Multi-Channel and Fiber-Spectroscopy in Astronomy

Dr. Andreas Kelz, Astrophysical Institute Potsdam (April 2010)

Application Note

Introduction

The Astrophysical Institute Potsdam (AIP) undertakes fundamental research in astronomy and develops instrumentation in the optical wavelength domain. The main activities include the design and manufacture of high-resolution and integral-field or 3D-spectrographs, with a particular emphasis on fiber-optics and CCD detector systems. Contrary to commercial imaging spectrographs, the multi-channel spectrographs can record a few hundred spectra in one exposure.

PMAS, the Potsdam Multi-Aperture Spectrophotometer, which is in operation at the German-Spanish Calar Alto Observatory, is a fibre-coupled instrument with the capability to simultaneously record more than 300 spectra across a 2-dimensional field of view (Figure 1).

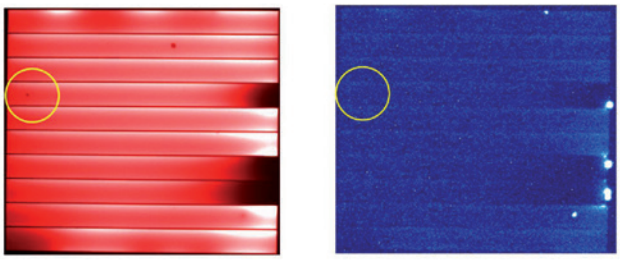

Figure 1: Raw images of spectral calibration data of the astronomical multi-channel spectrograph PMAS, featuring over 300 individual spectra (from top to bottom; dispersion direction from left to right).

Currently, the AIP is involved in the development of the largest optical spectrographs of its kind, namely the Multi-Unit Spectroscopic Explorer (MUSE) for the Very Large Telescope (VLT) of the European Southern Observatory (ESO) in Chile; the Visible Integral-field Replicable Unit Spectrograph (VIRUS) for the Hobby-Eberly Telescope at McDonald Observatory in Texas; and the Potsdam Echelle Polarimetric & Spectroscopic Instrument (PEPSI) for the Large Binocular Telescope (LBT) in Arizona.

The detectors used in optical ground-based astronomy are customized large format, thinned, back-illuminated CCD detectors. An example for state-of-the–art detectors are the 4000 x 4000 pixel CCD arrays used for MUSE or the 10,2k chip foreseen for PEPSI. As to reduce the unwanted dark current and to suppress the associated noise, astronomical detectors are cooled using liquid nitrogen (or liquid helium for satellite missions in the infrared). For the above reasons, commercial CCD camera systems are not implemented in astronomical instrumentation. However, thermoelectrically cooled cameras do play a role in the laboratory to test and evaluate the optical systems and components before integration into the overall instrument.

Experimental Applications

For various optical component tests, a iKon-M DU934N-BV CCD detector from Andor Technology was used. It features a 1k back-illuminated e2v-chip with a pixel size of 13 microns, which is comparable to the typical detector parameters used in astronomical instruments. For this application note, three test set-ups are described as examples:

1. Astronomical instruments require careful calibration. Amongst others, this includes a spatially homogeneous and temporally stable illumination – called a "flat field calibration" in astronomy. As to accurately calibrate the 24 individual spectrograph and detector systems for MUSE [2], a flat field at the entrance of the instrument with homogeneity of better than 0.1% is required. Using the Andor CCD at the focal plane of the MUSE Calibration Unit (Figure 2), its performance was evaluated. For this test, both the size and the linear response across the detector were of importance. A second aim of the experiment was to measure the flux rates that can be expected from the optical setup of the Calibration Unit.

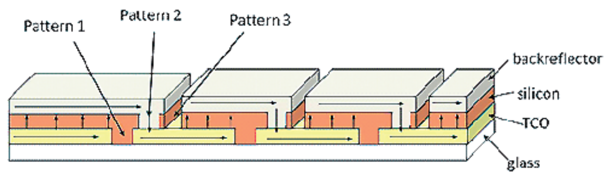

Figure 2: Experimental Setup in the AIP optics laboratory to measure the flatfield and illumination properties of a Calibration Unit for the astronomical instrument MUSE.

This foresees a coupling of remote light sources (white light and spectral lamps) to an integrating sphere using liquid light guides and a relay lens, to focus the sphere pupil output onto a focal plane. The CCD data were used to measure the overall transmission and the center-to-edge variance across the field.

