aTmcam: A Simple Atmospheric Transmission Monitoring Camera For Sub 1% Photometric Precision

Ting Li*[a], D. L. DePoy[a], R. Kessler[b], D. L. Burke[c], J. L. Marshall[a], J. Wise[a],
J.-P. Rheault[a], D. W. Carona[a], S. Boada[a], T. Prochaska[a], R. Allen[a]
[a] Department of Physics and Astronomy, Texas A&M University, 4242 TAMU,
College Station, TX 77843, USA
[b] Department of Astronomy & Astrophysics, University of Chicago, 5640 S. Ellis Ave,
Chicago, IL 60637, USA
[c] SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

ABSTRACT

Traditional color and airmass corrections can typically achieve ~0.02 mag precision in photometric observing conditions. A major limiting factor is the variability in atmospheric throughput, which changes on timescales of less than a night. We present preliminary results for a system to monitor the throughput of the atmosphere, which should enable photometric precision when coupled to more traditional techniques of less than 1% in photometric conditions. The system, aTmCam, consists of a set of imagers each with a narrow-band filter that monitors the brightness of suitable standard stars. Each narrowband filter is selected to monitor a different wavelength region of the atmospheric transmission, including regions dominated by the precipitable water, aerosol optical depth, etc. We have built a prototype system to test the notion that an atmospheric model derived from a few color indices measurements can be an accurate representation of the true atmospheric transmission. We have measured the atmospheric transmission with both narrowband photometric measurements and spectroscopic measurements; we show that the narrowband imaging approach can predict the changes in the throughput of the atmosphere to better than ~10% across a broad wavelength range, so as to achieve photometric precision less than 0.01 mag.

Keywords: photometric precision, atmosphere, transmission, extinction, Dark Energy Survey (DES), dark energy, CTIO, precipitable water

1. INTRODUCTION

The discovery of the accelerating universe ranks as one of the most important discoveries in Cosmology in the past decades. This mystery energy, Dark Energy, appears to be the dominant component of the physical Universe (more than 70% of the universe); there is yet no persuasive theoretical explanation for its existence or magnitude.[1] The Dark Energy Survey (DES)** is aimed at improving our understanding of this mystery using multi-band imaging over ~5,000 square degrees. The DES has a goal of reaching 0.01mag photometric precision in DES-grizY band to achieve the science goals of the survey. Recent studies have shown that precision determination of various dark energy parameters can be improved with better photometric precision. The systematic uncertainty of the measurements of the dark energy equation of state parameter, *w*, from the first three years of the Supernova Legacy Survey (SNLS3) is dominated by the photometric precision of the survey.[2] In addition to Cosmology, other forefront science issues also demand better performance on photometry. For example, reconstructing the structure of the Galaxy using the photometric properties of different stellar populations, is a key scientific program for the next generation of imaging surveys.[3] In many cases, the precision of results connect closely with the photometric precision of the survey.

---

* Email: sazabi@tamu.edu

** Dark Energy Survey will rely on DECam, an extremely red sensitive 520 Megapixel camera with 2.2 degree field of view. DECam will be installed at the prime focus of the Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory (CTIO), a southern hemisphere NOAO telescope. More details at http://www.darkenergysurvey.org/

Ground-based and Airborne Instrumentation for Astronomy IV, edited by Ian S. McLean, Suzanne K. Ramsay,
Hideki Takami, Proc. of SPIE Vol. 8446, 84462L · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.924792

It is difficult to achieve ground-based photometry measurements with precision below 1% for large surveys over kilo-degree^2 area. The Sloan Digital Sky Survey (SDSS), for example, achieved relative photometric calibration reproducible to 1-2% (rms) over the entire survey field. Unmodeled atmospheric variations are responsible for almost all the calibration error budget for SDSS. [3] Variations in the wavelength dependence of atmospheric transmissivity can induce systematic errors that depend on source colors. Ivezić et al. [4] found that, assuming a standard atmosphere, using synthetic photometry for stars from the Gunn-Stryker atlas, this effect can induce offsets of up to ~0.01 mag for the u- g and g - r colors when air mass is varied by 0.3 from its fiducial value of 1.3. Moreover, potentially larger errors could be induced even at a constant air mass if the wavelength dependence of atmospheric transmissivity is significantly different from the assumed standard atmosphere; this will be discussed substantial in the next section.

We conclude that unmonitored changes in the atmospheric throughput ultimately limit survey photometric precision to ~0.01-0.02 mag. Therefore, we plan to build an Atmospheric Transmission Monitor Camera, called aTmCam, to monitor the atmospheric transmission in real-time for the DES project and also potentially for other future surveys at CTIO.

This paper is organized as follows: In section 2, we will discuss how the atmospheric variation will induce the errors and then determine the requirements for the atmospheric throughput measurement. We used the program libRadTran* to simulate the expected variations in the atmospheric transmission above CTIO to gauge the monitoring system requirements. In section 3, we will talk about the method to measure the atmosphere throughput, the specifications of the system and the procedures of operation. Section 4 will describe the prototype system and the preliminary results. In section 5, we will show the plan for the next test we will do at CTIO this coming fall. Finally, we conclude in section 6.

2. REQUIREMENTS

Atmospheric transmission in the DES wavelength range (~300nm-1100nm) is mainly determined by 3 radiative processes in the atmosphere: [5] Rayleigh scattering from the molecules, which is simply dependent on the barometric pressure; Aerosol and dust scattering from small particles and; Molecular absorption, in particular by O_2, O_3, and H_2O. The O_2 lines are saturated and the so-called "rate of growth" is closely proportional to the square root of the barometric pressure. So it can be computed and scaled with the Rayleigh scattering appropriately.

We investigated the impact of atmospheric variations on the DES calibration with the variations in the four main components: water vapor, ozone, molecular scattering, and aerosols. Figure 1 shows the transmissivity of each component from a fiducial atmosphere over CTIO and the various DES bands. The DES-grizY bands conform to the anticipated performance of DECam on the Blanco telescope. DES has not yet decided to add a DES-u filter, so SDSS-u' filter is shown as a potential ultraviolet filter.(For remainder of the paper these bandpass will be referred to as ugrizY, although they are slightly different from other photometric system.)

