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Facility

The Kodaikanal solar vector magnetograph : laboratory evaluation of the polarimeter

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Abstract. The polarimetric assembly of the Kodaikanal vector magnetograph was tested in the laboratory for cross talk. The results show no evidence for cross talk at the 1% level. The scheme of polarimetry to be followed based on these results is outlined.

Key words : sun—vector magnetograph—polarimetry

1. Introduction

Measurement of all three components of the solar photospheric magnetic field provides vital information on the 3-D configuration of the sun's magnetic field above the photosphere. The estimation of empirical parameters of the magnetic stresses (*e.g.* magnetic shear) is also possible when the vector field is known. The magnetic stresses in turn give important clues about the probability for eruption of magnetic configurations of active regions into flares and allied ejective phenomena, which are of major interest in solar terrestrial physics.

For the conditions prevalent in the solar photosphere, the Zeeman broadening of spectral lines provides the best means of estimating the magnetic field. To obtain all three components of the field we need to measure all the four Stokes parameters (*I, Q, U* and *V*) at several wavelength positions along the Zeeman broadened line profile. The Kodaikanal solar tower/tunnel spectrograph (Bappu 1967) has a resolution of 6mm/Å in fourth order in the region of the Zeeman broadened FeI spectral line at 6302.5Å. Sunspot fields ($\approx$ 2000G) produce a peak linear polarization of $\approx$ 10% at this spectral resolution and thus the polarimeter must be capable of detecting a small portion of this polarization if weaker fields are to be detected. The Kodaikanal vector magnetograph consists of a polarimeter placed before the entrance slit of a 18m Littrow spectrograph. A 0.38 m image of the sun is formed at this slit. A CCD camera records the solar spectrum at the focal plane of the spectrograph camera.

In this paper we describe the laboratory experiments performed to evaluate the sensitivity of the polarimeter. Section 2 describes the polarimeter and the laboratory setup that was used for the evaluation. In section 3 we report on the results, whereas in section 4, we comment on the mode of polarimetry that must be adopted at the telescope in the light of the results of section 3.

2. Laboratory experiment

The optical layout of the experiment is outlined in figure 1. A half-wave plate (HWP) (half-wave retardance at 6303Å) rotates the plane of polarization of the input linearly polarized beam. This passes through an analyzer (polaroid sheet) whose transmission axis is the reference x-axis for the coordinate system of the Stokes vector. The rotation of the half-wave retarder modulates the intensity of the beam which is finally recorded by a Peltier cooled CCD camera.

In the laboratory, a heavy slab resting on a stack of thermocole pads served very well as a vibration free table. The polarimeter itself is built on a stable mild steel stand. A stepper motor drives the half wave retarder through a 100 : 40 gear. The stepper motor is driven at a speed of 2s per revolution. The least count in step is 1°.8 at the shaft leading to a step of 4°.5 at the half-wave plate. This high speed was designed to minimise the time between successive frame acquisitions. A longer time interval makes the data more susceptible to fluctuations in sky transparency, since the polarimeter is of single beam in type.

The camera operates at video rates, with a standard CCIR video signal as its output. This signal is digitized and stored in a $512 \times 512 \times 8$ bit frame buffer at reasonable speeds (~ 170 ms). More details of the mechanical properties of the polarimetric package and of the CCD camera will be described in another paper, along with results of preliminary field trials at the telescope. A quarter-wave plate (QWP) was available for

