Calibration of the DES & Rubin-LSST

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I - Introduction

The Dark Energy Survey (DES) conducted a 525 night, five-filter (*grizY*) imaging survey of 5000 square degrees (nearly one-eighth of the entire sky) in the southern hemisphere [1]. The survey area, see Figure 1, overlaps with other existing or planned surveys, notably the South Pole Telescope (SPT) survey [2] and portions of the Sloan Digital Sky Survey (SDSS). The entire footprint is contained within the Two-Micron All-Sky Survey (2MASS) [3], a near-infrared survey completed nearly two decades ago which ties near-infrared observations to the brighter DES targets. The DES probed the nature and the dark energy content of the Universe by employing four different methods; (1) Type Ia supernovae, (2) baryon acoustic oscillations, (3) galaxy clustering, and (4) weak lensing by gravitational masses [1]. The DES collaboration built the Dark Energy Camera (DECam) [4] which was installed on the Blanco 4m telescope at Cerro Tololo Inter-American Observatory (CTIO) outside La Serena, Chile for conducting the survey.

The observational requirements to achieve the science outcomes of the survey set the precision of magnitude (brightness) measurements to 2% uncertainty (0.02 magnitudes) for point sources at a S/N=10. With these data, the dark energy parameters should be constrained to a level expected of a Stage III experiment as defined by the Dark Energy Task Force [5]. To meet the survey science goals, there are stringent requirements on the absolute and color photometric calibrations [6]. The final photometric calibration of the survey must be accurate to 2%; the final color zero-points between the fiducial band-passes must be known to 0.5% rms with *z-Y* known to 1% rms; and *i*-band magnitude zero-point relative to the star BD+17:4708, and therefore the AB system, must be known to 0.5% rms. In short, these are the most stringent calibration requirements ever placed on a large-area sky survey. BD+17:4708 is the fundamental standard star used by the SDSS [7]. During operations, we developed a slightly different strategy to tie the zero-points to the Hubble Space Telescope (HST) CalSpec star C26202, and later to a network of HST CalSpec and other stars.

Calibration of large sky surveys performed in the digital age is an evolving science. In the days of photographic plate surveys, the sky images were obtained and rough brightness calibration performed on a few of the brighter stars to set a “bench mark” for the plate. An offset to the fainter stars was used often resulting in large uncertainties in the cataloged magnitudes. These uncertainties were a result of non-uniform emulsion thickness, halation near bright objects, non-uniform exposure illumination across the focal plane cause by the telescope optics, and other problems. With the advent of the solid state “charge coupled” devices (CCDs) many of these problems were minimized. In fact, the internal precision of CCD photometry was 2-3 orders of magnitude better than photographic plates. However, large area CCDs did not exist in the early days of the digital age. With passing time, electronics manufacturing now allows the development of large-area detectors. Placing many CCDs in a mosaic allowed even larger areas on the sky to be surveyed at once leading to the large digital sky surveys. One of the first large-area surveys was the Sloan Digital Sky Survey (SDSS) [8]. Calibration of the SDSS was an experiment in its own right. The initial approach was to develop a standard star network [7] and transfer these magnitudes to the survey fields [9]. This approach met the SDSS requirements but additional techniques were developed and applied to surpass the basic survey needs [10].

To successfully achieve the stringent science requirements of the DES however, a new survey calibration strategy was required. Several large-area surveys have nearly simultaneously come to realize the best approach appears to be that of internally calibrating the survey measurements in a relative manner and then "floating" the entire grid of observations to a flux standard to place the survey on an absolute flux scale. The DES employed this method. A calibration strategy was devised that compared DES measurements with the synthetic magnitudes of hydrogen atmosphere white dwarf (WD) stars (designated DA) distributed over the survey footprint. Synthetic magnitudes, where the model spectra of DAs are calculable, have also been used to help constrain SDSS photometry [11]. In addition, in the study of the systematic uncertainties associated with the photometric calibration, comparisons to measurements by other surveys such as the SDSS will be critical. For this reason, the DES footprint included SDSS stripe 82 (celestial equator) and a connecting region (-30°<dec<-1°) in addition to a large contiguous area around the Southern galactic cap; Figure 1.