Our simulation calculated the synthetic ugrizY photometry for an object-SED using a model of atmosphere transmission corresponding to a photometric night. The same object is then simulated using an atmosphere transmission in which one of the components has changed significantly. We added more water vapor so that the atmospheric transmission caused by water absorption was 20% deeper around 940nm (See the top left panel of Figure 2). We then calculated the errors induced by this change on the photometric precision of Type Ia Supernovae at various redshifts (bottom left panel of Figure 2). Note that this result assumes an initial successful calibration based on the use of standard stars to determine photometric zeropoints and the nightly color and airmass corrections. The systematic error in z-band photometry is approximately ±0.01 mag, which is the entire DES photometric precision goal. The primary reason is the variation in expected H_2O absorption around 940nm. There are significant effects on i and Y band as well. If we could monitor the water absorption better than ~10% (that is, measure the depth of the water absorption around 940nm with an accuracy of ~10%), we then could achieve photometric precision less than 0.005 mag.

---

* libRadTran is freely available at http://www.libradtran.org/doku.php

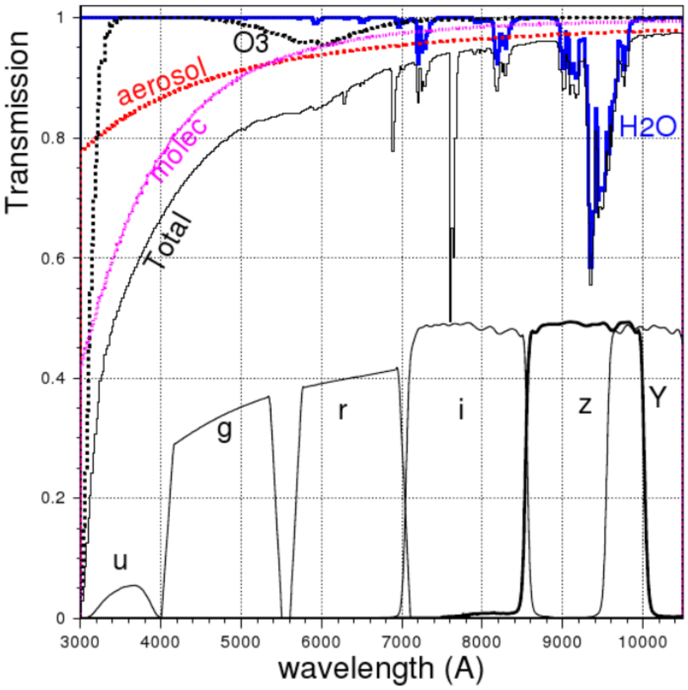


Figure 1. Typical normalized atmospheric throughput above CTIO showing the major sources of attenuation by the atmosphere, generated by Modtran. The normalized pre-construction estimates of the DES filters are also shown except that u-band is actually a SDSS-u' filter since DES-u is not yet defined.

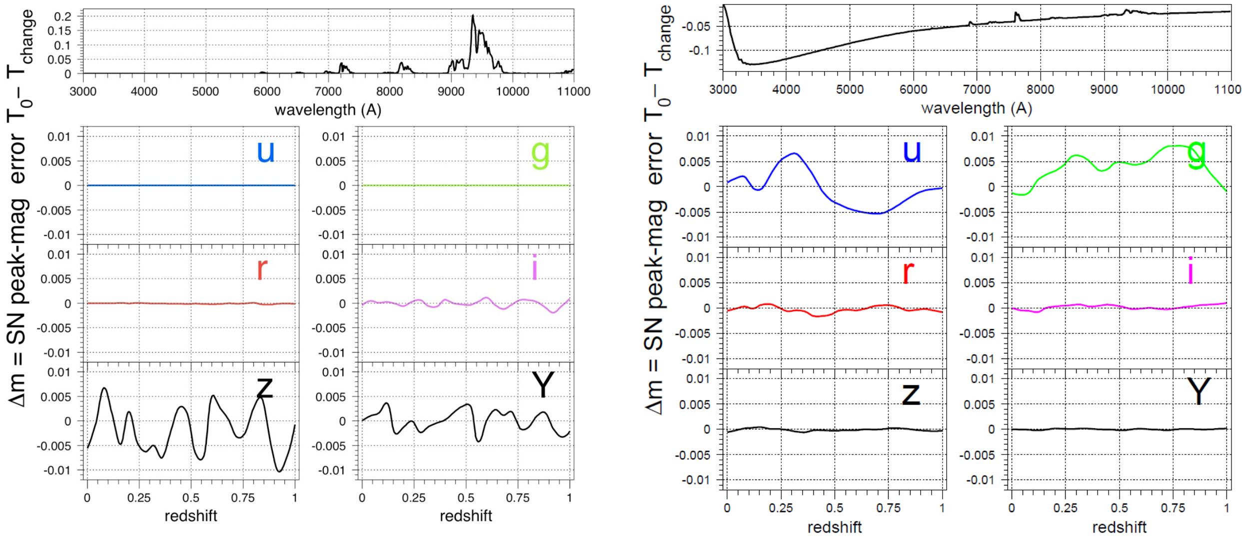


Figure 2. Top left panel: The fractional difference between the original atmospheric transmission and one with additional water vapor. Bottom left panel: Systematic error in SN photometry introduced by this change in the water absorption. Top right panel: The fractional difference between the original atmospheric transmission and one with lower optical depth of the aerosols. Bottom right panel: Systematic error in SN photometry introduced by this change in the aerosol. Note that all the errors are residuals after standard calibration techniques are applied.

The H_2O water absorption at CTIO varies significantly over the expected range of conditions. In particular, the amount of water varies from ~0mm to 9mm (units are an effective amount of water above the site; 1mm is equal to a column density of $1kg/m^2$) and the average is around 3mm over the year. We note that Hansen & Caimanque[6] see factors of 2-4 changes in the precipitable water on timescales of ~days during their 3-year study. Figure 3 demonstrates that the absorption due to the water vapor varies considerably, especially around 940nm.

