the southern sky in a reasonable amount of time, the DES collaboration will replace Blanco's prime focus cage with a new 3 deg^2 ($2\overset{\circ}{.}2$ diameter) optical CCD mosaic imager known as the Dark Energy Camera (DECam). The DECam is scheduled for design and construction during the 2005–2009 time period and, once commissioned, will be available for community use as well as for the DES.

Observations for the DES will encompass a total of 525 nights (30% of the telescope time) over the course of 5 years starting in 2009/2010. For best viewing of the southern Galactic Cap, the DES observations will be performed during the months of September through February.

2. DES Science: Four Probes of Dark Energy

The DES will measure the dark energy equation-of-state parameter w to $\sim 5\%$ in each of four complementary probes:

Galaxy cluster counting: DES will identify and measure redshifts and masses of 20,000 galaxy clusters with $M > 2 \times 10^{14}$ M$_\odot$ out to a redshift of $z = 1.3$. The number of clusters as a function of redshift is a strong function of cosmological parameters, including w (Wang & Steinhardt 1998; Haiman et al. 2001).

Weak lensing: DES will identify and measure the shapes of 300 million galaxies over 5000 deg^2. The clustering of mass as a function of redshift is also strongly determined by various cosmological parameters, including w (Hu 2002; Huterer 2002).

Spatial clustering of galaxies: DES will identify and measure the photometric redshifts of 300 million galaxies out to $z = 1$ and beyond. The spatial clustering of galaxies as a function of redshift is also a function of w (Cooray et al. 2001).

Standard Candles: ≈10% of DES observing time will be devoted to a supernova survey covering 40 deg^2 of sky. It is expected that DES will discover 1900 Type Ia supernovae in the redshift range $z = 0.25$–0.75 during the course of its supernova survey. Construction of a Hubble diagram using Type Ia supernovae as standard candles is a well-known means of measuring the parameters of dark energy (Riess et al. 1998; Perlmutter et al. 1999).

Note that, since the DES is purely an imaging survey, good photometric redshifts out to $z \sim 1.3$ are critical to its success (see Fig 1). To obtain sufficiently accurate photometric redshifts to achieve the DES goals, the all-sky photometry must be accurate to 2% or better. Such photometric accuracy is also necessary to obtain good light curves for the supernova survey part of the DES program.

3. Basic Survey Parameters

The DES will not only be a wide survey (5000 deg^2; see Fig. 5), but it will also be deep. For galaxies, it is estimated that the $10\,\sigma$ detection limit will be 24.6, 24.1, 24.3, 23.9 for g, r, i, and z, respectively. Likewise, for point sources, it is estimated that the $5\,\sigma$ detection limit will be 26.1, 25.6, 25.8, 25.4 for g, r, i, and z. For comparison, the Sloan Digital Sky Survey (SDSS) reports a 95% completeness limit for point sources of $r = 22.2$ (Adelman-McCarthy et al. 2006).

The observing strategy is to use 100-sec exposures, and observe (typically) two filters per telescope pointing. During dark time, these filters will be g and r; during bright time, they will be i and z, which are much less affected by sky brightness caused by moonlight. Multiple tilings[2] and large offset overlaps will allow the DES to achieve its desired depth and will be important in optimizing photometric calibrations. The current idea for survey strategy is to complete two full tilings in each filter each year, for a five-year final tally of 5 tilings each in g and r, 7 tilings in i, and 13 tilings in z. As noted in the previous Section, the DES requirement for all-sky photometric accuracy is 2% ($0\overset{\mathrm{m}}{.}02$); an enhanced goal is 1% ($0\overset{\mathrm{m}}{.}01$).

4. The DES Instrument (DECam)

The DECam focal plane (a.k.a., "the Hex"; Fig. 2) will be a mosaic containing 62 2k×4k imaging CCDs, yielding a camera having a grand total of 520 million

---

[2] A tiling is a single complete coverage of the 5000 deg^2 of the survey area in one filter.