Because of their relatively simple spectra, pure hydrogen atmosphere ("DA") white dwarf stars (WDs) are the current standard for absolute calibration of large astronomical surveys [see, e.g., 11; 12]. This method is being used to calibrate the Dark Energy Survey (DES) and the SkyMapper projects, and a similar method will be used to calibrate the Large Synoptic Survey Telescope (LSST). Observations to begin this effort are currently in work. The process requires calculating the synthetic *grizY* magnitudes from the well-modeled spectra of a good set of pure hydrogen white dwarfs and comparing their synthetic magnitudes with their observed *grizY* magnitudes. The measured differences between the synthetic and observed *grizY* magnitudes are the offsets required to perform the absolute calibration of the DES photometry by placing it firmly onto an AB magnitude system. To this end, we have observed and modeled a good sample of pure hydrogen white dwarfs within the DES footprint; see Figure 2.

Initially, we used data from the SuperCOSMOS Sky Survey as a starting point for a comprehensive southern hemisphere WD database which could be used to build the observing target lists. This survey covers about 75% of the sky, ignoring the dense regions near the galactic plane, and the WD portion of this survey [13] contains nearly 10,000 WDs to a mean depth of I ~ 19.2 based on a conservative tangential velocity cut of 30 km/s. The drawback is this work is based on photographic plates. Nonetheless, this survey contains a significant fraction of candidate white dwarf stars currently known and contains proper motion data to aid in their identification. Supplementing this work is the SDSS-DR4 catalog [14] which contains over 9000 spectroscopically identified WDs with their CCD-based magnitudes. While this set contains most of the information we need for the stars, the SDSS was a northern hemisphere survey, therefore, only the stars in Stripe-82 (SDSS equatorial scan) fall in the DES footprint. Selection of white dwarf candidates is accomplished using a combination of colors (the difference between two magnitudes in the short – long wavelength sense) and a reduced proper-motion plot. These are shown in Figure 3. As the Gaia astrometric spacecraft released data, we included this database which provided even more targets and additional information allowing selection of WDs.

The goals of this summer's work were to support the DES Calibration Scientist in two major areas related to calibration of the DES. **First**, perform a detailed analysis of the transformations between photometric filter systems to facilitate the DES calibrations work and prepare for expansion to the Rubin-LSST data when that survey begins operations (est. 2024). This was the work tasked to the Fermi National Accelerator Lab (FNAL) mentor (Dr. Douglas Tucker) and an Austin Peay State University (APSU) student (Ms. Meagan Porter). The **second** major task was the reduction of WD imaging data collected by Dr. J. Allyn Smith (APSU faculty member and VFP-PI) and Dr. Tucker on various observing sessions at CTIO and the Kitt Peak National Observatory (KPNO). This work would be the primary task for Dr. Smith and another APSU student (Mr. Sean Peete). The WD imaging data will provide the independent *ugriz* magnitudes for comparison to the synthetic magnitudes from the spectra of these same stars. This project would complete the development of an initial "golden sample" of well-characterized WDs for use as survey calibration stars. This is a major effort of the

DES White Dwarf Calibrations Sub-Group (J.A. Smith, lead; DES-docdb-2505 dated 17 September 2008). A third task was for all participants to participate in the Rubin-LSST DP0.2 data challenge.

II - Progress

The two major pieces of the project met with mixed success. The transformation work went well as initial code had been developed by Dr. Tucker early in the DES survey operations and to support the internal calibrations and verification work. Ms. Porter needed time to learn how the code operates and then how to modify it to support additional filter systems. Adding credence to this effort, the early DES Year-6 data is available for in-house efforts (17.9 million stars) and the SDSS Stripe-82 equatorial standard stars are also available [15]. This work yielded firm transformation equations between the two filter systems and provides the ground work for future work.

The approach to this portion of the project was straight forward. For the software coding, the algorithms to be used were mapped out by Ms. Porter and Dr. Tucker and then coded in python within the Jupyter environment. Once the base code for each of the programs was working, additional features were added to reach the final version of the code. This can now be modified to support additional filter systems.