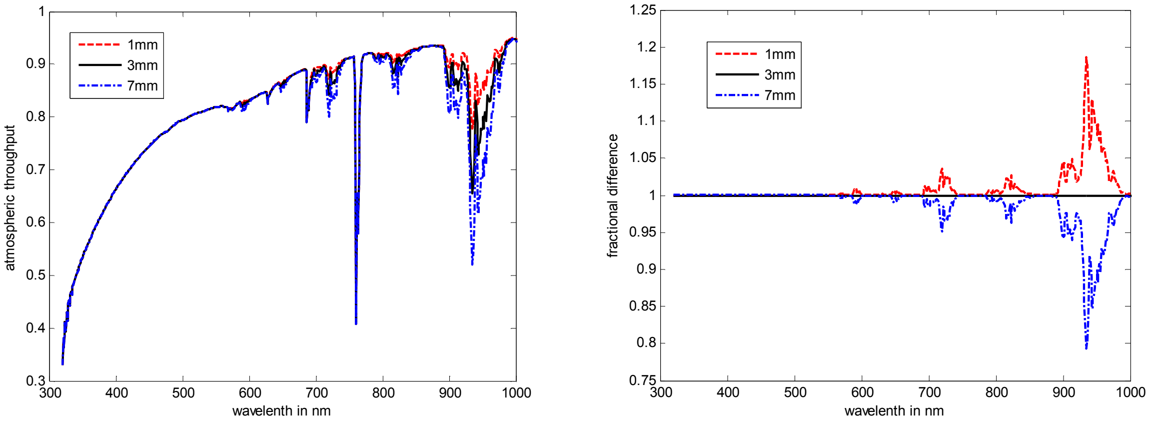


Figure 3. Left panel: atmosphere transmittance for water amount = 1, 3, 7mm. normalized to an average, generate with libRadTran. Right panel : take water = 3mm as the standard, plot the difference of changed atmosphere and the standard atmosphere. (water = 1/3, 3/3 and 7/3). Note the large change in the atmospheric throughput around 940nm, which strongly affects the DES-z band.

Similar errors are introduced into u- and g- band photometry by a significant variation in aerosol scattering in the simulation. For example, if we decrease the optical depth of the aerosols in the atmosphere so as to cause a ~15% change in the atmospheric transmission around 350nm (top right panel of Figure 2), photometric precision errors will be approximately ±0.005 mag in u-band and +0.008/-0.002 mag in g-band. Again, these are large fraction of the DES photometric precision goal. If we could monitor the aerosol scattering better than ~10% (that is, measure the depth of the aerosol scattering around 350nm with an accuracy of ~10%), we then could achieve photometric precision less than 0.005 mag.

O_3 can cause small changes in the atmospheric throughput, particularly around 600nm and below ~330nm. However, over the expected variation in the amount of atmospheric ozone the difference is small and will be well determined by standard calibration techniques. Unless DES conspires to create a “DES-u” filter that includes significant transmission below ~340nm, the ultraviolet absorption of ozone should have an insignificant impact on photometric precision. We will still try to monitor the variation in ozone but we won’t have a specific requirement until the DES decide to add a “DES-u” filter.

There is also significant variation in the Rayleigh scattering component of the atmospheric throughput over the expected range of pressures at CTIO. However, the strength and profile of this component is predicted by the local pressure, which is easily monitored.

To summarize, a system to monitor the atmospheric throughput above CTIO will need to measure the changes in the throughput of the atmosphere to better than ~10% across a broad wavelength range (mainly the changes from the water vapor and the aerosol optical depth), to achieve photometric precision less than 0.005 mag. Other quantities that will have to be monitored include atmospheric pressure (which will allow determination of the Rayleigh scattering component) and zenith angle (airmass) of target (which straightforwardly scales the observed optical depth).

3. SYSTEM DESIGN

We have turned the requirements given in the previous section into a system design, which we describe in this section.

3.1 Philosophy

The spectrum of the object observed on Earth is the spectral energy distribution (SED) of the object convolved with both the atmospheric throughput and instrument response function. We therefore can derive the atmospheric transmission with suitable observations of calibration stars using well-calibrated instrumentation. The calibration stars are expected to have the SED known already, such as spectrophotometric standards, White Dwarfs, or well-modeled main sequence stars.

Spectroscopic observations of relatively bright standard stars at ~5 minute cadence, over a range of airmasses, and at wavelengths of 400-1000nm can produce high quality atmospheric absorption profiles.[7] While this approach is ideal, it has a major drawback in requiring a high level of personnel commitment to aligning a relatively small aperture (~10 arcsec) on the target stars, a relatively large telescope, and a stable spectrograph.

We advocate a simpler system, the Atmospheric Transmission Monitor Camera (aTmCam), based on a set of imagers with different narrow-band filters that monitor the brightness of suitable calibration stars. The imagers will have a field-of-view and aperture large enough to enable automatic pointing and tracking of a catalog of stars (i.e. robotic operation). Each narrowband filter will be selected to monitor a different aspect of the atmospheric transmission, i.e. water vapor, aerosol and molecular scattering, etc, as described above. We show that this aTmCam system, which based on images through several narrow-band filters, will be sufficient to constrain a model that will be precise to better than 10% across the DES filter range. We assume that our goal will be to determine the relative transmission across the DES wavelength range; observations with DECam itself will be used to determine exposure-by-exposure grey terms, for example, and standard calibration procedures for multi-color extinction terms and color-corrections will be in place. Below we describe such a system, show the results of modeling to predict performance, and present preliminary results from a prototype system.

