# Ground-based observatory operations optimized and enhanced by direct atmospheric measurements

John T. McGraw[*a], Peter C. Zimmer[a], Mark R. Ackermann[a], Dean C. Hines[a], Anthony B. Hull[a], Lisa Rossmann[a], Daniel C. Zirzow[a], Steven W. Brown[b], Gerald T. Fraser[b] Keith R. Lykke[b], Allan W. Smith[b], Christopher W. Stubbs[c], John T. Woodward[b],

[a]Dept. of Physics and Astronomy, Univ. of New Mexico, Albuquerque, NM 87131;

[b]National Institute of Standards and Technology, Physics Laboratory, Gaithersburg, MD 20899;

[c]Dept. of Physics, Harvard University, Cambridge, MA 01451

## ABSTRACT

Earth's atmosphere represents a turbulent, turbid refractive element for every ground-based telescope. We describe the significantly enhanced and optimized operation of observatories supported by the combination of a lidar and spectrophotometer that allows accurate, provable measurement of and correction for direction-, wavelength- and time-dependent astronomical extinction. The data provided by this instrument suite enables atmospheric extinction correction leading to "sub-1%" imaging photometric precision, and attaining the fundamental photon noise limit. In addition, this facility-class instrument suite provides quantitative atmospheric data over the dome of the sky that allows robust real-time decision-making about the photometric quality of a night, enabling more efficient queue-based, service, and observer-determined telescope utilization. With operational certainty, marginal photometric time can be redirected to other programs, allowing useful data to be acquired. Significantly enhanced utility and efficiency in the operation of telescopes result in improved benefit-to-cost for ground-based observatories.

We propose that this level of decision-making will make large-area imaging photometric surveys, such as Pan-STARRS and the future LSST both more effective in terms of photometry and in the use of telescopes generally. The atmospheric data will indicate when angular or temporal changes in atmospheric transmission could have significant effect across the rather wide fields-of-view of these telescopes.

We further propose that implementation of this type of instrument suite for direct measurement of Earth's atmosphere will enable observing programs complementary to those currently requiring space-based observations to achieve the required measurement precision, such as ground-based versions of the Kepler Survey or the Joint Dark Energy Mission.

**Keywords:** atmospheric transmission, astronomical extinction, standard stars, lidar, spectrophotometry, radiometry, stellar calibration, absolute calibration

## 1. INTRODUCTION

The goal of astronomers is to make single-source photometric, imaging photometric and spectrophotometric measurements with accuracy limited by provable, reproducible, fundamental photon shot noise. Accomplishing this goal, in general, requires identifying all other sources of random and systematic noise and suppressing them to well below the level of target photon noise. Elements of the error budget for this robust measurement process include the accuracy with which the throughputs of the telescope, instrument, and bandpass filter or disperser are known. It also includes the quantum efficiency of the detector and the various well-known sources of error in the camera or instrument, including

* jmcgraw@as.unm.edu; phone 1 505 277-2705; fax 1 505 277-1520

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readout noise, dark noise and digitization errors. Less well known and addressed, and the topic of this work, is the identification and suppression of systematic and random noise sources associated with radiative transport through Earth's atmosphere.

Astronomers have long recognized the necessity to correct for scattering and absorption in Earth's atmosphere and end-to-end transmission through telescopes onto skillfully used detectors. One of the staunchest pioneers of investigating, understanding and obviating astronomical measurement errors is Andrew Young, who, with his colleagues, addressed a host of effects traceable through references included in "Precise Automatic Differential Stellar Photometry[1]," where we first join the saga. Recently, Stubbs *et al.*[2] reviewed the physics of astronomical extinction and proposed techniques to measure and correct for it and suggested[3] a logical partition of the astronomical measurement precision problem into a) transmission through the atmosphere, and b) transmission through the telescope. Stubbs and colleagues have now demonstrated precise end-to-end, wavelength-by-wavelength calibration of the PanSTARRS telescope using a tunable laser illuminating a flat field screen with spectral irradiance monitored by a NIST calibrated photodiode[4]. Our assessment of the importance and impact of precise and accurate astronomical radiometry in the next decade was recently summarized[5].

We assert that while throughput and detector noise sources have been thoroughly addressed by the astronomical community to greater or lesser effect, discovering and addressing noise sources associated with Earth's atmosphere has been largely ignored, or handled in a primitive way not in keeping with the sophisticated techniques used for CCD detector characterization[6,7,8]. All of ground-based astronomy will benefit from real-time characterization of Earth's atmosphere leading to three major astronomical goals:

1. providing quantitative information for informing observatory operational decisions, including, for example, detection of aerosols and sub-visual cirrus,
2. providing a time-, direction-, and wavelength-resolved metadata stream for accurate corrections for astronomical extinction, and
3. Helping enable SI calibration of astronomical radiometry, with measurements expressed in irradiance units of watts/m$^2$ or spectral irradiance with (astronomical) units watts/m$^2$/nm

Achieving these goals will enhance the productivity and benefit-to-cost ratio of ground-based observatory operations. It will also allow ground-based observations better to contribute to research programs requiring measurements of known photometric accuracy, such as the supernova-based quest for the nature of dark energy[9,10], clues from possible matter fluctuations induced by structure in dark energy[11], and the dependence of Supernova Ia light curves on the luminosity of the host galaxies[12]. Photometric precision and accuracy also allow ground-based observational contributions to a multitude of other research programs, including planned follow-ups to the highly successful Kepler mission[13], for example.

While many systems exist for monitoring Earth's atmosphere, and observatory weather in particular - typically based upon classical weather stations augmented by optical or infrared sky cameras - our developments are driven by the astronomical perspective of making accurate through-the-atmosphere integrated astronomical extinction measurements observed in the direction a "science telescope" is obtaining photometric or spectrophotometric observations, over the field-of-view and the entire optical bandpass being observed, and time-resolved over the integration time of each observation. These accurate, directed observations allow, in turn, accurate atmospheric transmission corrections that obviate well-known systematic errors deriving from astronomical extinction, and allow an approach to the fundamental photon noise limit for astrophysical observations of sufficiently bright and/or well-observed objects. These measurement techniques can be used in other astronomically useful modes, such as mapping the dome of the sky, recording the rate of change of extinction, resolving non-gray aerosol scattering and absorbing layers, and making accurate transmission measurements through gray clouds, such as light cirrus[14].

To accomplish these astronomical goals we have designed and built:

1. The Astronomical Lidar for Extinction (ALE), a 527nm eye-safe lidar designed to measure atmospheric transmission to high accuracy by calibrating to Rayleigh scattering from the stable, well-measured and modeled stratosphere[14,15,16].
    - The purpose of ALE is to measure the atmospheric extinction at the laser wavelength(s) with high accuracy (S/N > 100) at one minute cadence or faster. The ALE observations can be made in or very near the FOV of the supported science telescope.

2. The Astronomical Extinction Spectrophotometer (AESoP), an objective spectrometer that observes bright standard stars to obtain the wavelength dependence of extinction[15,16].
    - AESoP spectrophotometrically observes bright (V ≤ 5.5) standardized stars for which accurate stellar atmosphere models exist[17,18]. AESoP spectra are "pinned" at the ALE laser wavelengths and a MODTRAN5 model[19] informed by NOAA/NWS ground, balloon, and satellite measured atmospheric parameters is fit to the difference of the stellar spectrum and the calibrated observed spectrum, yielding the real-time spectrum of Earth's atmosphere. Integrating the telescope throughput (including the optical bandpass) convolved with the atmospheric spectrum provides a calibration point every minute of time, to be applied to each observation.
3. The Astronomical Camera for Extinction (ACE) is a wide FOV camera that confirms and angularly refines the ALE extinction measurements using time-resolved differential imaging photometry of field stars obtained through a narrow bandpass filter centered at the laser wavelength.
    - ACE imaging photometric observations over a nominal 3° FOV provide a "one way" check on the validity of atmospheric extinction corrections. Reasonably high S/N imaging photometric observations of (sensibly constant) field stars in and surrounding the science FOV acquired at typically 10s – 30s cadence and corrected by the ALE transmission factor should continuously show constant flux consistent with the individual star's measurement errors. Additionally, systematic photometric variations across the FOV can be interpreted as variable extinction from which an angular interpolation of the extinction corrections can be determined.