The second portion of the project, reduction of existing data from three KPNO and nine CTIO observing runs, met with limited success. In retrospect, this piece of the project was a large effort. All of the observing runs were processed. The KPNO runs had been previously reduced (2012 VFP effort) though these reductions need to be revisited. The KPNO data suffered from issues with some of the observational data (poor weather, some camera issues, multiple projects interleaved into an observing run, etc.). One of these runs was discarded as non-reducible due to errors committed by the observers. The other two runs from KPNO were reduced through all the image processing steps and astrometric matching to identify the stars of interest in each field. We ran into several issues with the matching routines we employed in 2012. We now have better astrometry matching software and will complete this work early this fall. The KPNO image data contain nearly 50 white dwarfs along the equator.

Of the CTIO runs, one used a different telescope and camera than the others, compounded with a different set of filters for the first three nights and there were also electronic issues with the camera for this run. The image processing was completed, but the final science reductions were put off to the end (and not yet completed). We developed a plan to complete these data but this will be more time consuming and it was deferred to this fall. The remaining the CTIO observations were all processed and finder charts for all of the standard and target stars were completed. Magnitude extraction took longer than expected. Most runs are completed, but not all of them. This work will continue upon our return to Austin Peay. One of the runs was completed through all processing steps to verify our processing steps. The standards stars on this particular run showed higher residuals than expected for CTIO causing us to question if the nights were truly photometric and requiring further investigation. However, we had observed a separate target (star cluster) during three of the seven nights for a colleague. Reductions of the star cluster yielded good, consistent results so we determined the run was usable for our work but had higher than normal residuals. Overall, these data contain nearly 600 separate WD observations. Most of these were targeted by the independent spectroscopy effort. Both of these efforts were outlined in the Plan for Calibration of the DES in the Early Years [16].

For the image reduction, Mr. Peete used standard processing techniques. The initial steps of the processing — bias frame subtraction, flat field division, fringe frame corrections, and bad pixel masking — were performed using IRAF, the Image Reduction and Analysis Facility, developed by the

National Optical Astronomical Observatory [17, 18]. The astrometric fits were performed using Astrometry.net [19]. Graphical fits to the data to determine extinction coefficients and nightly zeropoints were performed using TOPCAT [20] and all magnitudes will be reduced using the SDSS *u'g'r'i'z'* standard star network [7].

When the image processing is completed, those WDs will be matched to the DA spectral sample with modeled temperatures $14{,}000 < K < 45{,}000$ surface gravities. A subset of these will be selected for the DES "golden sample" of calibration stars and subjected to continued monitoring to ensure against variability. Early results from the spectroscopic effort (DES-docdb-15116-v3) indicate we will achieve the DES Science Requirements goals for the survey.

III - Future Work

In the near term, we will continue processing these sets of imaging data to obtain the magnitudes of all of the white dwarfs and match them with the synthetic magnitudes from the spectra. This will complete the development of the "golden Sample of WDs" which can be used for future surveys. The manuscript for this effort is already in preparation and we hope to finish it this fall for journal submission late 2023 or early 2024.

Development and refinement of a similar calibration effort for the Rubin-LSST will continue based on this work. We will continue to pursue the observations as quickly as we can. To support the observing effort, a funding request will be submitted to the NSF-MPS this fall (Nov. 2023) and a proposal for a "Survey Program" will be submitted to the NOAO next March (2024). Our goal is to have the initial set of well-characterized white dwarfs in place by the start of the first full year of LSST operations and expand the breadth of coverage within the footprint for the remainder of the survey. Some of this work could also be pursued in an additional year in the VFP program should the opportunity arise.

IV - Impact on Laboratory or National Missions

This project directly supports the Dark Energy Survey – a Department of Energy flagship experiment to investigate Cosmic Frontiers and the forthcoming Rubin-Large Synoptic Survey Telescope, a DOE/NSF/Private effort. The DES is a collaborative effort of DOE labs and universities and the world. DOE labs directly involved with DES are the Fermi National Accelerator Lab, Argonne National Lab, and the Stanford Linear Accelerator Center. Several U.S. Universities are involved and international partners can be found throughout Europe and South America.

Funding for the DES Project was provided by the U.S. Department of Energy, the U.S. National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute of Cosmological Physics at the University of Chicago, Financiadora de Estudos e Projetos, Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq - Brazil) and the Ministério da Ciência, Tecnologia, e Inovação (MCTI - Brazil), the Deutsche Forschungsgemeinschaft and the Collaborating Institutions in the Dark Energy Survey.

