Measurement Astrophysics (MAP) First Steps: A New Decade of Ground-based Photometric Precision and Accuracy

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Technology Development Panel:

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Abstract. Within the next decade a suite of observatory-class instruments directly measuring Earth's atmosphere and telescope throughput will enable routine, provably accurate photometric measurements to sub-1% accuracy, often achieving the fundamental photon noise limit. This measurement capability is of significant benefit and importance to all of astronomy and astrophysics. Techniques currently under development designed to prove this concept address two elements: simultaneous measurement of the directional-, wavelength- and time-dependent absolute transmission of Earth's atmosphere in the same column of air through which a telescope is observing, and NIST-traceable telescope throughput calibration systems. Examples of requirements for precise and accurate photometry for research ranging from stars to dark energy are described. An assessment of cost and capability impacts on the astronomical community is discussed, including the necessity for interdisciplinary research potentially resulting in enhanced social relevance for astronomical observations in support of atmospheric science, climate change and modeling Earth's energy balance.

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1.0 Overview of Measurement Astrophysics First Steps: Enabling Fundamental Science

Within the next decade a suite of observatory-class instruments directly measuring Earth's atmosphere and telescope throughput will enable routine, provably accurate photometric measurements to sub-1% accuracy, often achieving the fundamental photon noise limit. This measurement capability is of significant benefit and importance to all of astronomy and astrophysics. Techniques currently under development designed to prove this concept address two elements: simultaneous measurement of the directional-, wavelength- and time-dependent absolute transmission of Earth's atmosphere in the same column of air through which a telescope is observing (*e.g.* Dawsey *et al.* 2006), and NIST-traceable relative telescope throughput calibration systems (*e.g.* Stubbs and Tonry 2006, Stubbs *et al.* 2007b).

The highly variable transmission of Earth's atmosphere is the largest source of systematic error in photometric measurements. Knowing the absolute real-time atmospheric transmission obviates these errors allowing sub-1% and possibly photon noise limited measurement errors to be achieved by implementing ancillary "observatory-class" instruments to measure the atmosphere directly. Calibrating the throughput of a telescope, including the atmospheric transmission, using NIST-traceable detectors and/or sources assures accurate photometric measurements in SI units.

The emerging sub-field of astrophysics directed towards the goal of enabling accurate, NIST-traceable, photon noise limited observations we refer to as Measurement Astrophysics (MAP).

Development of MAP techniques to correct for atmospheric extinction and telescope throughput are underway. A prototype suite of ancillary instruments that demonstrates precise and accurate real-time correction for astronomical extinction has been conceived, constructed, and is in operation. The suite includes the Astronomical Lidar for Extinction (ALE, Dawsey *et al*. 2006) to obtain monochromatic absolute transmission, the Astronomical Extinction Spectrophotometer (AESoP) to determine the wavelength dependence of transmission, and wide-field cameras that monitor the sky and confirm the atmospheric transmission measurement by simultaneously observing stars in the field of the science telescope, ALE and AESoP. Together these instruments produce a record of atmospheric transmission with less than 1% uncertainty at one minute cadence. Telescope calibration can be accomplished by collimated projection techniques, or by using monochromatically illuminated flat-field screens (Stubbs and Tonry 2006, Stubbs *et al.* 2007b).

The development of adaptive optics (AO), which addresses atmospheric optical turbulence, provides a paradigm for the development of MAP atmospheric transmission measurement techniques. Development and worldwide deployment of atmospheric transmission measurement systems will require a major effort, analogous to that required to develop and transition AO into general use at observatories worldwide. This is a center-class technology development problem requiring interdisciplinary research amongst astronomers, atmospheric physicists and measurement scientists. Experience to date indicates that the costs to develop, then replicate and distribute the suite of instruments that provides calibrated sub-1% photometry at most observatories will be significantly less than the community investment in AO. The scientific return from accurate photometry will be immense, making these developments extremely cost-effective. The decadal review must describe appropriate organizational and funding mechanisms to develop and implement these techniques. It must also consider and assess the impact and importance of astronomical and astrophysical research enabled by ground-based observations that regularly attain demonstrable sub-1% measurement precision and NIST-traceable accuracy for photometry expressed in units of spectral irradiance. That is, within the upcoming decade the community can routinely expect sub-1% photometric accuracy for optical and infrared ground-based observations.