3.2 Filter Selection

We initially selected five filters that span 390nm to 940nm as a prototype monitoring system, since there are mainly four components in the atmosphere that vary. These filters were not optimized to match the atmospheric transmission features, but were simply close to what seemed like good choices to monitor the water, aerosol, Rayleigh scattering, and ozone components of the atmosphere. They were also available from Edmund Optics[*] and Astrodon[**] at relatively low cost. These filters had central wavelengths and bandpasses as shown in Table 1. Figure 4 also shows the central wavelengths of the filters on a fiducial atmospheric throughput model. We used these five filters for our prototype system described in the next section.

Table 1. Central wavelengths and bandpasses of the prototype filters

Filter central wavelength	*Filter FWHM*	*Parts # (from Edmund if not specified)*
390 nm	~50 nm	u'2-50R (from Astrodon; equivalent to SDSS-u')
520 nm	10 nm	NT65-215
610 nm	10 nm	NT65-225
852 nm	10 nm	NT65-242
940 nm	10 nm	NT65-246

---

[*] http://www.edmundoptics.com/

[**] http://www.astrodon.com/

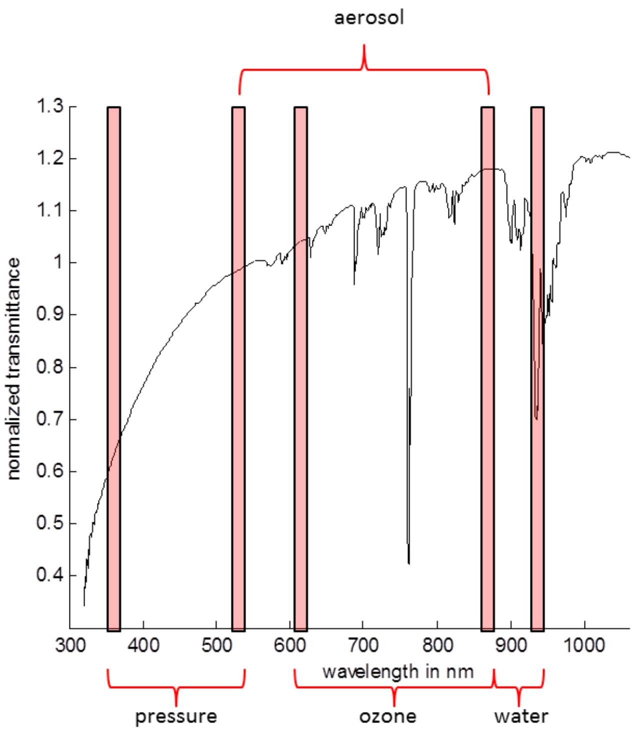


Figure 4. Wavelengths of prototype filters relative to a representative atmospheric throughput model.

From the five filters we can define four ratios or color indices: flux in one filter divided by that in another; each of them is chosen to be most sensitive to one atmospheric component (see Figure 4). We again take water absorption as an example. The ratio from the flux in the 940nm filter relative to that in the 852nm filter is sensitive to the water absorption. Figure 5 shows the results of modeling the expected brightness ratios over the range of conditions experienced at CTIO. The ratio changes by ~30% (depends on the airmass of the measurement) over the expected range of anticipated water vapor amount at CTIO. To determine the water absorption to 10% accuracy, therefore, the imaging system must be capable of providing signal-to-noise ratio (S/N) of ~50 through the 852nm and 940nm filters.

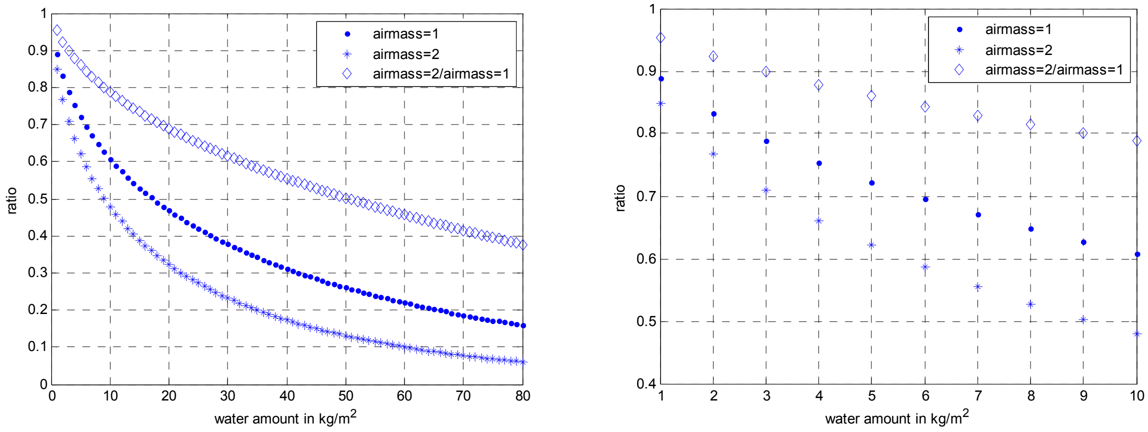


Figure 5. Left panel: plot of ratio (defined in the text) as a function of water vapor; other conditions held constant. Right panel: zoom of left panel. Assuming the water vapor amount at CTIO varies from 1mm to 10mm, the ratio (defined in the text) changed from 0.88 to 0.61 at airmass=1, which corresponds to a ~30% change compared to the average.

Similarly, the ratio of the brightness in the 390nm filter relative to that in the 852nm filter changes by ~15% with optical depth from 0.01 to 0.20, which implies that to determine the aerosol optical depth to 10% requires S/N of ~100 in those two bands.

Determination of the ozone is difficult. The range of ratio is only ~2.5%, so determination of the ozone component will be challenging and require S/N greater than 100. Fortunately, we do not believe that ozone monitoring will be required, since such a small change impacts photometric precision minimally.

In principle we could also monitor a ratio to determine the Rayleigh scattering. The range of expected values is ~7.5%, so S/N of ~100 per filter would give a ~20% accurate measurement of the strength of the Rayleigh scattering component. However, we believe that atmospheric pressure monitoring, which is already available at CTIO, should be sufficient to constrain the Rayleigh scattering component adequately well.

