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Two-Dimensional Phase-Diverse Stokes Spectrometer

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Abstract. Optical fibers may be used to rearrange a two-dimensional field of view into a slit-like configuration feeding a spectrometer. In theory, such input reconfiguring permits two-dimensional Stokes spectrometry with phase-diverse/speckle restoration to the diffraction limit and represents an alternative to adaptive optics for small telescopes. In practice, the question is whether current fiber technology achieves such reconfiguration without loss of angular resolution at acceptable spectrograph speed and light loss. A feasibility study is undertaken for application at the Dutch Open Telescope.

1. Introduction

The simple idea behind 2D fiber spectrometry is to use optical fibers to reformat a two-dimensional input field into a linear spectrometer slit arrangement (Fig. 1). For example, 2K$\times$2K CCD's in the spectrum plane might be fed with 45$\times$45 fibers sampling a 5$\times$5 arcsec^2 field of view at 0.1 arcsec pixel resolution. Adding liquid-crystal polarization encoding before the fiber pickup would permit multi-line full-profile Stokes polarimetry. Adding an extra camera out of focus would permit phase-diverse/speckle reconstruction per spectral element.

With phase-diverse/speckle registration, the scheme represents a poor-man's alternative to adaptive optics using post-detection computer processing rather then real-time wavefront monitoring and correction. In both cases detailed spectral information including Stokes vector analysis may be obtained with angular resolution down to the diffraction limit. In both cases the price paid is that the angular field is very small — although with off-line processing it may exceed the isoplanatic patch through tessellation into independent subfields and separate (parallel) restoration.

The scheme differs intrinsically from the now ubiquitous application of fibers in nighttime astronomy (see the conference proceedings edited by Bardeen 1988 and by Gray 1993). There, fibers are usually used to reduce confusion between close stars or galaxies, each fiber accepting a field patch larger than the seeing disk. In the solar case, the fibers should map the focal plane with angular resolution at the diffraction limit, an order of magnitude smaller than the seeing disk. The resolution elements are also geometrically small because solar telescope diameters are an order of magnitude smaller than nighttime telescope diameters.

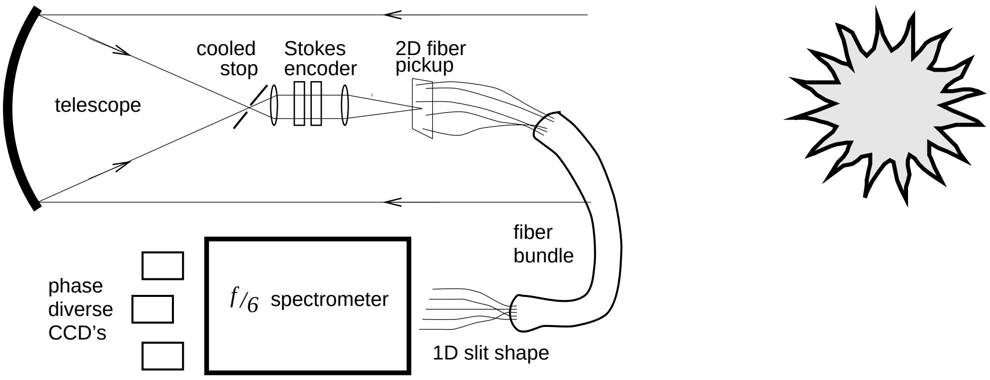

Figure 1. Scheme for a solar fiber spectrometer at the DOT. The fibers reformat a square input field into a linear slit-like arrangement. Stokes encoding is done before the fiber pickup, for example with liquid crystal modulation. Phase diverse registration is realized by having one CCD register the continuum out of focus.

The problem is in the fibers. The scheme requires very thin fibers to permit fast input beams that do not suffer too much from beam spreading ("focal ratio degradation") within the fibers. Otherwise, the spectrometer size grows out of bounds or the light loss becomes unacceptable.

2. Solar 2D spectrometry

The intrinsically intricate structuring of the solar atmosphere and its rapid changes require fast 2D field registration. In addition, the even faster wavefront perturbations added by our own atmosphere, even at good sites such as La Palma, are intrinsically 2D in character (or even 3D) and so require 2D (or 3D = phase diverse) registration at sampling times no longer than 10 ms in order to be hardware corrected in real time or software restored post detection.

On the other hand, the intricacy of solar phenomena and processes requires all the diagnostic constraints provided by precise multi-line Doppler mapping and Stokes magnetometry. These require spectral resolution of narrow bands within selected spectral lines. Height discrimination also requires narrow bands within selected spectral lines. The more spectral elements, the larger the number of lines, the wider the line formation variety, the preciser the Stokes polarimetry, the better the diagnosis and the astrophysical interpretation. High spectral resolution and high spectral variety require a spectrometer, intrinsically a 1D instrument, and long exposure times, exceeding the 10 ms seeing freezing limit by one or two orders of magnitude.

Let me review some examples. The extreme of spectral resolution and spectral variety are of course reached by the NSO/Kitt Peak FTS (Brault 1978) in broad-band ("solar atlas") mode, at nearly complete sacrifice of both temporal and spatial resolution.

