The NIST STARS Program – Update 2017

Introduction

Vega and Sirius, are currently considered as fundamental standards. However, there are two main problems in applying these standards to WFIRST. The first is that they lack the requisite accuracy. An ongoing program at NIST aims to improve the accuracy of Vega and Sirius, and will be described in the paragraphs below. The second problem is that, with apparent brightnesses of V= 0 mag (Vega) and V=-1.2 mag (Sirius), they are 1 000 000 times brighter than the V=14-19 mag stars suitable for large (8+ meter-diameter) telescopes and similarly, they are much too bright for the surveys planned for WFIRST. This problem has been reviewed separately (Bohlin et al 2014).

Vega (Alpha Lyrae) is an A-type, main sequence star (A0V) whose SI pedigree originates in experiments carried out almost 45 years ago relying on thermal standards (black-body furnaces) to set the scale in the infrared between 1 and 5 micrometers (Mountain et al 1985, Blackwell et al 1983, Selby et al 1983), and in the visible between 300 nm and 900 nm (Hayes & Latham 1975, Hayes, Latham & Hayes 1975, Oke & Schild 1970). However, the uncertainties in the IR measurements were larger than the uncertainties in models of Vega, and the systematic uncertainties in the visible are on the order of 5%.

Sirius (Alpha Canis Majoris) is an A1V star. Its spectral energy distribution was calibrated with MSX (Midcourse Space Experiment) using emissive reference spheres that were ejected at various times during the mission (Price et al. 2004). The uncertainties at the MSX wavelengths are of order 1% to 2%.

Significant effort has been made to extend these absolute measurements to other wavelength ranges and stars (cf. Engelke et al 2010 and Bohlin et al 2011). Historically, Vega is considered the primary standard star and undergirds the commonly used photometric systems, despite the relatively large uncertainties. However, due to Vega's (variable) dust disk, Sirius has become the primary standard in the mid infrared, but lacks direct SI traceable calibration at wavelengths shorter than about 3 micrometer.

To address these shortcomings, the NIST Stars program aims to determine the top-of-the-atmosphere, SI-traceable, absolute spectral irradiance of bright stars to with an uncertainty of better than 1 % from a ground-based observatory.

Observation Overview:

NISTStars has developed a novel, fully SI[1] lab traceable calibration strategy that will enable achieving the desired accuracy. This strategy has two key components. The first is the SI-traceable calibration of the entire instrument system, and the second is the repeated spectroscopic measurement of the target star throughout the night.

[1] International System of Weights and Measures

A) Calibration of the telescope-spectrograph system

This is carried out by measuring the flux of a laboratory traceable calibration light source with a transfer standard spectrograph with an SI-traceable spectral irradiance responsivity mounted to a 10 cm telescope and then observing the source with the telescope-spectrograph system. The light source is located approximately 100 m from the telescope. This allows us to determine the absolute spectral responsivity scale of our telescope-spectrograph system.

B) Stellar Observations

A bright star is continuously observed at a variety of air masses as it transits the sky. This allows us to use a Langley analysis which exploits the Beers-Lambert-Bouger Law to calculate the spectral atmospheric extinction and correct out ground based measurements to a top-of-the-atmosphere spectral flux. We have conducted successful observations at the Fred Lawrence Whipple Observatory on Mt. Hopkins in southern Arizona. Our targets have been Vega and Sirius, (see Figures 5 and 6) and we would like to add some southern sky targets as well. These observations would benefit from the more consistent photometric conditions available at Paranal and the atmospheric characterization facilities available at the Observatory.

Beers –Bouger-Lambert Law

This extinction law states that extinction (absorption and scattering out of the line of sight) is linear with radiation intensity and with the amount of matter through which the radiation traverses under the assumption that the material's physical state is constant. This relation can be expressed as:

$$I_\lambda = I_o e^{-m_o \tau(\lambda)}$$

where I_0 is the incident radiation at wavelength λ, $\boldsymbol{I_\lambda}$ is the emerging radiation, m_0 is the airmass at zenith, and $\tau(\lambda)$ is the optical depth.