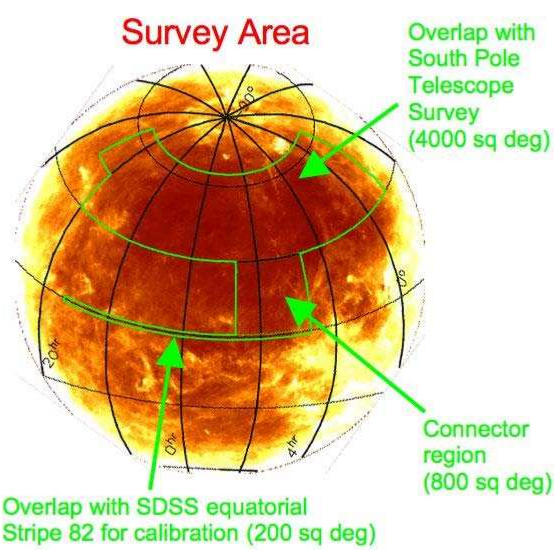

Figure 2. Equal-area projection of the Southern Galactic Cap. A black body color scaling indicates interstellar extinction from the Schlegel et al. (1998) dust maps (dark equals low extinction, bright is high extinction). The region delineated in green is the proposed survey area for DES (credit: Jim Annis).

pixels. At the prime focus of the Blanco, the pixel scale of this camera will be 0.27 arcsec pixel^{-1}. The CCDs themselves are a Lawrence Berkeley National Laboratory (LBNL) design. They are fully depleted and 250 microns thick, yielding high quantum efficiency in the z band (QE $>$ 50% at 1 micron). The CCD electronics will permit the full camera to be read out in only 17 seconds.

5. DES Calibrations Flow Diagram

In Fig. 3 we present a flowchart which is our current vision for the photometric calibration of the DES. The eight boxes represented therein are as follows:

Instrumental calibration: This box contains those aspects of calibration that are necessary for image processing. It is here where raw bias frames, dome flats, and twilight flats are processed and combined to create master bias frames, dome flats and twilight flats, respectively. (Although the thickness of the LBNL CCDs may mean that i and z fringing will not be a problem, it is also here where fringe frames would be created, if necessary.) This box is also the domain where scattered light maps, shutter timing maps, CCD linearity curves, and chip-to-chip cross-talk corrections would be be created.

Photometric monitoring: This box contains the apparatus for independent real-time monitoring of the photometric quality of the sky. Inputs could include images from a 10-μm all-sky camera, images from an optical all-sky camera, or flux measurements from an automated differential image motion monitor

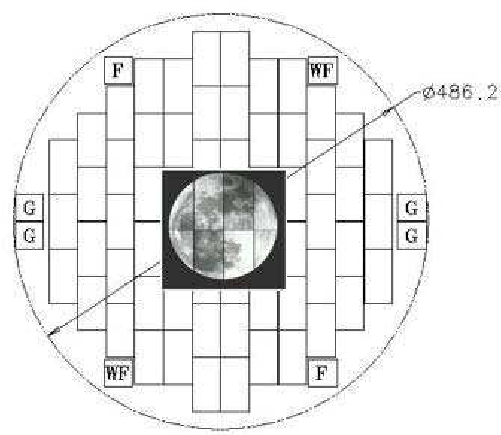

Figure 3. The DECam focal plane. To illustrate its field-of-view, an image of the full moon reproduced to scale is superimposed on the DECam mosaic (credit: Brenna Flaugher).

(DIMM). Outputs would include diagnostic information output to a webpage during observations (for real-time observing strategy decisions) and a photometricity flag added to the FITS header of each image (for off-line decisions relevant to data processing). We describe Photometric Monitoring in more detail in Sec. 6 below.

Single-frame, astrometry, and catalog modules: Here, the raw science and standard-star frames are processed using the master calibration frames, scattered light and shutter timing maps, CCD linearity curves, and cross-talk correction coefficients from the Instrumental Calibration box. Output is a catalog of objects from each processed science and standard star frame with measured RA, DEC positions and instrumental magnitudes (as well as other measured properties not necessarily of direct importance to calibration). Information from Photometric Monitoring concerning the sky conditions at the time an image was taken will be carried along with the catalogs generated from that image. This information will aid in determining whether or not data from a that image is used downstream of this box for photometric calibration. The Single-Frame, Astrometry, & Catalog Modules box represents the main image processing and object detection portion of the DES data processing pipeline; for more information on the DES data processing pipeline, see Ngeow et al. (2006) and Mohr et al. (2007).