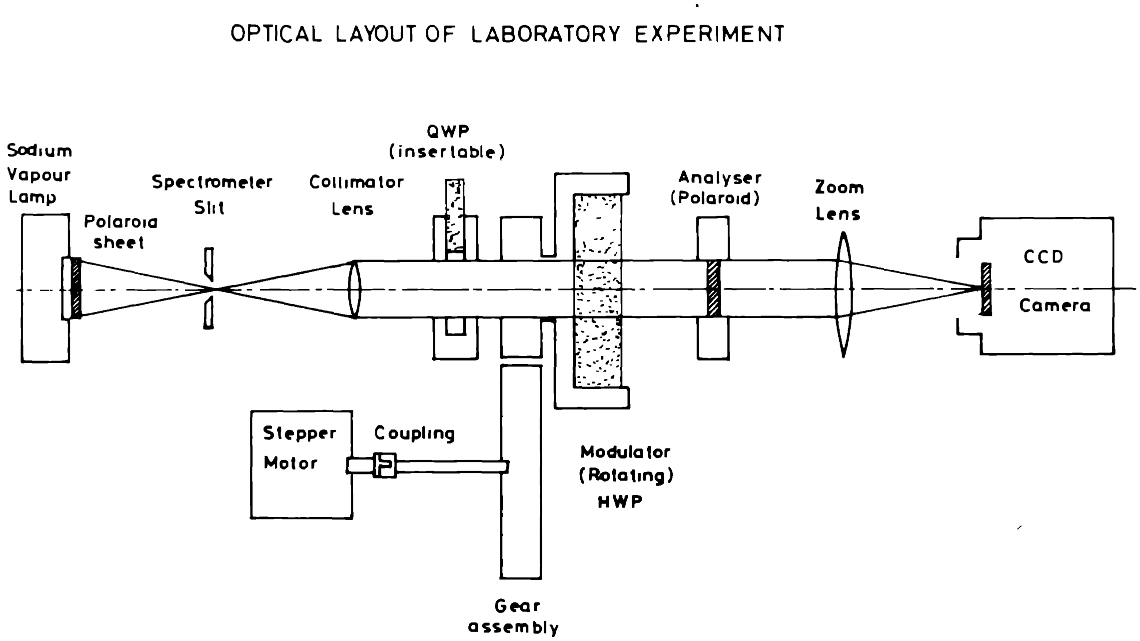

Figure 1. Optical layout of the laboratory experiment. Light travels from left to right. The various components are labelled in the figure.

insertion into the beam before the half-wave plate to enable the detection of circularly polarized light. In this case, the circular polarization would be converted to linear polarization and detected. A sodium vapor lamp served as a source while a spectrometer provided a slit and a collimator lens. The telescope of the spectrometer was removed. The parallel beam from the collimator was sent through the polarimeter and focused on to the CCD chip of the camera by a zoom lens arrangement screwed onto the camera. The image of the slit was thereby formed on the CCD chip. This was displayed by the DT-2861 frame grabber card on a monitor using the DT-IRIS software package (both procured from Data Translation Inc.).

3. Results

To test the sensitivity of the polarimeter, the input light was polarized by covering the lamp aperture with a polaiord sheet. The source polarization was first estimated by sending the beam directly through the analyser (after removing the intervening half wave plate). The analyzer axis was kept at 0°, −45°, −90° and −135° to the vertical (x-axis) of reference system) giving measurements of $I+Q$, $I-U$, $I-Q$ and $I+U$ respectively. The same procedure was repeated with the initial position of analyzer axis at −22°.5, −45°, −67°.5 and −90° to the vertical. The $I-U$, $I-Q$ and $I+U$ measurements then required the turning of the analyzer by −45°, −90° and −135° with respect to the respective initial position. Thus we obtained a total of 5 measurements of I, Q, U and V each vector being related to the others by the law of transformation of Stokes vectors under rotation of reference axis.

The two invariants under the transformation are the total polarization given by $(Q^2+U^2)^{1/2}/I$; and the angle made by the source polarization vector to the vertical given by

$$\theta = \frac{1}{2}\tan^{-1}\frac{U}{Q} + \Phi$$

where Φ is the angle made by the initial position (reference axis) to the vertical. The results of the measurement at one pixel of the CCD are given in table 1.

The half-wave retarder was now introduced and measurements of the intensity were obtained at different positions corresponding to every step of the stepper motor starting from an arbitrary position. The results are shown in figure 2. The expected output light

Table 1. Measurement of source polarization for different initial orientations of the analyzer transmission axis

Sr. No.	θ_{ref}	Q/I	U/I	P/I	θ_p
1.	0°	−0.43	0.70	0.82	60.8
2.	−22°.5	−0.75	0.22	0.78	59.3
3.	−45°	−0.67	−0.47	0.82	62.5
4.	−67°.5	−0.23	−0.74	0.77	58.9
5.	−90°	0.45	−0.64	0.78	62.6