Thus, we feel that a system based on three narrow bandpass filters (i.e. filters with central wavelength 520nm, 854nm and 940nm) should be adequate to provide information to select a reasonable atmospheric throughput model. Five monitoring filters would, in principle, allow additional information to be measured about the atmosphere throughput., but would complicate operations and increase system cost. Observation with three filters should be sufficient to determine the water absorption and aerosol optical depth with enough accuracy to use to correct photometric precision to better than ~0.005 mag precision.

3.3 Imaging System Configuration

The S/N requirements help determine the characteristics of the individual imaging systems. These are coupled to a reasonable catalog of bright stars with sufficient UV to NIR brightness and known spectral energy distributions that have adequate distribution around the sky.

There are more than ~3 stars per degree^2 brighter than ~9th mag in R-band [8] (surface density of stars at the galactic pole) in the sky. Roughly 75% of these stars are late-type giants; of the remaining main sequence stars about 75% are unsuitable as atmospheric monitoring stars (most G- or K- dwarfs), because their inadequate flux in UV and blue. Thus there are ~0.2 suitable stars (B-, A-, or F-type main sequence stars) per degree^2 or more than ~1 star in each ~5 degree^2 over the entire sky.

We design our aTmCam for 5-minute temporal sampling. If we allocate ~3 minutes for re-positioning of the telescope (easily achieved with modern small telescope mounts), that suggests exposure times for the individual measurements of not more than ~2 minutes. The pointing and tracking of the system should be good enough to not require manual input or autoguiding. A likely field-of-view is ~5 arcminutes, so pointing accurate to ~1 arcminute should be adequate. Tracking accurate to ~1 arcsec in ~1 minute should also be adequate to not seriously compromise image quality. The throughput should, obviously, be as high as possible. We adopt a conservative estimate of ~10% for each filter, telescope, CCD, and atmosphere. The required S/N is ~100 on R=9 mag stars, which suggests the diameter of the telescope must be larger than ~0.12 m.

We wish to sample the expected point-spread-function well to allow for accurate photometry of the catalog stars. This suggests a pixel scale of ~0.5 arcsec/pixel (the diffraction limit is ~0.6 arcsec and seeing should be ~0.75 arcsec, which should produce images generally ~1 arcsec). For 5.4 μm pixels (typical of the Kodak CCDs commonly found in commercial systems) this implies a focal length of ~2220 mm.

Together these considerations define the characteristics of the individual imaging systems.

3.4 Operation

After we take the observation of calibration stars with aTmCam, as described before, we will pick up the best fit atmospheric model constrained by the measured color indices from a database with a discrete set of models.

A more detailed description for identifying a suitable atmospheric throughput model is shown as follows:

1) First, we produce a database, generated by an atmospheric throughput program (such as libRadTran), containing the possible atmosphere throughput models for CTIO varying all parameters in reasonable steps. The parameters

include the precipitable water, aerosol optical depth, barometric pressure and ozone (optional). The range and the grid space will be determined by the further test at CTIO in the future. From each atmospheric transmission model, the synthetic color indices will be calculated.

2) Second, we calibrate the instrument system (including filters, optics, and detectors) for each of the several narrowband imagers. DECal[9], the Spectrophotometric calibration system for DECam, is good example of the calibration system that could produce suitable calibration measurements. This step needs to be repeated periodically to determine if there have been changes to the system throughput. It is not clear how often this step will have to be performed
3) aTmCam will measure a selected star simultaneously through the narrow bandpass filters. We then determine the color indices of the atmospheric transmission from the observed images after removing the instrument throughput and the SED of the selected star. (Below we will use Vega (A0V) as our standard star since the absolute flux of Vega is reasonably well measured. However, we can observe any star if we know the spectrum well and it has adequate flux from UV to NIR.) Then we sort through the database and find the atmospheric transmission model that matches the color indices of the measurement. We currently plan to execute the measurements every ~5-10 minutes all night at a range of positions on the sky. This will allow determination of the atmospheric throughput on a relatively fast timescale, as mentioned previously. A set of stars should be selected that allow reasonable sky coverage, so that the spatial variations in the throughput can be estimated throughout the night.

4. PROTOTYPE SYSTEM

4.1 Setup and Performance

We have deployed a prototype system to test the notion that an atmospheric model derived from a few color indices measurements of stars with known spectral energy distributions can be an accurate representation of the true atmospheric transmission. The system mimics the characteristics of the complete setup mentioned above, but on a smaller scale. The prototype was used to measure only bright stars (principally Vega and Sirius) and uses a smaller aperture (effectively only 40mm) and the filters described in Table 1.

We coupled the measurements of the stellar narrowband photometry with simultaneous observations of the spectrum of the same star; we get the atmospheric throughput from these two independent measurements; the two were found to agree to ~10%.

Figure 6. Setup of the aTmCam prototype.

Figure 6 shows the prototype setup. There are two 8-inch telescopes: one with a fiber at the focal plane that feeds an Ocean Optics JAZ spectrograph*, another with an SBIG ST-402ME CCD** at the focal plane. The imaging telescope has a cap on the front that holds five filters (given in Table 1), each coupled to a "wedge prism" that diverts a ~40mm part of the pupil ~2 arcminutes. This creates five individual images on the CCD of the same star. The two telescopes are co-mounted on a tripod and are aligned to look at the same star, so we simultaneously obtain a spectrum and five narrow-band images of a star.

Unfortunately, we found that the filters had a significant amount of optical power (i.e. they were not flat). That, coupled with chromatic focus changes from the telescope corrector optics, caused focus shifts between the images, which is shown in Figure 7. The relatively poor image quality had a significant impact on the photometric results (particularly the accuracy of the UV measurement). Nonetheless, we were able to generally confirm the performance of the system (on bright stars) and better define the requirements on the final imaging system configurations. In particular, we learned that individual detector systems should be coupled to individual filters, so as to enable better image quality control and stable performance.