Langley Extrapolation (Langley Analysis)

The Langley analysis exploits the Beers-Bouger-Lambert Law to estimate the above the atmosphere incident radiation, taking into account that the path length through the atmosphere changes with altitude, i.e.

$$I_\lambda = I_o e^{-m\tau(\lambda)}$$

where m is the airmass, i.e. $m = m_0 \sec(z)$ where z is the angle from the zenith. Taking the natural logarithm, the above equation becomes

$$\ln I_\lambda = \ln I_0 - m\,\tau(\lambda)$$

Ideally, a plot of ln $\boldsymbol{I_\lambda}$ versus m is a straight line with a slope equal to $\tau(\lambda)$. I_0 is obtained by linear extrapolation to $m = 0$, on the assumption that $\tau(\lambda)$ is constant during the observations.

Langley analyses have been successfully applied to solar observations.

Calibration Chain:

Figure 1 shows a schematic of the calibration chain used for these measurements. At the heart of the calibration is a commercial compact array spectrograph (CAS) with an irradiance head that has been well characterized and calibrated in the NIST laboratory. To calibrate the spectrograph we use a type FEL lamp (FEL is not an acronym – it is a designation for the lamp design), which is a quartz halogen lamp with an SI-traceable irradiance through a standard NIST calibration. NIST has tested the repeatability of the spectrograph calibration and finds that when the spectrograph is maintained in the laboratory the calibration varies less than 0.05 % over months of observation as seen in Figure 2. NIST has also recalibrated the spectrograph over a series of field campaigns and finds that the calibration holds to ~0.2 % between deployments to mountaintop locations as seen in Figure 3. NIST has also used a tunable laser system in the lab to calibrate the wavelength scale of the spectrograph and periodically verify this with a HgNe pen lamp. NIST also uses the tunable laser system (part of SIRCUS, described separately) to perform stray light correction (Zong 2006). This reduces errors associated with calibrating to a 3000 K lamp and observing a star with different spectral profile.

In the field the irradiance head of the CAS is placed on a translation stage and aligned to the optical axis of the source. Irradiance measurements of the source are made at different distances and fit to the inverse square law. This fit both verifies the expected radiometric behavior of the system and provides the distance between the source and irradiance head. The CAS is then used to measure the spectral irradiance of the source.

The observing telescope/spectrograph then observes the source. The distance from the telescope to the source is measured with a laser range finder. Using the inverse square law, and the measured distances, we know the expected irradiance at the telescope, if there is no extinction along the light path. The correction for the extinction along the ~100 m horizontal path between the source and telescope is described below. This gives us a telescope/spectrograph system with an SI-traceable spectral irradiance responsivity.

The final step is to observe a star with the telescope. We again need to correct for the extinction of the star light along the path through the atmosphere. To calculate a top-of-the-atmosphere spectral flux, we observe the star through the night at a number of airmasses and use a Langley analysis to extrapolate the measurements to zero airmass.