A significant broader impact that must be recognized and planned results from astronomers' long-term regular application of the techniques and instruments required for direct measurement of Earth's atmosphere to realize accurate photometry. These instruments, including lidar, spectrophotometers and time-domain imaging photometers, and the techniques and algorithms for accurately measuring the transmission of Earth's atmosphere, enable a unique network for observatory-based atmospheric measurements, especially useful for characterizing the nighttime atmosphere. Because of the nightly operation of observatories over decades and even centuries, observatory monitoring and operational records will establish a unique data set for evaluating long-term climate change. These measurements also help verify atmospheric radiative transfer models, and can be used for "ground-truth" weather and climate satellite calibrations. This addresses the national agenda for environmental sustainability and enhances the astronomical community's social relevance.

The first product of the enhanced measurement capability we describe will be the definition of a network of spectrophotometric standard stars calibrated to NIST standards enabling both enhanced astronomical and atmospheric physics research.

A second product will be enhanced operational efficiency for telescopes with real-time atmospheric monitoring in terms of: 1) accurate photometry, 2) increased fraction of time for photometric observations rigorously correctable using atmospheric metadata, 3) robust queue scheduling based upon actual atmospheric conditions, and 4) decrease in data acquired but lost upon reduction and analysis because they are of lower photometric quality than perceived.

1.1 The Astronomer's Atmosphere

Earth's atmosphere is a turbid, turbulent angle-, time-, and wavelength-dependent refractive medium through which ground-based telescopes must peer to observe the heavens. Photons traveling for millennia are lost within the last 300 microseconds prior to detection as they are absorbed or scattered by molecules and their information is lost – a collective effect classically known as astronomical extinction. Sharp images are blurred by optical turbulence – the effect known as astronomical seeing. The positions of stars are anomalously refracted by quasi-periodic wave-like structures in the atmosphere, and their positions shift by unexpectedly large amounts relative to the measurement precision. Certainly Earth's atmosphere is an incredibly important fluid that supports life on Earth, and is the "thermostat" for Earth's energy balance. Within Earth's atmosphere is thus embedded a large number of physical mechanisms, all of which are time dependent, and all of which result in systematic observational uncertainties significant for ground-based astronomical observations.

The ever-changing turbidity and mechanical structures embedded in the atmosphere cause the limiting systematic errors affecting achievable measurement precision and accuracy. For centuries astronomers have looked *through* the atmosphere with their telescopes, and have accomplished observations that are literally astounding. But the state-of-the-art of measurement science and calibration technology has now developed in precision and field applicability to the point where we must look *at* the column of atmosphere through which light travels to our telescopes to realize the precision and accuracy now required for astrophysical measurements.

The largest telescopes are ground-based, and will remain so for the immediate future. The only eight and 10 meter telescopes are currently on the ground, and 30 and 100 meter telescopes are planned for ground-based observatories. The conceptual, design, fabrication and implementation work associated with these telescopes is immense and the community must ensure optimal return from its telescope investments. To impart some perspective on the necessity to accurately characterize Earth's atmosphere as a telescope refractive element, one might consider the investment made in a wide-field corrector lenses, for example. One element of a large telescope corrector might be a one meter diameter asphere 0.2m thick and, with stringent homogeneity and surface requirements for the glass, represents a ~ $1M investment. The index of refraction of air at sea level under standard conditions is $n \approx 1.003$. Depending upon the altitude of the observatory, telescopes look through ~ 100km of atmosphere so the optical path difference (OPD) of the atmosphere is one to two meters. The atmosphere is effectively a very thick refractive element for every ground-based telescope. It behooves observatories to correct for the scattering and absorption of the atmosphere commensurate with the care that is applied to other telescope refractive elements. This can be accomplished, and at a capital cost on the order of that invested in any other large refractive optic.

2.0 Measurement Astrophysics (MAP): Approaching the Photon Statistical Limit

The real problem addressed by MAP techniques is to eliminate the known and unknown systematic errors imposed by the signature of Earth's atmosphere on astronomical data, allowing the fundamental photon statistical noise to dominate.

2.1 The Need for MAP: Young Stellar Objects and the Formation of Planets

In the upcoming decade we must plan observations and theoretical approaches to understanding the formation of planets orbiting Young Stellar Objects (YSOs), physical evolution of the disks associated with YSOs, and the implications for the formation of terrestrial worlds. Observations now support the concept that during their formation all young solar mass stars probably evolve disk structures from which planetary systems might form within but a few million years (e.g. Meyer *et al.* 2007 and references therein). We now know of more than 300 extrasolar planets that exhibit a variety of planetary physical and orbital parameters (*e.g.* Butler *et al.* 2008), and we know about our own, still unique planetary system, though we have observed extrasolar debris disk systems that appear similar to what we would expect of the solar nebula (Meyer *et al.* 2007).