V - Conclusions

The Dark Energy Survey completed on-sky operations in 2019 and final processing and calibration of the data are in work. The goal of the DES was to study the nature of dark energy and its content in the Universe using four complementary approaches. The DES was, in many ways, the most complex sky survey conducted to date. It required a new imaging camera (the DECam) to be built and installed on the 4m "Blanco" telescope at CTIO. Commissioning of the camera will began in September 2012 with survey operations beginning in November 2012 and finishing in January 2019. To achieve the science goals for the survey, the requirements for data quality were stringent. Calibration of the survey was therefore, extremely challenging and critical to the success of the DES. The project we undertook this summer contributes to two different aspects of the DES calibration effort.

The software effort to enhance the filter transformation code will support the continued calibration efforts of the DES. Further, it will be folded into support for LSST operations as that survey will use yet another set of filters that differs from SDSS or DES.

The DES has two phases of magnitude calibration. The first, a relative calibration, ensures all of the non-variable stars yield a uniform brightness in each of the five filters in all of the observations. Ten observations per object were planned per filter over the five year survey. Each of the observations will took place with the object at a different location in the focal plane. The final survey catalog is then "stitched together" via co-adding each of the individual magnitudes to form a seamless catalog. The second aspect of the calibration is the absolute calibration – that is setting the entire catalog to an absolute flux scale (ergs/cm^2/sec/Hz). To do this, a set of known calibration sources must be used. DA white dwarfs, those with pure Hydrogen atmospheres, and therefore "simple" spectra are used for this portion of the calibration. The spectra are modeled to yield accurate surface temperatures and gravities. Once these are known, the mass of the WD and the absolute flux can be determined. Having several of these well-characterized WDs in the DES footprint will allow us to set the flux scale for the DES.

The white dwarf reductions from this summer factor in to the second aspect of the project. Currently, there are few well-characterized WDs in the southern hemisphere which are faint enough to be observed with DECam. These data will help identify and characterize WDs to be used as faint calibration stars for use in future survey efforts, such as LSST

In addition to the two student projects undertaken this summer, we contributed to several of the DES commissioning and calibration documents, had the chance to attend and participate in the Calibration Working Group and the DES Science group weekly meetings. These activities exposed the students to an even larger group of the astronomers and physicists working on the overall project and the community of physicists and engineers working on other projects at FNAL.

In the course of the summer, we identified four items which can be taken back to our home institution and continued over the next year (or more). First, the white dwarf characterization effort will continue. We have several observing runs for which the final reductions need to be finished. Second, the filter transformation code refinement and expansion will continue. This will also feed into some of our on-going observation programs at our home institution. Third, we will be supporting manuscript preparation to summarize all of the DES calibration efforts as the survey data processing completes.

For the VFP program in particular, the experience this summer was wonderful. As a faculty member from a Tier-2 school (non-R1), the chance to work at a major national laboratory for a few weeks was an invaluable experience. For my students it was an eye-opening experience to work at the premier accelerator laboratory and be exposed to all of the disciplines involved in the operations of such a facility. Working with scientists involved in the day-to-day support of a major survey is an education in its own. Seeing a “real world” application of classroom lectures and exercises allowed the students to appreciate all of the hours of homework they do during the academic year. For those of us at smaller schools this experience allowed the students to work with scientists with different skill sets than the teaching faculty have, furthering their own development.

In general, the VFP program was well run and the integration with the students in the other FNAL summer programs was seamless, at least from my point of view. The housing and transportation arrangements were adequate. It provided a valuable learning experience for both the students and the faculty and staff mentors. Continuation, and expansion, of this program should be a high priority for the DOE/NSF. As more universities look to hands-on “industrial” experiences for their students, programs such as this fill a large void in the educational experience arena.

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Appendix

VFP Member	Institution	Role
Dr. Douglas L. Tucker	Fermilab, Center for Particle Astrophysics	Management, software development, data analysis
Dr. J. Allyn Smith	Austin Peay State University	Management, data analysis
Mr. Sean M. Peete	Austin Peay State University	Image work, data analysis
Ms. Meagan N. Porter	Austin Peay State University	Software, data analysis

Dr. Douglas L. Tucker – Dr. Tucker is the Calibrations scientist for the Dark Energy Survey (DES) and served as the host at Fermilab. He was responsible, together with Smith, in determining the tasks and priorities for the summer work plan. He also served as mentor for the team and directed the software development effort for the summer. Involved in discussions of survey calibration.