Nightly absolute calibration: Simply refers to the process of fitting the nightly standard star observations to a photometric equation to solve for (for instance) the nightly photometric zeropoints and atmospheric extinction coefficients. Input includes the instrumental magnitudes of standard stars observed on a given night, their airmasses, and their known standard magnitudes and colors. The photometricity flag from Photometric Monitoring can be used to cull out standard star observations obtained under non-photometric conditions. Output from this box includes the photometric zeropoints and atmospheric extinction coefficients to place the instrumental magnitudes onto the AB magnitude scale (Fukugita et al. 1996). We describe Nightly Absolute Calibration in more detail in Sec. 7.

Intermediate calibration: Merely refers to the step of applying the photometric zeropoints and extinction terms measured in Nightly Absolute Calibration to all the observations for a given night. The result is calibrated magnitudes for all the observations on that night. Since these calibrated magnitudes may be "tweaked" downstream of this box, we refer to this step as Intermediate Calibration.

Global relative calibration: Concerns measuring two tweaks to the calibrated magnitudes from the Intermediate Calibration step, one of which is a correction to any uncorrected vignetting or scattered light effects in the photometry (Star Flat analysis) and the other of which is the calculation of relative field-to-field ("Hex-to-Hex") photometric zeropoint offsets. We describe Global Relative Calibration in more detail in Sect 9.

Global absolute calibration: Applying the zeropoint adjustments from the Global Relative Calibration step might offset the observed standard star magnitudes from their catalog values. The Global Absolute Calibration step calculates the final overall zeropoints needed – one zeropoint per filter – to place the global relative calibrations onto the AB magnitude scale. We describe Global Absolute Calibration in more detail in Sec. 10.

Final calibration: Here, the zeropoint adjustments from the Global Relative Calibration and the Global Absolute Calibration step are applied to the science field observations. The output is calibrated AB magnitudes for all the science observations.

After the Final Calibration step, the DES data should be ready for image and/or catalog co-addition to achieve final images and catalogs of the depth required by the DES science goals. Barring problems in bookkeeping – and, in particular, barring problems in keeping track of photomeric zeropoint offsets – there should be no need of further calibration steps. Thus, we do not discuss any further steps beyond Final Calibration in this paper.

We now discuss some of the above boxes in further detail, starting with Photometric Monitoring.

6. Photometric Monitoring

Not all DES imaging will be done under photometric conditions. Those images observed under photometric conditions will be useful both for increasing the magnitude limit of the final co-added survey and for photometric calibration; those images observed under non-photometric conditions will only be useful for increasing the magnitude limit of the final survey.

Therefore, photometric monitoring is necessary and should provide real-time estimates of sky conditions for survey strategy. In other words, real-time photometric monitoring should be able to answer the question, "Should the

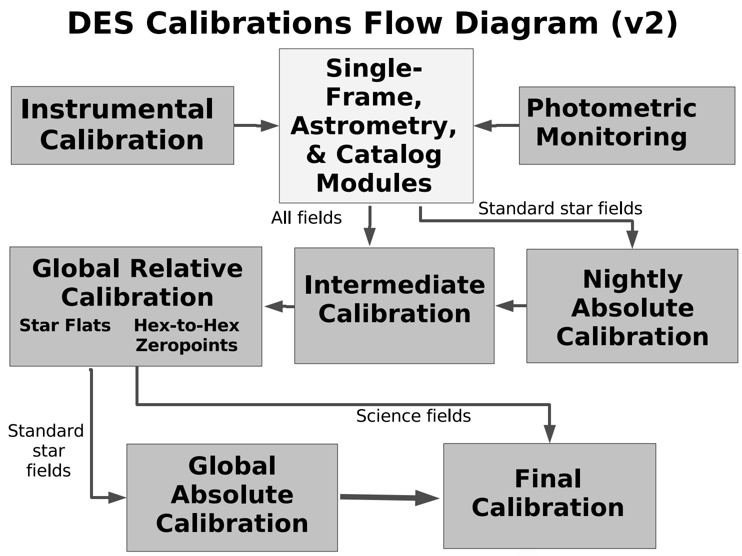

Figure 4. Proposed plan for DES Calibrations.

next image be a photometric calibration (standard star) field, a science target, or something else?"

Photometric monitoring should also provide a quality check or photometricity flag that is usable offline during data processing. In this case, photometric monitoring should be able to provide some sort of measure of the photometric quality of an image already taken and thus be able to answer the question, "This image was obtained under such conditions; is it good enough to be used for photometric calibrations?"