These instruments are designed to produce a "sub-1%" transmission measurement for airmasses ≤ 3 using ALE, ~ 0.5nm resolution spectral transmission from 350nm to 1050nm with precision of sub-1% per resolution element, and confirming extinction measurements, all with a cadence of one minute. These merged data provide a time-based atmospheric transmission metadata stream that can be used to calculate accurate extinction corrections for astrophysical observations made with the "science telescope" being supported, over the FOV of that telescope and at the time the observations are being made.

## 2. GROUND-BASED ASTRONOMY

The majority of astronomical telescopes is and will remain at terrestrial observatories. The major reasons for this are obvious and long recognized:

1. The conduct of terrestrial observational astronomy is generically less expensive than observations made from space
2. Architectures for the evolving generation of 10 m to 100 m diameter telescopes are inherently terrestrial, again principally driven by cost
3. Observatories can rather blithely (compared to space operations) change and add instrumentation
4. You (not I!) can walk up to a terrestrial telescope with a crescent wrench and a bottle of Windex to service a ground-based telescope and fix whatever is wrong!

It is clear that access to the electromagnetic spectrum blocked by Earth's atmosphere will continue to require access to space and space-based telescopes. The policy amongst agencies and astronomers has long been, "go to space only for those sufficiently scientifically well justified observations one cannot acquire from the ground." The maxim has also been stated, "if you can do it from the ground, do it!" This has led to a highly complementary program in astronomy and astrophysics that makes parallel use of ground- and space-based observing capabilities, and this program will necessarily continue. The key question we address is, "With what radiometric accuracy can we provably, routinely and inexpensively observe through Earth's atmosphere?" We envision providing a cost-effective suite of instruments implemented at observatories and telescopes to enhance their accuracy, productivity, and the benefit/cost of their operation.

The intent of the research discussed herein is to bolster the contribution, efficiency and accuracy of ground-based observations within the electromagnetic spectrum available to terrestrial observatories. We concentrate here on the optical spectrum detected with CCDs. This is driven by the cost and availability of these detectors and their ubiquitous use as the detector of choice at terrestrial observatories. The plan of action is to extend this program into the infrared as soon as possible, building upon the success of the current program.

# 3. EARTH'S EVIL ATMOSPHERE

Earth's atmosphere is both turbulent and turbid. These are orthogonal aspects of the atmosphere's effect on ground-based astronomical observations. Turbulence is a factor in generating astronomical "seeing," a bad thing that limits the angular resolution of terrestrial telescopes to well below their fundamental diffraction limits. Astronomical seeing is addressed by adaptive optics (AO), which corrects for the "blurring" effects of turbulence and improves the angular resolution information provided by telescopes to near their fundamental diffraction limits. We do not do AO!

Turbidity is a bad thing that includes all the scattering and absorption effects in the atmosphere that modulate transport of light into astronomical images and limits measurement of the brightness of those images to well below the fundamental photon noise limit. This effect is historically known by the catch-all name of "astronomical extinction." Our atmospheric monitoring (AM) techniques allow correction for the systematic directionally-, time- and wavelength-dependent loss of light, providing extinction corrections to the measurements of images and allowing radiometric improvements that allow approach to the fundamental photon shot noise limit. We do AM! There are certainly parallels between the development of correction schemes for atmospheric turbulence and turbidity, one of which is not the amount of money spent on that development! In the future, telescopes combining AO and AM will allow recovery of both angular and radiometric information approaching the fundamental limits of diffraction and photon statistics. This is a good thing.

The astronomical community needs to invest resources in AM for two reasons: the first is that our research provides direction for useful research and development, a direction that was heretofore largely missing, and the second is that having invested millions of dollars (or euros, or yen, …) in telescope optics, including refractive correctors of various descriptions, it is reasonable and cost-effective to invest a bit more in characterizing the most significant refractive element common to all ground-based telescope – Earth's atmosphere.

To illustrate this statement, integrating the refractive index of the atmosphere above an observatory yields the optical path difference (OPD) induced by that atmosphere. As shown in Figure 1, the atmospheric OPD above even the highest observatories is somewhat greater than one meter. While we spend time and money specifying the transmission, inclusions, surface defects, homogeneity and index variations of an element of a refractive corrector, and then producing, measuring and verifying that lens providing an OPD of typically a few tens of millimeters, we then blithely use it to peer through more than a meter-equivalent of atmosphere - a refractive medium we have rather sadly ignored for some decades. While we cannot manufacture the atmosphere we'd like, we certainly can measure and verify the atmospheric transmission.

## 3.1 Astronomical Extinction

The term "astronomical extinction" incorporates all the scattering and absorption mechanisms in the atmosphere. The optical spectrum of the atmosphere above Albuquerque, New Mexico modeled by MODTRAN5[19] from 300nm to 1100nm on the nominally clear day of 17 August 2009 is shown in Figure 2. Also shown are the PanSTARRS grizy filter bandpasses normalized to 50% transmission for clarity. The MODTRAN5 model was informed by the ozone column measured in Dobson Units (0.01mm at STP) by the orbiting Ozone Monitoring Instrument (OMI)[20] aboard the NASA Aura spacecraft. Precipitable water vapor is measured locally by NOAA radiosondes on the usual 0h and 12h UT schedule, and the aerosol optical depth at 550nm derives from daytime Aerosol Robotic Network (AERONET) sun photometer observations[21]. Aerosols were incorporated into the spectrum as an Angstrom Law with wavelength-variable extinction. Meteorological data were recorded at the University of New Mexico Campus Observatory (UNMCO). During five succeeding days of nominally clear weather the ozone column ranged from 286 to 298 DU, the precipitable water vapor column from 6.3mm to 18.8mm, and the aerosol optical depth from 0.059 to 0.124. Clearly, the atmospheric spectrum changed markedly and rapidly, with the fastest and most astronomically significant changes exhibited by water vapor absorption.

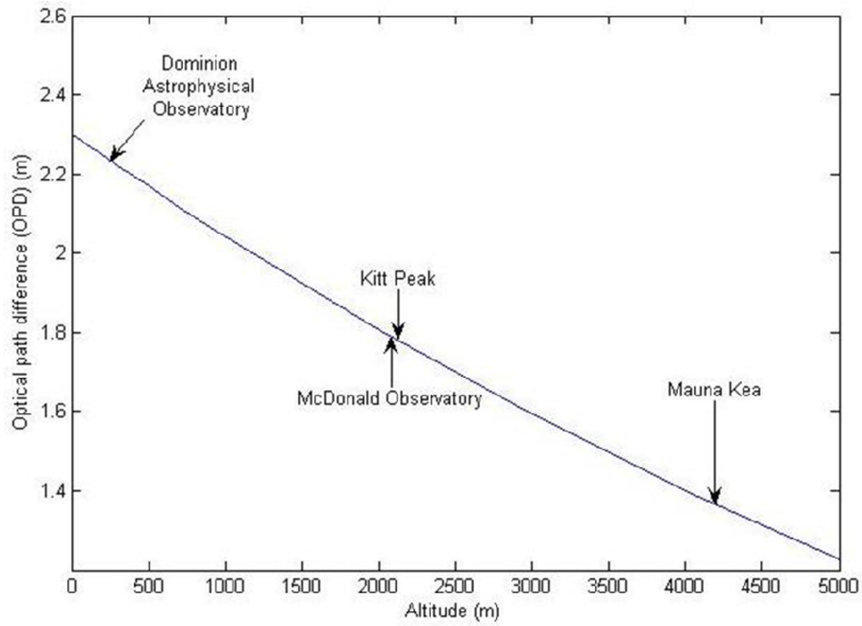


Figure 1. The Optical Path Difference (OPD) induced by Earth's atmosphere as a function of observatory altitude. The OPD can be interpreted as a refractive element with effective thickness of approximately 1.4 meters for a high altitude observatory to 2.2 meters for a sea level observatory.

