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Initial Calibration of CCD Images for the Dark Energy Survey

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Abstract

Astronomical images taken from a telescope must go through "astronomical image processing" to remove instrumental signatures. The Dark Energy Survey (DES), which will start operations in 2012, will use a 570 megapixel Dark Energy Camera (DECam) to study the mystery of the acceleration of the expanding universe. The DECam will use DES filters and 74 of a new type of astronomical Charge Coupled Device (CCD) that is particularly efficient in detecting near-infrared light. Together, the DES filters and DECam CCDs are optimized for the measurement of redshifts of distant galaxies. In preparation for the DES, data were collected from the 1 meter telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile, using a DES filter set and a DECam CCD as a test set for the initial analysis of data. Here, these CTIO-1m data were used to determine the relationship between the apparent measured brightness of stars of known brightness (standard stars) and the amount of atmosphere the telescope looks through (angular distance from the zenith or "airmass"). This relationship was tested against the results from another telescope using similar filters. Finally, this relationship was used to calibrate the brightness of stars of unknown brightness that were also observed in the CTIO 1m data set.

Introduction

Dark energy, a form of energy that counteracts gravity and accounts for more than 70 percent of the universe, is the source of the current expansion of the universe. Although many studies have now confirmed the existence of dark energy, there is yet to be a compelling explanation for it. The acceleration of the universe suggests that our model of fundamental particles and gravity is either incorrect or incomplete[1].

This mysterious dark energy is being studied by looking at light coming from distant galaxies. Light traveling through an expanding medium will experience a redshift, where the wavelength and the frequency of light increases and appears "redder". Studying the redshift of light coming from distant galaxies can uncover the nature of dark energy, since such phenomena is a direct result of expansion of the universe (space medium), driven now primarily by dark energy.

The Dark Energy Survey (DES) is a five year galactic survey that will look at a 5000 square degree area in the Southern Galactic Cap over 525 nights, designed to observe the properties of dark energy[5]. The DES will be using the Dark Energy Camera, DECam, which is a 570 mega pixel camera with 74 Charge Coupled Devices (CCD) sensitive to the light coming from distant galaxies. It is installed and operated on the Blanco 4m telescope at the Cerro Tololo Inter-American Observatory (CTIO) located in Chile[8]. The data taken with DECam will be used to study the mystery of the accelerated expansion of the universe[5]. DES will use this powerful new camera to identify and count clusters of galaxies as a function of the redshift, to study how galaxies and dark matter cluster as a function of the redshift, and to identify and measure the brightness of Type Ia supernovas as a function of the redshift. All these measures depend on the properties of dark energy and how dark energy affects either the expansion of the Universe (e.g., supernova brightness vs. redshift relations) or the growth of structure over time (e.g., the number of clusters of galaxies vs. redshift or the clustering of dark matter vs. redshift). All these measurements depend on the redshift. The most precise redshifts are of course obtained using spectrographs, but obtaining spectrographic redshifts for large numbers of objects is a very time-consuming process. The DES plans to get around this bottleneck by the much faster method of using a 5-filter imager, which in essence acts like a low-resolution spectrograph (one with 5 wavelengths); in fact the DECam CCDs have been chosen to be very sensitive in the near-infrared (to about 1 micron in wavelength) in order to use this method out to large redshifts (z ~ 1), or the distant it takes light to travel in about 6.6 billion years[12]. Redshifts obtained this way are called photometric redshifts (or "photo-z's"). To measure photometric redshifts accurately, however, requires good photometric calibration. This paper focuses on one of the steps towards good photometric calibration of the DES.

Prior to the main survey starting in 2012, the PreCam Survey, designed to provide better calibration of this new filter system, will be conducted at CTIO[11]. PreCam will be using the same type of CCD's and filter system as the DES. Prior to PreCam, a test run using a DECam CCD and DES filters was perform on the CTIO 1m, telescope. By comparing the relationship between the brightness of stars and the amount of atmosphere the telescope looks through (angular distance from the zenith or "airmass") from the CTIO 1m telescope, these first data taken in the DES filter system will provide a first look at real stars and galaxies in this filter system, including non-standard stars with unknown brightness. These will provide the first astronomical calibration data in the new DES filter set.

Materials and Methods

Using images (shown in figure 1) taken from the 1m-telescope during a week long observing run in July of 2010[5], several calibrations were performed to get rid of the noise in the images. Nights of July 10 and 11 (nights 6 and 7 of the observing run) were chosen, since the observation log indicated some technical problems with the telescope for the first couple of nights of the observing run.