Dr. J. Allyn Smith – Dr. Smith is a faculty member in the Physics, Engineering & Astronomy Department at Austin Peay State University, Clarksville, TN. He served as the faculty lead for this project and mentor for the students. Dr. Smith is an external collaborator for calibration and white dwarf studies in the DES. Dr. Smith worked on reductions of white dwarf data obtained at the Cerro Tololo Inter-American Observatory which may be used as calibration sources for the DES. Involved in discussions of survey calibration. Participated in the LSST-DP0.2 data challenge.

Mr. Sean M. Peete – Mr. Peete is a rising junior majoring in Physics at Austin Peay State University. His role in the project was image reduction and data analysis; working to produce magnitudes for the white dwarf calibration targets. Participated in the LSST-DP0.2 data challenge.

Ms. Meagan N. Porter – Ms. Head is a rising junior Physics major at Austin Peay State University. Her role in the project was software development and testing for the transformation issues between the SDSS and DES filter systems. Participated in the LSST-DP0.2 data challenge.

Scientific Facilities:

This project made use of imaging data collected at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. The software portion of the project used data from CTIO (DECam data, SDSS standard star data) and the US Naval Observatory (USNO) in Arizona for test purposes. Application of the developed software is in support of data calibration of images collected by the DES at CTIO.

Notable Outcomes:

Internal Presentations:

1. Report to the Dark Energy Science Group meeting, Wed. July 19, 2023 on the white dwarf calibration effort including the issues with absolute photometric calibration.
2. Weekly meetings of the DES VFP group to review progress and plan the following week work.

Contributed Conference Presentations:

Planned for the Jan. 2024 American Astronomical Society (AAS) meeting, New Orleans, LA.

1. M. Porter on her work over this summer. Author list is TBD, will include Smith, Tucker plus others.
2. S. Peete on his work over this summer. Author list is TBD, will include Smith, Tucker and others.
3. D.L. Tucker and J.A. Smith on the final steps of the use of White Dwarfs in DES calibration.
4. J.A. Smith and D.L. Tucker on the use of white dwarfs as calibrators planned for the 24th European White Dwarf Workshop; summer 2024, Barcelona, Spain.

Peer-Reviewed Journal Articles:

The work from this summer will contribute to several articles, but neither of two student projects -by themselves- will warrant a separate publication. The results produced by both students will contribute to the final calibration paper for the DES photometric calibration effort. These results will also contribute to early calibration efforts with the Rubin-LSST. More analyses are required to ready these data for publication.

Student Results Overview

Mr. Peete reduced all of the unprocessed image frames obtained by the PI (Smith) and Dr. Tucker from the CTIO observing runs, produced finder chart for the standard stars, and extracted the magnitudes for each of the standard and target stars. He is completing the setups for the atmospheric correction and transformation to the standard system of the data. Most of these reductions used standard IRAF (Image Reduction and Analysis Facility) techniques and specialized python-based code written by. Dr. Tucker. These will be completed early this fall once we return to APSU.

Ms. Porter became familiar with use of Jupyter notebooks for running the existing transformation scripts with Dr. Tucker, including how to modify and add new code. She extended the existing transformation work to a detailed investigation of the SDSS to/from the DES magnitude systems using the observational results of the SDSS (Stripe-82) and DES (Y6A1-FGCM-V3-3-1). These two data sets allow a direct comparison of roughly 550,000 stars. This work will be expanded to additional filter systems once we return to APSU.

Research Vibrancy

The work performed under the VFP will result in continued collaboration with the DES and with the Rubin-LSST program: especially the personnel at Fermilab. This project could easily continue with another VFP in the summer of 2024 and evolve into additional LSST work as preliminary data should be available by then. Smith and Tucker will continue to collaborate on Rubin-LSST calibration issues and aspects of dark energy science.

This work will form the basis of a planned NOIRLab observing program for additional observations of some of the calibration stars with a goal for submission to NOIRLab in March 2024. Many of these stars will be used for calibration by the Large Synoptic Survey Telescope (LSST) when it begins operations in ~2024. A funding proposal to support this work is planned for NSF submission in November 2023.