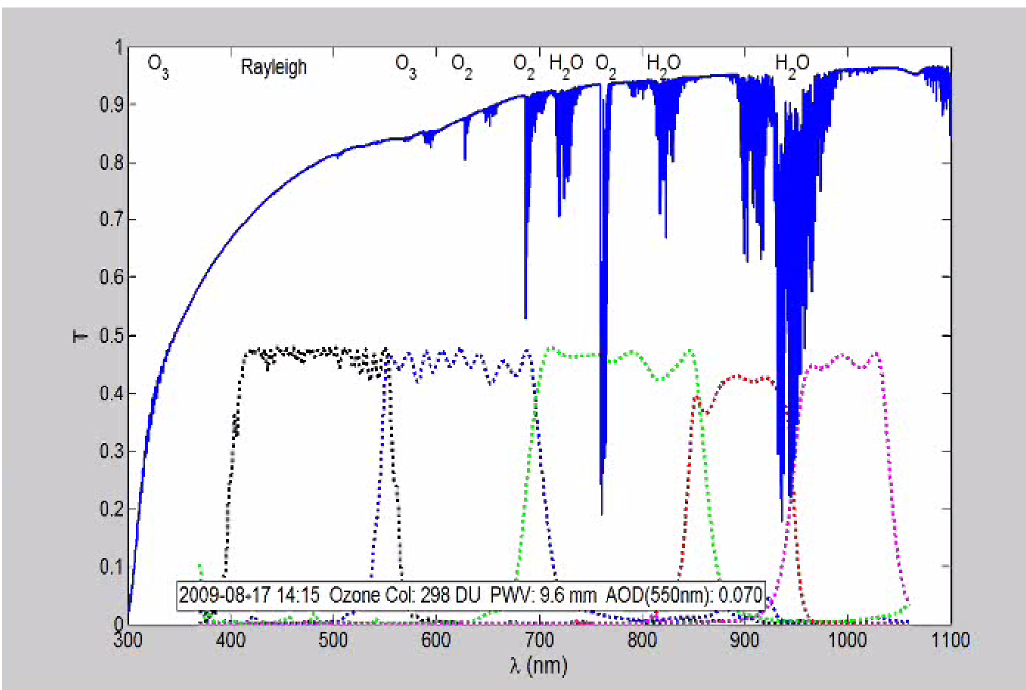


Figure 2. The optical spectrum of Earth's atmosphere is complex and time-variable. Scattering from molecules and aerosols is the major effect, with significant contributions from water, oxygen, and ozone absorption. Rayleigh scattering dominates the blue spectrum while highly time variable water absorption dominates the red. PanSTARRS grizy filters normalized to 50% transmission are shown to indicate the effects the atmosphere on filter bandpasses, especially the modulation of filter edges. The atmosphere was modeled using MODTRAN5 using input data measured at Albuquerque, NM for five days starting on 17 August 2009.

General commentary about spectral changes induced by changing composition and weather includes:

- Rayleigh scattering trends with atmospheric pressure
- The oxygen/nitrogen ratio is rather constant throughout the atmosphere, thus oxygen absorption is strongly present but slowly changing with pressure
- Ozone absorption changes at a few percent are relatively small but significant for accurate astronomical radiometry
- Aerosol scattering and absorption are complicated because of their varying particle size and wavelength dependence, and their modulation of the atmospheric spectrum can be rapid and significant
- Changing atmospheric water vapor content induces the most rapid transmission variability, especially in the red region of the optical spectrum, and the effect of water becomes more significant into the infrared
- Because cloud particles are large compared to optical wavelengths, clouds are essentially gray across the optical spectrum

Precise differential photometry has been demonstrated multiple times[1,22,23]. The lesson to be learned is that highly precise relative photometry can be accomplished under well-selected atmospheric conditions over limited, homogeneous regions of the sky over which extinction does not vary at appreciable levels.

More generally, common sense observations of the dome of the sky, even done by eye and during the day, demonstrate that the integrated optical depth of "astronomical extinction" experienced by a telescope along any line-of-sight depends upon the direction the telescope is pointed, the time interval over which observations are attempted, and specifically over the bandpass or free spectral range the observation is recorded. Though crucial to many astronomical programs, precise and accurate "all sky" photometry, especially involving calibration to a standard, is significantly more difficult to obtain. This model of the astronomer's atmosphere leads to the critical thought that if astronomers want to understand the transmission of the atmosphere that applies to a particular observation they must simultaneously look <u>at</u> the column of air <u>through</u> which they observe.

The classical technique for correcting for atmospheric extinction to "outside the atmosphere" and thus attaining photometric precision and accuracy is to create a Langley plot of instrumental magnitude as a function of airmass, typically for "red" and "blue" stars to approximate the variation of extinction with the target spectral energy distribution. The slopes of these lines, assuming a plane-parallel, homogeneous, stationary atmosphere, provide mean extinction coefficients averaged over the interval between extinction measurements (usually one night) and over the dome of the sky in units of magnitudes/airmass. These "mean extinction coefficients" allow estimation of atmosphere-corrected instrumental magnitudes by correcting an observation made at some (hopefully reasonable) airmass to zero airmass, or "above the atmosphere," as described by Lena[24] and elsewhere. We have already agreed that based upon common observations this homogeneity and stationarity is not to be expected of our atmosphere. The correct technique for measuring accurate atmospheric extinction is to do so continuously, as noted by Stebbins and Whitford in 1945, "it is impractical to determine the extinction thoroughly and accomplish anything else[25]." This statement presupposed that the "science telescope" would be used to measure extinction, as well as making the measurements for the science program. We instead propose facility instruments that obviate the need for taking "science telescope" time to measure extinction, but which also correctly and accurately measures astronomical extinction continuously!

We need an instrument that measures the entire column of atmosphere through which we make our astronomical observations. The instrument is a lidar (light detection and ranging), and our version of this instrument, the first "clear air lidar," is designed not only to report that extinction exists, but to accurately measure the transmission as a function of time at the laser wavelength(s)[14,15,16]. Surprisingly, the UNM and GTRI scientists and engineers who designed and built the lidar named it the Astronomical Lidar for Extinction (ALE). ALE is shown in operation at the UNMCO in Figure 3. ALE is an eye-safe micropulse lidar operating at 527nm with a 1500Hz repetition rate providing 15m range resolution to 30km range. It is on an alt-az mount with a 315mm transmitter, a 100mm short-range receiver and a 670mm long-range receiver.

