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A New Technique for Solar Imaging Spectro-polarimetry using Shack-Hartmann and Fabry-Pérot

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Abstract. A new technique for solar imaging spectro-polarimetry is presented. Using the combination of a Shack-Hartmann (SH) and a Fabry-Pérot (FP) interferometer, high-cadence spectroscopic observations can be obtained at discrete wavelength positions simultaneously, thereby avoiding errors due to non-simultaneity of the wavelength scans. A SH mask is used to generate multiple images of the same field-of-view (FOV). These multiple images when passed through the FP in a collimated-beam arrangement are shifted in wavelength due to the angular dependence of the FP filter transmission profile. Thus, by re-imaging one obtains multiple images of the FOV which are tuned to different wavelength points across the spectral line, in a single exposure. The schematic of the setup and the laboratory simulation of such a configuration is presented. The technique has an advantage of simultaneity over conventional wavelength scanning filtergraphs and has potential for observing highly-dynamic phenomena like solar flares. Also, one can exploit the method to perform snapshot spectropolarimetry by designing a special polarization modulator. The limitation of this technique is that it downgrades the spatial resolution due to the downsampling of the pupil into smaller sub-apertures. However, for large aperture telescopes like 4 meter class telescopes (ATST) this is not a major issue and one can still work at sub-arcsec resolution, though not at the diffraction limit of the full aperture.

1. Introduction

The remote sensing of the physical parameters of the astrophysical objects is typically achieved through spectroscopic analysis of the radiation coming from these objects. Traditionally, spectroscopic techniques are broadly classified into two categories, (i) imaging spectroscopy: in this approach typically one uses tunable narrow bandpass filters to obtain monochromatic images at different wavelengths across the spectral line, and (ii) slit spectroscopy: in this approach one samples one-dimensional slices of the image typically along the slit of a grating spectrograph and obtains the spectra simultaneously along a 1-D field-of-view (FOV). The two-dimensional imaging can be achieved in the latter approach by performing a raster scan across the slit. A few representative examples of filter based imaging spectrographs are described in Gosain et al. (2004) and Cavallini (2006), while examples of slit scanning spectrographs can be found in Elmore et al. (1992) and Sankarasubramanian et al. (2006). Each of these approaches have their advantages and disadvantages. In summary the filter based approach using Fabry-Pérot etalons provides higher throughput but has limited spectral resolution while the dispersion spectrograph based approach provides high spectral resolution but requires longer exposure times to achieve an equivalent signal-to-noise ratio (SNR). For studies where the detailed shape of the spectral line is not important and one can derive information from limited wavelength sampling of the spectral line, the filter based approach has a definite advantage in terms of spatial-resolution and time-cadence.

In solar applications polarimetry is another important component of spectroscopy where the full Stokes vector, $S = [I, Q, U, V]^T$, is measured across the spectral line (Gosain 2007). This requirement for polarimetry increases a typical observing scan duration by a factor of four. A major limitation of the non-simultaneity of filter based observations of the spectral profile is due to atmospheric seeing as well as the evolution of the small scale features during the duration of wavelength scan. The severity of this affect has been demonstrated by Padinhatteeri et al. (2010). The seeing and solar evolution limits the performance of slit spectroscopy also, so as to cause geometric distortions. Although adaptive optics (AO) systems help in reducing the seeing induced blurring to some extent during the scans, it is nevertheless desirable to devise methods by which one can obtain two-dimensional images along with simultaneous spectral coverage in order to study rapidly evolving phenomena like solar flares or chromospheric jets etc. One such approach designed for slit spectroscopy is the so called Integral Field Spectroscopy (IFS) technique, where one images the FOV over a 2-D array of fiber bundles which are then mapped onto a 1-D array of fibers aligned along the slit of the spectrograph (Barden & Wade 1988; Lin & Versteegh 2006). This technique allows simultaneous spatial and spectral coverage of the FOV instantaneously. For full Stokes polarimetry, however, one needs to obtain multiple exposures with different polarization modulation states. For the case of filter based spectroscopy such simultaneity can be achieved by using Shack-Hartmann imaging of the FOV together with a tunable filter whose transmission peak varies as a function of angular FOV (Sankarasubrmanian et al. 2012).

In this paper we present the schematic details of this method and discuss its potential application with the upcoming large aperture solar telescopes. Also, we discuss the advantages and limitations of this technique. Further, we discuss the potential of performing "snapshot polarimetry" with this technique where one can obtain all four Stokes parameters along with spatial and limited spectral coverage in a single snapshot.

