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BALLOON- AND SATELLITE-MOUNTED LIGHT SOURCES AS PHOTOMETRIC CALIBRATION STANDARDS FOR GROUND-BASED TELESCOPES

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ABSTRACT

Significant and growing portions of systematic error on a number of fundamental parameters in astrophysics and cosmology, especially those related to dark energy, are due to uncertainties from absolute photometric and flux standards. A path toward achieving major reduction in such uncertainties may be provided by well-calibrated light sources above the atmosphere, resulting in improvement in the ability to precisely characterize the magnitude scale and atmospheric extinction, and thus helping to usher in the coming generation of precision results in cosmology. Future instrumentation is briefly outlined.

Subject headings: balloons, instrumentation: photometers, cosmology: large-scale structure of universe

1. INTRODUCTION

While our understanding of the Universe has changed and improved dramatically over the past 25 years, the improvement of our knowledge of absolute spectra and flux from standard calibration sources, upon which the precision of measurements of the expansion history of the Universe [Albrecht *et al.* (2006)], and of stellar and galactic evolution [*e.g.* Eisenstein *et al.* (2001)] are based, has been far slower and not kept up with reduction of other major uncertainties. As a result, uncertainties on absolute standards now constitute one of the dominant systematics for measurements such as the expansion history of the Universe using type Ia supernovae [*e.g.* Wood-Vasey *et al.* (2007), Astier *et al.* (2006), Knop *et al.* (2003)], and a significant systematic for measurements of stellar population in galaxy cluster counts [Kent *et al.* (2009)], [Koester *et al.* (2007)], and upcoming photometric redshift surveys measuring growth of structure [Connolly *et al.* (2006)]. As shown in, *e.g.*, Fig. 1, future surveys, such as those by JDEM and LSST, will be limited **not by supernova statistics, but by photometric systematic uncertainty** [Huterer *et al.* (2004)], [Kim *et al.* (2004)]. There are prospects for improvement in uncertainties from standard star flux and spectra [Kaiser *et al.* (2008)], but the traditional techniques of measurement of standard stellar flux from above the atmosphere suffer from basic and inherant problems: the variability of all stellar sources, and the difficulty of creating a precisely calibrated, cross-checked, and stable platform for observation above the Earth's atmosphere.

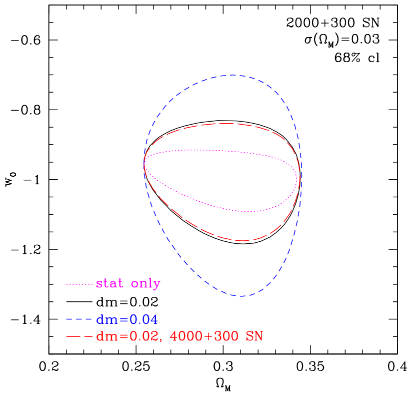

FIG. 1.— Plot from Kim *et al.* (2004) showing the that uncertainty from photometry is, by far, the dominant uncertainty on the measurement of w of dark energy in upcoming surveys.

The presence of an absolute flux standard in orbit above the Earth's atmosphere could provide important cross-checks and potential significant reduction of photometric and other atmospheric uncertainties for measurements that depend on such calibration. For calibration of telescope optics and detector characteristics, authors [Stubbs *et al.* (2006)] have both conceived of and used a wavelength-tunable laser within present and upcoming telescope domes as a color calibration standard. Although a wavelength-tunable laser calibration source in orbit [Albert *et al.* (2006)] does not exist yet, at present there is a 532 nm laser in low-Earth orbit pointed toward the Earth's surface, with precise radiometric measurement of the energy of each of the 20.25 Hz laser pulses, on the CALIPSO satellite, launched in April 2006 [Winker *et al.* (2009)]. We have collected data from a portable network of seven cameras and two calibrated photodiodes, taken during CALIPSO flyovers on clear days in various locations in western North America. The cameras and photodiodes respectively capture images and pulses from the eye-visible green laser spot at the zenith during the moment of a flyover. Using precise pulse-by-pulse radiometry data from the CALIPSO satellite, we have compared the pulse energy received on the ground with the pulse energy recorded by CALIPSO. The ratio determines the atmospheric extinction at 532 nm at the zenith, but the precision is limited by atmospheric scintillation due to the extremely short pulse duration of the laser.

For calibration of the full visible spectrum, a broadband source is required. Major developments in stable, long-lifetime, high-efficiency, broad-spectrum light sources in recent years have made it possible to consider a calibrated point source in space as a reference for astronomy (and additionally Earth observation and climate studies). We propose the development of a calibrated source that is suitable for this purpose, and a regimen of testing and observation of the light source in the laboratory and on a high-altitude balloon.