Mean $P/I = 0.79 \pm 0.02$
Mean $\theta_p = 60°.82 \pm 1°.6$

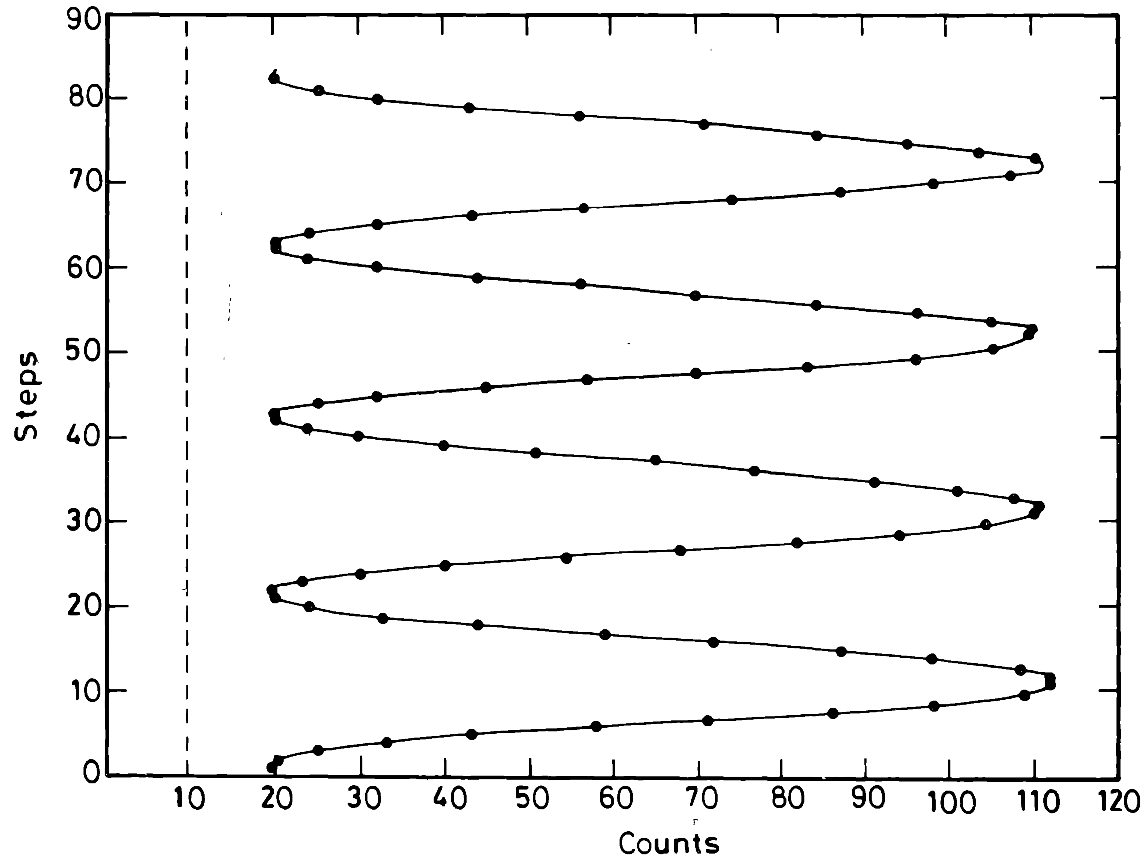

Figure 2. Variation of light output for linearly polarized light. The ordinate measure steps of the stepper motor starting from an arbitrary position. Each step corresponds to an angular increment of 4°.5. Dark level is represented by the dashed line.

intensity is given by (Makita 1985)

$$O(\theta) = \frac{1}{2}\left[I + \frac{1}{2}(1 + \cos\,\delta)\,Q + \frac{1}{2}(1 - \cos\,\delta)\,(Q\,\cos\,4\theta\;\;U\,\sin\,4\theta) + V\,\sin\,2\theta\,\sin\,\delta\right] \qquad \ldots(1)$$

For sodium light, $\delta = 192.5$ degrees,

Figure 2 shows no evidence for 2θ modulation confirming that there is no detectable cross talk of linear into circular polarization. The modulation shows a total linear polarization of 81% which is within the range of values measured directly (table 1). To judge whether there is any cross talk between Q and U, we found out the physical angle made by the fast axis of the half-wave plate to the vertical, when the output light attains a minimum. At this position, the output light of the half-wave plate must have a polarization vector perpendicular to the analyser axis. Since the half-wave plate rotates the input polarization by twice the angle between the input polarization and the fast axis of the plate, one can predict the angle of the fast axis at which the output light is a minimum. The predicted and observed angles to the vertical for three positions of the analyzer axis, showed total coincidence to the limit of measurement of the observed angles. This conclusively proves that the half wave modulation does not introduce cross talk between the parameters U and Q.

To check the sensitivity of the polarimeter to detect circular polarization, we inserted a quarter wave plate in the path of the input linearly polarized light. A V-signal is generated which depends on the angle made by the linear vector to the fast axis of the quarter wave plate. The new Stokes vector seen by the modulator is given by equations (A1)-(A4) in the Appendix. In the present experiment, $\alpha = 40°$ and $\delta = 96°.3$ while $Q_o/I_o = -0.326$, $U_o/I_o = 0.670$ and $V_o/I_o = 0.0$. Substituting these values in equations (A1)-(A4), we oblain

$$\frac{V'}{I'} = 0.64. \qquad \ldots(2)$$

One now expects a sin 2θ modulation along with the sin 4θ modulation. Figure 3 shows the result of the measurement of this modified polarization. If θ_{max} is the angle at which any local maximum is obtained, the difference between a primary and secondary maximum is given by [vide equation (1)],

$$\Delta I' = V' \sin \delta \sin 2\theta_{max},$$

where $\theta_{max} = (1/4) \tan^{-1} (U'/Q')$ and $\delta = 192°.5$ is the retardance of the modulator.