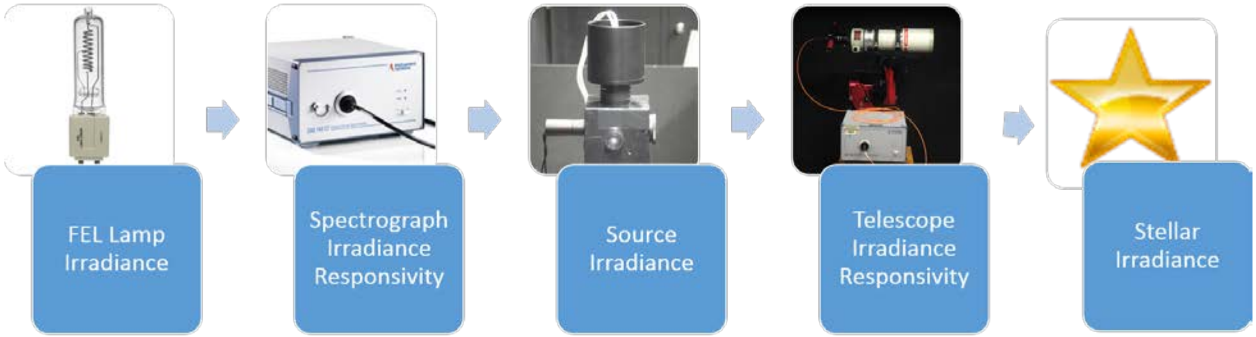


Figure 1. A schematic representation of the calibration chain. An SI-traceable FEL lamp is used to calibrate the spectral irradiance responsivity [counts per irradiance in each wavelength bin] of a spectrograph in the lab. The spectrograph is then used to measure the spectral irradiance [energy per second per unit area per unit wavelength] of a source in the field. The source is then observed by the telescope. Thus, through this sequence, the spectral response of the telescope is traceable to the original FEL lamp, and one considers the telescope to be calibrated. When that telescope measures the stellar spectral flux, the latter is directly comparable to the FEL lamp. Calibration of the telescope to the field source and the determination of the true stellar require a correction for atmospheric extinction along the line of sight.

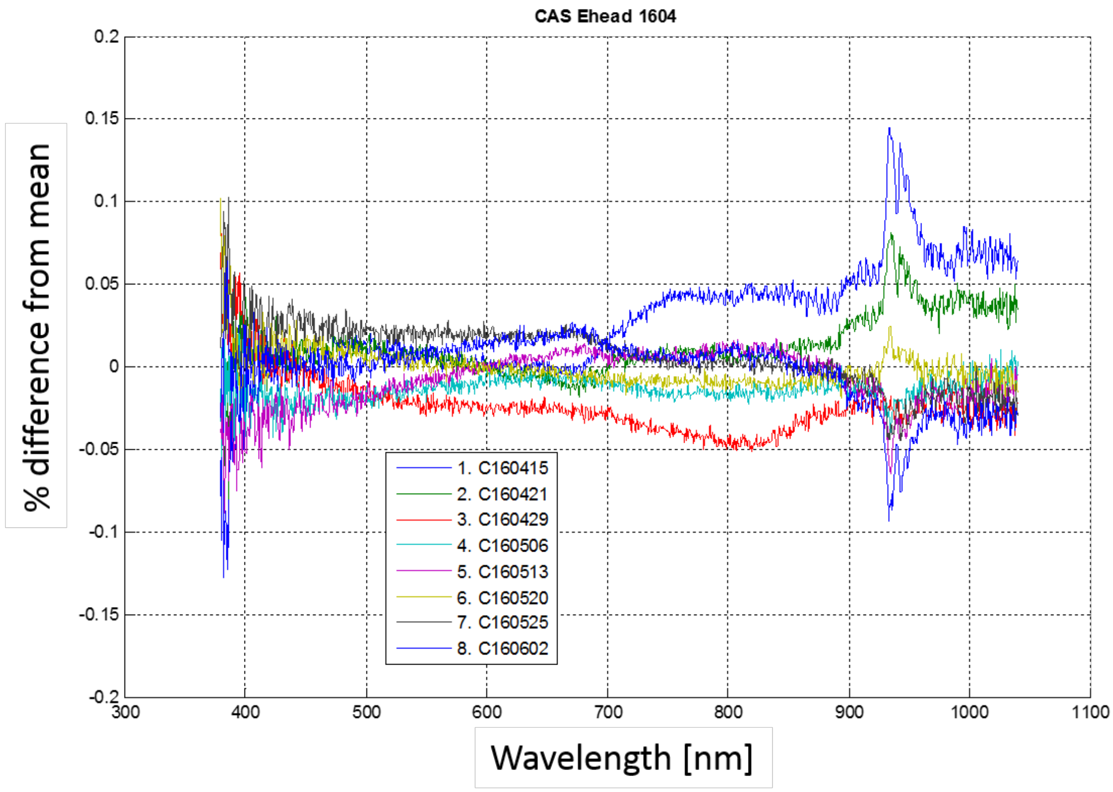


Figure 2. The stability of the transfer standard spectrograph measure the FEL lamp calibration source demonstrated by weekly measurements over two months. The calibration varies by less than 0.05 % outside of the water absorption bands.

