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Absolute flux calibration of stars: calibration of the reference telescope

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Abstract

Absolute stellar photometry is based on 1970s terrestrial measurements of the star Vega with instruments calibrated using the Planckian radiance from a Cu fixed-point blackbody. Significant advances in absolute radiometry have been made in the last 30 years that offer the potential to improve both terrestrial and space-based absolute stellar photometry. These advances include the development of detector-based radiometry utilizing spectrally tunable laser sources and improved atmospheric transmittance modelling and characterization. We describe the applications of these new technologies for ground-based spectral irradiance measurements of standard stars at wavelengths ranging from 0.35 µm to 1.7 µm.

1. Introduction

Current and anticipated uncertainty requirements for astronomical and astrophysical applications of absolute stellar photometry motivate a re-examination of the fundamental measurements underpinning the field. In essence, all absolute stellar photometry is based on 1970s measurements of the flux from α Lyr (Vega) over a limited range of wavelengths, mostly visible, calibrated against terrestrial standards [1–3]. These measurements have been compared using a stellar flux model for Vega by Mégessier, who recommends a best value of $3.46 \pm 0.025 \times 10^{-11}$ (W m^{-2} nm^{-1}) for the spectral irradiance of Vega at 555.6 nm, with a stated uncertainty of 2%, $k = 1$ [4]. Extrapolation of the Vega spectral calibration to other wavelengths (stellar radiometry) or to broadband filters (stellar photometry) is only accurate if the stellar physics is well understood. The use of such models as a foundation for absolute stellar photometry is challenged by recent observations [5] which revealed large asymmetries in the spatial distribution of Vega's visible emission, not considered in Vega stellar atmospheric models, attributed to rapid stellar rotation and alignment of the rotation axis along the line of sight. Further challenging the models are flux measurements which show Vega to be brighter in the infrared than predicted. An examination of Vega visible flux determinations finds a 4.4% variation in the measurements [4], a variation significantly larger than the estimated combined standard uncertainties of the measurements.

Astronomical uncertainty requirements are driven in part by the investigation of type-Ia supernovas as probes of the expansion history of the universe [6, 7]. For type-Ia supernova measurements for cosmological studies, an absolute spectral radiometric uncertainty of better than 1% ($k = 1$) is required from 350 nm to 1.7 µm. For example, the proposed SuperNova/Acceleration Probe (SNAP) space telescope [8] will depend upon the astronomy community to provide a large set of standard stars measured with an absolute photometric uncertainty of better than 1% (0.01 mag) over this range. The demanding uncertainties required to support the SNAP science goals are achievable in principle as numerous stars have photometric stabilities better than 1% [9].

Sky surveys, such as the Sloan Digital Sky Survey (SDSS), require accurate photometric measurements to maximize the value of the data to present and future users. The SDSS has a typical photometric zero-point calibration error of 0.01 mag in the g, r and i bands, 0.02 mag in the z band and 0.03 mag in the u band within the $u'g'r'i'z'$ photometric system [10]. Point-spread function modelling errors, atmospheric transmittance and stray light are some of the issues identified by the authors that can increase the photometric uncertainty to as much as 0.05 mag.

In this work, an approach is proposed for the ground-based absolute spectral irradiance calibration of astronomical telescope systems. Sources to be used in the calibration include laser- and monochromator-based tunable systems and new, synthetic sources based around digital micro-mirror device

(DMD) technology. Finally, a new calibration facility for telescope systems is described.

Utilizing these new approaches, along with improved atmospheric modelling, we are re-examining the 1970s spectral flux calibrations of Vega to validate or improve the previous results with the goal of reducing the measurement uncertainties in absolute stellar photometry. These approaches build upon the long and rich history of stellar photometry and spectrophotometry [11–14], complementing and extending recent research targeting 1% (0.01 mag) absolute photometric measurements of stars from ground-based telescopes [15].

