Spectroradiometric Calibration of Bright Stars, Vega and Sirius

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We discuss our ground-based approach to making sub 1% spectroradiometric measurements of the top-of-the atmosphere flux from bright stars. We will present results from measurements of Vega and Sirius made from Mount Hopkins, AZ. We present our calibration strategy and discuss the challenges of making high quality radiometric measurements outside of a controlled laboratory environment. We describe the characterization and calibration of our spectrographs that are required for high-accuracy measurements and the development of an uncertainty budget.

INTRODUCTION

The earliest and most widely cited measurements of stellar spectral flux were made on Vega (α-Lyr) by Hayes, Latham, and Hayes at Mt. Hopkins in southern Arizona in the 1970's [1]. Although the details of our calibration differ, the basic strategy is very similar to that used for these measurements.

There are two main parts to our calibration strategy for making top-of-the-atmosphere measurements using a ground-based telescope. The first is to calibrate the telescope+spectrograph by observing a calibration source of known spectral flux located on the ground. This source is calibrated in the field with a reference spectrograph. This allows us to put an absolute spectral responsivity scale on our telescope+spectrograph system. The second is to use that telescope to observe the astronomical target at a variety of air masses as it transits the sky. This allows the use of a Langley analysis which exploits the Beers-Lambert-Bouger Law to calculate the spectral atmospheric extinction and correct ground-based measurements to top-of-the-atmosphere spectral flux.

CALIBRATION

The calibration source is a 50 mm diameter, lamp-illuminated integrating sphere. To calibrate the sphere in the field we use a reference spectrograph with an irradiance head. This in turn is calibrated to an SI-traceable FEL lamp in the lab before and after deployment to the field [2]. Figure 1 shows the calibration reproducibility over multiple field deployments. In addition, the spectrograph response linearity was characterized using a beam conjoiner system, and a thermal chamber was used to measure effect of temperature on the wavelength solution and responsivity. Stray light response was measured using the NIST Spectral Irradiance and Radiance Calibration using Uniform Sources (SIRCUS) tuneable lasers and Zong stray light correction algorithm [3,4].

OBSERVATION

The observing instrument is a 107 mm refracting telescope, shown in Figure 2, mounted on a computerized German equatorial mount, with an optical fibre at the focus leading to the spectrograph. Prior to the optical fibre, an optical cross with a 90/10 beamsplitting cube allows 90% of the light to be focused directly into the fibre while the other 10% goes to a guide camera that keeps the star centred on the fibre. A camera looking at the reflected light from the fibre tip and beamsplitter is used for the initial centring of the star on the fibre.

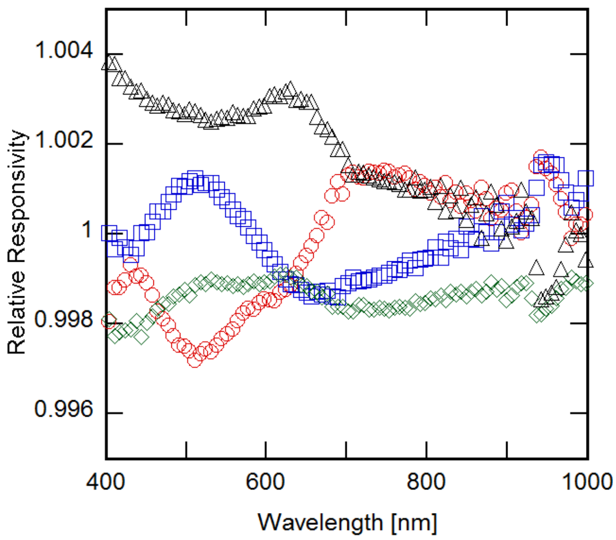

Figure 1. Relative responsivity of calibration spectrometer over multiple deployments. Nov 2012 (blue squares), Jan 2013 (red circles), July 2013 green diamond, and June 2014 (black triangles).

Figure 2 The stellar observation telescope on its mount. On the right side are the red cameras for aligning and guiding on the target star and the orange optical fibre.

The telescope tracks the target as it transits the sky and records spectra once per minute. The autoguiding camera keeps the target centred on the same place on the fibre. The calibration source is located approximately 100 m from the observing telescope and the irradiance is measured by the reference spectrograph placed 0.5 m from the source. The measurement telescope observes the source either immediately before or after making stellar measurements. The inverse square law is used to transfer the reference spectrograph calibration to the telescope with a small correction for the atmospheric extinction along the path from the source to the telescope. We have tested this calibration scheme by verifying the inverse square law in our Telescope Calibration Facility [5].

ANALYSIS

We use a Langley extrapolation to correct our ground based measurements to top-of the-atmosphere stellar flux. Observations at different zenith angles go through an amount of atmosphere or airmass proportional to the secant of the angle. If the optical properties of the atmosphere stay constant over the course of the observations a valid extrapolation is possible. Even at a mountain top observatory, relatively few nights yield a stable atmosphere, but those that do yield reproducible spectral flux. In Figure 3, we show a comparison to one such night to the model spectrum of Vega in the Hubble Space Telescope CALSPEC data base [6]. This atmosphere model of Vega is a Kurucz at T_{eff}=9550 K [7].

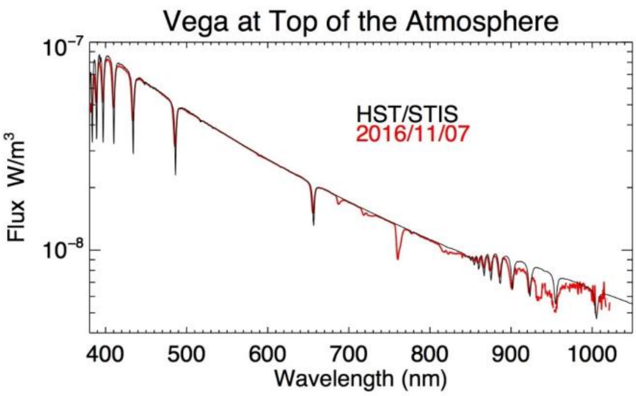

Figure 3 Comparison of the Vega spectral irradiance measured at Mt. Hopkins on Nov. 7, 2016 compared to the HST.

CONCLUSIONS

We are able to transfer an SI traceable irradiance scale in the field using a well characterized spectrograph. This enables SI traceable, top-of-the-atmosphere spectral flux measurements of bright stars, Vega and Sirius.

REFERENCES

1. D.S. Hayes et al., Measurements of the Monochromatic Flux From Vega in the Near-Infrared, Astrophysical Journal, 197, 587-592, 1975.
2. H.W. Yoon et al., FASCAL 2: a New NIST Facility for the Calibration of the Spectral Irradiance of Sources, Metrologia, 40, S30-S34, 2003.
3. Y.Q. Zong et al., Simple Spectral Stray Light Correction Method for Array Spectroradiometers, Applied Optics, 45, 1111, 2006.
4. S.W. Brown et al., Facility for Spectral Irradiance and Radiance Responsivity Calibrations Using Uniform Sources (SIRCUS), Applied Optics, 45, 8218-8237, 2006.
5. A.W. Smith et al., Absolute Flux Calibration of Stars: Calibration of the Reference Telescope, Metrologia, 46, S219-S223, 2009.
6. Bohlin, R.C. et al., Techniques and Review of Absolute Flux Calibration from the Ultraviolet to the Mid-Infrared, PASP, 126, 711, 2914.
7. Bohlin,Hubble Space Telescope CALSPEC Flux Standards: Sirius (and Vega), Astronomical Journal, 147, 127, 2014.