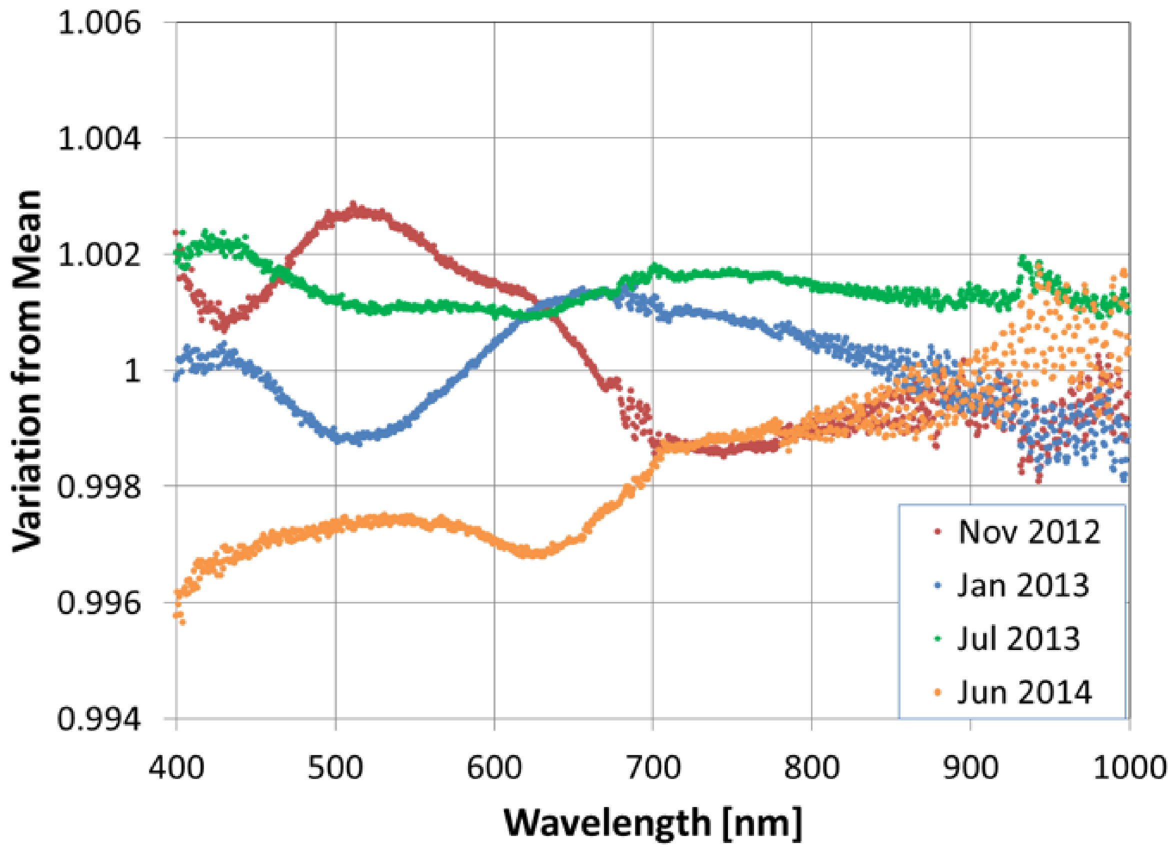


Figure 3. The transfer standard calibration over the course of multiple field deployments to Mt. Hopkins, AZ. Calibration values were typically within 0.2 % of the mean.