The best example of precise Stokes spectrometry is the HAO ASP here at the DST (*e.g.,* Elmore et al. 1992, Lites et al. 1994, Lites 1996), which is currently the most accurate and productive magnetograph. It uses detailed Stokes profile information of 2 to 5 spectral lines with different Landé factors simultaneously to derive the vector field with an elaborate calibration procedure (Skumanich et al. 1997, cf. Westendorp Plaza et al. 1998). The French-Italian THEMIS telescope on Tenerife aims to perfect this technique using yet more lines, of order 10 simultaneously (Mein & Rayrole 1991, Semel 1994).

The best example of height tomography obtained by combining spectral detail from diverse lines in the optical part of the spectrum is Beckers' classic HIRKHAD setup of the Echelle Spectrograph at the DST, registering Ca II H & K, Na I D_1, Hα and the Ca II infrared lines next to each other on a single detector (70 mm film at the time) in order to span most of the optically-accessible solar atmosphere (Beckers et al. 1972).

The filter instruments are exemplified by the versatile Lockheed SOUP tunable filter (*e.g.,* Title et al. 1989) and the superb G-band imaging at the Swedish Vacuum Solar Telescope (*e.g.,* Loefdahl et al. 1998).

The advantages and disadvantages of these various techniques are obvious. It takes a spectrometer to obtain varied line profile information simultaneously, whereas it takes a filtergraph to measure many spatial elements simultaneously. As a result, solar observing strategies have concentrated on filter instruments emphasizing surface patterning at the cost of measurement precision, and on spectrometers emphasizing quantitative measurement at the cost of 2D spatial coverage and resolution. Each strategy has its pros and cons; neither suffices by itself. How to combine the advantages of 2D registration with spectrometer-type spectral resolution and spectral variety?

Classical spectrometer slit stepping as in spectroheliography builds up the solar scene too slowly, or samples only a narrow strip if a higher cadence is required (for example, only 11 arcsec with the ASP in the dynamics study of Lites et al. 1999). In addition, there is no easy method for resolution restoration (cf. Keller & Johannesson 1995).

Rapid tuning of a Fabry-Perot, with a co-tuned birefringent or Fabry-Perot prefilter, delivers a large field with good spectral resolution but is usually limited to spectral elements in just one spectral line. Examples are the Fabry-Perot at the Sac Peak DST (*e.g.,* Bonaccini et al. 1990, Rimmele et al. 1995), the MISC at the German VTT (Bendlin et al. 1992, Kneer 1997, Al et al. 1998, Stolpe & Kneer 1998), and the IPM on THEMIS (Bonaccini et al. 1989). Taking simultaneous wide-band images enables off-line wavefront restoration with the multi-channel deconvolution method of Keller & von der Lühe (1992; cf. Tritschler et al. 1997).

The MSDP instruments (see Mein 1991, Roudier et al. 1991, Mein 1992), of which one will be the major post-focus instrument of THEMIS, represent a hybrid compromise between spectral and spatial resolution. They trade most of one spatial dimension against multiple (well-defined but fairly wide) spectral channels. This is done by projecting a relatively wide entrance slot onto the CCD's, with intermediate slits selecting spectral passbands within sufficiently wide spectral lines. They are subsequently de-dispersed by a reversed ("subtractive") grating pass in order to regain full spatial resolution (Evans 1956).

The end result consists of narrow more-or-less monochromatic strip maps per bandpass, typically measuring 10–30 arcsec by 100-300 arcsec.

A fiber-fed spectrometer similarly sacrifices field size for spectral information and spatial simultaneity while maintaining 2D registration. Compared with the MSDP, it obtains full spectral resolution and spectral variety by sacrificing most of the second spatial dimension as well, down to about 5×5 arcsec^2 for diffraction-limit pixels. Its strength is that it permits full spectral detail including Doppler imaging and Stokes vector magnetometry in multi-line tomography for its small 2D field. Addition of phase-diverse/speckle restoration of atmospheric wavefront degradation makes it do so at the diffraction limit in reasonable seeing, which implies gathering high-resolution sequences of desirable duration (hours) reasonably frequently rather than just on very rare fluke super-seeing days. There are obvious science applications for such capability — essentially the same as for adaptively corrected spectrometry.

3. Solar fiber spectrometry

The basic scheme of a solar fiber spectrometer is shown in Fig. 1. In principle, it resembles the multi-fiber spectrometer inputs now regularly used in nighttime applications. Most of these achieve low focal-plane filling because they are intended to pick up discrete objects avoiding confusion, but some integral-field fiber pickups are used as well (Vanderriest 1993).

In practice, the solar implementation is quite different. In the solar case, the fibers should sample image elements at the diffraction limit of a small-diameter telescope instead of just picking up stars of galaxies in the image plane of a large telescope. Even in integral-field spectrometry with the VLT at its expected best-seeing resolution, the required 0.2 arcsec pixels correspond to as much as 100 μm in the Nasmyth foci. Solar diffraction-limited resolution elements are far smaller geometrically than the seeing disks at large nighttime telescopes. Direct prime-focus pickup therefore requires very thin fibers, with diameters of order 1–10 micron only, at the edge of fiber technology if not beyond.

