Proposal: Mich 126949 - Precision Spectrophotometric Calibration System for Dark Energy Instruments

Final Report

June 2015

PI: Michael Schubnell, University of Michigan

Summary

This final report to the Department of Energy summarizes the research that was performed to study a precision calibration system for spectroscopic dark energy instruments. In order to demonstrate the high calibration precision that can be achieved, a precision spectrometric calibration system capable of providing a complete spectrophotometric calibration at the sub-pixel level was designed and built. The system uses a fast, high precision monochromator that can quickly and efficiently scan over an instrument's entire spectral range with a spectral line width of less than 0.01 nm corresponding to a fraction of a pixel on the CCD. The system was tested and evaluated in the laboratory. A planned field evaluation by means of calibration of the BOSS instrument at APO could not be performed due to scheduling conflicts. Instead we performed extensive measurements in the laboratory.

Project Overview and Goal

The study of baryon acoustic oscillations (BAO) and the growth of structure with an all-sky galaxy redshift survey are powerful survey tools to investigate dark energy using ground-based facilities. Spectroscopic surveys have not enjoyed the same calibration efforts as imaging surveys, and therefore their full potential has yet to be realized. The goal of this project was to develop a fast, high precision spectrophotometric calibration scheme for in-situ calibration of future large fiber spectrometers. We performed extensive laboratory evaluations to demonstrate the capability of this system.

Project Description

This project targets the development and demonstration of a fast, high precision spectrophotometric calibration scheme for in-situ calibration for multi-fiber dark energy spectroscopic instruments. The demonstrator unit consists of three elements: a high intensity light source with f-number matching optics feeding a monochromator; a projection system to illuminate the telescope; a fiber bundle to bring the light from the monochromator output to the projection system. The system has been tested and evaluated in the laboratory. This effort was supported by several undergraduate students. One of the undergraduate students, Jonathon Hunacek, wrote his senior thesis on “Precision calibration of Dark Energy Surveys”. Hunacek received awards at the departmental and college level and was one of seven finalists for the APS Apker award. To fully evaluate the demonstrator we had planned to perform a calibration of the BOSS instrument on the Sloan telescope at Apache Point (Fig. 1). This was originally planned for the summer of 2013 but due to a very short summer down-time and scheduling conflicts, the calibration run had to be cancelled. Instead we performed extensive measurements in the laboratory to evaluate the calibration performance.

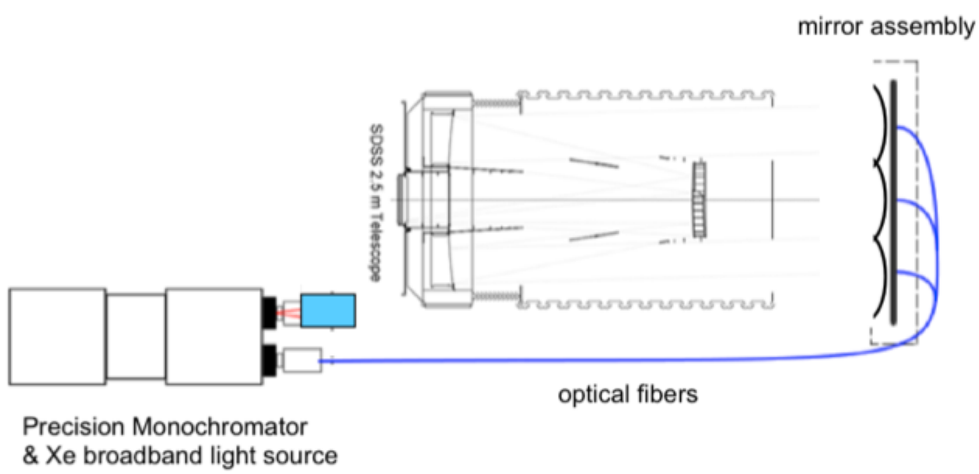

Figure 1: Schematic overview of the demonstrator for precision calibration. The system is shown as it is anticipated to be used for a calibration run with a telescope (here it is shown atop the BOSS instrument on the Sloan telescope at Apache Point Observatory.)