NIST Stars Telescope, Instrument, and Field Calibration

The NIST Stars observing telescope is a 106 mm, f/5 refractor (Takahashi FSQ 106) with a 600-micrometer diameter optical fiber at the focal plane to couple the light into a spectrograph. A 90/10 beam splitter cube placed before the optical fiber allows for an optical cross where the 10 % beam allows a guide camera to image the target star and a second camera with a small lens focused on the optical fiber can view the back reflection of the star off the fiber. This second camera allows the star to be reproducibly centered in the fiber. The fiber carries the light to a commercial Czerny-Turner spectrograph with a 1024 pixel, cooled CCD array detector (Instrument Systems, CAS 140CT-153). The spectrometer has a 3 nm spectral resolution with a 0.65 nm pixel spacing covering a wavelength range from 380 nm to 1040 nm. The telescope is positioned with a computerized alt-az mount that is controlled by a PC running The Sky X software. The spectrograph is controlled with a separate PC running Labview. A picture of the system on Mt. Hopkins is shown in Figure 4.

Figure 4. The observing telescope (right) and collimated laser for horizontal extinction (left) on the ridge at Mt. Hopkins. The calibration source was located in the support building in the background.

The field calibration source consists of a 50 mm diameter integrating sphere with a 1 mm diameter aperture. The sphere is illuminated by a 10 W quartz tungsten halogen (QTH) lamp. A second spectrograph, of the same design as that used on the observing telescope but with an irradiance head fiber-coupled into the spectrograph, is used to measure the output of the calibration source. The calibration of this spectrograph is described below. The irradiance head is mounted on a 300 mm linear translation stage, which is attached to an optical rail on which the calibration source in mounted. A set of removable irises and a laser pointer are used to align the irradiance head and translation stage to the optical axis. The calibration source/optical rail assembly is mounted on a telescope mount and the same irises are used to align the calibration source to the observing telescope.

Data Collection

The target star is acquired in the telescope and the camera looking at the fiber is used to position the image of the star in the center of the optical fiber. The auto-guiding camera is then used to control the mount to keep the starlight at that position on the fiber. With the telescope tracking the star, the spectrometer is set to acquire data in a 60 s time cycle consisting of a 5 s dark frame, followed by 9 spectra with 5 s exposures. The remaining time is used for data transfer. This cycle repeats for several hours as the star traverses through a range of air masses.

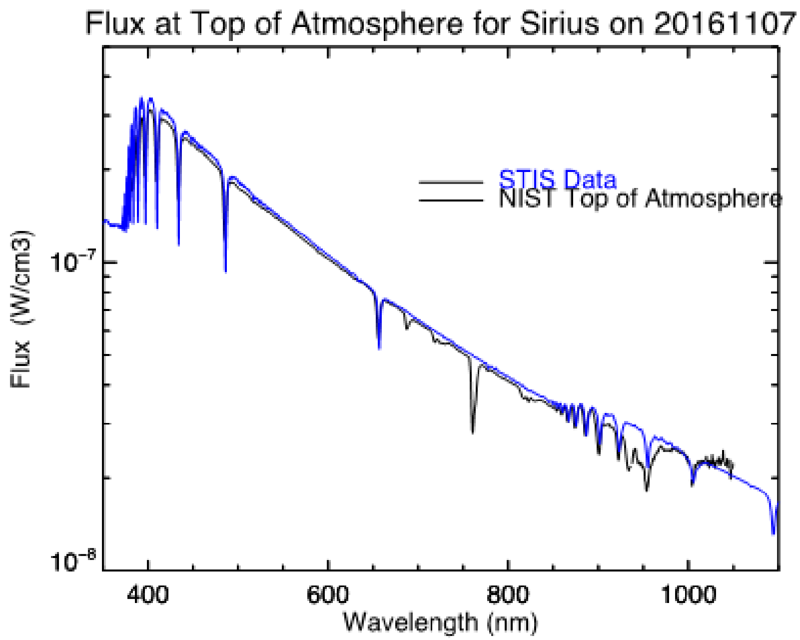
At least once per night, the telescope is turned to observe the calibration source. The same data acquisition protocol is used as for the stellar flux observations. Typically, 20 min to 30 min of calibration data is collected.