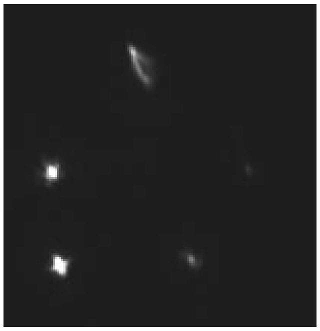


Figure 7. An image of Sirius taken by the system A in Jan 11th, 20101(multi-filter cap + 8-inch telescope + SBIG CCD). The point spread function of the image is not azimuthally symmetric because the filters are not perfect image quality filters.

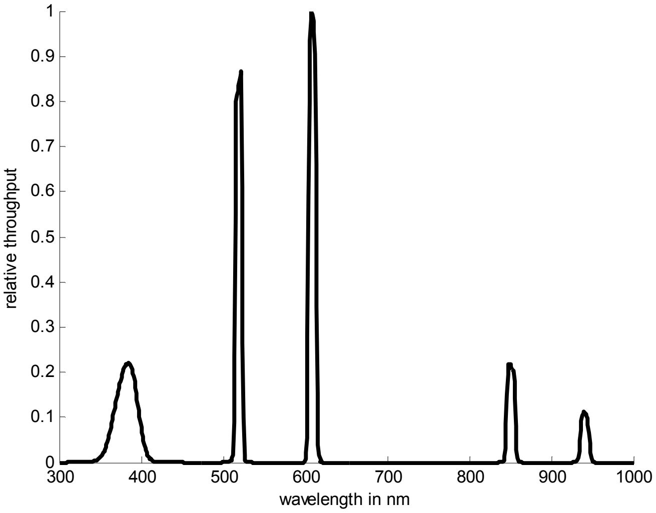


Figure 8. Relative throughput of the imaging system (cap + telescope + SBIG CCD).

---

* http://www.oceanoptics.com/Products/jaz_el350_200.asp

** http://www.sbig.com/ST-402ME-C1.html

The throughput of the system was measured through each filter with a prototype DECal-like system. The results are shown in Figure 8. The throughput in the ultraviolet and far-red was not outstanding, although it is as good as the assumed throughput in the previous section. This is largely due to the response of the CCD, although the filters themselves also have relatively poor transmission.

We also calibrated the JAZ spectrometer; the results are shown in Figure 9. The throughput was found to be relatively low in the far-red, particularly beyond ~800nm. This compromised the S/N of water absorption features.

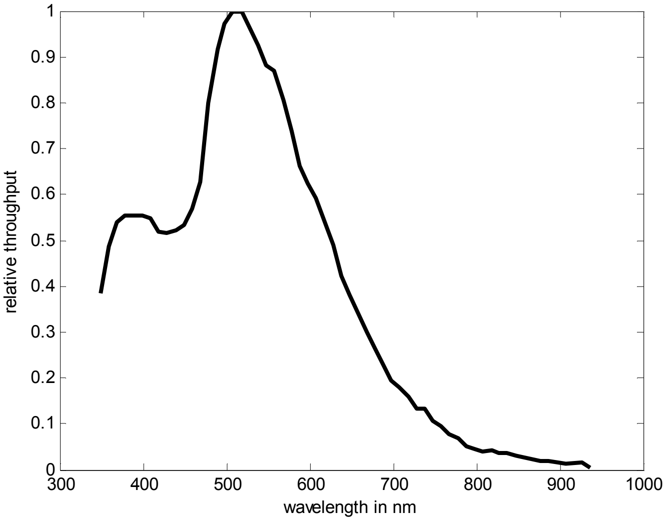


Figure 9. Relative throughput of Jaz Spectrometer and telescope. The throughput is low in red (> 800nm).

4.2 Results

We have made multiple photometric and spectroscopic measurements simultaneously with the prototype system described above at both Texas A&M observatory* and McDonald** observatory and we take one measurement each as an example hereafter. We used Vega (A0V) as our standard star since the absolute flux of Vega is reasonably well determined. However, we can observe any star if we know the spectrum and it has adequate UV and NIR flux.

We obtained a set of test observations on July 12, 2011 at Texas A&M observatory on Vega and one of the raw spectrum from the Jaz Spectrometer is shown in Figure 10. We used the SED of Vega from the spectrophotometric standards held in the STScI CALSPEC database***, to derive the atmospheric throughout from the observed spectrum from Jaz Spectrograph, after removal of the instrumental throughput and the Vega SED, shown as the blue dots in the left panel of Figure 11. Images from the narrow-band imaging system had relative poor S/N, particularly the 940nm filter because the high water vapor amount at Texas A&M observatory. This is, of course, consistent with the ridiculous humidity we often experience in eastern Texas. We, therefore, didn't use the color indices measured by the narrowband imager. Instead, we used the synthetic color indices from the atmospheric throughput measured by the spectrograph (i.e. blue dots in the left panel of Figure 11), but we changed the 940nm bandpass to 910nm for convenience and higher S/N. Then we found the atmospheric model from the database matched best with the derived color indices (minimized χ^2). The best fit model has precipitable water = 60mm, aerosol optical depth ~0.15, plotted with black line in left panel of Figure 11. The selected model has residuals compared to the actual measured atmospheric throughput of less than ~10% at all wavelengths (right panel of Figure 11). Most of the errors, we believe, are due to the low S/N at the far-red end of the spectrum.