2. Laser-based characterization

Many standard stars have radiance temperatures significantly higher than those available from blackbody calibration standards. For example, the radiance temperature of Vega is 9300 K, while the maximum thermodynamic temperature of blackbodies at the National Institute of Standards and Technology, USA (NIST) is 3400 K. Spectral mismatches between the flux distribution of a star and that of the blackbody calibration standard can lead to significant errors in the measured absolute irradiance of the star, primarily due to unaccounted for spectrally dependent stray or scattered light in the telescope and spectrograph or spectral filter system. These effects can be particularly severe at shorter wavelengths where the amount of radiation from the terrestrial calibration standard is low due to the rapid fall-off in the Planck function. Under such conditions, even a small amount of long wavelength contamination or out-of-band leakage can lead to significant error. Such stray light issues were of concern in the studies of Oke and Schild [1] and Hayes *et al* [2] in the 1970s and continue to be of concern to this day.

Spectrally dependent out-of-band stray light can be quantitatively assessed using techniques developed in the NIST facility for Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources (SIRCUS), a facility designed to measure instrument spectral irradiance and radiance responsivities with low uncertainty [16]. SIRCUS uses laser-illuminated integrating spheres to generate uniform radiation fields with narrow spectral distributions throughout the UV and NIR regions. This irradiance distribution is then calibrated using high-level irradiance transfer standards that have been calibrated against an electrical substitution cryogenic radiometer [17]. The laser systems are sufficiently compact, fitting on a 0.9 m × 1.8 m (3′ × 6′) laser table, such that they can be transported to other sites, for example large telescope facilities and calibration laboratories.

2.1. Spectrograph stray light correction algorithm

Correction algorithms based on the instrument characterization can be applied to reduce systematic errors in stellar photometry. For filter instruments using standardized filter functions, spectral mismatch correction algorithms developed for photometry are appropriate [18]. For spectrographs, a new algorithm has been developed to correct spectrographs for scattered light [19, 20]. The algorithm reduces errors caused by stray light by one to two orders of magnitude. Extended to two dimensions, the stray light correction algorithm provides a correction for the finite point-spread in stellar images.

3. Atmospheric transmittance

Accounting for the atmospheric attenuation along the line of sight from the telescope to the star is expected to be the dominant uncertainty component in stellar calibrations in many spectral regions. The major contributing components to atmospheric absorption are molecular (telluric) absorption, aerosols and Rayleigh scattering. Molecular lines (ozone below 360 nm and around 600 nm; O_2 at 762 nm; H_2O at 720 nm, 810 nm, 940 nm, 1100 nm, 1400 nm and 1900 nm; and CO_2 at 1400 nm and 2000 nm) can be mostly avoided in the visible/NIR or can be measured. Rayleigh scattering can be calculated and is relatively constant. Aerosols are variable but can be measured with light detection and ranging (LIDAR).

In the simplest approach, if stars are measured with enough accuracy outside the atmosphere using a retrievable instrument [21], they can be used to measure the atmospheric transmission in that particular direction of the sky. By letting the Earth rotate slightly, another star will enter that atmospheric column and can be calibrated. By transferring the calibration to neighbouring stars, most of the stars can be calibrated, up to a certain magnitude.

4. Absolute calibration: proposed approach

Figure 1 illustrates the major features of the proposed calibration approach at telescope observatories. Radiant flux from a light source is introduced into the integrating sphere from an optical fibre. A Lambertian output beam exits the sphere through a small aperture (∼1 mm diameter) whose diameter is several times smaller than that of the integrating sphere. A monitor photodiode on the sphere enables the determination of the sphere throughput such that the ratio between the input radiant flux and the output spectral irradiance can be found. Sources available for calibrating and validating the performance of observatory telescope systems include tunable lasers, supercontinuum-source monochromator systems and spectrally tunable DMD systems.

The input radiant flux and the spectral irradiance output of the sphere can be adjusted to obtain the optimal signal-to-noise ratios. The irradiance distribution follows a $1/r^2$ law. Vega delivers about 3.46×10^{-15} W cm^{-2} nm^{-1} at 555.6 nm. Therefore, if the sphere-to-telescope distance is 500 m, the irradiance at 1 m from the sphere should be about 1 nW cm^{-2} (if the spectrograph resolution is 1 nm), an easily obtainable and measurable quantity. Transfer standard irradiance detectors (typically Si trap detectors for 300 nm to 1000 nm [16] and InGaAs detectors for 1000 nm to 1700 nm) are positioned between the sphere and the telescope.