Clues to the early history of planet formation and evolution of the YSO disk system appear as optical/infrared variability. Two Herbig Ae objects, HD 31648 and HD 163296, show 2 – 10μm correlated variability on timescales of months to years, *i.e.* the timescales that have been sampled during 25 years of observations (Sitko *et al.* 2008). The UX Ori variable SV Cep shows correlated optical/infrared variability that can be modeled as a changing inner disk thickness, possibly due to a changing stellar accretion rate (Juhasz *et al.* 2007). A similar mechanism, coupled with a companion star in an eccentric orbit is invoked to explain the extreme optical/infrared variability of V1184 Tau (Grinin *et al.* 2009).

The generic class of YSOs can be expected to vary on periodic timescales associated with planetary orbits and irregular periods associated with disk structure. Shorter timescales can and will be sampled, including with ground-based observations, in the effort to decipher the structures associated with YSOs. Of course direct imaging of these nearby objects leads to fundamental structural information that will be used in conjunction with photometry to describe the evolution of the stellar/planetary environment (e.g. Lagrange *et al.* 2008, Kalas *et al.* 2008).

Synoptic ground-based photometric observations of YSO systems will contribute to understanding these important, dynamic systems, both with respect to star formation and the stellar nebula, its evolution and the formation of planets within it. Because important photometric changes can have small amplitude, precise, provable optical/infrared observations are required to derive key information from the photometric record obtained over decades. MAP techniques for obviating atmospheric systematic effects and for calibrating measurements to NIST spectrophotometric standards allows robust interpretation of the entire light curve. Additionally, reduction of the light curves to SI units of spectral irradiance allows directly embedding measurements in the YSO SED, and comparison of optical/infrared observations to the space-based x-ray, uv, mid- and long-wavelength infrared observations necessary to fully understand YSOs, their evolving disks and their planetary systems.

2.2 The Need for MAP: Supernovae and the Nature of Dark Energy

The accelerating cosmic expansion inferred from observations of distant Type Ia supernovae (Riess *et al.* 1998; Perlmutter *et al.* 1999) indicates the dominating presence of a "dark energy." Increasingly incisive samples at redshifts $z<1$ have reinforced the significance of this result (Tonry *et al.* 2003; Knop *et al.* 2003; Barris *et al.* 2004; Conley *et al.* 2006; Astier *et al.* 2006; Wood-Vasey *et al*. 2007).

Using the Advanced Camera for Surveys (ACS) and the NICMOS camera on the Hubble Space Telescope (HST), observations have also been secured of 24 supernovae at $z>1$, which helped confirm the reality of cosmic acceleration by delineating the transition from cosmic deceleration during the matter-dominated phase and by ruling out simple sources of astrophysical dimming (Riess *et al.* 2004, 2007).

With essentially all cosmological observables now lending support to the existence of dark energy, the contemporary challenge is to deduce the underlying physics from higher precision measurements. Specifically, the equation-of-state parameter of dark energy relating the pressure, P, to the energy density, ρ, $w = P/\rho$, determines the evolution of the density of dark energy.

As the scientific focus shifts from confirming the existence of dark energy to teasing out hints of the underlying physics, the precision frontier shifts to 1% or better flux determinations. Characterizing the optical transmission of the atmosphere and the astronomical apparatus is an essential ingredient in attaining this goal. The DOE, NSF and NASA commissioned a task force to lay out a strategy for pursuing dark energy research. This Dark Energy Task Force (DETF) published its findings in 2006 (DETF 2006) and recommended a coordinated program that involves observations of Baryon Acoustic Oscillations, Galaxy Clusters, Supernovae, and Weak Lensing by a sequence of facilities including ground-based optical surveys (e.g. LSST). However, the DETF stressed that the name of the game is now systematic uncertainties. It is straightforward to propose methods to increase statistical samples, but such observations will be pointless if limited by systematic error. Therefore the DETF recommended that “high priority for near-term funding should be given ”…to projects that will improve our understanding of the dominant systematic effects in dark energy measurements...,” specifically calling for “(C) Establishing a high-precision photometric and spectrophotometric calibration system..."