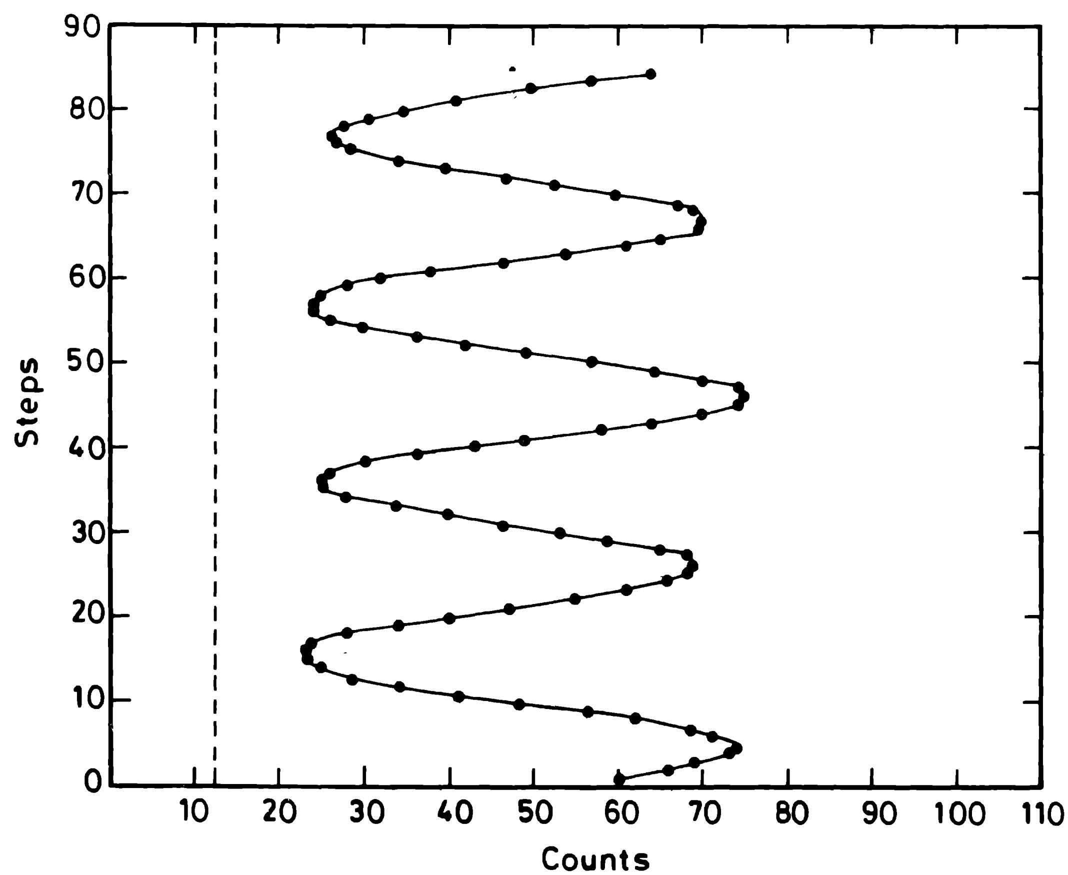

Figure 3. Variation of light output for general elliptically polarized light. Dark level is represented by the dashed line.

Thus,

$$\frac{V'}{I'} = \frac{\Delta I'/I'}{\sin\,\delta\,\sin\,2\theta_{max}}. \qquad \ldots(3)$$

From equation (3) we get the measured $V'/I' = 63\%$, while the predicted value [vide equation (2)] is 64%. Thus the device is capable of accurate measurement of the V polarization when the signal is large. When used at 6303Å for which the polarimeter is designed, $\delta = 180°$ and then one must insert the quarter wave plate to convert circular to linear polarization which can then be modulated. In the present experiment we used the quarter wave plate to generate a V-signal from a linear polarization which was then detected directly by the half wave retarder. For wavelengths that are retarded by phases much different from 180°, this direct detection is possible.