Figure 5 shows 'out of the box' results for two nights of data for Sirius obtained on Mt. Hopkins in November 2016. Each night's observation were fit, wavelength by wavelength, using the Bouger-Beers-Langley formulation to compute the 'top of the atmosphere' (TOA) flux. The TOA spectrum is shown in black, and the HST/STIS spectrum of Sirius is in blue. Although the two nights' spectra were acquired under different conditions, key is that the shape of the two TOA spectra match that of the HST/STIS over most of the wavelength range of the ground system, with the exception of the water vapour features at about 900 nm. Figure 6 shows the same type of results, but for the one night of Vega data.

To establish confidence in this method it is imperative to obtain repeated measurements of each star, over many nights, so as to build a statistically significant sample. Additionally, independent measurements of atmospheric extinction and characteristics (such as water content) along the lines of sight are needed to further reduce the systematic effects due to the Earth's atmosphere.

Horizontal Atmospheric Extinction

The light path between the source and telescope is long enough that there is a significant attenuation of the light along the path. To measure the attenuation, we use a collimated, stabilized HeNe laser mounted near the telescope and directed toward the calibration source. To measure the collimated light, we use a 15 cm diameter integrating sphere with a 2.5 cm diameter aperture and a photodiode mounted on the side wall. A current-to-voltage amplifier and voltage logger is used to measure to output of the photodiode. The sphere is held in front of the collimated laser beam at the telescope and then transferred to a position several meters to the side of the source. The ratio of these measurements provides a measure of the transmittance along the path at 633 nm. MODTRAN is then used to model the transmittance at different wavelengths with this as a tie point.



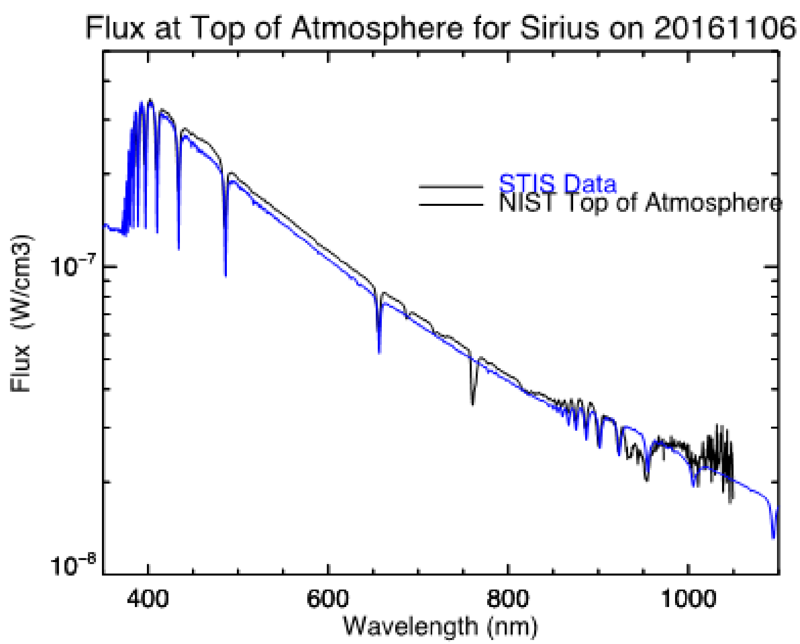


Figure 5. Preliminary results from the November 2016 MT. Hopkins campaign. Ground observations of Sirius compared to the HST/STIS spectra of Sirius. In the good, photometric night (top figure), the difference between the HST and ground derived top of the atmosphere spectrum is small;l, of order 3%