MAP techniques go to the heart of the primary challenge in extending the precision of ground-based flux measurements, and will allow the next generation supernova cosmology measurements while avoiding the introduction of subtle systematics in photometric redshift determination for galaxies used in weak lensing surveys. Both the ESSENCE and SNLS supernova teams’ results (Wood-Vasey *et al.* 2007, Astier *et al.* 2006) demonstrate the need to increase the photometric precision of these measurements.

MAP will provide essential input into studying what is arguably the most profound open question in fundamental physical science today: the nature of the dark energy.

2.3 Towards MAP: Measuring Astronomical Extinction

To measure the monochromatic absolute extinction the UNM MAP Research Group commissioned the Astronomical Lidar for Extinction (ALE, Dawsey *et al.* 2006). This eye-safe elastic lidar operates at 527nm with pulse energy of 79 µJ at 1500 Hz and range resolution of 30m with useful data typically returned from up to 30km. ALE is designed to operate in its most significant mode as data are being acquired by a nearby telescope during a sensibly clear night. It is principally designed as a “clear air” lidar to support astronomical observations.

The key idea to deriving absolute extinction is that the integrated stratospheric Rayleigh return from above about 15km is accurately predictable, principally because of the relative stability of the stratosphere. The stratospheric model used derives from recent sonde measurements. The integrated return provides approximately one million backscattered photons per minute from above 15km, allowing sub-1% measurement of the total tropospheric extinction with one minute cadence. ALE can be pointed near the science field to provide the record of time-dependent extinction experienced by that telescope during its integrations.

A second instrument, the Astronomical Extinction Spectrophotometer (AESoP), an objective spectrometer mounted on a 106mm refractor, provides precise spectrophotometry of bright stars near the ALE field with 1nm resolution from 450nm to 900nm at one minute cadence with S/N > 100 per resolution element. AESoP throughput will be calibrated to NIST irradiance standards, allowing traceable calibration of the instrument. Using bright stars as sources, AESoP will measure the wavelength dependence of extinction, which will be tied to absolute extinction at 527nm, the ALE wavelength.

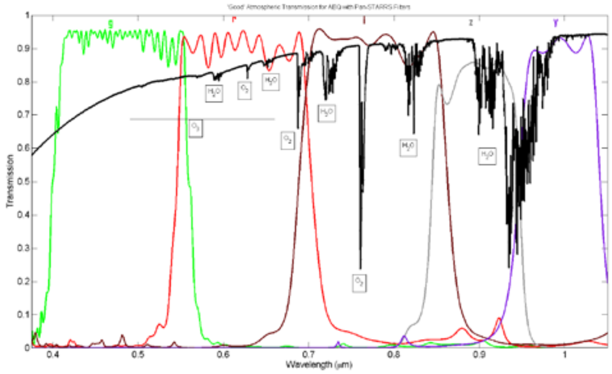

Figure 1 Schematic normalized transmission of the Pan-STARRS filter set and the atmosphere modeled by MODTRAN.

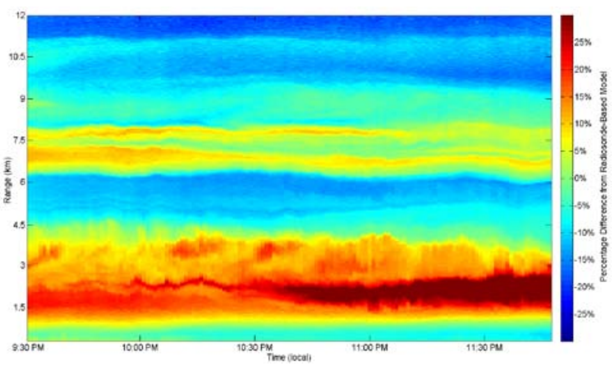

Figure 2 A 2 ¼ hour time-height plot demonstrates the range of time scales for “clear air” atmospheric extinction changes. Significant changes (> 1%) occur on minute time scales.

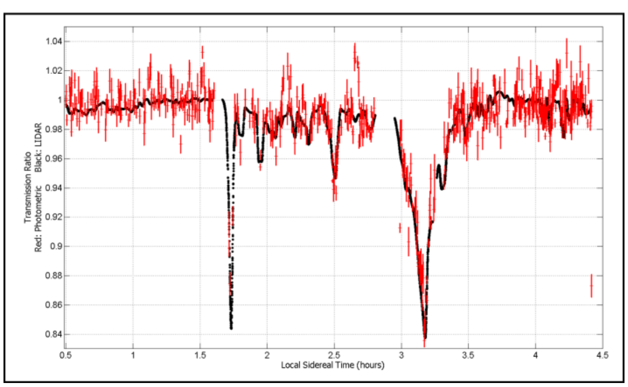

Figure 3 Night-to-night ratio of transmission of the atmosphere measured by ALE (black line) compared to measured stars (red dots with 1σ error bars) demonstrates utility of lidar transmission measurements.