Figure 3. The Astronomical Lidar for Extinction (ALE) in operation at the UNMCO. The 315mm diameter transmitter operates at 527nm (the green light, eh?) and a 1500Hz repetition rate. The transmitter is flanked by a 100mm diameter short range receiver (on the right of the transmitter, just below the centerline), both of which are mounted on a 670mm diameter long-range receive on an alt-az mount allowing all-sky access.

Figure 4 shows a one-minute summed lidar return at 1.3 airmasses to a range of 30km measured as total detected photons. Below 10km the return is accurately what is expected based upon Rayleigh scattering. Enhanced backscatter at 11km indicates a cirrus deck with vertical structure starting at about 10km. This layer is near the tropopause and the slightly attenuated return above the cirrus deck is from the homogeneous, stable stratosphere. The absence of clouds and significant aerosols in the stratosphere ensures that returns from this altitude are (usually) purely Rayleigh scattered. Twice daily (0h and 12h UT) balloon-borne radiosonde measurements ensure that the very slowly changing density of stratospheric molecules is accurately known as a function of time. A power meter on the transmitter provides a 0.05% measurement of the transmitted light per minute. The stratospheric molecules provide a "Rayleigh screen" that can be integrated in range, 18km to 24 km in this example, to provide $10^6$ detected backscatter photons, creating well-defined known backscatter source from which the two-way transmission of the atmosphere can accurately be calculated. This technique allows direct measurement of the monochromatic atmospheric transmission to 0.25% per airmass accuracy at one minute cadence.

The first task for ALE was to allow astronomers to investigate the "astronomer's atmosphere" to assess the nature of the nominally clear atmosphere and our ability to correct for atmospheric effects better than canonical techniques. The top panel of Figure 5 shows an ALE time-height (TH) diagram constructed by plotting color-encoded return intensity as a function of range on the vertical axis and time on the horizontal axis. The time resolution is one minute. The lidar returns are normalized to a "standard atmosphere" with an exponential aerosol component and color encoded as a fractional return expressed as (return – model)/return, with the corresponding legend at the right. The fractional transmission is over-plotted in black with units shown on the right. The night was astronomically useful, and would have been judged "clear." The lidar shows a significant, structured aerosol component below 6km that dissipates with time, causing the atmospheric transmission to increase.

The lower panel of Figure 5. replicates the transmission curve with ~ 0.2% single measurement, one standard deviation error bars shown. Black error bars for the standard deviation of the mean transmission over 15 minute intervals are also shown. These are uniformly larger than the standard deviation of individual measurements, reflecting the overall change in transmission over the 90 minute measurement interval. This demonstrates one source of enhanced uncertainty in the calculation of mean extinction coefficients. The more insidious aspect of this effect is that with a measured 5% transmission change over 90 minutes, use of a mean extinction coefficient applied to measurements made over this interval *guarantees* that a systematic error of at least 1% will occur. Classical techniques for correcting for astronomical extinction can introduce systematic photometric errors.

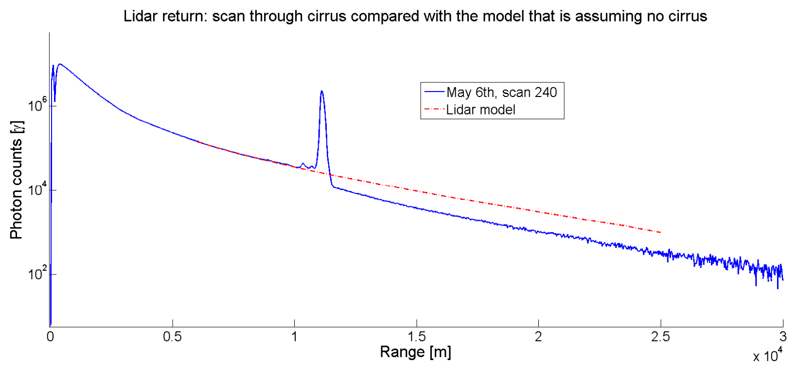


Figure 4. A typical lidar return shows backscattered photon count as a function of range. This return, acquired at an airmass of 1.3 from north of UNMCO shows a typically structured cirrus deck at about 11km range. Below the cirrus deck the return is accurately Rayleigh scattering, as is in the stratospheric range of 18km to 24km. The integrated return from this range provides ~ $10^6$ photons from which the transmission of the atmosphere can be measured by reference to the radiosonde-determined stratospheric density. This technique provides monochromatic transmission to an accuracy of about 0.25% per airmass per minute.

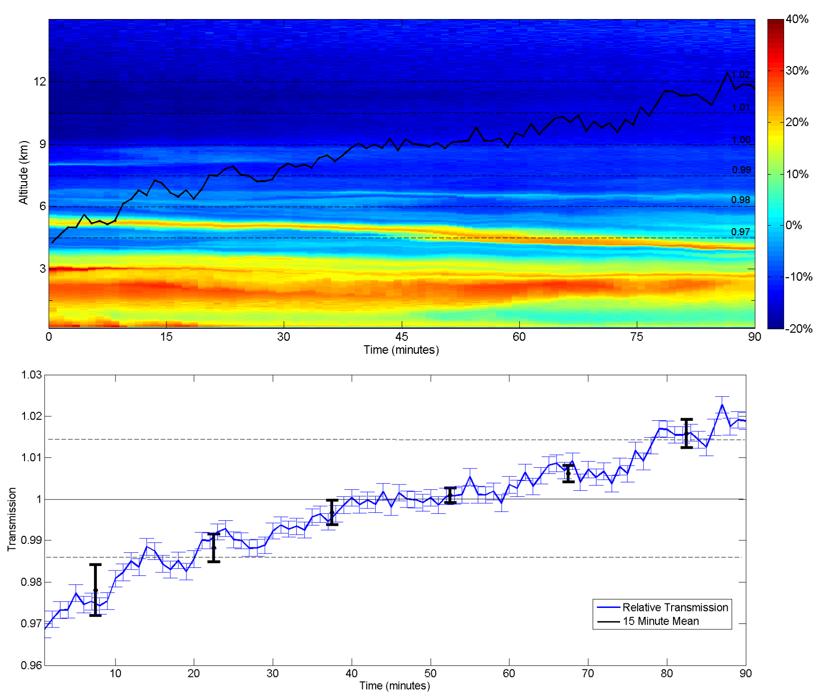


Figure 5. The upper panel shows an ALE zenith TH diagram for 18 April, 2008 acquired by averaging lidar returns in one minute of time bins over an interval of 90 minutes. The returns are depicted as the fractional difference (data – model)/model, where the model is a standard atmosphere plus an exponential aerosol component. The black trace shows the relative transmission which is replicated in the lower panel (blue) with one minute, 0.2% single measurement standard deviations shown. Fifteen minute means with the standard deviation of the mean are shown with black error bars. These data derive from a clear night that would have been used for astronomy. Use of a mean extinction coefficient during this night *introduces* a systematic error of at least 1%!

### 3.2 The monochromatic transmission of the atmosphere above your observatory

Observatory reports, observing manuals and generic apocrypha claim "30% (or perhaps 40%) of nights are photometric" at the Star Studded Observatory. Lidar observations allow these glowing claims to be quantified. The issue is no longer "is it photometric," but rather "quantitatively, how photometric is it?"

Figure 6 shows the atmosphere as every observatory director wishes it to be and/or portrays it. This night is clear, Rayleigh scattering dominates the entire atmosphere, and there are no discernible extinction features: this really is a photometric night. When lidar returns look like this, schedule your truly photometric programs and observe madly!