An excellent resource for all-sky photometric monitoring is a 10-μm all-sky camera. One of these has been used successfully at Apache Point Observatory (APO), and has proved essential for survey operations and image quality assurance for the SDSS (Hogg et al. 2001; Tucker et al. 2006).[3] The 10-μm all-sky camera has also proved useful for photometric monitoring for observations on the Astrophysical Research Consortium (ARC) 3.5-m telescope, also located at APO. One of the main advantages of the 10-μm all-sky camera over an optical one is that the infrared camera can detect even light cirrus under a full range of moon phases (from new to full); see Fig 3. Another infrared all-sky camera is being built by Joshua Bloom and Onsi Fakhouri for the Pairitel telescope at Whipple Observatory.[4] Currently, there is no 10 micron all-sky camera based at CTIO, but there are plans by the DES to construct one.

[3] `http://hoggpt.apo.nmsu.edu/irsc/tonight/`

[4] `http://astro.berkeley.edu/~onsi/clic/`

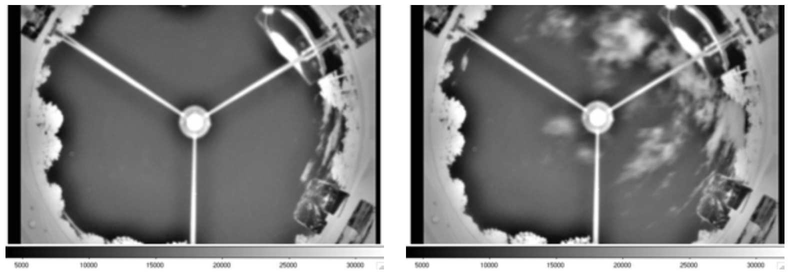

Figure 5. Two images from the APO 10-μm all-sky camera: *(left)* clear, *(right)* light clouds. The bright spidervane is the camera support structure (credit: Astrophysical Research Consortium and the Sloan Digital Sky Survey Collaboration, `http://www.sdss.org`).

Other resources for monitoring the photometricity of the sky include optical all-sky cameras (like TASCA[5] and CONCam[6]) and the RoboDIMM[7] seeing and flux monitor, which are already available at CTIO.

7. Nightly Absolute Calibration

By nightly absolute calibration, we mean fitting observed magnitudes of standard stars to photometric equations for a night's observations. Our standard star observation strategy is currently evolving, but we believe the general plan will be as follows:

1. Observe 3 standard-star fields, each at different airmass (X =1–2), between nautical (12°) and astronomical (18°) twilight (evening & morning).

2. Observe up to 3 more standard-star fields (at various airmasses) throughout the night.

3. Also observe standard-star fields when the sky is photometric but seeing is too poor for science imaging (seeing $>$ 1.1 arcsec FWHM).

4. Use fields with multiple standard stars.

5. Keep an eye on the photometricity monitors.

The plan for absolute calibration is to calibrate the photometry to the DES "natural" system. By using the natural system of the telescope+camera+filters, no system response color terms are needed in the photometric equations, thus simplifying calibration of the imaging data as there is no need to couple science images obtained in different filters.

Due to the similarities in the SDSS and DES filter response functions, DES calibration can be achieved by using SDSS $u'g'r'i'z'$ and $ugriz$ standards

---

[5] `http://www.ctio.noao.edu/~david/tasca.htm`

[6] `http://nightskylive.net/cp/`

[7] `http://www.ctio.noao.edu/telescopes/dimm/dimm.html`

transformed into the DES *griz* natural system. Since the SDSS $g'r'i'z'/griz$ and DES *griz* filter responses are very similar, the transformations from SDSS to DES should be well behaved. (Strictly speaking, the the filter response curves of the SDSS z', the SDSS z, and the DES z are not as similar; so transformations from the SDSS magnitudes to the DES magnitudes may need special treatment.)

This absolute calibration strategy is similar to that employed by the SDSS. Although SDSS photometry is published in the SDSS 2.5-m telescope's *ugriz* natural system, it is in fact calibrated based upon observations of $u'g'r'i'z'$ standard stars by the SDSS 0.5-m Photometric Telescope (Tucker et al. 2006).

8. Standard Stars

The DES will rely on a set of standard stars to establish its absolute calibration. Currently, we plan to rely on two particular sets of standard stars that are now becoming available in the SDSS filter system: the southern $u'g'r'i'z'$ standards and the SDSS Stripe 82 *ugriz* standards.