---

[*] Department of Physics & Astronomy Teaching Observatory, Texas A&M University , College Station, TX. http://observatory.tamu.edu/

[**] McDonald Observatory is located on Mount Locke in the Davis Mountains of West Texas. It is a property of the University of Texas at Austin. http://www.as.utexas.edu/mcdonald/

[***] available at http://www.stsci.edu/hst/observatory/cdbs/calspec.html

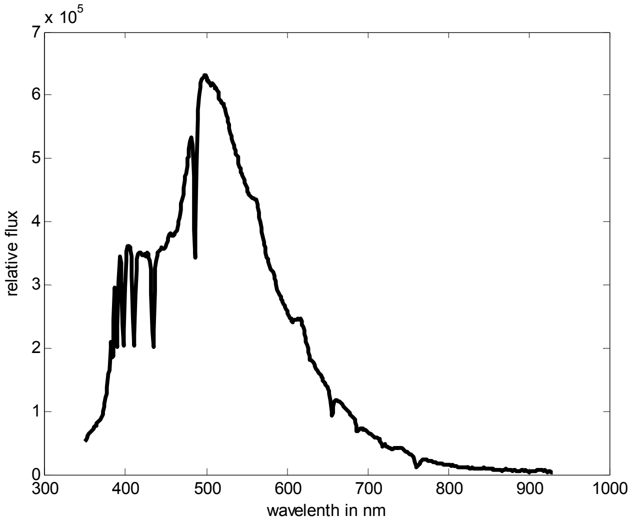


Figure 10. Raw Vega spectrum from the Jaz Spectrometer taken on July 12th, 2011 at TAMU observatory

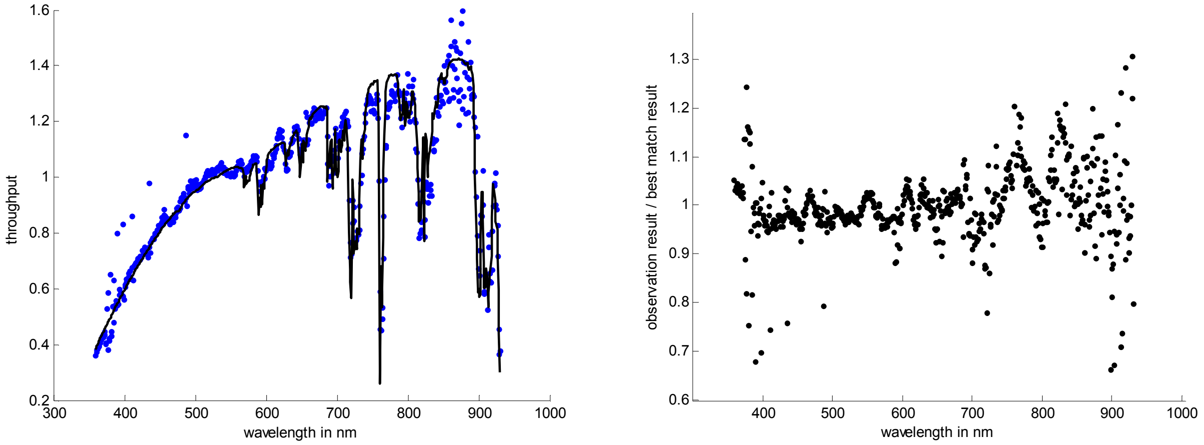


Figure 11. Left panel: the measured atmospheric throughout (blue dots) from the observed spectrum, after removal of the instrumental throughput and the Vega spectrum and best fit model (black lines) from the synthetic color indices of that measured atmospheric throughput. Right panel: ratio of measured atmospheric throughput and selected model from the synthetic color. The selected model has residuals compared to the actual measured atmospheric throughput of less than ~10% at all wavelengths

We obtained similar observations at McDonald observatory in Oct 18, 2011. McDonald is much drier compared to College Station, which makes these measurements much more comparable to CTIO, and we obtained reasonable signal through the 940nm filter. Therefore, we were able to derive the atmospheric models from both the spectroscopic measurements and the narrowband imaging. Figure 12 shows the best model from these two different measurements. The blue dashed line is the best fit model from the spectroscopic measurements, after comparison to all the atmospheric models in the database; the black line is selected by the measurements with the narrow-band imager, after comparison to all the synthetic color indices of each atmospheric model in the database. Two models from independent measurements shows good agreement with residuals less than 5%. The main errors, we think, are from the coarse grid spacing in our modeling database, which is 2mm for water and 0.05 for aerosol optical depth. We therefore believe that the atmospheric model derived from color measurements can be an accurate representation of the true atmospheric transmission with an adequate database and a better imaging quality system.

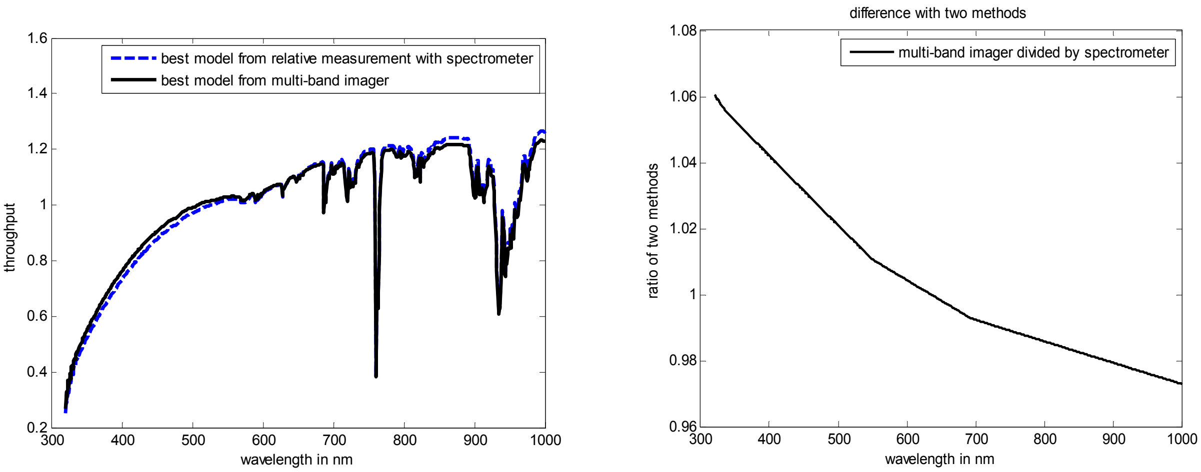
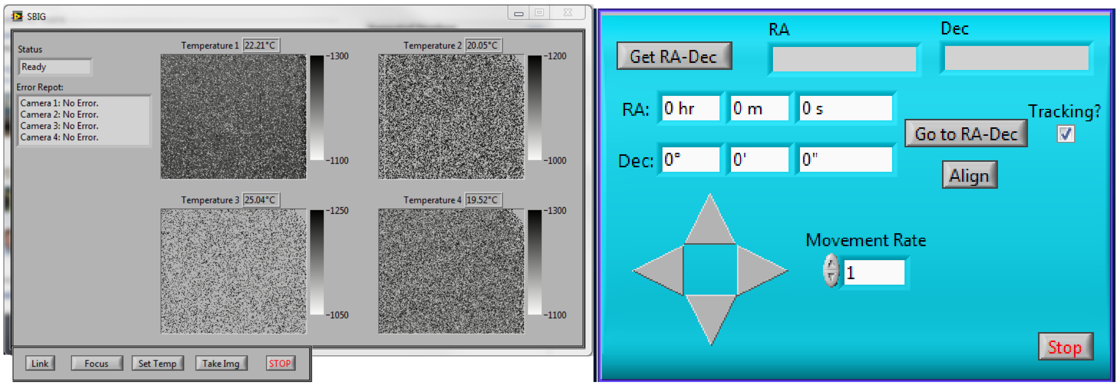