The images named "bias" and "flat" are for calibration purposes and images named "fits" are the images of the sky taken from the telescope. Each "fits" file name has a letter right after indicating the kind of filter used to take the image: g, r, i, z or y filter.

The purpose behind taking "bias" and "flat" images is to provide calibration for the telescope's electronics system and other external variables. The "bias" images are taken with closed shutter and zero exposure time and provide a 2D map of the electronic signature that was added to the data during readout. The "flat" images are taken with uniform luminosity in the inside of the dome and provide a 2D map of the photon-detection efficiency variations across the CCD (for a given filter). Grouped into two kinds of calibration images, they are processed with a computer using a Python script ("fastreduce" script), which takes the list of the calibration files and for every pixel on the images takes the median-valued pixel to create a single master "bias" or "flat" image. Then the master "bias" and "flat" images can be used to calibrate for efficiency of the CCD and to remove the instrumental signature from the telescope's electronics.

After the calibration of the efficiency of the CCD and the removal of instrumental signatures from the telescope's electronics are performed, astrometric calibration (calibration of the star positions) on an image is done in order to correct the star's location in the images. First, using a program called sExtractor[3], the stars in the images are identified. sExtractor also compiles the location of the identified stars and the brightness for each star that was identified. Using these sets of information about the stars in the image, the image is matched up with the images of the same part of the sky from an online database. Then using the information about the position of the stars from the database, the measured positions of the stars in the images were corrected (both sExtracted and calibrated images shown in figure 3).

After the instrumental signatures were removed and the stars and their positions were identified, a field of the sky named E8-A was chosen: the field E8-A is a field containing standard stars (stars of previously known brightness) and it had the most observations at different airmasses that could be plotted.

The instrumental magnitude (or measured magnitude) is determined by a formula:

minstr = -2.5log10(counts/sec)

where the instrumental magnitude is proportional to the negative log of counts(number of photons detected by the telescope) over time. The brighter objects will have smaller magnitudes.

After all of the instrumental magnitudes of the identified stars were determined, the graph of the same stars in two different airmasses were plotted (shown in figure 7). The slope of the graph (k) and the y-intersept of the graph (a) were determined.

minstr-mtrue = a + k*X

The above formula shows the relationship between the brightness of a star measured by the telescope and its true brightness, where minstr is the instrumental magnitude of the star, mtrue is the true magnitude or how bright the star really is, (a) is the y-intercept of the relationship plot (which accounts for the photometric

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zeropoint of the system in that filter system), (k) is the slope of the relationship plot (or the atmospheric extinction coefficient in that filter), and X is the airmass (and is approximately equal to the secant of the distance of the star from the zenith).

Once the values of minstr, a, k, and X are determined, mtrue can be determined for other stars using the formula below.

mtrue = minstr - a - k*X

Results

For this work, we concentrated on the observations done in the g filter. The raw images (such as in figure 1) were calibrated with master bias and flat images (shown in figure 2). The resulting calibrated image, with minimized experimental error, is shown in figure 3.

From the graph of airmass versus the minstr-mtrue for the standard stars, the extinction (k) and the zeropoint (a) of the telescope were determined (shown in figure 4).

Using the determined extinction (0.1699) and zeropoint (-23.809), and the given airmass of the image, magnitudes of standard stars in the SA-112 field (another star field observed on the same night) were calibrated. The average difference between the true magnitude and the calibrated magnitude was around 0.15 magnitude, and much smaller for brighter stars (magnitude less than 16) (Graph of the differences shown in figure 5).