2. LIGHT SOURCES ABOVE THE ATMOSPHERE

Throughout history prior to 1957, the only sources of light above the Earth's atmosphere were natural in origin: stars, and reflected light from planets, moons, comets, etc. Natural sources have of course served extremely well in astronomy: through understanding the physical processes governing stellar evolution, we are now able to precisely understand the spectra of stars used as calibration sources. Nevertheless, in all stars the vast bulk of material, and the thermonuclear processes that themselves provide the light, lie beyond our sight below the surface of the star. Superb models of stellar structure are available, but uncertainties of many types always remain.

Since the launching of the first man-made satellites, a separate class of potential light sources in space has become available. Observable light from most satellites is primarily due to direct solar reflection, or reflection from Earth's albedo. While providing a convenient method of observing satellites, this light is typically unsuitable for use as a calibrated light source due to large uncertainties in the reflectivity (and, to a lesser extent, the precise orientation and reflective area) of satellites' surfaces. Reflected solar light has, however, been successfully used as an absolute infrared calibration source by the Midcourse Space Experiment (MSX), using 2 cm diameter black-coated spheres ejected from the MSX satellite, whose infrared emission was monitored by the instruments aboard MSX [Price *et al.* (2004)]. This technique proved highly effective for the MSX infrared calibration; however, the technique is not easily applicable to measuring extinction of visible light in the atmosphere.

Many satellites have retroreflective cubes intended for use in satellite laser ranging. Reflected laser light from retroreflectors is critical for distance measurements using precise timing; however, like solar reflection, retroreflected laser light unfortunately also suffers from uncertainties in the reflectivity of the cubes, and in reflectivity as a function of incident angle, that are too large to provide a means of measuring atmospheric extinction [Minott (1974)]. Thus we are left with dedicated light sources aboard satellites themselves as the sole practical means of having a satellite-based visible light source for calibration of ground-based telescopes.

Many satellites carry some means of producing observable visible light, for self-calibration purposes or otherwise. The Hubble Space Telescope is one of many satellites carrying tungsten, as well as deuterium, lamps for absolute self-calibration purposes [Pavlovsky *et al.* (2001)]. Lamps for self-calibration are not limited to space telescopes for astronomy; earth observation and weather satellites also commonly use internal tungsten lamps as calibration sources [Nithianandam *et al.* (1993)]. Such internal calibration lamps are typically limited by the fact that they can degrade individually, and can be compared only with astronomical sources after launch, leaving stellar light as the only practical way to "calibrate the calibration device." Thus, such devices typically provide a cross-check rather than the basis for a true absolute irradiance calibration, or provide a means for a separate calibration, such as flat-field [*e.g.* Bohlin and Gilliland (2004)]. Furthermore, present-day internal calibration lamps aboard satellites are certainly not intended for, nor are capable of, a direct calibration of the atmospheric extinction that affects ground-based telescopes.

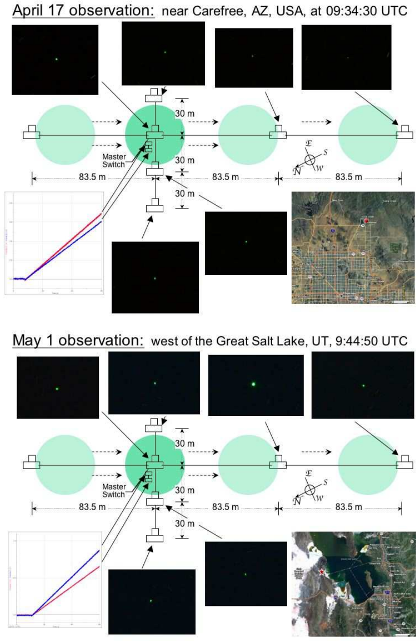

FIG. 2.— Multi-camera observations of pulses from the CALIPSO laser taken on (top) Apr. 17 and (bottom) May 1, 2007 in the southwestern U.S.