Figure 12. Left panel: best fit model from the spectroscopic measurements (dashed blue line) and that from narrow-band imaging(black line). Right panel: ratio of the two models.

5. PROGRESS AND FUTURE WORK

We plan to execute additional observations at CTIO in Sept-Oct 2012 with an updated prototype of aTmCam. The goal of this observing run is to finalize the observing strategy for aTmCam as it would be used as an auxiliary system for the Dark Energy Survey. Specifically, we will measure the temporal and angular variability scales of the atmospheric transmission at CTIO over many nights in a variety of conditions. For example, if the angular variability is low or sufficiently smooth, then an eventual system would not need to co-point with the telescope for Dark Energy Survey (i.e. 4-meter Blanco Telescope) but could instead cycle around the sky to a fixed list of bright stars; that would presumably allow a smaller aperture and would decouple the system from the survey telescope.

The test system would include up to 4 small telescopes mounted on 2 tripods. Right now, we are working on camera and mount control. The software, ISMAIL, Imaging Software for Munnerlyn Astronomical Instrumentation Lab, is under development in the Labview[*] environment. ISMAIL is able to take images simultaneously with 4 SBIG cameras. It also can control the Celestron Mount (or any other commercial mount) through interaction with TheSky[**] program. Screenshots of the camera control panel and the mount control panel are shown in Figure 13.



Status: Ready

Error Repot:
Camera 1: No Error.
Camera 2: No Error.
Camera 3: No Error.
Camera 4: No Error.

Temperature 1: 22.21°C
Temperature 2: 20.05°C
Temperature 3: 25.04°C
Temperature 4: 19.52°C

RA: 0 hr 0 m 0 s
Dec: 0° 0' 0"
Tracking? ☑
Movement Rate: 1

Figure 13. Screenshots of the camera control panel and the mount control panel from ISMAIL. Images could be taken with four cameras simultaneously.

---

[*] LabVIEW is a system design platform and development environment for a visual programming language from National Instruments. http://www.ni.com/labview/

[**] TheSky is an astronomy program designed to be used for various educational and observational purposes. The software is developed and distributed by Software Bisque. http://www.bisque.com/sc/

We plan to use the Hubble's Next Generation Spectral Library (NGSL) as the calibration stars for this test. This library contains 379 spectrophotometric standard stars and covers the wavelength range 0.2-1um with resolution R~1000. About 50 bright stars (V < 7) in this library would be available in the Southern hemisphere in fall and have adequate UV and NIR flux. We plan to use these stars along with A0V stars in the Bright Star Catalog to determine the spatio-temporal atmospheric variation at CTIO.

6. CONCLUSION

Understanding atmospheric variation is an important step toward 1% photometry. We proposed a relatively simple narrowband imaging system that should allow derivation of an atmospheric transmission model that could improve photometric precision to less than 1%. We have tested a prototype of the system and confirmed, using simultaneous spectroscopic measurements, that the principle works adequately well for Vega. We plan to have some more test observations at CTIO in Fall 2012.

ACKNOWLEDGEMENTS

Texas A&M University thanks Charles R. '62 and Judith G. Munnerlyn, George P. '40 and Cynthia Woods Mitchell, and their families for support of astronomical instrumentation activities in the Department of Physics and Astronomy. The author would also like to thank the support staff at Texas A&M Observatory and McDonald Observatory for their assistance.

REFERENCES

[1] Albrecht, A., et al., "Report of the Dark Energy Task Force", arXiv:astro-ph/0609591 (2006).
[2] Conley, A., et al., "Supernova Constraints and Systematic Uncertainties from the First Three Years of the Supernova Legacy Survey", ApJS, 192, 1 (2011)
[3] Padmanabhan, N., et al., "An Improved Photometric Calibration of the Sloan Digital Sky Survey Imaging Data", ApJ, 674, 1217(2008)
[4] Ivezić, Ž., et al., " Sloan Digital Sky Survey Standard Star Catalog for Stripe 82: The Dawn of Industrial 1% Optical Photometry", AJ, 134, 973 (2007)
[5] Stubbs, C. W., et al., "Toward More Precise Survey Photometry for PanSTARRS and LSST: Measuring Directly the Optical Transmission Spectrum of the Atmosphere", PASP, 119, 1163 (2007)
[6] Hansen, O. L., Caimanque, L., "Precipitable Water Above Cerro ToIolo Between 1971 and 1975", PASP, 87, 935(1975)
[7] Burke, D. L, et al, "Precision Determination of Atmospheric Extinction at Optical and Near-infrared Wavelengths", ApJ, 720, 811 (2010)
[8] Bahcall, J. N., "Star counts and galactic structure", ARAA, 24, 577(1986)
[9] Rheault, J.-P., et al. "Spectrophotometric calibration system for DECam", Proc. SPIE Vol., 7735, 201 (2010)