Demonstrator Unit and Evaluation Results

1. Monochromator

The monochromator serves as a precision wavelength reference standard that reduces the spectral line width of the light source to a fraction of a spectrograph pixel (on the order of 0.01

nm). We selected the Horiba FHR 1000 f/9.0 monochromator which is specified to achieve ±0.03 nm wavelength accuracy and ±0.015 nm wavelength repeatability and which can scan from 340 nm to 1060 nm at an impressive scan rate of >300 nm/sec. A two-grating turret with 1200 l/mm holographic gratings blazed at 330 nm and 750 nm, respectively, provide 0.8 nm/mm spectral dispersion and sufficient efficiency across the entire wavelength range of interest. The monochromator can quickly and efficiently scan over the instruments entire spectral range with a spectral line-width that corresponding to a fraction of a pixel on the CCD.

2. Monochromator Stability and Repeatability

The monochromator, as delivered by the company, failed extended repeatability tests in our lab. Horiba engineers initially suspected flawed device driver software, then the motor control boards (which were replaced twice), then the RS-232 communication board but the monochromator still failed our tests after on-site replacement of these parts. Eventually the equipment was shipped back to France where the monochromator's firmware was found to be flawed. After several repairs and a software fix by Jonathon Hunacek we could verify that the monochromator's stability and repeatability are satisfactory. Illuminate with short-arc Xe light source. In order to test the monochromator's repeatability, it was repeatedly scanned over the entire spectrum (from the same direction to eliminate lash) and a pre-selected "fixed monochromator line" was measured on an external spectrograph spectrograph. Without re-initialization monochromator accumulates errors linearly over time but re-initialization at each scan and correction for temperature drifts resulted in superb performance as illustrated in Fig. 2. The reproducibility was monitored by registering several of the Xe spectral lines. This method turned out to be the most successful and accurate for applying drift corrections. For the measurement the monochromator was thermally insulated and we purposely introduced extreme external temperature variations with a 2000W heat lamp (Fig. 3). This was done to mimic the large temperature variations that can occur at a telescope site. Our set-up however produced temperature variations far in excess of any real environment. In fact, the heat of the lamp caused the thermal insulation to bubble.

3. Light Source

Originally it was planned to use a very high power (1000 W) Xenon light source (kiloarc) and we designed and manufactured an optical system that brings the light from the output of the kiloarc light source into the monochromator. The f/4.3 kiloarc outputs needed to be matched to the f/9 input of the monochromator. The very high intensity of the kiloarc (100W in photon energy) requires special attention to the associated heating of the opto-mechanical elements and complicates tests. After the design was finished and parts had been machined it was found that the focus quality of the kiloarc was insufficient and our design did therefore not work as expected. We therefore selected a different light source (Newport 75 W Xe arc lamp). This lamp

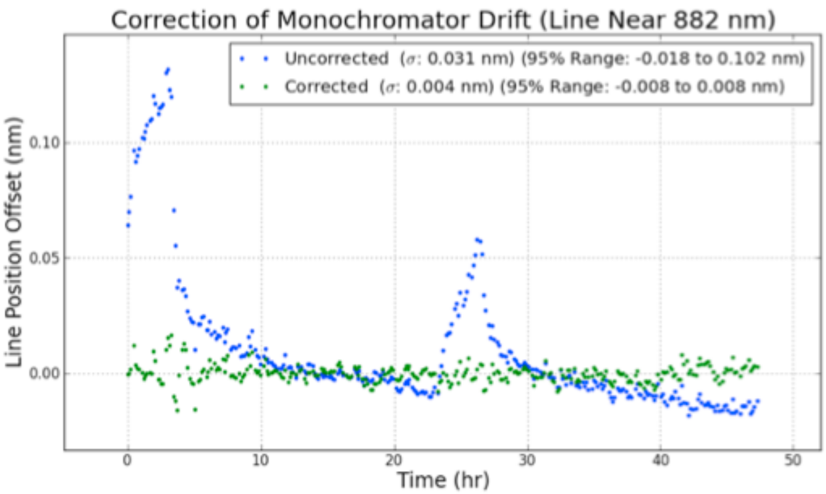

Figure 2: Linear wavelength scale and offset correction achieves accuracy of σ=0.004 nm, (95% range ± 0.008 nm) exceeding manufacturer's specifications (accuracy 0.03 nm, repeatability 0.015 nm).