Connection to Programs at Home Academic Institution

Many aspects of the project will continue at my home institution. Completion of the photometric reductions of the WDs from CTIO will occur early this fall along with additional observations collected at KPNO. Both Mr. Peete and Ms. Porter will present talks on their experiences to fellow students and faculty. The experience will allow better planning for student projects which will be conducted on our small campus telescope. These projects, and observing at national telescopes, are used to introduce our students to observational astronomy. The results of these projects are presented at our student research forum, held in April of each year and at two regional meetings – the Tennessee Academy of Science and the Kentucky Area Astronomical Society (the American Astronomical Society regional organization.

Figures

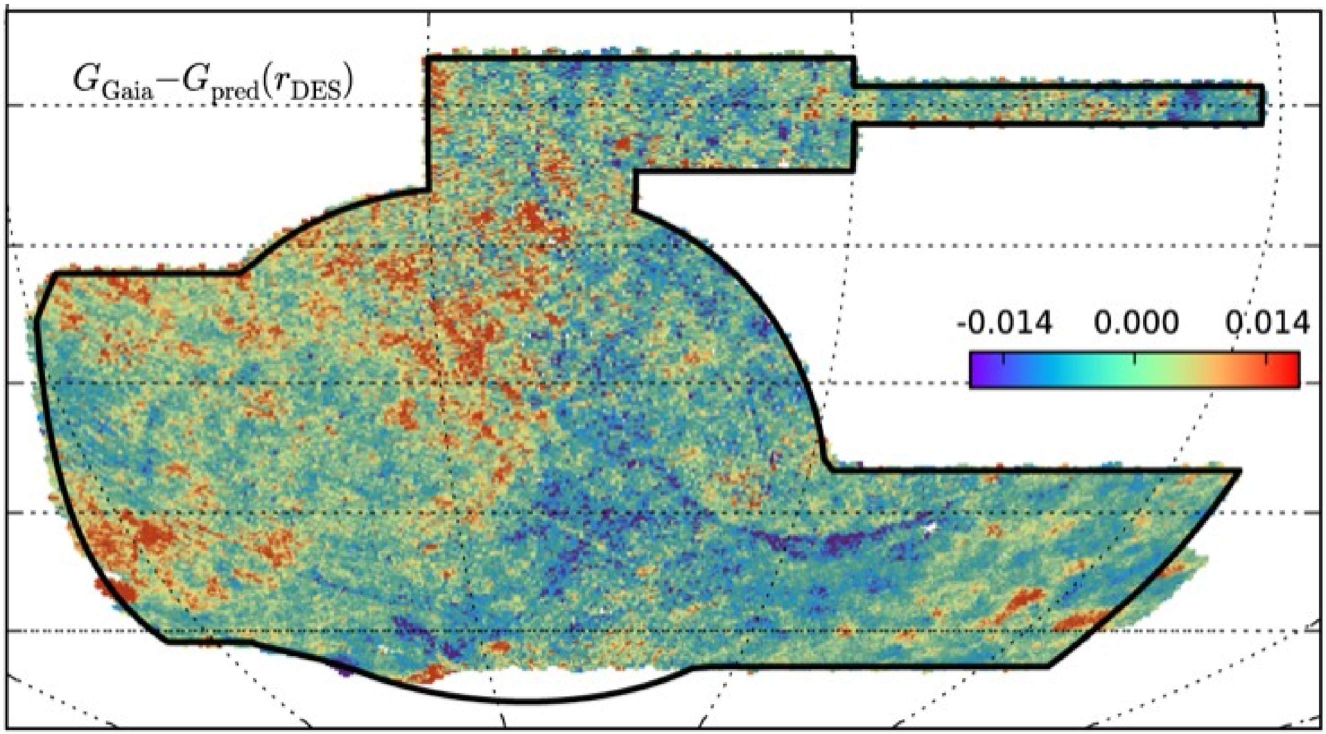
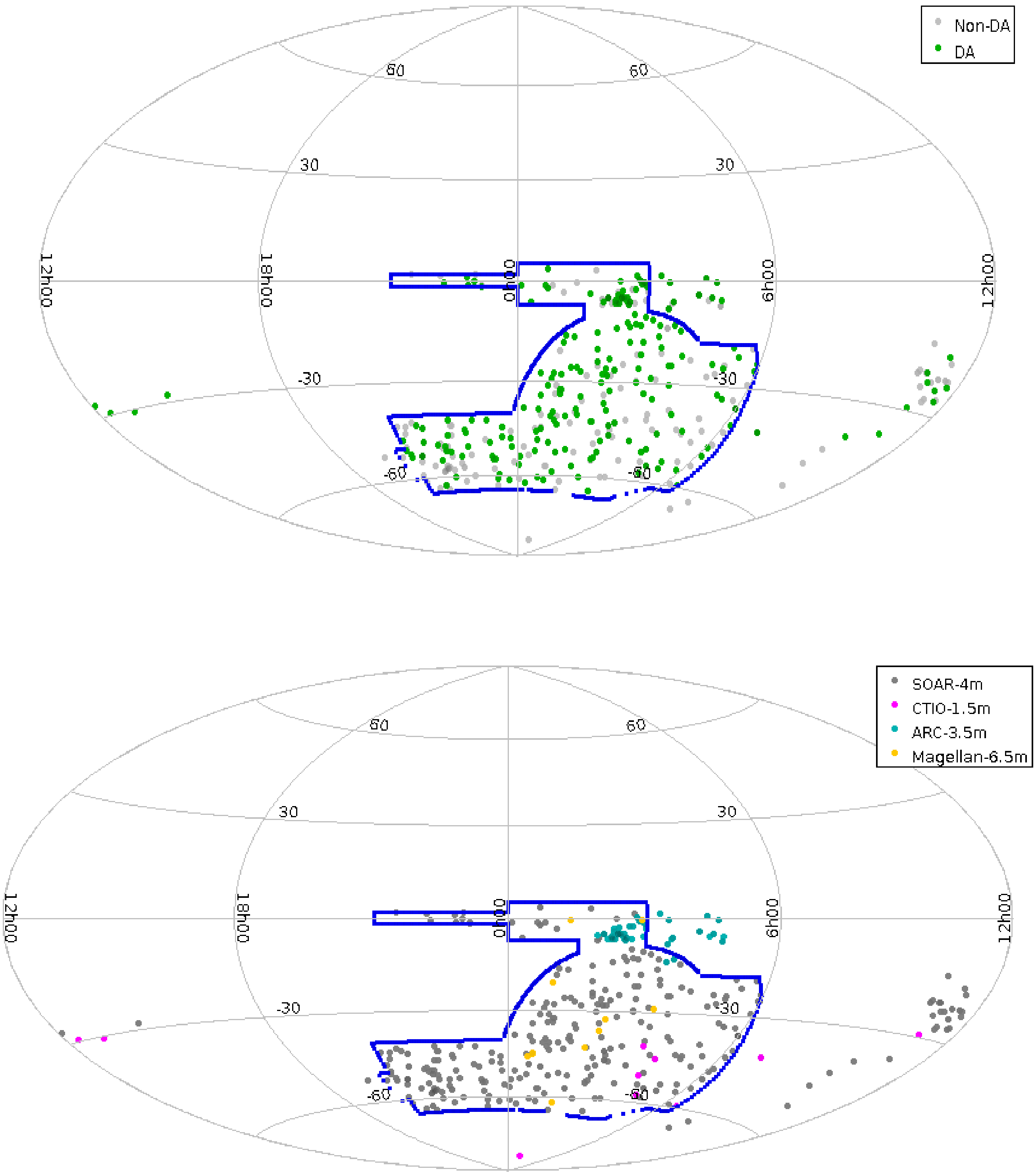