8.1. The Southern $u'g'r'i'z'$ Standards

One excellent set of standard stars we plan on using is the southern $u'g'r'i'z'$ standard star network of Smith et al. (2006), observations for which were obtained on the CTIO 0.9-m telescope over the 2000–2004 time frame. This set of standard stars is an extension of the northern+equatorial $u'g'r'i'z'$ standard star network that Smith et al. (2002) established for the photometric calibration of the SDSS. The southern $u'g'r'i'z'$ standard star network consists of approximately sixty $13'.5 \times 13'.5$ fields. Each field contains typically several tens of standard stars in the magnitude range $r = 9$–18. Altogether, there are $\sim$16,000 standards stars in southern $u'g'r'i'z'$ standard star network. (Further details of the southern $u'g'r'i'z'$ standard star network can be found in Smith's contribution in these Proceedings).

For the DES, stars as bright as $r \approx 13$ can likely be observed by DECam with 5+ second exposures under conditions of poor seeing or with de-focusing (FWHM=$1''.5$), making the southern $u'g'r'i'z'$ standard star network an essential resource for the photometric calibration of this survey.

8.2. SDSS Stripe 82 *ugriz* Standards

One of the priceless data sets that the SDSS has provided is Stripe 82, a $2^\circ.5$-thick region extending along the celestial equator from $20^{\rm h}40^{\rm m}$ to $3^{\rm h}20^{\rm m}$ (250 deg^2 in total). Observable in the northern autumn when the main SDSS area (the Northern Galactic Cap) is inaccessible, Stripe 82 has been imaged $\gtrsim 10\times$ under photometric conditions by the SDSS 2.5-m telescope (Adelman-McCarthy et al. 2007). The quality and multi-epoch nature of the Stripe 82 data make them an ideal source for creating tertiary SDSS *ugriz* standard stars. An effort by Ivezić and collaborators has already yielded a Stripe 82 standard stars catalog containing $\sim 10^6$ *ugriz* tertiary standards – on average $\sim$4000 standards per deg^2 – in the magnitude range of $r = 14.5$–21 (Ivezić et al. 2006; see also Ivezić's contribution in these Proceedings).

The SDSS Stripe 82 is already a part of the DES survey region (recall Fig. 5). It is readily observable at a range of airmasses throughout most nights during the DES program, and the $2.^\circ5$ width of Stripe 82 compares favorably with DECam's $2.^\circ2$-diameter field-of-view. A Stripe 82 standard stars catalog will therefore play a critical role in the photometric calibration of the DES.

8.3. Other Sources of Standard Stars

As the SDSS *ugriz* filters become more popular, other large scale projects are making use of them, and even create their own standard star catalogs for these filters. These include standards for the VST OmegaCam and for the SkyMapper survey (see contributions in this volume by Kleign and Bessell, respectively). These other sources of standards may also prove useful for the DES.

9. Global Relative Calibrations

Global Relative Calibrations cover two topics: the removal of any residual photometric effects due to vignetting and/or scattered light (star flat corrections), and the removal of any field-to-field ("Hex-to-Hex") photometric zeropoint offsets due to observing different fields under different photometric conditions. Let us consider each in turn.

9.1. Star Flats

Due to vignetting and stray light, a detector's response function differs for point sources and extended sources. Standard flat fields (domes, twilights, skies) may flatten an image sky background well, but not necessarily the stellar photometry. This is particularly true of wide-field imagers, in which these effects can produce systematic photometric errors of 10–20% or more across an imager's field-of-view. The solution is to create and apply star flats (Manfroid 1995). A star flat can be created simply by offsetting an uncalibrated field (like an open cluster) multiple times and then fitting a spatial function to the magnitude differences for matched stars from the different exposures (Manfroid, Selman, & Jones 2001). Likewise, a star flat can be created by observing a well-calibrated field once and then fitting a spatial function to the observed−standard magnitudes for the stars in the field (Manfroid 1996; Koch et al. 2004); this of course assumes the availability of a densely populated standard star field that is at least as wide as the imager's field-of-view. In either case, however it is created, the star flat can then be applied directly to the measured photometry.