1.1. Description of the Spectroscopic Technique

Figure 1 shows the schematic layout of the proposed new spectroscopic method. The primary imaging lens (PL) forms the image at the field stop (FS) where the field-of-view (FOV) is selected for the observation. The FOV is then collimated using lens (L1) and multiple images of the FOV are created by using a Shack-Hartmann lenslet array (LL). The multiple images of the FOV are again collimated using a lens (CL) and passed through a Fabry-Pérot etalon (FP). The angle-of-incidence that the collimated beam from each sub-image makes with respect to the FP varies as a function of distance of the sub-image from the principal axis. The central maxima of the FP transmission profile shifts ($\delta\lambda$) blue-wards with the FOV angle (θ) according to the relation $\delta\lambda \propto \lambda(\theta/\mu)^2$, where μ is the refractive index of the FP cavity. The sub-images are therefore tuned

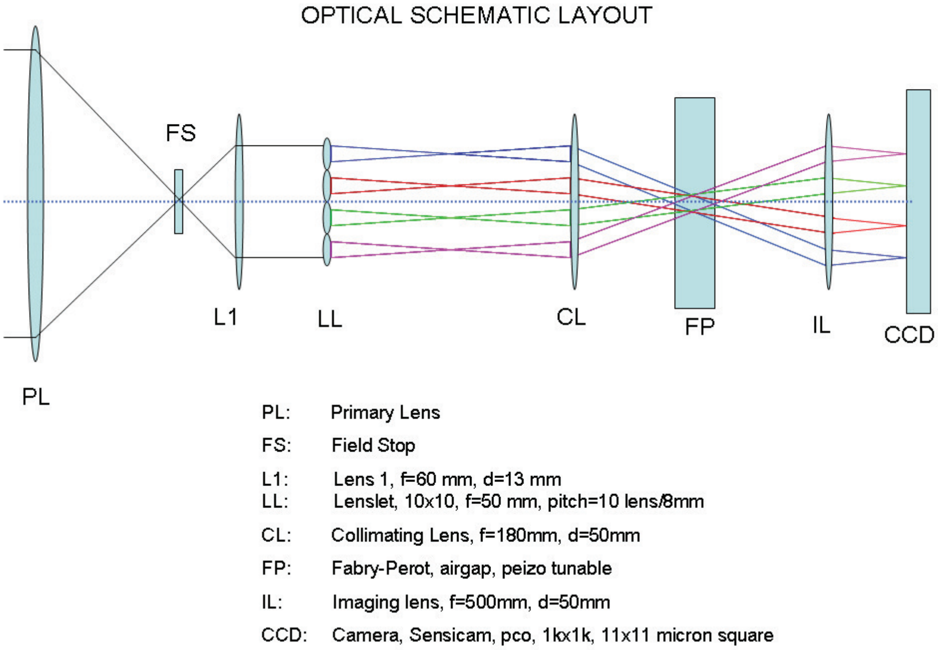

Figure 1. Optical Scheme of the new spectroscopy concept using a Shack-Hartmann lenslet array with a Fabry-Pérot system.

to different peak transmission wavelengths and result in simultaneous imaging of the FOV in different wavelengths. The laboratory evaluation of this concept was carried out using a laser light source and with optical setup parameters as listed in Figure 1. A wavelength shift of about 1 Å between the central and peripheral sub-image, in a 10×10 array, was achieved using this setup. The details of the results of this laboratory simulation are described elsewhere (Sankarasubrmanian et al. 2012).

However, the wavelength shift that was obtained in our setup was for a point source (laser). The consequences for an extended FOV in case of the solar application needs to be discussed briefly here. In addition to the wavelength shift for the sub-apertures there will also be a finite amount of wavelength spread depending on the half-cone angle for each sub-beam. However, with a careful design one can minimize the spread by choosing smaller FOV and a large f-number lens in the lenslet array. The angle of the beams from each sub-aperture with respect to the optical axis of the FP system will however lead to a larger amount of wavelength shift than the spread caused inside the extended FOV. For example, in Figure 2, λ_1 will have a spread of $\delta\lambda$ due to this half-cone angle and λ_5 would also have the same spread. Hence the relative wavelength shift of the two beams would still be $\lambda_1 - \lambda_5$ only. However, the absolute value of λ would differ for each point. So all the points in the FOV would give an independent full line profile but shifted with respect to one another by a small amount. Since the full line profile is available (but with slight offsets between different points in the FOV), this is not going to give any reduction in the spectral resolution. In other words, each image