Figure 1. The DES footprint showing an early (year 3) photometric calibration effort and deviation from the expected values in the Gaia G-band based on comparing our observation results with the Gaia spacecraft observed values. This figure is from Burke et al. 2018 [21]. The latest survey results (in preparation for the Year 6 paper) have improved significantly from these deviations.



Figures 2. The locations of the observed and modeled DA white dwarfs for the DES calibration effort. The top figure shows the white dwarf locations in the DES footprint coded by DA (green) or non-DA (grey). The bottom plot shows where the spectra were collected. Some of the white dwarfs which lie outside of the DES footprint will be used to start the expanded LSST calibration effort.

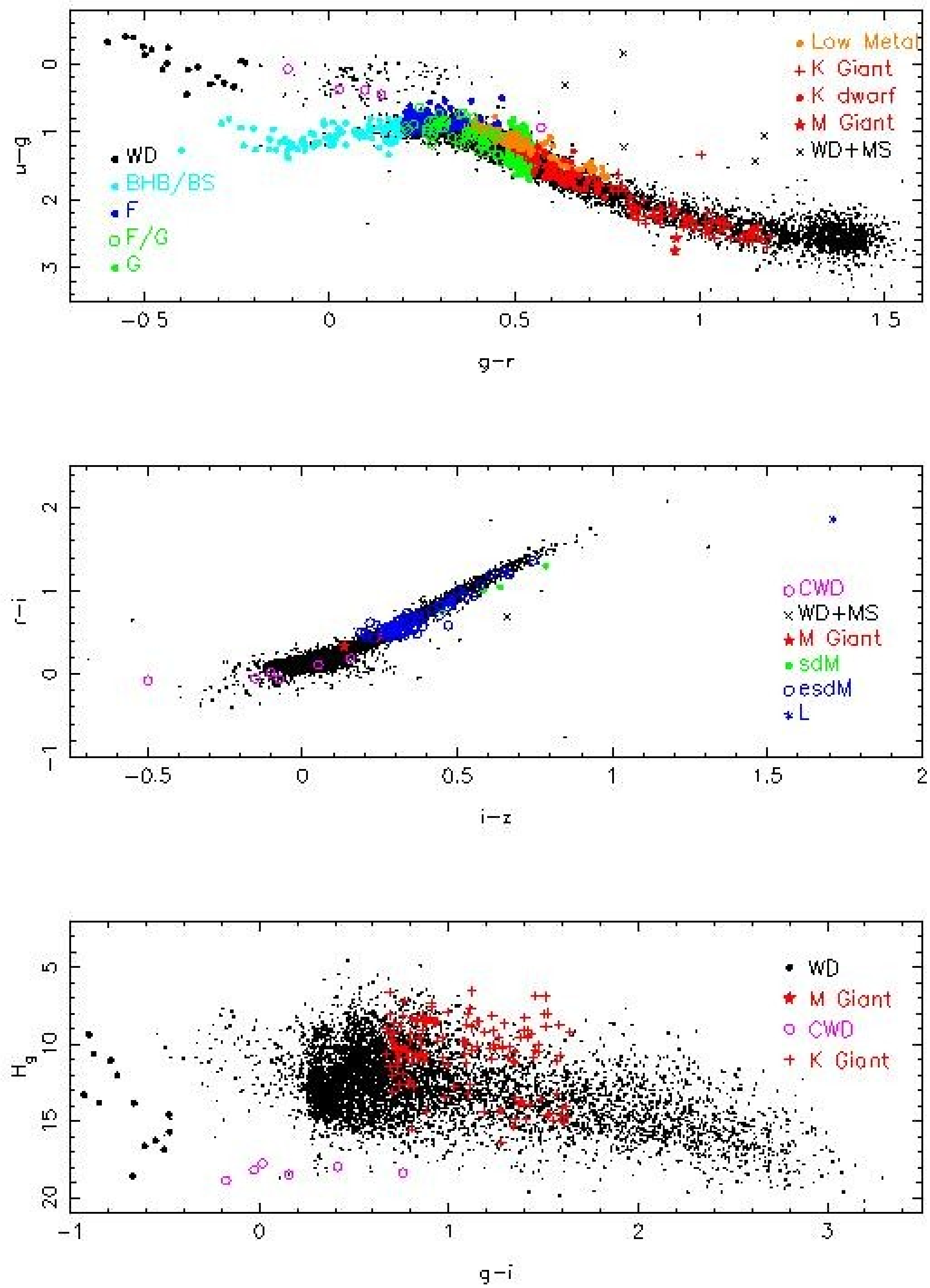


Figure 3. White dwarfs identified in SDSS data. Top: The (*u*-*g*)-vs.-(*g*-*r*) color-color plot. The hot WDs suitable for calibration sources (WD) cleanly separate from the main sequence stars. Middle: The red filter color-color plot. Though not shown the hotter WDs do not cleanly separate here, demonstrating the need for the *u*-band data. Bottom: A reduced proper-motion plot showing the clean separation of the hotter WD stars. Figure courtesy Brian Yanny.