4. Discussion and conclusions

The polarimeter as such does not produce significant cross talk but certain precautions must be taken for accurate results. Firstly, the 4θ modulations showed a slight variation in the period of the wave over the four cycles measured. Thus, any analysis scheme which wholly depends on measurement at two orthogonal positions, *e.g.* $I + Q$ and $I - Q$ will require to position the half wave plate at different number of steps depending on the absolute position of the half wave plate with respect to any reference position. A scheme which performs a least squares fit of a fairly large number of measurements at different angular positions of the half plate to the expected 4θ and 2θ modulations will provide more accurate estimates to I, Q, U and V. This will involve more time for observations. Secondly, the fluctuation in measurement (shot noise) can be reduced to small values only when a large number of measurements are taken at each individual angular position of the half-wave plate. This will further increase the observation time. A severe restriction would then be caused by the fluctuations in the atmospheric conditions like sky transparency (which will mean fluctuations in the total light). A separate channel measuring the total solar radiation in the spectral passband of interest will provide the necessary calibration against such transparency fluctuations.

An important question is the sensitivity of the polarimeter. This is clearly dependent on the detector performance. The video output of the CCD used by us is digitized with 8 bit resolution giving 256 grey levels. In principle, the detector is capable of detecting a modulation of one count in 512 giving a sensitivity of $\approx 0.2\%$. This translates to a sensitivity of 40G given the high spectral resolution of the Kodaikanal telescope. In practice, however, several effects will reduce the sensitivity. First, the read out noise and dark noise of the CCD will prevent us from detecting a one count modulation with confidence. Secondly, the illumination available at the spectrograph camera focal plane might well be below the required 1-3 lux or so which makes the camera operate at the peak output of 256 counts. This can be tackled by on-chip integration. Thirdly, the instrumental polarization is quite large for the Kodaikanal telescope ranging from 10% to 2% depending on the sun's declination and hour angle (Balasubramanian, Venkatakrishnan & Bhattacharyya 1985). Even a 10% error in its determination can lead to $\approx 1\%$ error in polarization measurements in the worst case and to 0.2% error in the best case. Finally, the laboratory trials have shown $\approx 1\%$ difference between the polarization measured and expected. Thus, the sensitivity of the polarimeter will be restricted to about 1%, until we implement procedures like microstepping of the motor to improve the sensitivity. The present sensitivity of 1% polarization translates into a 100G detection (*cf.* Harvey 1985). Even this level is reasonably good considering the fact that we are attempting to measure the vector magnetic field of the sun. This is also comparable with the sensitivity of vector magnetographs currently in operation elsewhere in the world.

References

Balasubramaniam, K. S., Venkatakrishnan, P. & Bhattacharyya, J. C. (1985) *Solar Phys.* **99**, 333.

Bappu, M. K. V. (1967) *Solar Phys.* **1**, 151.

Harvey, J. (1985) in *Measurements of solar vector magnetic fields* (ed.: M. J. Hagyard) NASA CP-2374, p. 109.

Makita, M., Hamana, S. & Nishi, K. (1985) in *Measurements of solar vector magnetic fields (ed.: M. J. Hagyard), NASA CP-2374, p. 173.*

Shurcliff, W. A. (1962) Polarized light, Harvard Univ. Press.

Appendix

The effect of inserting a retarder into a beam of polarized light $[I_o, Q_o, U_o, V_o]$ can be summed up as follows (Shurcliff 1962)

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = [-\alpha]\,[R_\delta]\,[\alpha] \begin{bmatrix} I_o \\ Q_o \\ U_o \\ V_o \end{bmatrix}$$

where

$$[\alpha] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

is the transformation from the original axes to the axes of the retarder plate making an angle α to the original positive x axis.

$$[R_\delta] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta & \sin\delta \\ 0 & 0 & -\sin\delta & \cos\delta \end{bmatrix}$$

is the Mueller matrix for the wave plate of retardance δ. The $[-\alpha]$ matrix is required to transform the Stokes vector back to the initial reference axes. The resultant vector is [I', Q', U', V']. Thus,

$$I' = I_o \quad \text{...(A1)}$$

$$Q' = (C_2^2 + S_2^2 C_\delta)\, Q_o + C_2 S_2 (1 - C_\delta)\, U_o - S_2 S_\delta V_o \quad \text{...(A2)}$$

$$U' = C_2 S_2 (1 - C_\delta) Q_o + (S_2^2 + C_2^2 C_\delta) U_o + C_2 S_\delta V_o \quad \text{...(A3)}$$

$$V' = S_\delta (S_2 Q_o - C_2 U_o) + C_\delta V_o \quad \text{...(A4)}$$

where $C_2 = \cos 2\alpha$, $S_2 = \sin 2\alpha$, $C_\delta = \cos \delta$ and $S_\delta = \sin \delta$.