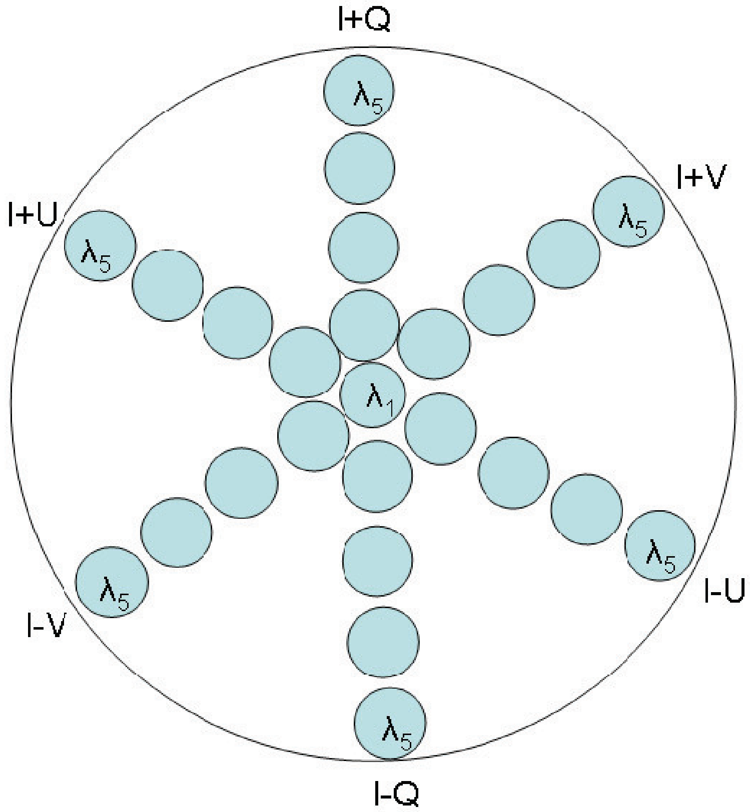

Figure 2. Conceptual design for performing snapshot polarimetric measurements with the new spectroscopy method.

point in the FOV will equally sample different points of the line profile. As far as the full line profile is obtained with enough sampling, one would be able to make use of it.

1.1.1. Extension to Polarimetric Mode

An interesting possibility of this technique is to perform snap-shot polarimetry with limited wavelength sampling in the spectral lines to obtain high-cadence magnetic field measurements. The schematic of such a possible arrangement is shown in Figure 2. Since each of the six radial arrays of sub-images is tuned across the same spectral position, say from λ_1 through λ_5, one can design a fixed polarization modulator plate such that each of the six radial arrays is measuring separately the $I + Q$, $I - Q$, $I + U$, $I - U$, $I + V$ and $I - V$ profile. Such polarization modulation requires fabrication of a special type of modulator such that each lens-let has its own polarizer and/or retarder oriented in specific directions in order to measure the desired polarization state. It may be noted that these modulators do not require temporal modulation as all the required modulations are done simultaneously along various image sub-arrays from λ_1 through λ_5. Such arrangement will then simultaneously yield the Stokes vector across the spectral line at five wavelength positions in a single snapshot. The SNR can be increased with long exposure times since all sub-images will see the same seeing variations, which however, one can minimize with an adaptive optics system.

1.2. Discussion

We have presented a new method of performing filter based imaging spectro-polarimetry where a SH and FP allows one to obtain simultaneous images of the FOV at different wavelength positions, while a polarization modulator array allows one to obtain the full Stokes vector, in a single snapshot. Now let us discuss the properties of this method as compared to the conventional method where wavelength tuning is done at different times.

- Simultaneity: Since the sub-images tuned at different wavelength positions are obtained in a snapshot the seeing induced affects in the spectral profile reconstruction are absent. The quality of the spectral profile reconstruction at a given point in the FOV is limited by (a) the degree to which the sub-images are identical, which is governed by the identicalness of the lens-lets, and (b) the quality of flat-fielding for each sub-image. With the present day solar adaptive optics (AO) systems also, the simultaneity is useful because there can be residual variable image blurring (even with AO) when the seeing is highly variable.

- Signal-to-Noise: For a symmetric optical arrangement all of the sub-images at a given angular distance from the center of the FOV are tuned to the same wavelength. This allows us to maximize the SNR, while keeping the same exposure time, in the line core where typically the absorption lines have smaller intensities. This is also useful to maximize the polarization SNR in the Zeeman sensitive spectral lines when used in polarimetric mode where all six radial sub-arrays (shown in Figure 2) are tuned to measure the same Stokes parameter, say Stokes-Q or U or V alone.

- Spatial Resolution: The technique has a disadvantage in terms of the angular resolution, since the effective telescope diameter for each sub-image is equal to D/N, where D is the actual telescope diameter and N is the number of sub-images across the diameter. However, for upcoming large aperture telescopes like Advanced Technology Solar Telescope (ATST) of 4 meter aperture one can still design the systems with five to six wavelength sample across the spectral line and work at sub-arcsec resolution. In this case the large aperture telescope will be used for its large photon collection efficiency rather than for its diffraction limited angular resolution.

- High Time-Cadence: Since the technique obtains all sub-images tuned to different wavelength simultaneously it allows one to obtain velocity as well as magnetic field information at a very high cadence without seeing induced confusion. The technique is optimally suited to study dynamic phenomena like flares and chromospheric jets or the evolution of the magnetic field in a bright point etc., especially with large aperture telescopes equipped with an AO system.

In summary the technique has the potential to exploit the large photon collection efficiency of future large aperture solar telescopes like the ATST. Also, the technique can be used with large aperture night-time telescopes for studying stellar phenomena.

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