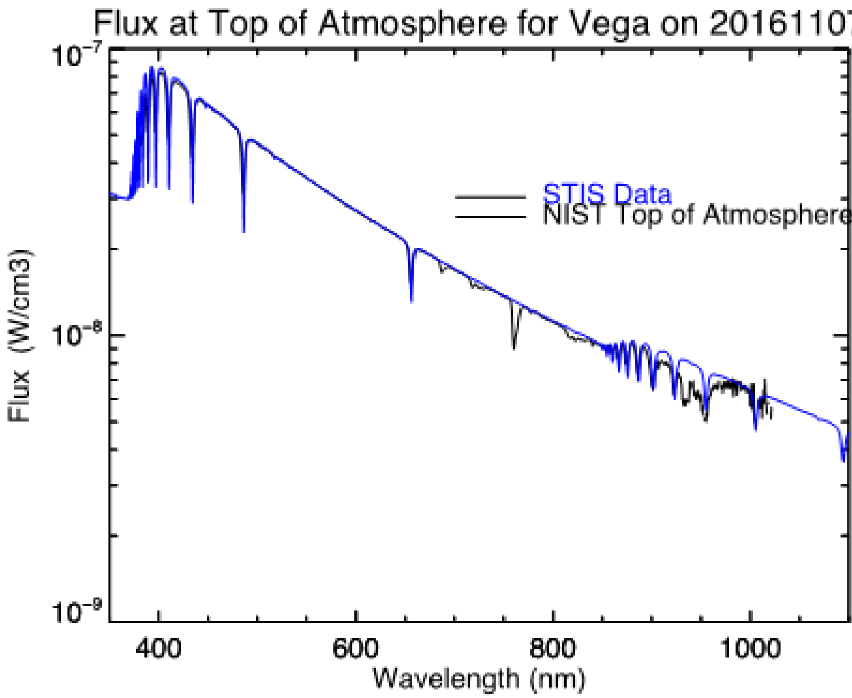


Figure 6. Plotted are the STIS spectrum and the NIST top of the atmosphere spectrum of Vega (Alpha Lyrae), obtained on a good night from Mt. Hopkins (Preliminary results).

Future Plans

One shortcoming of the current approach is that the Langley analysis assumes that the atmospheric extinction is constant over the time that the measurements are made. NIST currently does not have any independent monitor of the atmosphere at Mt. Hopkins, and there is significant water vapor and aerosols. NIST is proposing to the European Southern Observatory (ESO) for permission to take the NIST Stars equipment to a site nearby the ESO Paranal Observatory. ESO operates a unique array of instruments in support of Science Operations that can provide NIST with the relevant information that can help to independently assess the quality and stability of the atmosphere on a given night. NIST also plan to acquire a duplicate of the 183 GHz water vapor profiling radiometer that exists at ESO but just looks zenith. The intent would be to coordinate an intercomparison with the ESO existing system and then co-locate the NIST water vapor profiling radiometer with the line of site of the NIST Stars telescope to measure along the same line of site when observing stars. NIST also has access to two LIDAR systems, in development, which could be used for the aerosol determination along the line of site, if needed.

After obtaining statistically significant data (i.e. 20 or more nights per star) at Paranal on a set of bright stars and showing that the 'proof of concept' is successful – i.e systematic effects are controlled, the next steps are to:

1) Apply the same calibration method to a larger telescope and obtain accurate spectrophotometry of fainter (e.g. V~14 mag) stars in the 0.3 to 1.0 micrometer range, which benefits the entire astronomical community. This step is straightforward, and could be done with existing telescopes.
2) Extend the method into the near infrared (to 2 micrometers) which would then provide SI traceable absolute flux calibration for a crucial wavelength range.. The infrared extension will require additional R&D to verify the precision of the calibration chain.

   In both cases, just as with the current hardware suite, systematic monitoring of the atmosphere with additional instrumentation, e.g water vapor monitors, LIDAR systems, are necessary.

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