The distances d_1 and d_t are measured either directly or by using the inverse distance squared dependence of the irradiance. The transfer standards measure the output of the sphere, followed by the telescope/spectrograph. Atmospheric corrections for a short horizontal path should be small at most

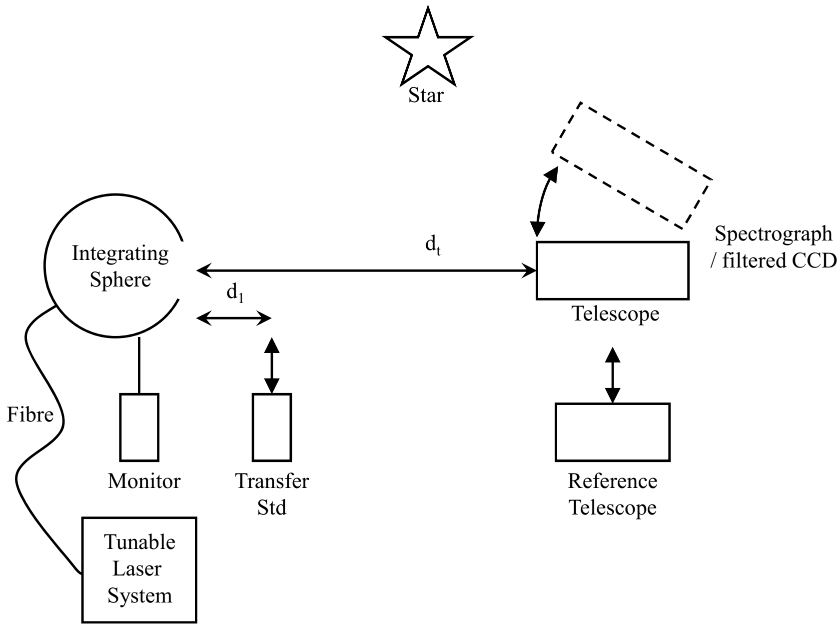

Figure 1. Schematic of on-site telescope calibration.

wavelengths and as such can be modelled with low uncertainty. The modelling can be validated by varying the distance d_1 or by looking for spectral features in the atmospheric transmittance that are not part of the telescope spectrograph responsivity. The wavelength is changed and the process is repeated until the full spectral irradiance responsivity for the telescope has been measured. The now-calibrated telescope then measures the spectral irradiance from the star at the telescope aperture.

Alternatively, a portable telescope can be calibrated for spectral irradiance responsivity in the laboratory and then taken out to the site of the main telescope. The two telescopes can be placed side by side, each nearly the same, known distance from the laser-irradiated integrating sphere source. Since the portable telescope has been calibrated for spectral irradiance responsivity, the spectral irradiance from the laser-irradiated sphere can be determined at the input plane of the on-site telescope for a substitution calibration of the main telescope. With a substitution calibration, the on-site horizontal atmospheric transmittance corrections are eliminated. However, the stability of the spectral irradiance responsivity, from the laboratory out into the field, of the portable telescope would need to be assessed. At least initially, both techniques would be used at the same site to validate the irradiance responsivity calibration of the astronomical telescope and to establish the uncertainties in the measurements.

After the telescope has been calibrated with a narrow-band tunable source, an artificial star will be generated with the spectrally tunable DMD source [22]. This source can approximate most stellar spectra and can be used to validate the absolute calibration of the telescope system. In the absence of the full stray light characterization of the telescope spectrograph, the similarity of the spectrum generated by the DMD source and an actual star will significantly reduce stray light artefacts that are often an issue with blackbody calibrations.

5. Telescope calibration facility (TCF)

In addition to the irradiance standard detectors, figure 1 shows a reference telescope situated next to the primary telescope, viewing either the integrating sphere or a star of interest. The reference telescope will be calibrated before and after deployment to a field site in a new TCF recently developed at NIST (figure 2). The TCF allows for precision calibrations under laboratory controlled conditions. The facility consists of a source laboratory with a 40 m long, 0.9 m^2 tunnel that connects to a 40 m measurement hall. A telescope under test is typically placed in the measurement hall in line with the tunnel and focused on the aperture of an integrating sphere located in the source laboratory. A total source to detector distance of up to 80 m is feasible in this facility.

