A Fiber-Linked Four Stokes-Parameter Polarimeter for the SOFIN Spectrometer on the Nordic Optical Telescope

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Abstract. We are building a new, improved version of the Bill Wehlau polarimeter, originally designed and constructed by N. Piskunov for the CFHT. We intend to use the new polarimeter at the NOT, and it should be ready in 1999. The instrument will allow us to measure all four Stokes parameters in three exposures. The polarimeter is designed to be free from instrumental polarization and will feed the light via two fibers to the high-resolution SOFIN spectrometer, thus improving its performance and stability. We include some new solutions related to the orientation of polarizing components and the fiber coupling.

1. Stellar Spectroscopy in Polarized Light

The polarization status of radiation can be characterized by four Stokes parameters: $I$, the total intensity, $Q$, the difference between intensities of linearly polarized light at $0^\circ$ and $90^\circ$, $U$, the difference between intensities of linearly polarized light at $45^\circ$ and $135^\circ$, and $V$, the difference between intensities of right- and left-circularly polarized light.

Two different approaches can be taken while registering a polarized signal. If the source is bright and the detector supports fast read-out mode one can send the light through a periodic modulator that will extract different polarizations in different parts of the circle. The detector must be synchronized with the modulator. The main advantage of this technique is that all Stokes parameters are registered quasi-simultaneously by exactly the same parts of the detector. The most advanced implementation of such a design is the ZIMPOL instrument for solar polarization measurements (Keller et al. 1992).

In case of a faint target all the Stokes parameters can be obtained in three consecutive exposures if two polarizations can be recorded simultaneously (two circular polarizations in one, and two linear polarizations in each of the others). If a CCD is used as detector, the maximum accuracy would be limited by the quality of flat-fielding unless the image is projected onto exactly the same pixels in every exposure. This can be achieved by using a fiber feed with one end fixed relative to the detector. In fact, in this configuration one can totally eliminate the flat-fielding by splitting each exposure in two and switching the two fibers (Semel et al. 1993). Such a design is typically used for stellar-polarization spectroscopy where small fluxes and slow detector readout prevent the use of a modulator. The polarimeter described here belongs to this type.
The main component of such a polarimeter is the beam-splitter that separates the light, linearly polarized in two perpendicular planes. Therefore, to measure circular polarization it must be converted to linear with appropriate orientation relative to the beam-splitter. This is done with a quarter-wavelength plate (QWP) that adds a phase shift of 90° to the component of electromagnetic field parallel to its axis. Since the circular polarization can be described as a superposition of two linear waves with a phase shift of 90°, the QWP converts a circularly polarized beam to a linearly polarized one. The axis of the QWP must be rotated by 45° relative to the axis of the beam-splitter. Circularly polarized light will come out of such a combination as a single linearly polarized beam. If we now turn the QWP by 90°, the same circular polarization will come out of the beam-splitter as the second beam. When two circular polarizations are present in the input beam, the output will consist of two linearly polarized beams with intensities proportional to the left and right polarized components. Any additional linear polarization can be considered as a superposition of the two opposite circular polarizations and will cancel out in the resulting V value.

The measurement of linear polarization requires a half-wavelength plate. The Q Stokes parameter is recorded by orienting the axis of the half-wavelength plate parallel to the axis of the beam-splitter while for measuring U it must be rotated by 22.5°. As before, any additional circular polarization will be equally distributed between the two output beams and will not influence the result.

2. New Polarimeter for the NOT

The new polarimeter under construction at Uppsala Astronomical Observatory is a Cassegrain-focus instrument that feeds two polarizations to the spectrometer using optical fibers. We aim at using the polarimeter with the 2.6-m NOT on La Palma with the high-resolution SOFIN spectrometer although we will try to make it as portable as possible. SOFIN (Ilyin 1993) is a cross-dispersed echelle instrument with standard resolutions of 180000 and 80000. The optimal slit sizes are 45 μ and 100 μ. The optical design leaves enough space between echelle orders to record the second polarization spectrum.

SOFIN is normally mounted at the Cassegrain focus of the NOT. When used with the polarimeter, SOFIN will remain on the dome floor. The use of a fiber feed will also help to eliminate the flexure problem of SOFIN.

The new polarimeter will consist of the following parts: an entrance pinhole diaphragm, a lens collimator, two QWPs with rotation mechanisms, a Wollaston prism (beam-splitter), a camera, a fiber adapter, and the fibers. Two optional elements are: a Glan–Taylor polarizer with an additional QWP (used for calibrations only) and a fourth QWP that can be used to convert linear polarization to circular after the beam-splitter if the fibers show strong sensitivity to the polarization of the beam. For portability, the collimator can be adjusted to accommodate different focal ratios.