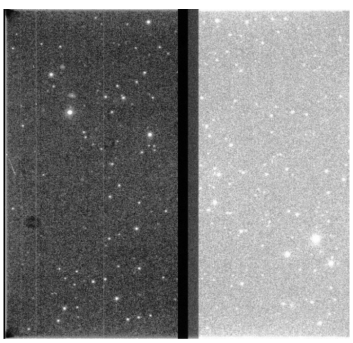
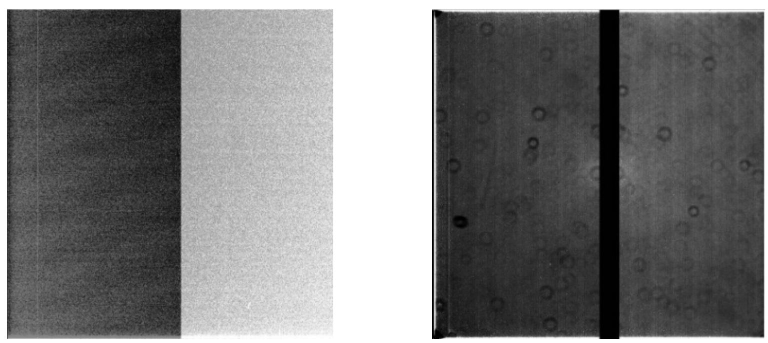
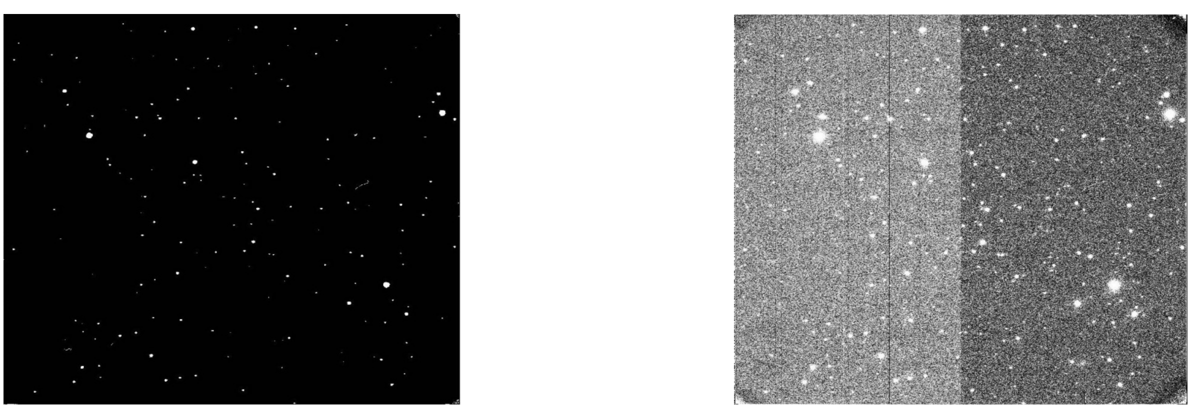


Figure 1: Raw image from the telescope



a b

Figure 2: Sample images of a bias image (a) and flat image (b). The “donuts” in figure 2(b) are due to out-of-focus dust specks on the camera window



a b

Figure 3: Images of sExtracted image (a) and calibrated image (b)

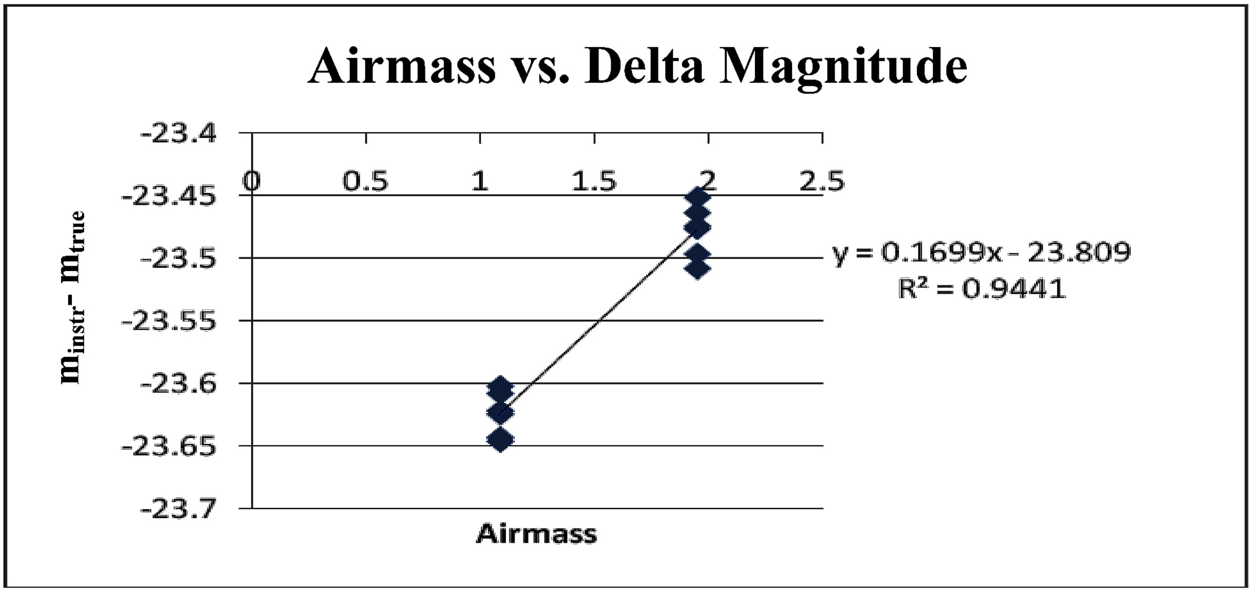


Figure 4: Graph of airmass versus difference in instrumental and true magnitude (minstr- mtrue) for the standard stars showing the values for the extinction and the zeropoint. [Both the airmass and the magnitude are dimensionless]