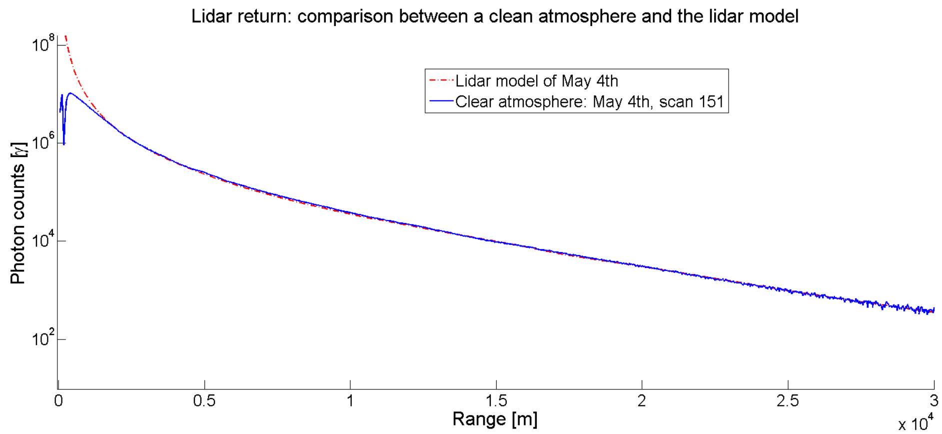


Figure 6. A lidar return showing that 4 May 2010 was a truly photometric night. This one minute summed return shows negligible deviation from pure Rayleigh scattering from the surface layer through the stratosphere. Deviations from the lidar model in the surface layer are due principally to incomplete pulse overlap corrections at high photon count rates, and a small amount of the ever-present surface layer extinction. Nights don't get much better than this!

Unfortunately, the atmosphere is not always this transparent. Additionally, all large telescopes, and certainly the large synoptic surveys, are going to have to push the transparency limits in terms of observing schedule if they are ever to complete their missions. The "usual condition" will be that observations are carried out in less than classically photometric conditions, and that observations through some clouds will be planned for and accomplished. Cirrus is the most usual cloud type through which observations will occur. Figure 4 depicts a cirrus deck, and it is well within the capability of the lidar and other instruments we propose to enable useful observations through a less than photometric atmosphere at the expense of loss of light and/or longer integration times. The ability to intelligently observe in varying conditions without sacrificing measurement accuracy is, in fact, a primary benefit of this research and the instrument suite it will evolve. We assert that this facet of the project alone will justify the development expense in terms of usefully recovered observing time.

Figures 7 and 8 depict the nasty part of observing that our techniques will either preclude or correct, depending upon the accuracy requirements of the observing program. This set of figures depicts our ability to distinguish and accurately measure atmospheric transmission, even in heretofore "marginal" conditions. Clearly, *in situ* lidar observations of the same column of atmosphere through which astronomical observations are made provides significant benefits in scheduling to accommodate current observing conditions, precluding data losses because of undetected transparency effects, and enhancing the accuracy of atmospheric extinction corrections, thus eliminating systematic errors and reducing random errors to below the fundamental photon shot noise limit for those observations for which a sufficient number of photons are acquired.

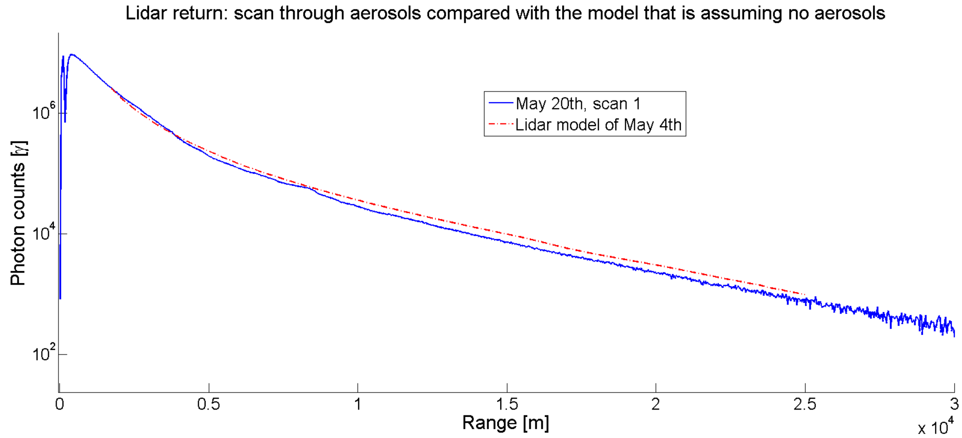


Figure 7. A lidar return characteristic of an insidious night. There are no clouds present, but there certainly are aerosols that clearly remove significant flux, and probably in a wavelength-dependent manner. This is the type of night judged photometric by eye and camera, through which observations are obtained, only to learn during the data reduction process that the required accuracy cannot be attained. These data are usually discarded after a heroic but futile effort to save them.

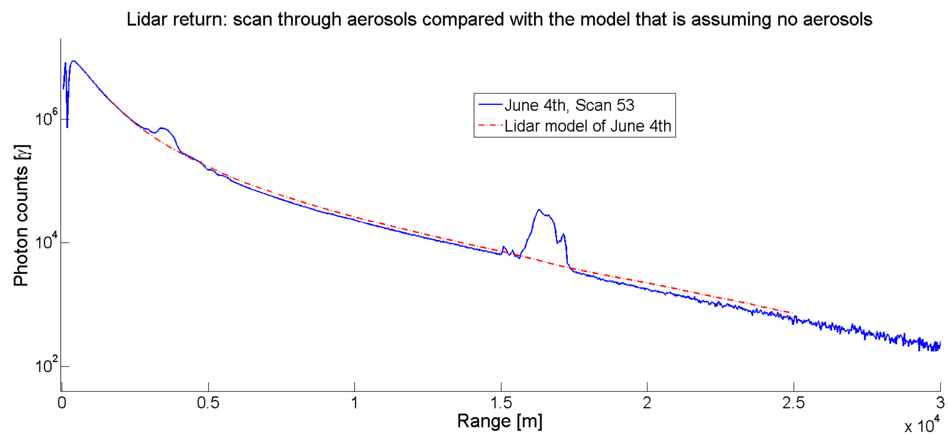


Figure 8. A night with light cirrus at 15km and low-lying aerosols. This is the "usual" state of affairs through which astronomers should and could be prepared to work, provided accurate wavelength-dependent transmission data are available.

While clear air lidar, as pioneered by ALE, is a necessary first step and the technique of choice for determining atmospheric transmission and determining the presence of turbidity, aerosols in particular have wavelength-dependent extinction properties, and water vapor absorption must be resolved and measured. Spectrophotometric measurements must parallel lidar measurements to attain the accuracy required for measurement of astronomical extinction.

### 3.3 Spectrophotometric observations of the atmosphere above your observatory

In a role unusual for astronomers, we set about designing a spectrophotometer to accurately measure Earth's *atmosphere* at a cadence of one minute, with sub-1% precision per resolution element over the free spectral range of 350nm to 1050nm, by the simple expedient of observing bright spectrophotometric standard stars near the science field being observed. The strategy is to observe the "standard star" with a sufficiently well known spectrum – a "NIST Star"[15,16,26] nearest the science field being monitored. The Astronomical Extinction Spectrophotometer (AESoP) will provide spectral data at one minute cadence in synchrony with the one minute monochromatic transmission measurements generated by ALE. The difference between the observed spectrum and the standard star spectrum, which can be calibrated at the lidar laser wavelength(s), represents the spectrum of the sky. The sky spectral data can be modeled with MODTRAN5, informed by weather data acquired at the observatory and from NOAA, NWS and NASA sites. The result will be a spectrum of Earth's atmosphere, expressed in fractional transmission, over the observed spectral range. That range will include any optical bandpass filters or the spectral range used by the imaging photometer or spectrophotometer acquiring the scientific data. Application of real-time atmospheric extinction can be carried out on a wavelength-by-wavelength basis over the spectral bandpass used for the scientific observations.