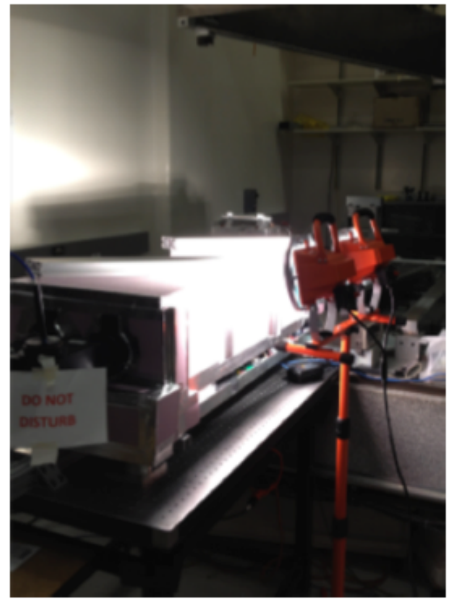

Figure 3: Monochromator stability test with thermal

was chosen over more powerful bulbs because of its small 0.4 mm × 0.8 mm arc size which provides a good light coupling to the f/9 monochromator, using a narrow input slit.

4. Projector (Mirror Assembly)

A novel projection system was developed as an alternative to a dome flat. Dome flats greatly overfill the telescope aperture and result in wasted light. We have investigated a projection system consisting of an array of fiber collimators, holographic diffusers and large parabolic mirrors. Light from the monochromator is coupled into fibers that run to each mirrors focal point. The fiber output is then collimated by an off-axis parabolic mirror and sent through a holographic diffuser (Fig. 4) which creates an extended source that diverges to fill the mirror. For the BOSS calibration measurement the finite size of the collimator output is sized to concentrate as much light as possible into a few hundred densely populated fibers. This corresponds to an area of about 22 cm (1 degree). A photodiode fed by a spare fiber at the monochromator output monitors light intensity fluctuations. The mirrors are inexpensive 29 front surface Al coated mirrors which were mounted to a hexagonal Al structure matching the entrance aperture of the SDSS telescope. The Al structure was designed to be light weight and can be easily assembled and disassembled for transport. The acrylic mirrors are supported by a PVC backplate. Fig. 5 shows a picture of the projector assembly. The quality of the projector was evaluated with a small CCD camera and a single mirror. The position of the collimator was adjusted to produce

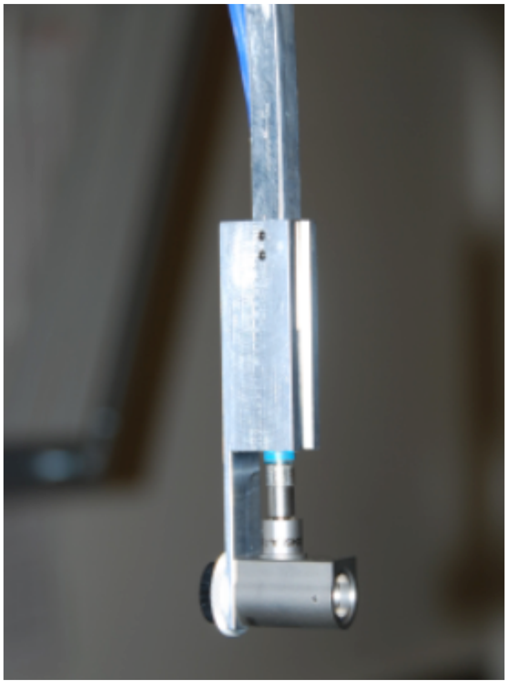

Figure 4: A collimator with attached holographic diffuser illuminates each of the six parabolic mirrors.