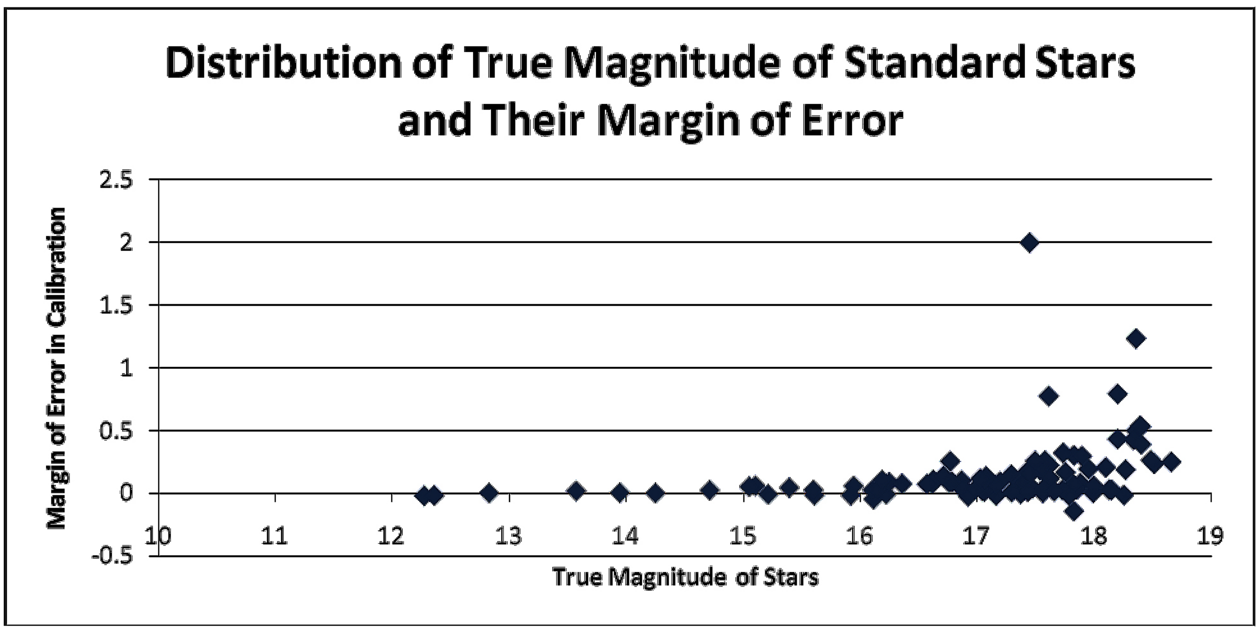


Figure 5: Scatter plot of the identified standard stars and their difference between the known magnitude and the estimated magnitude

Discussion

The extinction at the CTIO 1m- telescope was determined and used to determine the brightness of standard stars in another field. The resulting data suggests that the brightness of the stars could be calibrated with determined extinction and the zero-point since the brightness of star with unknown brightness could be calibrated using the measured extinction and zeropoint values.

While all the calibrations were designed to eliminate most of the errors in measurements made by the telescope, other factors such as the fluctuation in the apparent brightness of standard stars could have affected the result by either over or underestimating the true brightness (due primarily to fluctuations in the Earth's atmosphere in the direction of the standard stars). Also, traces of asteroids in the images could have been mistaken as a star in the images. Such noise would affect the calibration in pointing of the telescope as well as the value of extinction and zero-point. However, these possible errors in the system are thought to be minimal and will not affect the calibration and the result in a major way since the ratio of amount of stars versus amounts of asteroids in the images is huge.

As postulated, the unknown brightness of non-standard stars can be calibrated in similar way to that in other telescopes. Also the extinction value of the new DES filter turned out to be very close to that determined by the Southern Standard Stars Project which used similar filters as DES[11].

Most experts believe that nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration[1]. The DES will improve the measurements of dark energy by a factor of 3 to 5 over previous estimates[9]. The calibration of a telescope with a DES filter system will help in calibrating the DECam, which will be used to uncover the nature of dark energy.

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