Spectrophotometry requires counting all of the photons entering the well-defined aperture of the telescope. Given that the simplest possible spectrometer results in the most accurate spectrophotometry, we designed AESoP as an objective grating refracting telescope[27]. AESoP provides the important advantage that there are no color-dependent optics, slits, fibers or cameras (except for an order-separating filter) beyond the objective. All of the light entering the objective can be accounted for by accurately measuring the first-order spectrum on the detector, thus the system is spectrophotometric. The drawbacks to the objective spectrometer include the fact that the seeing and telescope tracking affect the spectral resolution, but AESoP was designed to minimize these effects.

This simple spectrophotometer has several very positive benefits for this project. The most significant is that once light enters the telescope there are no other light losses or chromatic effects. The photometric accuracy of AESoP is determined by 1) the calibration of telescope throughput, 2) the area of the aperture, and 3) extraction, reduction and analysis of the spectrum imaged onto the CCD. Other benefits include small aperture size, low cost, ease of replication, and portability – attributes important for an observatory facility instrument. Additionally, night sky emission lines, which radiate from every point on the sky, become part of the diffuse background light and do not add line contamination to the stellar spectrum. If necessary, the spectrometer can be rotated to orient a standard star spectrum so that it is uncontaminated by spectra of other stars in the field of view. The instrument has very high throughput from 320 nm (ozone opacity limit) to 1,050 nm (silicon detector sensitivity limit). Sequential selection of one of two order separation filters just in front of the CCD allows obtaining second-order spectra from 320 nm to 550 nm and first-order spectra from 550nm to 1050nm. AESoP is small enough that it can be calibrated by observing a monochromatically-illuminated flat-field screen, by collimated light projection techniques, or both. AESoP is shown in its dome in Figure 9.

Characteristics of AESoP:

- Built on a 106 mm f/5 Takahashi 106ED apochromatic refractor
- Equatorially operated on Software Bisque Paramount ME
- Newport Optics 102 mm square 90 line/mm transmission grating blazed at 700 nm in 1st order mounted at the entrance aperture
- Filter wheel with selection of order separating filters and narrowband wavelength calibration filters
- Thermoelectrically cooled, back-illuminated 2048 x 512 E2V 42-10 CCD detector yielding 5.3 arcsec/pixel in spatial direction and 0.28 nm/pixel in dispersion direction
- Free spectral range 320 nm to 1050 nm
    - 320 nm to 550 nm with shortpass filter
    - 525 nm to 1050 nm with longpass filter
- Two pixel spectral resolution 0.57 nm, R=1140 at 650 nm
- Seeing $\leq 3$ arcsecond (FWHM), *i.e.* smaller than one pixel
- Autoguiding to ~ 0.3 arcsecond resolution
- S/N > 100 per pixel achieved by controlling instrumental and background noise and observing bright stars

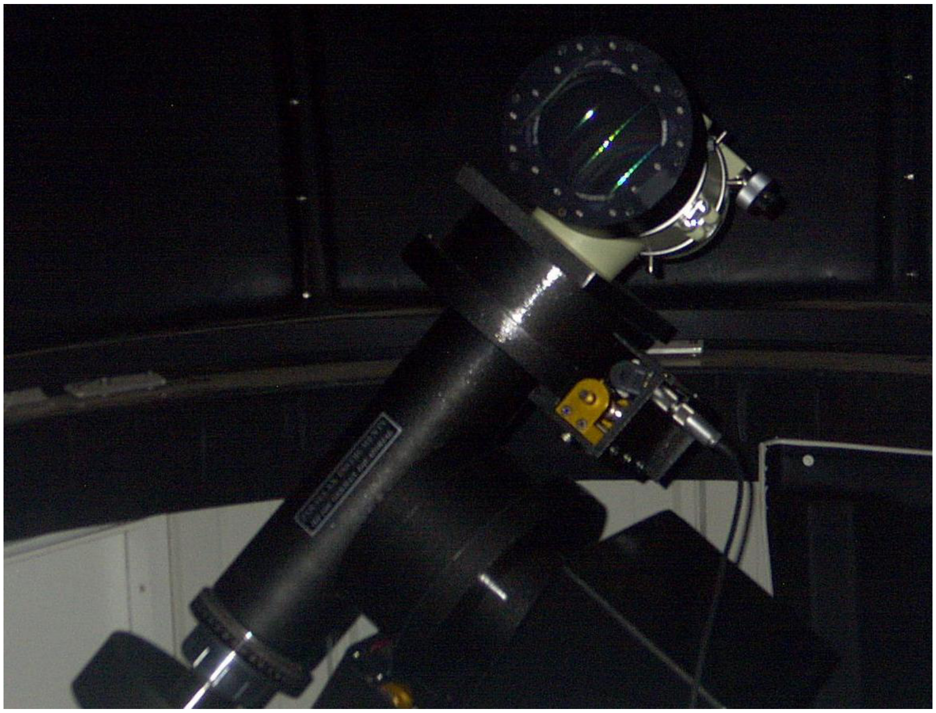

Figure 9. The Astronomical Extinction Spectrophotometer (AESoP). The transmission grating can be seen in its black mounting cell at the aperture of the 105mm refractor. AESoP is equatorially mounted and autoguided to ensure that the spectrum remains on the same pixels for the duration of each exposure.

Though Vega is a rather pathological standard star[28,29], it remains the primary calibrated stellar flux reference[30,31], thus we have accomplished proof-of-concept observations with AESoP using Vega as the initial target. An AESoP spectrum of Vega acquired as 10 one-second exposures, resulting in signal-to-noise greater than 200 per pixel, is shown in Figure 10.

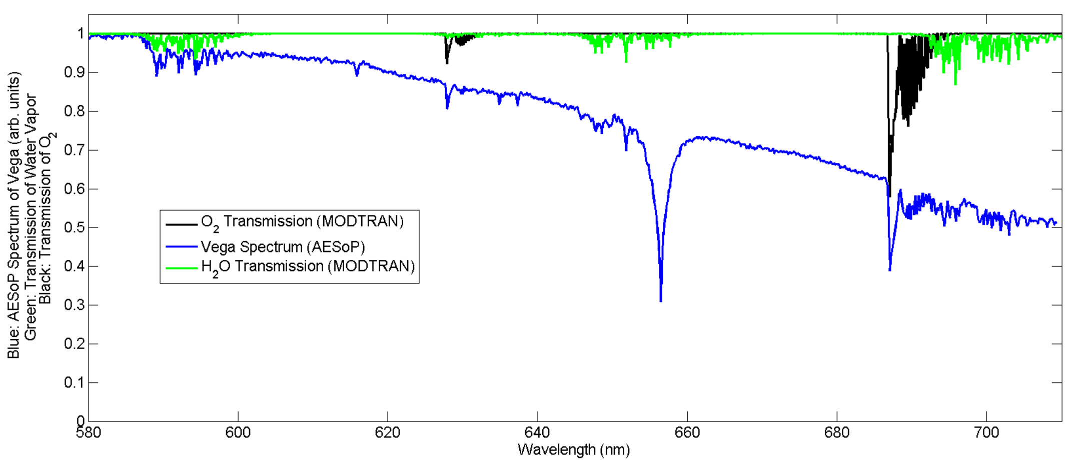


Figure 10. A normalized spectrum of Vega at Hα acquired by AESoP. The resolution is 0.15 nm pixel resolution with S/N > 200 over the majority of the spectrum, which, to prevent detector saturation, is the sum of 10 one-second integrations. MODTRAN-modeled atmospheric $O_2$ for the nominal pressure at the UNMCO and $H_2O$ for 20 mm PWV are shown. AESoP can use stars V ≤ 5.5 to measure atmospheric spectra to sub-1% per resolution element every minute of time.