However, a satellite-based absolute calibration source for ground-based telescopes is not technically prohibitive. As an example, a standard household 25-watt tungsten filament lightbulb (which typically have a temperature of the order of 3000 K and usually produce approximately 1 watt of visible light between 390 and 780 nm) which radiates light equally in all directions from a 700 km low Earth orbit has an equivalent brightness to a 12.5-magnitude star (in the AB system, although for this approximate value the system makes little difference). In general, the apparent magnitude of an orbiting lamp at a typical incandescent temperature which radiates isotropically is approximately given by

$$m \approx -5.0 \log_{10} \left(\frac{\left(\ln \left(\frac{P}{1 \text{ watt}} \right) \right)^3}{h} \right) + 5.9, \qquad (1)$$

where P is the power of the lamp in watts, and h is the height of the orbit in kilometers. The dominant uncertainties in the precise amount of light received by a ground-based telescope from such an orbiting lamp would stem from degradations of both the lamp and the power

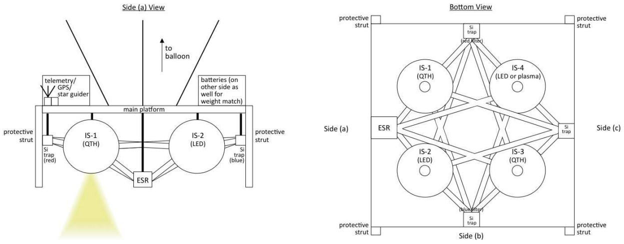

FIG. 3.— (Left) Side view and (right) Bottom view of high-altitude balloon payload concept. Four integrating spheres, with internal quartz-tungsten-halogen (QTH), LED, or plasma lamps are used as sources, and an electrical substitution radiometer (ESR) and silicon trap photodiodes provide onboard power monitoring. Only one source would be visible at a time; shutters would close off the light paths to all but one of the sources at any given time.

source over the lifetime of the lamp, the comparison of the spectrum of the lamp with that of typical stars, background from reflected earthshine, sunshine, moonshine, or starlight from the surface of the satellite itself, and potential deviations from perfect isotropic output of the light from the lamp.

The uncertainty on the apparent magnitude of an orbiting light source stemming from uncertainties in radiometrically-monitored power would be limited by the precision of current radiometer technology. Modern solar radiometers, using electrical substitution radiometry, can achieve a precision of approximately 100 parts per million [Kopp *et al.* (2005)].

The uncertainties considered above assume that the exposure time is long compared with the coherence time of the atmosphere. With short exposures, or in the case of a light source that either quickly sweeps past, or is pulsed, atmospheric scintillation can play a major role in uncertainty in apparent magnitude. For very short (sub-millisecond) exposure times in otherwise idealized conditions, for small apertures $D <\sim 5$ cm, the relative standard deviation in intensity $\sigma_I \equiv \Delta I/\langle I\rangle$, where ΔI is the root-mean-square value of I, is given by the square root of

$$\sigma_I^2 = 19.12\lambda^{-7/6}\int_0^\infty C_n^2(h)h^{5/6}dh, \tag{2}$$

where λ is optical wavelength (in meters), $C_n^2(h)$ is known as the refractive-index structure coefficient, and h is altitude (in meters) [Tatarski (1961)]. Large apertures $D >\sim 50$ cm have a relative standard deviation in intensity given by the square root of

$$\sigma_I^2 = 29.48D^{-7/3}\int_0^\infty C_n^2(h)h^2dh \tag{3}$$

Tatarski (1961). The values and functional form of $C_n^2(h)$ are entirely dependent on the particular atmospheric conditions at the time of observation, however a relatively typical profile is given by the Hufnagel-Valley form:

$$C_n^2(h) = 5.94\times10^{-53}(v/27)^2h^{10}e^{-h/1000}+ \\ 2.7\times10^{-16}e^{-h/1500}+Ae^{-h/100}, \tag{4}$$

where A and v are free parameters [Hufnagel (1974)]. Commonly-used values for the A and v parameters, which represent the strength of turbulence near ground level and the high-altitude wind speed respectively, are $A = 1.7\times10^{-14}$ m$^{-2/3}$ and $v = 21$ m/s [Roggemann and Welsh (1996)]. Using these particular values, for a small aperture, the relative variance σ_I^2 would be expected to be approximately 0.22 for 532 nm light, which is not far from experimental scintillation values for a clear night at a typical location [*e.g.* Jakeman *et al.* (1978)]. For a single small camera, this is an extremely large uncertainty. Other than by increasing integration time (not possible in the case of a pulsed laser source), the only way to reduce this uncertainty is to significantly increase the viewing aperture.

In addition to such issues with a pulsed source, precisely pointing a directed source such as a laser (or moving telescopes to intersect the path of the beam) can be a major challenge. Thus the use of isotropic, continuous light sources (lamps) is a favourable approach. We therefore intend to test a lamp-based source for use on a high-altitude balloon (and, following satisfactory results and testing, on a future satellite).

3. INSTRUMENTATION

We intend to construct a high-altitude balloon payload similar to that in Fig. 3, for overflight of and observation at major observatories, to provide photometric calibration across the visible and near-infrared spectrum at the 0.1% uncertainty scale or better.

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