The DES can profit from both methods of star flat creation. First, due to its survey strategy of large offsets between each tiling (see Sec. 9.2 below), star flat correction maps can be generated from previously all the uncalibrated stars in the survey area at the end of the survey using the information from the multiple tilings of the full survey region. Second, observations of SDSS Stripe 82 (and its dense population of tertiary *ugriz* standard stars) during normal DES operations will permit the creation of high quality star flats very early within the survey. Since fields within SDSS Stripe 82 are targetted throughout the 5-year course of DES operations, we will also be able to track any evolution of the star flats themselves over time.

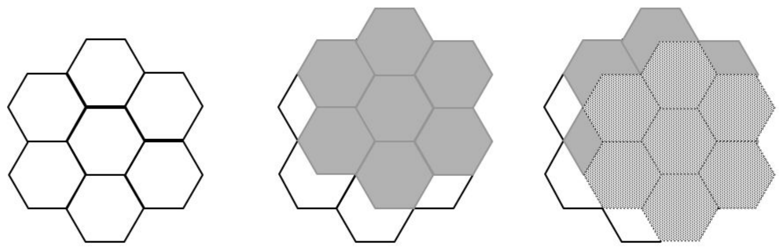

Figure 6. Hex offset tiling strategy: *(left)* 1 tiling, *(middle)* 2 tilings, *(right)* 3 tilings (credit: Jim Annis).

9.2. Hex-to-Hex Zeropoint Offsets

Recall from Sec. 3 that the current idea for survey strategy is to cover the entire 5000 deg^2 of the survey area twice per year per filter. Each full coverage of the sky in a filter is called a tiling. The goal is, after 5 years, to have tiled the survey region 5 times each in g and r, 7 times in i, and 13 times in z. For a 3 deg^2 wide-field camera, it takes $\sim$1700 hexes to tile the whole survey area. Our recipe for covering the survey region is as follows (see Fig. 4):

1. Tile the survey region.
2. Then, tile the survey region again with the hexes offset half hex over and up (this gives 30% overlap with three hexes).
3. Repeat, with different offsets.

We note that this recipe is similar to PanStarrs strategy (see Magnier's contribution in this volume). The large overlaps provide very robust hex-to-hex relative calibrations. Relative offsets between tiles can be solved for using a large matrix inversion.

9.3. Simulation

To test whether our recipe of multiple offset tilings could achieve our survey requirements of 2% ($0\overset{\mathrm{m}}{.}02$) all-sky photometry, we performed a simple survey simulation. For sky conditions, we assumed $\approx$10% variations in photometric zeropoints for the hexes. For the camera itself, we included a multiplicative flat field gradient of amplitude 3% from east to west across the focal plane, an additive scattered light pattern with a $1/r^2$ amplitude from the optical axis (reaching 3% at the edge of the focal plane), and an additional additive 3% rms scattered light per individual CCD on the focal plane. We find that we can indeed achieve our survey requirements after only 2 tilings ($\sigma = 0\overset{\mathrm{m}}{.}018$); in fact, we can even achieve our enhanced goal of 1% ($0\overset{\mathrm{m}}{.}01$) all-sky photometry after 5 complete tilings (see Fig. 6).

10. Global Absolute Calibration

For a firm Global Absolute Calibration, we need one or more spectrophotometric standard stars which have been calibrated (directly or indirectly) to a

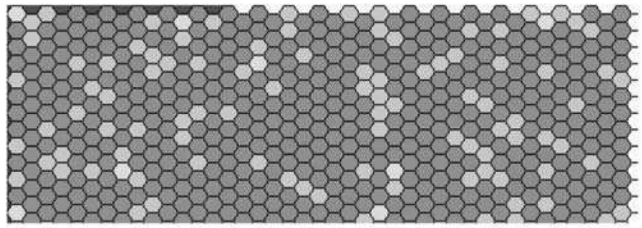

Figure 7. Simulation of the photometric calibration error using relative photometry. The full range of the scaling bar is $-0\overset{\text{m}}{.}20$ to $+0\overset{\text{m}}{.}20$. the map is that resulting after 3 tilings and has an rms scatter of $\sigma = 0.013$ mag, starting from 10% photometry and a variety of flatfielding and scattered light systematics embedded at the $\sigma = 0\overset{\text{m}}{.}03$ level (credit: Jim Annis & Huan Lin).