The two largest challenges for AESoP are wavelength calibration and wavelength-dependent absolute throughput calibration. Because there is no slit in this system, variations in telescope pointing are confused with the wavelength calibration (*i.e.* what pixel position corresponds to what wavelength). In addition, system sensitivity is a function of field position due to field dependent throughput and pixel-to-pixel variations in the quantum efficiency of the CCD. We solve these issues straightforwardly.

Light can be injected into AESoP only at the primary aperture, thus calibration lamps normally used in astronomical spectrometers cannot be used. Stubbs and collaborators[3,4] addressed calibration of telescope throughput based upon a luminous flat-field screen. For AESoP, calibration sources must be collimated light injected at the primary optic, and in order to maintain spectrophotometric integrity, they must correctly fill the entire aperture. There are two ways of filling a telescope aperture with collimated light: collimate the source with optics of the same size or larger, or move the source a long distance away. We shall use both techniques and cross-check the results to ensure the integrity of the instrument and its measurements.

For calibration using a distant source, NIST has developed radiometric techniques using stable, uniform sources and stable detectors that form the basis of the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources Facility (SIRCUS)[32]. For the specific purposes of repeatedly calibrating AESoP (and other spectrophotometric telescopes), a simple derivative of SIRCUS has been developed. A wavelength selectable, point-like source can be placed approximately one kilometer from the telescope and used as a flux standard for absolute throughput calibration. The distant source requires correction for absorption and scattering by the atmosphere, which is provided by an ancillary NIST-calibrated telescope, identical to AESoP *sans* grating, co- mounted with AESoP.

For the *in situ* calibration, AESoP will be pointed at a 400mm parabolic collimator, the output aperture of which simultaneously overfills both AESoP's aperture and that of the calibration telescope. The collimating telescope is illuminated by an optical fiber in turn illuminated by a monochromator. The output of the fiber appears simultaneously to AESoP and the calibrator as a distant point source that can be stepped in wavelength, thus transferring the calibration established on the calibrator telescope to AESoP.

Wavelength scale and wavelength sensitivity calibrations are coupled with AESoP. Therefore, it is essential that the telescope put the same wavelength on the same pixel every time and keep it there. This will be accomplished by always placing the image at 532 nm (doubled YAG), for the blue second order spectral range, and at 632.8 nm (HeNe), for the first order red spectral range, in the same place on the detector both in calibration images and science object images. This is accomplished by first observing the bright standard star through a 532nm or a 632.8nm bandpass filter and registering that image, both in wavelength and position, with the appropriately located pixel on the detector.

Spectra will be measured every minute of time using the logic shown in Figure 11. The measured stellar spectrum, as well as the resulting modeled atmosphere, will be archived in the ATM data base for science program data reduction use.

### 3.4 Closing the photometric loop with the Astronomical Camera for Extinction (ACE)

A new feature of our photometric reduction system "closes the photometric loop" thus helping to ensure the precision and accuracy of radiometric measurements supported by the ALE/AESoP instrument suite. The third element of the suite is the Astronomical Camera for Extinction (ACE), a small, wide-field (~ 3°) reflecting telescope that images the science field through a narrow-band (~ 20-50nm) filter centered on the lidar laser wavelength. ACE makes time-resolved (e.g. 10s – 30s) imaging photometric measurements of "bright" stars in its field of view allowing differential photometry of stars at the same wavelength at which ALE measures the atmospheric transmission. Applying the ALE transmission corrections to the differential measurements will produce constant relative "light curves" for all the stars in the field of view (barring stellar variability) within their photon noise limits. This procedure tests the "one-way" extinction correction associated with the imaging photometry of stars with the "two way" direct measurement of extinction derived from the atmosphere itself using the *in situ* lidar measurements. The MAP Research Team is currently using a refurbished 310mm AstroMak telescope, shown in Figure 12, for "closed loop" testing purposes.

A significant ancillary function for this procedure is that it also maps angularly variable extinction across the field of view, and thus also across the field of view of the supported "science telescope."

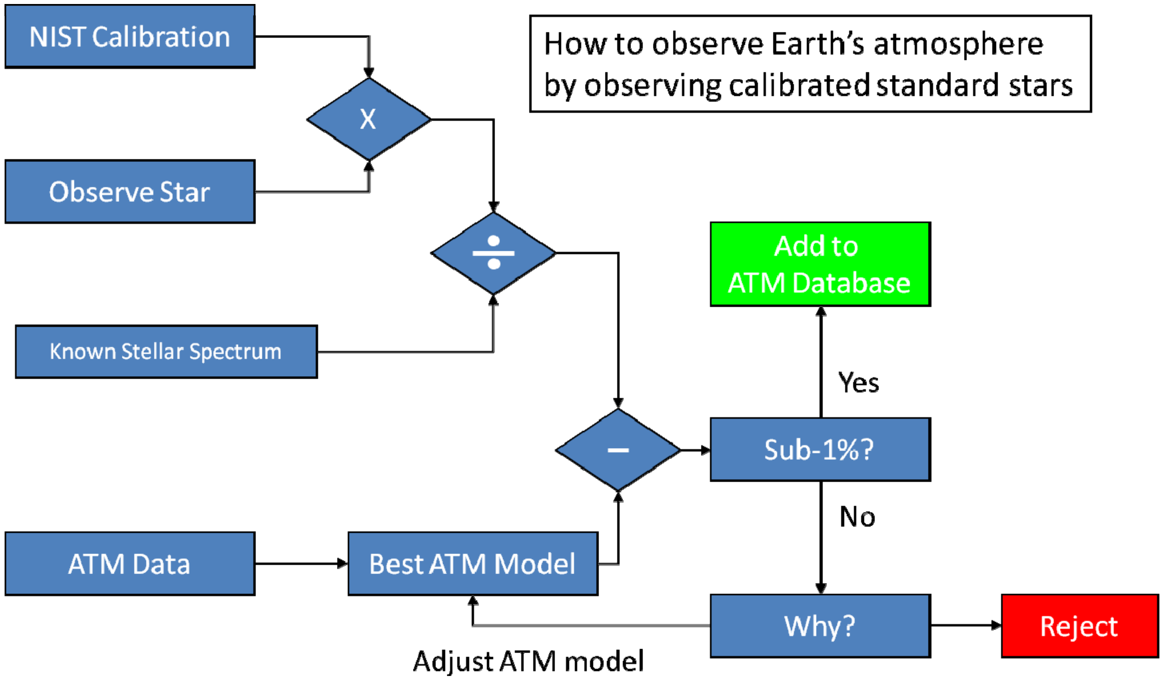


Figure 11. Previously NIST-calibrated standard stars ("NIST Stars") are compared to NIST-calibrated AESoP spectrophotometric observations to produce the ATM database of atmospheric data – principally a MODTRAN model in transmission units, from which wavelength-by-wavelength atmospheric extinction corrections can be derived.