In addition to the TCF, we have identified a site within NIST to simulate a field campaign configuration. This site will enable us to establish proper calibration protocols before travelling to a remote telescope observatory site. Specifically, a telescope will be placed in a van in the parking lot and will view an irradiance source located at a meteorological station on a rooftop 500 m away.

As a preliminary operational test of the TCF facility, an 80 mm refracting telescope (Stellarvue[3]) with a CCD detector (Santa Barbara Instrument Group; ST-8XME[3]) was characterized and calibrated in the facility. For this calibration, the source laboratory contained a set of tunable and fixed wavelength laser systems that span a wavelength range from below 350 nm to beyond 1700 nm. The lasers were fibre coupled into an integrating sphere centred at one end of the tunnel. A calibrated silicon irradiance detector was used to determine the irradiance from the sphere. A monitor detector

[3] Certain commercial equipment, instruments or materials are identified in the article to foster understanding. Such identification does not imply recommendation or endorsement by NIST, and it does not imply that the materials or equipment are necessarily the best available for the purpose.

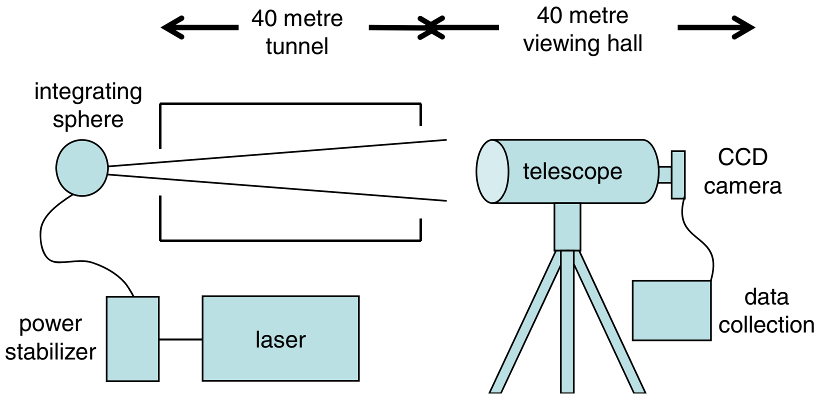

Figure 2. Schematic of telescope calibration facility.
(This figure is in colour only in the electronic version)

on the sphere was used to stabilize the laser power and to correct for any drift in laser power between the source calibration and subsequent telescope measurements.

5.1. *Laser speckle*

Illumination of a surface with a coherent laser source leads to a speckled appearance of the reflected light, and the interior of an integrating sphere is no exception. This speckle is resolved by the CCD camera and has the potential to be a large contributor to the overall uncertainty budget. Images taken at 800 nm with our titanium-doped sapphire (Ti : S) laser, not mode-locked, yielded a standard deviation of 3.7% in the counts/pixel. If the laser is mode-locked (picosecond pulses yield larger spectral bandwidth), the standard deviation is reduced to 0.54%. A similar reduction can be achieved by looping the optical fibre in a sonication bath. This compares well with the 0.4% standard deviation expected from counting statistics at this signal level, and similarly can be reduced by averaging images.

5.2. *CCD characterization*

To characterize the telescope–CCD system we measure the linearity of the CCD as a function of flux, the accuracy of the exposure time and the absolute responsivity of the CCD–telescope system. The linearity was measured at 514.5 nm using an argon ion laser by taking a series of 1 s images as the laser power was varied. At each point, the resulting irradiance was measured with the silicon detector and a series of images was taken. Multiple images were taken and averaged to reduce the uncertainties associated with counting statistics. The data points containing fewer than 25 000 counts were fitted versus the monitor voltage to a line. The fit yields a 61 ± 5 count offset. The plot in figure 3 shows the normalized responsivity versus CCD counts after subtracting the 61 count offset. We find that the CCD is linear to within 0.1% up to 25 000 counts with a 1% loss by 45 000 counts. To assess the exposure accuracy, the irradiance was fixed and exposures ranging from the camera minimum of 0.12 s to 3 s were taken. The resulting number of counts was corrected for the non-linearities in the CCD. These data were then fitted versus exposure time to a line. The fit indicates a systematic $0.003\ \mathrm{s} \pm 0.003\ \mathrm{s}$ overexposure.