NIST standard source and an accurately measured total system response for each filter passband for at least one CCD, including filter transmissions, CCD QE responses, optical throughput, and atmospheric transmission. We then perform synthetic photometry for each of these spectrophotometric standard stars, simply calculating the expected photon flux F_{exp} in each filter passband. Then, we measure the magnitude for each spectrophotometric standard in each filter passband with the Blanco+DECam. Finally, for each passband, we can compare the expected magnitude m_{exp} for each standard based upon its expected photon flux F_{exp} against its observed magnitude m_{obs}; the resulting zeropoint offset can then be applied to the photometry for absolute calibration.

The DES filter transmissions, the CCD QEs, and the optical throughput for the Blanco+DECam can be measured via a monochromator. (Another possibility to measure these is via a tunable dye laser flatfielding system; please see Chris Stubbs', David Burke's, and Yorke Brown's contributions to these Proceedings). The atmospheric transmission spectrum for CTIO has already been measured (Stone & Baldwin 1983; Baldwin & Stone 1984; Hamuy et al. 1992, 1994). Furthermore, several potentially useful spectrophotometric standards are available (e.g., GD 71, G 158-100, GD 50, and G 162-66). All are white dwarf spectrophotometric standards, all are visible from CTIO, and all are faint enought ($V \geq 13.0$)that they will not saturate the DECam at exposure times of 5 sec for seeing/focus of $1\overset{''}{.}5$ FWHM. Therefore, most of the information for Global Absolute Calibration is either already in hand (e.g., CTIO atmospheric transmission spectra and well-calibrated spectrophotometric standards) or will eventually be available (e.g., DES filter transmission curve measurements, DECam CCD QEs, Blanco+DECam optical throughputs.)

11. Conclusions

We have discussed the Dark Energy Survey and the current plans for its photometric calibration. To achieve the survey's science goals, all-sky photometry of 2% ($0\overset{\text{m}}{.}02$) rms is required, with an enhanced goal of 1% ($0\overset{\text{m}}{.}01$) rms. This is a challenging but achieveable goal.

Acknowledgments. The FNAL contribution to this work was supported by the US Department of Energy under contract DE-AC02-76CH03000.

References

Adelman-McCarthy, J., Agüeros, M. A., Allam, S. S., et al. 2006, ApJS, 162, 38
Adelman-McCarthy, J., Agüeros, M. A., Allam, S. S., et al. 2007, ApJS, submitted
Baldwin, J. A., & Stone, R. P. S. 1984, MNRAS, 206, 241
Beck, R. 2005, Astron. Nachr., 326, 608
Cooray, A., et al. 2001, ApJ, 557, L7
Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748
Hamuy, M., Walker, A. R., Suntzeff, N. B., et al. 1992, PASP, 104, 533
Hamuy, M., Suntzeff, N. B., Heathcote, S. R., et al. 1994, PASP, 106, 566
Haiman, Z., et al. 2001, ApJ, 553, 545
Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J., & Gunn, J. E. 2001, AJ, 122, 2129
Hu, W. 2002, Phys.Rev.D, 66, 3515
Huterer, D. 2002, Phys.Rev.D, 65, 3001
Ivezić, Ž, et al. 2006, AJ, submitted
Koch, A., Odenkirchen, M., et al. 2004, Astron. Nachr., 325, 299
Manfroid, J. 1995, A&AS, 113, 587
Manfroid, J. 1996, A&AS, 118, 391
Manfroid, J., et al. 2001, ESO Messenger 104, 16
Mohr, J., et al. 2007, in Astronomical Data Analysis Software & Systems XVI, (ASP: San Francisco), in press
Ngeow, C., et al. 2006, Proceedings of the SPIE, 6270, 68
Perlmutter, S., et al. 1999, ApJ, 517, 565
Riess, A. G., et al. 1998, AJ, 116, 1009
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Smith, J. A., Tucker, D. L., Kent, S., et al. 2002, AJ, 123, 2121
Smith, J. A., Allam, S. S., Tucker, D. L., et al. 2006, in preparation
Stone, R. P. S., & Baldwin, J. A. 1983, MNRAS, 204, 347
Sweeney, D. W. 2006, Proceedings of the SPIE, 6267, 6
Tucker, D. L., Kent, S., Richmond, M.W., et al. 2006, Astron. Nachr., 327, 821
Wang, L. & Steinhardt, P. J. 1998, ApJ, 508, 483

Discussion

Stubbs: Will the zeropoint of the DES filter system be Vega-based or *AB*-based?

Tucker: It will be an *AB* magnitude system.