ALE and AESoP provide input data for MODTRAN (Berk *et al.* 2005) and the spectral output from this atmospheric radiative transfer model is used as the interpolated transparency to remove the atmospheric signature. A typical atmospheric transmission model is compared to the Pan-STARRS g, r, i, z, y filter bandpasses in Fig. 1 showing that atmospheric extinction affects all bandpasses, with greatest time variability caused by highly variable water vapor absorption in i, z and y. Significant transparency changes on minute time scales recorded in an ALE time-height diagram for a sensibly clear night are shown in Fig. 2, where vertically resolved fractional departures from a standard atmosphere model are color encoded.

The utility of ALE for measuring transmission corrections is demonstrated in Fig. 3 where the ratio of the absolute monochromatic transmissions measured by ALE at one minute cadence on two consecutive nominally clear nights is plotted as the black curve, and the ratio of V bandpass photometry for matched stars is shown with one standard deviation error bars. While this comparison is limited by the stellar photometric measurement uncertainties, transmission corrections at the sub-1% level for atmospheric transmission greater than 85% are demonstrated.

3.0 Measurement Astrophysics First Steps: A Community Roadmap

Accurate correction for the transmission losses in Earth’s atmosphere and calibration of telescopes to NIST standard detectors to provide accurate spectral irradiance measurements will require significant community efforts in the upcoming decade.

3.1 Real-time Measurement of Atmospheric Transmission

For decades astronomers have corrected for astronomical extinction with insufficient fidelity; for example, using nightly derived mean atmospheric extinction solutions while the atmosphere changes by the minute introduces often unrecognized systematic error. Inferring extinction for any single image or observation by observing stars through the atmosphere is insufficiently precise to obviate the systematic effect of extinction changing on multiple time and angular scales, even with a simultaneously operating ancillary “calibration” telescope. One key realization of MAP astronomers is that precise correction for extinction requires direct, precise, time- and range-resolved observation of Earth’s atmosphere. Experiments currently underway are investigating the appropriate combination of instruments, including monochromatic, multi-frequency and tunable lidar with depolarization and Raman detector channels, as well as spectrophotometers and imaging cameras to sample the airmass through which observations are being made to measure and correct for astronomical extinction.

In the next decade the community will fund research and development of the optimum suite of direct atmospheric remote sensing instruments capable of real-time measurement of atmospheric transmission to better than 1% accuracy. The community will also be called upon to fund deployment of these instrument suites at observatories worldwide.

3.2 Telescope Throughput Calibration

The second astronomical requirement is that precise observations be calibrated to produce accurate radiometric measurements. Stubbs *et al.* (2007) have demonstrated the feasibility of calibrating the wavelength-dependent throughput of astronomical telescopes by providing a tunable monochromatically illuminated flat-field screen and using NIST irradiance standard diodes in the telescope pupil to measure flux. The resulting flat-field data cube (x, y, λ) is applied at consecutive wavelengths across a filter bandpass, for example, to calibrate the image in radiometric units. Applying the wavelength-dependent (and time-dependent) similarly calibrated atmospheric transmission correction allows complete correction for the instrumental signature of the atmosphere and the telescope and its instrument over the bandpass of the observation. This procedure effectively corrects the observations to “outside the Earth’s atmosphere” to use the historical terminology.

In the next decade, research and development of the flat-fielding and illumination techniques required to absolutely calibrate existing and future telescopes will be funded. In addition, once throughput calibration systems are proven, the systems will need to be retrofit to existing telescopes and designed into future telescopes.

3.3 Discipline Support for MAP

MAP will produce instruments, techniques, software and training programs that result in a robust, affordable, integrated suite of instruments for astronomical observatories worldwide. These instruments will accomplish two spectral throughput measurements: the atmospheric transmission and telescope throughput. The goal is to measure the total wavelength-dependent transmission from "space" through the detector with sufficient precision and accuracy that when applied to individual observation made by the supported science telescope(s) the resulting systematic errors associated with the atmosphere and telescope are reduced to well below the noise limit set by photon shot noise in the target and its background. Spectrally-dependent calibration of the telescope to NIST irradiance standards allows calibration of data in physical units of spectral irradiance. The popular expression of the MAP goal is to attain space-based precision and accuracy with ground-based telescopes.