2. As part of a diploma thesis, a polarimetric observing mode was developed for the PMAS spectrophotometer [1]. Before such an optical system is integrated in the instrument and commissioned at the telescope, various verification tests are done in the laboratory. Therefore, the entire polarimetric system, including collimator, retarder, polarizing prism and camera optics was setup on an optical table and the Andor CCD detector was placed at the re-imaged focal plane of the telescope. In a test series, the CCD was used to record the intensity across the image plane as function of the polarization axis of the retarder. In addition, the setup was used to evaluate the image quality as compared to the ray tracing models. Taking advantage of the dynamical range of the CCD, weak ghost images, caused by reflections between the prism and retarder surfaces, could be detected at a sub-per mille level (Figure 3). These measurements were used to verify the properties of the polarimetric components, to determine the instrumental polarization of the assembly with an accuracy of 0.2% and to optimize the overall optical path as to avoid the ghost images in the final setup.

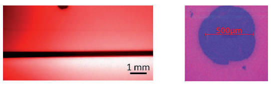

Figure 3: Image of a white light source obtained through the PMAS polarimetric unit. The ghost image in the lower left corner is at an intensity level of 10^{-3} of the main image. The above image was obtained using a cooled 1k x 1k iKon-M CCD detector from Andor.

3. Given that many instruments built at AIP use optical fibers (Figure 4), the testing and characterization of fiber properties is an essential task in the laboratory. One test measures the F-number (or numerical aperture) of the exit beam as function of the input beam.

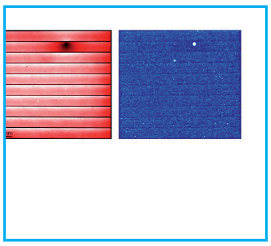

Figure 4: Custom-made multi-fiber-slit (with 248 fibers), developed at AIP for the astronomical spectrograph VIRUS.

Due to an effect called focal ratio degradation (FRD), the exit beam is always faster than the fiber input, resulting in potential losses if the optical system downstream does not accommodate for this beam widening. For FRD tests of optical fibers used in the PMAS and VIRUS [3] instruments, the CCD was placed on a linear stage behind the fiber output. Recording the far field light distribution (Figure 5) at several distances from the fiber end, yields the exit cone of the light.

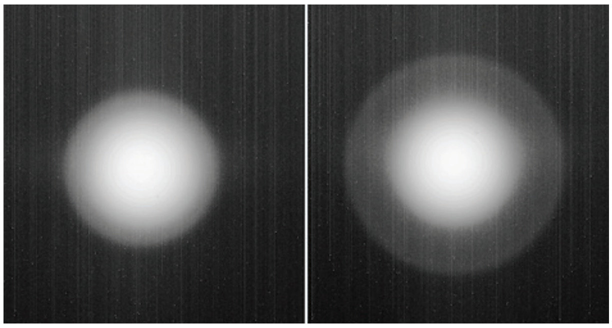

Figure 5: Comparison of the output light cone of a 'standard' fibre with NA=0.22 (right) to a fibre with 'tuned' NA of 0.16 (left). Given an input beam of f/3.5 (NA=0.14), the standard fibre shows an extended halo that may cause scattered light within the spectrograph.

To measure the wavelength depending transmission, the fiber was illuminated by a white light source and the fiber output was fed into a Shamrock SR-303i-B spectrograph, using the Andor CCD to record the spectrum at the output (Figure 6).

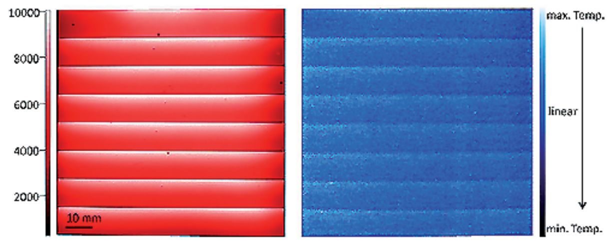

Figure 6: Experimental Setup with a fiber-coupled light source to a Shamrock SR 303i-B spectrograph and an iKon-M DU934N-BV CCD detector (both from Andor Technology).

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Summary
Given that astrophysical research is done in the low photon regime, CCD detectors in astronomical instruments need to have high quantum efficiency, low dark current and read-out noise, exhibit a large dynamical range with a linear response and preferable have large formats.

The above cases illustrate the use of a commercial CCD and a spectrograph in the laboratory to test and evaluate components and systems that are being developed for astronomical instrumentation. While in a laboratory application the light levels can usually be adjusted, most of the above mentioned CCD features are still of interest, for example to detect weak stray light levels in optical spectrographs or low level intensities of the light distribution in optical fibres.

References

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