Figure 5: Projector prototype. A total of 6 mirrors, each attached to an aluminum hexagon structure with attached collimator and holographic diffuser system.

parallel light. To evaluate the irradiance distribution the infinity focussed CCD camera was moved in and x,y grid and at each mirror location the spot location and size was recorded. For a perfect mirror the spot position will be constant and spot size verifies proper angular spread. The summation image which evaluates the overall performance of illuminator is shown in Fig. 6 together with the angular intensity distribution of individual spot size measurements. The resulting 1 degree spot was chosen as it is a perfect match for the BOSS instrument. The result shows that the quality of the simple (inexpensive) acrylic mirrors exceeds expected requirements for planned dark Energy multi-fiber spectrographs such as DESI and are quite adequate for the calibration system.

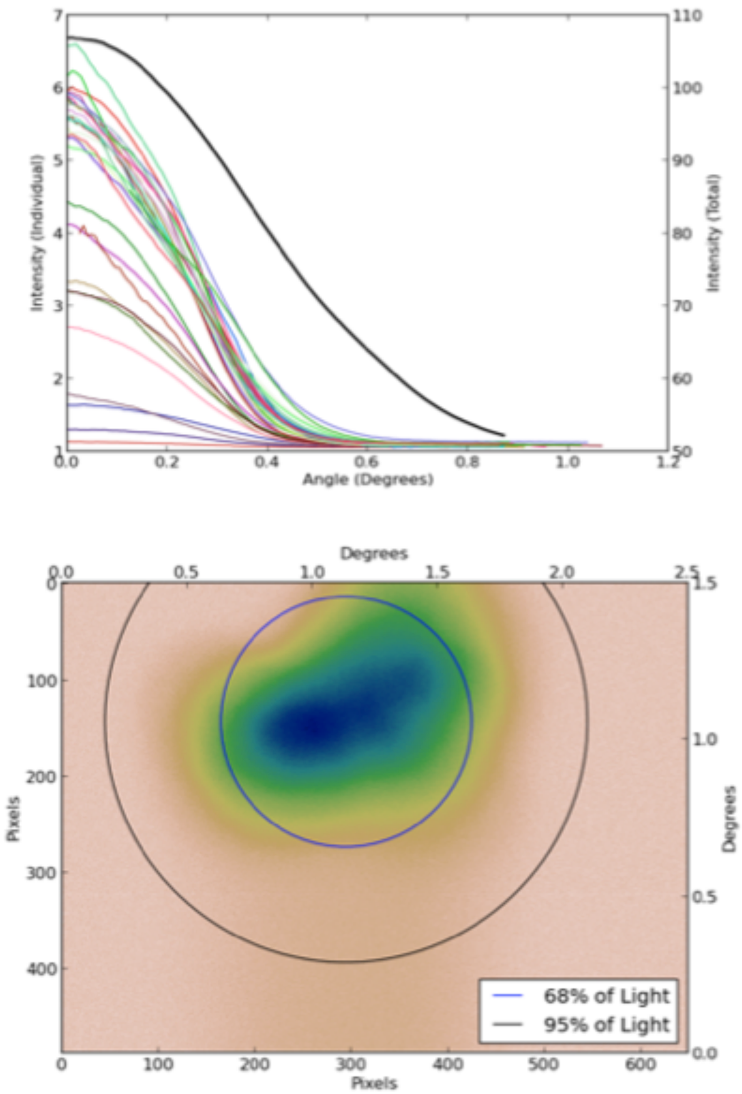

Fig. 6: Measured radial profiles. The optics was designed for a roughly 1 degree spot for BOSS and measurements verified that this was achieved. The spot size can easily be expanded to a full FoV for a DESI like instrument (increase EFL of collimator).

Conclusion

This research showed that a complete spectrophotometric calibration standard for spectroscopic survey instruments such as DESI is possible. The monochromator precision and repeatability to a small fraction of the DESI spectrograph LSF was demonstrated with re-initialization on every scan and thermal drift compensation by locking to multiple external line sources. A projector system that mimics telescope aperture for point source at infinity was demonstrated.