4.0 Interdisciplinary MAP - Atmospheric Physics: Synoptic Upward Surveillance of the Atmosphere

The community has the opportunity and necessity to engage in significant interdisciplinary research on MAP techniques with colleagues in atmospheric physics. The same techniques used to obviate astronomical extinction provide precise, synoptic atmospheric observations of use to the atmospheric physics, climate change and terrestrial energy balance modeling communities. Some of the MAP measurement techniques, for example time-resolved spectrophotometry of bright stars distributed across the celestial sphere, complement techniques developed by atmospheric scientists. In turn, atmospheric science techniques, such as GPS limb measurements and ground-based microwave radiometers will help astronomers measure atmospheric water vapor (Vivekanandan *et al.* 1997). Also, precision measurements of atmospheric optical depth by a High Spectral Resolution Lidar (HSRL) are capable of estimating measurements of extinction (Eloranta, 2005). This interdisciplinary research should be acknowledged, planned, and capitalized on by both communities.

Thus, the highly accurate atmospheric measurements required by astronomy to characterize extinction are also of enormous interest for atmospheric science: the spatial and temporal variations in water vapor, ozone, aerosols, and optically thin clouds (*e.g.* cirrus). These atmospheric constituents directly affect the balance of the Earth's radiation budget and influence subtle but important feedback between Earth's physical and chemical systems that, in turn, have been identified as the dominant sources of error in the prediction of future climate (IPCC 2007). Aerosols, which affect all cloud types, are particularly challenging (Ghan and Schwartz 2007). Water vapor is also critical in the poorly understood exchanges between the upper troposphere and lower stratosphere. Thus the proposed observations needed for astronomy naturally have large impacts on important areas of atmospheric sciences.

The need for networks of atmospheric physics instrumentation coincides well with the requirements of astronomical measurement suites deployed around the world. Certainly an atmospheric monitoring network based at astronomical observatories, operating principally at night but in the future perhaps also during the day, will both complement and supplement the networks deployed by the atmospheric science communities. The proposed measurements at mountain tops would complement and enrich the ongoing DOE-sponsored 24/7 observations conducted by the Atmospheric Radiation Measurement (ARM) program (Ackerman and Stokes 2003). NASA's ground-based AeroNet web of sun photometers will also benefit greatly as they track the aerosol globally, but not at night (Holben *et al.* 1998). NASA's current and future satellite program (NRC 2007) will gain invaluable ground truth for remote sensing product validation that will be inherited by NOAA for its operational weather satellite program.

5.0 Summary: MAP Research Plans and Objectives

The long-range vision of MAP is to enable routinely photon noise dominated observations with ground-based telescopes. A plan to attain this objective necessitates a series of steps.

MAP will produce instruments, techniques, software and training programs that result in a robust, affordable, integrated suite of instruments for astronomical observatories worldwide. These instruments will accomplish two spectral throughput measurements: the atmospheric transmission and telescope throughput. The goal is to measure the total wavelength-dependent transmission from “space” through the detector with sufficient precision and accuracy that when applied to individual observations made by the supported science telescope(s) the resulting systematic errors associated with the atmosphere and telescope are reduced to well below the noise limit set by photon shot noise in the target and its background. Spectrally-dependent calibration of the telescope to NIST irradiance standards allows calibration of data in physical units of spectral irradiance.

Astronomers must know the spectral transmission of Earth’s atmosphere integrated through the airmass affecting the science telescope. The instruments and techniques to measure the spectral transmission of the atmosphere with sufficient precision and accuracy to reduce the errors associated with time variability of the atmospheric transmission to sub-1% levels and approach the photon noise limit of the science exposure will be devised. Using stars as sources to make “absolutely” calibrated spectral transmission measurements of the atmosphere, MAP will establish the observed stars as spectrophotometric standards traceable to NIST standards, itself exceedingly valuable product for astrophysics. It should be noted the proposed observation need for astronomy naturally promotes significant interdisciplinary research in the areas of climate change and Earth’s radiation budget studies.

Stubbs and Tonry (2006, 2007b) and their colleagues have devised techniques for measuring the calibrated spectral throughput of astronomical telescopes, and these techniques can be applied to new and existing radiation-detecting instruments that monitor the atmosphere. Using a tunable laser as the source, they have demonstrated that the necessary flat-fielding procedure for removing the instrumental signature from area-format data can be used to calibrate the telescope end-to-end in units of spectral irradiance. These techniques will be generalized and improved to be used with other telescopes.

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