The two super-achromatic QWPs can be combined to form one quarter-wavelength retarder used for measuring circular polarization or one half-wavelength retarder for linear polarization. This is achieved by rotating the QWPs around the optical axis. The rotation of each QWP is performed with a step size of <0.1° and is computer controlled.
Fiber-Linked Four Stokes-Parameter Polarimeter

The light from the QWPs passes through the Wollaston prism and splits into two orthogonally polarized beams. The camera images the entrance diaphragm on the fibers constructing a f/5.5 beam in order to prevent any significant degradation of the focal ratio. On the spectrometer end focal enlargers (one per fiber) bring the focal ratio in agreement with the spectrometer (f/11 for SOFIN). Two pairs of fibers, 25 μ and 50 μ, are planned for use with the high- and medium-resolution cameras of SOFIN.

A typical observing sequence includes three pairs of exposures to register the V, Q, and U Stokes parameters. For the first two the axis of the second QWP (the one next to the beam-splitter) is aligned with the axis of the Wollaston prism. We register circular polarization with the first QWP rotated ±45° from the second QWP. The operation is repeated with the two QWPs forming a half-wavelength plate with the axes at 0° and 90° for Q, and at ±22.5° for U. The values of Stokes parameters are then found from the relations:

\[
\frac{(I-V/2)^2}{(I+V/2)^2} = \frac{S_1^-}{S_1^+} \cdot \frac{S_2^+}{S_2^-} \\
\frac{(I-Q/2)^2}{(I+Q/2)^2} = \frac{S_1^-}{S_1^+} \cdot \frac{S_2^+}{S_2^-} \\
\frac{(I-U/2)^2}{(I+U/2)^2} = \frac{S_1^-}{S_1^+} \cdot \frac{S_2^+}{S_2^-}
\]

where \( S_j^\pm \) is the signal per pixel of the CCD registered in the first or second half-exposure (indicated by + or −) through fiber \( j \). The ratios on the right-hand side do not depend on the sensitivity of the individual pixels. Hence the degree of polarization, \( V/I \), \( Q/I \), and \( U/I \), can be determined without flat-fielding. A flat-field is still needed to obtain the absolute values of Stokes parameters.

3. Calibration of the Polarimeter

During calibration, the polarimeter will have an additional calibration element that consists of a Glan–Taylor polarizer and a test QWP. It is inserted into the beam just before the first QWP. The light coming through this element becomes circularly polarized. We assume knowledge of the positions of the two standard QWPs to within a few degrees. The problem is to use the polarized light to locate the axes precisely so as to eliminate the cross-talk between the Stokes parameters when the observations are made.

The axes can be precisely located if we can measure the flux in each beam coming from the Wollaston prism. The procedure is based on the fact that the intensities in two fibers is identical for QWP2 = ±45°. This is independent of the rotation of QWP1 because the output from QWP2 is elliptically or linearly polarized with an axis at 45°, or circularly polarized, so the two beams from the Wollaston are equal, regardless of the position of QWP1.

1. Set QWP1 to (approximately) 0° (±90° will do as well)

2. Set QWP2 to 45° (−45° will do just as well). Rotate QWP2 until the difference of the output signals from the two fibers is zero. That happens
when then angle between the axis of the Wollaston prism and QWP2 is precisely 45°.

3. Set QWP2 to precisely 0° (±90° will do just as well). Set QWP1 to (approximately) 0° (±90° will do just as well) and adjust the angle in order to get identical output in two beams. Now the axis of QWP1 is precisely at 0°. Note that the greatest sensitivity to the position of QWP1 occurs when QWP2 is located at 0° or ±90° (i.e. farthest from 45°).

4. Fibers

The fibers should be chosen with care concerning both the spectral transmission properties, damping properties, and the reaction to focal-ratio degradation (FRD). Several manufacturers, produce off-the-shelf fibers with suitable core dimensions, diameters of 50 µ and 100 µ. They also market fibers that have a good spectral coverage with good to excellent transmission in the region 300–1000 nm (high OH content) or 500–2500 nm (low OH content). For observations longwards of ~700 nm the latter fiber should be preferred, at the expense of the UV region, to avoid the strong absorption features produced by the high content of OH necessary for the good UV transmission. This consideration remains necessary until broad-band fibers become available.

The focal-ratio degradation is very dependent on how the fiber ends are mounted. Extreme care must be exercised to prevent excessive stressing here, as this will result in severe FRD. As a rule input f-numbers larger than about 6 will inevitably produce FRD, however staying at f/5.5 and transforming the resulting beam to the required f/11 should not present a problem. For a discussion of FRD, see, for example, Carrasco & Parry (1993).

The polarization properties of the fibers have to be carefully studied to ensure that different polarization modes suffer the same FRD and intensity losses, as this is important for the beam-switching technique through the fiber pair. Experiences from an earlier version of the polarimeter, built by Piskunov and collaborators have shown that there may be a problem with different amounts of FRD through one and the same fiber, depending on the direction of polarization of the entering light beam. This will cause the illumination of the pixel elements to differ in the different polarization modes and will jeopardize the flat-fielding accomplished through the beam switching. We intend to conduct a series of tests on the fibers we eventually decide to use to clarify this problem.

References


Ilyin, I. 1993, High resolution échelle spectrograph SOFIN, User’s Manual, Helsinki Observatory


Part 7: Overview