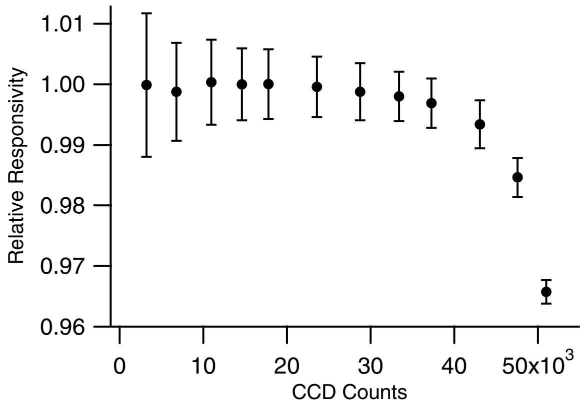

Figure 3. Responsivity of CCD pixels with varying flux for fixed integration time.

5.3. *CCD–telescope responsivity*

To measure the absolute responsivity of the CCD–telescope system, measurements were made as a function of wavelength using a tunable Ti : S laser from 1000 nm to 680 nm, helium : neon lasers at 633 nm, 612 nm, 594 nm and 543.5 nm, argon ion laser lines at 514.5 nm and 488 nm and a doubled Ti : S from 370 nm to 455 nm. At each wavelength the irradiance of the integrating sphere was measured with a calibrated silicon detector. The sphere was imaged and the CCD counts and exposure times were corrected as necessary. The sphere-to-detector distance and the sphere-to-telescope distance were measured using a Leica[3] laser range finder and used to compute the irradiance at the telescope. The responsivity of the telescope–CCD system is shown in figure 4.

6. Summary

We have described two different approaches to calibrate stars, both in magnitude and in colour. One approach uses a transfer standard irradiance meter while the second uses a reference telescope. The reference telescope can be equipped with either a spectrograph or a broadband detector. Sources introduced into the integrating sphere include both narrow-band sources, e.g. lasers and monochromators, as

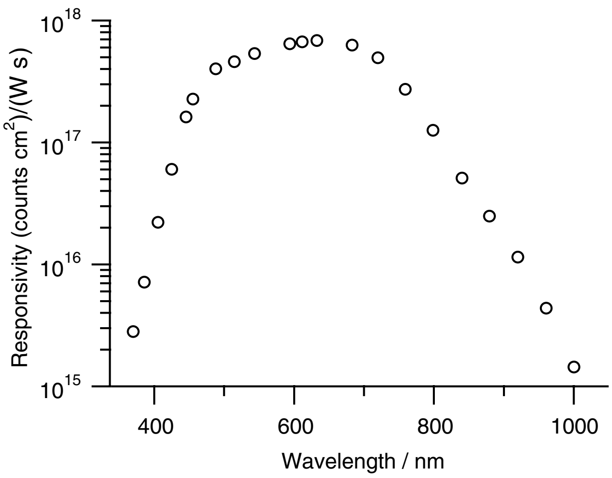

Figure 4. Response of CCD to irradiance at telescope aperture as a function of wavelength.

well as broadband tunable sources, e.g. the DMD source, to characterize and calibrate astronomical filter bands and telescopic spectrographs absolutely for spectral irradiance responsivity. The two calibration methods complement each other and can be done simultaneously, providing redundancy in the calibration, which may be important for establishing the uncertainty in the absolute calibration.

A TCF has been developed at NIST to calibrate the reference telescope and, potentially, other telescopes, including flight instruments. Flight instruments, for example instruments on the rocket-borne ACCESS program [21], may be able to calibrate stars outside the atmosphere with enough accuracy that they can become primary standard calibration stars. These stars may subsequently be used to measure the atmospheric transmission in a particular direction of the sky. By letting the Earth rotate slightly, another star will enter that atmospheric column and the calibration of the primary star can be transferred to a secondary star. By transferring the calibration to neighbouring stars, a reference suite of the stars can be calibrated, up to a certain magnitude.

The penultimate goal of the program is to provide new calibrations of a suite of standard stars with uncertainties lower than those achievable in the past. The expectation is that these lower stellar uncertainties will aid astronomical science activities, for example by leading to lower uncertainties in the different models for the cosmological constant, giving astronomers additional insight into models that ultimately determine the fate of the universe.

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