Thicker fibers may be used after magnification, but that brings the problem of beam spreading known as focal ratio degradation. Fibers do not conserve étendu (the product of beam cross-section and solid angle) or intensity (measured per unit cross-section and unit solid angle), but produce fast output beams with speed of order $f/6$ for beams with slower input speed, whatever it is, due to "microbending" within the fibers (*e.g.,* Ramsey 1988, Carrasco & Parry 1993). The Dutch Open Telescope, for example, has prime focus at $f/4.4$ with 1 μm pixel size per 0.1 arcsec diffraction-limit resolution element. Magnification to 10 μm or 100 μm pixels to match fibers that are possibly or readily available produces input at $f/44$ or $f/444$, respectively, but the output yet requires an $f/6$ spectrometer which grows with the fiber diameter — the effective slit length growing to well over 20 cm for 2K fibers of 100 μm— to impossible size. Thin fibers are therefore required, but their cladding produces increasing fill fraction loss and necessitates an array of square microlenses feeding the fibers individually.

If these problems are solved it seems relatively straightforward to add nematic liquid-crystal Stokes encoding before the fiber pickup (cf. Sanchez Almeida et al. 1997, Del Toro Iniesta et al. 1997) and to add phase-diverse/speckle restoration as demonstrated by Paxman et al. (1996) by registering a (sufficiently wide) continuum segment out of focus. The individual narrow-band spectral channels may then be restored through the multi-channel deconvolution technique developed by Keller & von der Lühe (1992).

Phase-diverse/speckle restoration makes a fiber-fed spectrometer directly comparable to an adaptive-optics fed spectrometer. The advantages are the cheapness of off-line processing over real-time wavefront measurement and control, and the potentially larger field size which at 0.2 arcsec resolution grows beyond the isoplanatic patch with fiber arrays and CCD cameras beyond 2K spatial pixels. The disadvantages, apart from the fiber problems discussed above, are the need to acquire sufficient speckle samplings without swamping by read-out noise and the diminishing effectiveness of speckle restoration at larger aperture due to decrease of speckle S/N (A. Title, private communication). Adaptive optics is clearly the way to go for future large-aperture solar telescopes — short of putting them in space — but a highly attractive niche for multi-line Stokes spectrometry at 0.2 arcsec resolution over fairly long duration at reasonable frequency seems available for computer-restored fiber spectrometry with small telescopes at good sites.

4. Solar fiber spectrometers

A fiber feed has recently been put into use at the spectrograph of the Tatranska Lomnica Observatory in Slovakia (Kucera et al. 1990) and is described by Kucera *et al.* (1997, 1999). It is not an integral-field feed but is designed to sample a fairly wide solar scene containing a sunspot at 23 discrete locations with 200 μm fibers for photometric spectrometry. Four additional fibers add iodine absorption lines for wavelength calibration.

During the present NSO workshop, Dr. Haosheng Lin of NSO/Sacramento Peak informed me that he has submitted a proposal for a fiber-fed near-infrared spectrometer along the lines discussed here, and was so kind to show me its details. It concerns a 16×16 integral-field prototype of which the bundle size is set by the presently available cameras at NSO/Sacramento Peak, in particular the 256×256 NICMOS 3 array. The tentative design uses microlenses, 200 μm fibers with 10 μm cladding, and an accompanying high-speed $f/6$ spectrometer with a 20×40 cm^2 grating. The latter addition makes clear that fiber feeds require custom spectrometers that are much faster than solar spectrometers usually are. An obviously worthwhile goal is to achieve high-resolution 2D Stokes magnetometry at 1.6 μm.

Presently, the Netherlands Foundation for Research in Astronomy (NFRA) is embarking on a feasibility study for a fiber-fed spectrometer at the Dutch Open Telescope (DOT, see my description elsewhere in these proceedings). The requirements are harder than for Dr. Lin's proposal since it is intended for application in the visual with much smaller resolution elements (0.1 arcsec instead of 0.5 arcsec) and much larger detector arrays. Hence the need for a feasibility study. The DOT is an on-axis parabolic reflector with nearly axial symmetry and should enable precise Stokes magnetometry with relatively simple time-independent calibration. Also, it has no diurnal image rotation thanks to its parallactic mount. These properties make a DOT fiber spectrometer particularly attractive.

An obvious advantage of a fiber feed that is essential for application at the DOT is that the spectrometer may be detached from the telescope. The DOT is an open telescope with prime focus at its top (Fig. 1) where there is neither sufficient space nor a sufficiently non-harsh environment to place any spectrometer, let be a large fast one. Using a fiber bundle as feed, the spectrometer may be placed in an enclosure just below the telescope, or perhaps on the ground below the telescope, or perhaps even in the nearby building of the Swedish Vacuum Solar Telescope from which the DOT is operated.

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