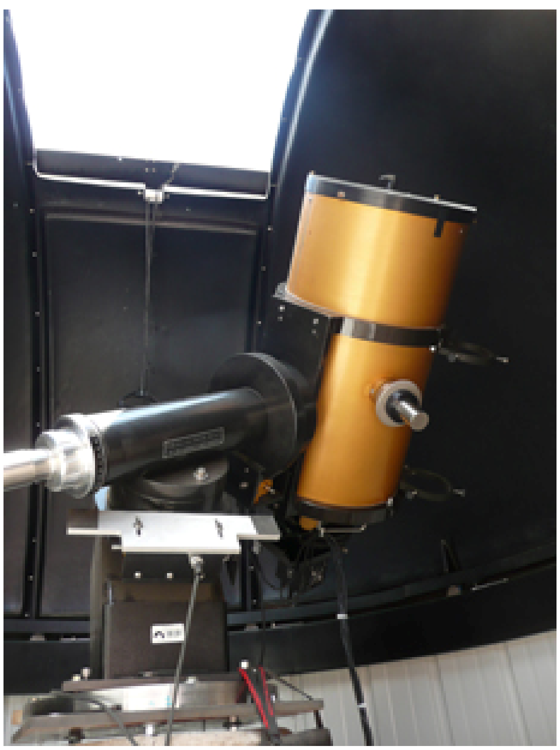

Figure 12. The current incarnation of the Astronomical Camera for Extinction (ACE) is a 310mm diameter AstroMak telescope capable of imaging a 3° field of view. The wide-field ACE images the same field as the supported "science telescope" and performs time-resolved differential photometry of field stars observed through an intermediate band filter centered on the lidar laser wavelength. ACE differential photometry obtained during a science telescope integration must track the amplitude of atmospheric transmission variations (ideally nil!) measured by ALE consistent with the S/N of each photometered star and during the. Systematic extinction variations across the field can be interpreted as angularly-dependent atmospheric extinction and this correction can be applied to the resulting area-format science integration, as well.

# 4. SUMMARY: HIGH ACCURACY PHOTOMETRIC OBSERVATIONS FROM GROUND-BASED OBSERVATORIES

We assert that fundamentally photon noise limited photometric observations can be obtained with ground-based telescopes provided that a significant contributor of systematic and ransom noise – Earth's atmosphere – is accurately measured. The measurements required are in the direction of the supported "science" telescope, across its field of view, and resolved in time sufficiently well to track atmospheric extinction changes that might occur during or between science observations. The facility instrument suite we have developed to accomplish this function for observatories or individual telescopes includes:

1. A lidar to range-resolve all detectable extinction sources, and to measure the atmospheric transmission to 0.25% per airmass in or near the field of the supported telescope at one minute cadence.
2. A spectrophotometer to provide the wavelength dependence of extinction to high accuracy by attaining S/N > 100 per resolution element spectrophotometry over the bandpass observed by the supported telescope with a cadence of one minute.
3. A wide-field camera that includes the science field of view as a subset, observing through a narrow band filter centered at the wavelength of the lidar laser, and producing precise differential photometry of field stars as an independent check on the precision of extinction corrections provided by the lidar (in particular) and the spectrophotometer.

While this remains a research program in progress, every indication is that this instrument suite will perform as designed. Data from a stringent test of the ALE and ACE instruments is shown in Figure 13.

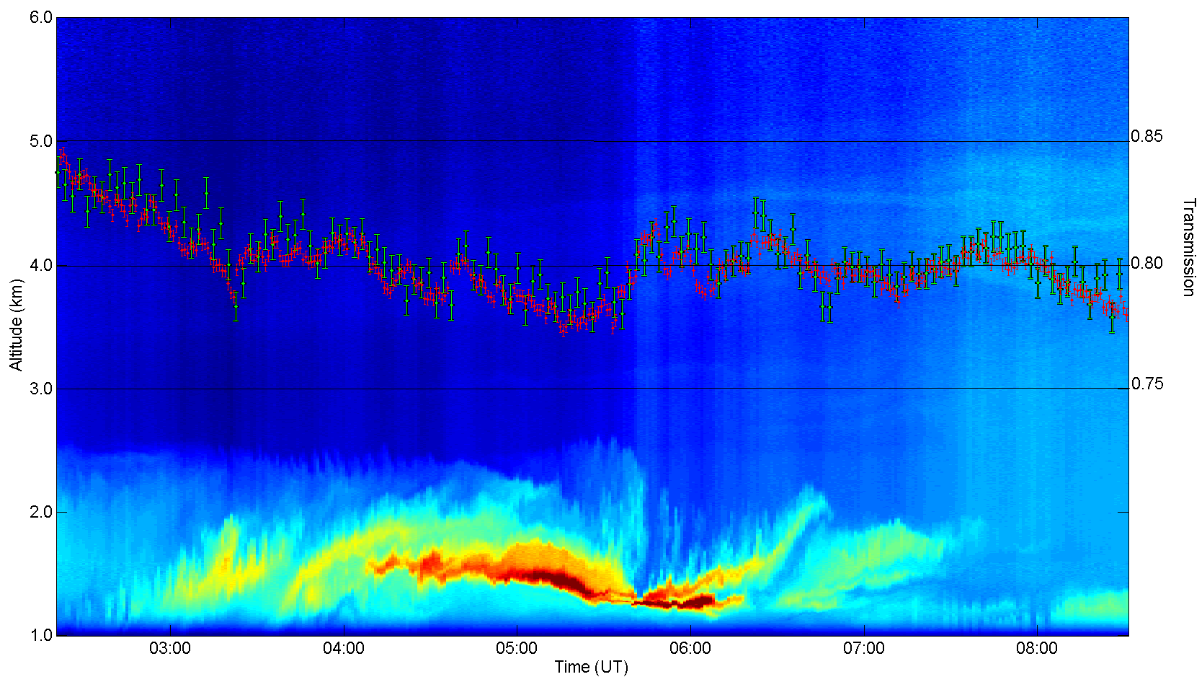


Figure 13. A color-encoded TH diagram for a nominally clear night for which transmission was modulated by an evolving smoke layer below 2.5 km. As forest fire smoke passed over the UNMCO the overall transmission varied by ~ 5% over approximately six hours, with ~ 1% variations on few minute time scales. Red data points and error bars derive from ALE lidar transmission measurements. Black data points are the normalized Bessell V ACE measurements of three field stars. The photometric data are the sum of photon counts for the three stars normalized by their mean and scaled to the nominal 85% atmospheric transmission characteristic of the V bandpass. The photometric error bars are set at 0.5%, dominated by scintillation. Note that the lidar data, with no bandpass corrections, reasonably track the photometric measurements to within sub-1% precision. The ability to reasonably correct for atmospheric extinction in this pathological case shows the promise of our techniques.

On a nominally clear night during which smoke from a forest fire approximately 150 km to the north passed over UNMCO, stellar photometry of three (constant) field stars was carried out by ACE observing through a Bessell V filter, while transmission was measured by ALE at 527nm, within the V bandpass. The figure shows the excellent agreement between total atmospheric transmission derived from imaging photometry and that derived from direct measurement of the atmosphere using the ALE lidar. The uncertainties on the red lidar transmission values are determined by photon statistics from the stratospheric layer used as the Rayleigh source. The photometric uncertainties are set at a constant 0.5%, because the photometric uncertainties for the small ACE telescope are dominated by scintillation. Even without wavelength-dependent bandpass corrections the correspondence is remarkably good, even for this pathological night. We contend that this example demonstrates we are on a reasonable path towards attaining routine atmospheric transmission corrections that largely obviate the atmosphere as the significant factor limiting the precision and accuracy of ground-based astronomical observations.

Our planned near future developments include construction of two mobile observatories, one containing AESoP and its near-field calibration system, and the other containing an upgraded lidar system and ACE. We anticipate visiting other observatories with this instrument suite for onsite observations of the atmosphere. In future we anticipate making the final instrument suite available worldwide.

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