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MEASUREMENT OF SOLAR MAGNETIC FIELDS

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Abstract

The paper reviews several methods of estimation of solar magnetic fields so far employed. The possibility of measurement of the vector magnetic fields by using two dimensional detector arrays is discussed. A program for vector measurement of strong field around solar active regions is described and experiments for determining the errors in these measurements described.

The role of magnetic fields in the creation of the visible features and in energy release mechanisms in the solar atmosphere is well recognised. But the speculation of the existence of magnetic fields on the Sun was first made from an altogether different context. The dipole nature of the Earth's magnetic field was well known for sometime; when the use of photography for astronomical imaging was introduced in 1880's, it was noticed that the shape of the solar corona bears a close resemblance to the lines of a bar magnet. The explanation, that the alignment of inhomogeneities in the corona results in these coronal rays, came much later.

The first direct measurement of solar magnetic fields was achieved by Hale in 1908, when he showed existence of large Zeeman splittings of some spectral lines originating from sunspots regions. The displacement of the split components were small, and only very strong magnetic fields of the order of a few kilogauss could be measured. For the extension of the measurements to lower fields, the Hale-Nicholson grid was invented, which allowed fields down to a hundred gauss to be measured. Many features of solar activity cycle were discovered through the study of these active region magnetic fields; detection of any polar field of the Sun which could provide an explanation of the coronal ray structure, however, remained elusive.

In 1952, Babcock and Babcock could bring out the first direct measurements of weak fields. In their photoelectric solar magnetograph, they used a differential measurement technique which could bring out traces of circular polarisation at the wings of the Zeeman affected lines. The instrument was capable of detecting fields of the order of two gauss with one second integration and still lower fields with longer integration times. Several instruments of this type came up and the mapping of either the global magnetic fields or detailed magnetic structure of selected regions was started in a regular manner.

The instrument still continued to have major limitations. First, it measures only the longitudinal component of the field; it fails to detect transverse fields. Second, the basic instrument measures fields at one point only at a time, requiring enormous time for coverage of even a small area. Elaborate arrangements employing a multipoint fibre optic pick-up device and a bank of photomultipliers and lock-in amplifiers are incorporated in the Kitt Peak Solar Magnetograph to reduce the time of scanning by a factor of forty. But in this arrangement, random doppler shifts of the measured line are difficult to separate which introduces some uncertainties in the results. Third, the measurements are possible only near the photosphere, where reasonably strong lines, with high Lande' factor, originate; application of Zeeman method in rarefied coronal regions creates enormous difficulties. Fourth, some of the line profiles are strongly dependent on temperature, which makes the interpretation of measured polarisation profiles difficult. For a proper understanding of the physics and dynamics of the solar atmosphere, it is necessary to know the total vector magnetic field unambiguously at several depths extending from the corona down to sub-photospheric layers. All these cannot be achieved by one technique only; a combination of several methods are needed for this task.

In table 1, we summarise some of the methods which have been used in the measurement of solar magnetic fields. Most of them provide a qualitative idea of the field strength and some give information about the orientation of field lines.

The idea of using the Zeeman effect for the measurement of total magnetic fields was first mooted by Sears (1913) when he calculated the state of polarisation of light from the wings of spectral lines for arbitrary orientation of the field lines. Owing to intrinsic difficulties in the measurement of transverse fields no success was reported. It was Unno (1956) who reopened the question; in this pioneering investigation he showed that the polarisation profiles of Zeeman sensitive lines can give information about the magnetic field vector. He calculated the profiles in the four Stokes parameters I, Q , U and V. He considered absorption of radiation by the solar gases in the presence of magnetic field, which modifies the absorption profiles due to the Zeeman effect. His idea opened the possibility of estimating vector magnetic fields from a set of measurements on solar spectra.

Several modifications in the photoelectric magnetographs were devised to enable them to measure vector magnetic fields following the ideas of Unno (e.g., see Stepanov, 1960) and some of them were employed in actual measurements. The main problem arose in securing a good signal-to-noise ratio which limited some of the attempts to relatively strong fields only.

The use of fourier transform spectrometer (FTS) as a polarimeter has given a larger impetus to the study of magnetic field regions. Properties of spatially unresolved magnetic flux tubes like intrinsic field strengths, relative cross sectional area, velocities, thermodynamic properties etc., have been derived from the measurement of Stokes profiles of spectral lines (Stenflo, et al., 1984).

Availability of sensitive panoramic solid state detector arrays have now opened the possibility of simultaneous vector magnetic field measurements over several points which can be employed to map areas on the solar disc. The use of on-line computers are mandatory for such experiments; we hope to see such systems to be operational in a short time.

In an experiment undertaken at Kodaikanal, this idea is being employed to measure the magnetic field vector over solar active regions. Six sets of spectra of Zeeman sensitive lines are recorded with analysers isolating the four Stokes parameters. At present the detector used is a sensitive photographic film, which after exposure and development is digitised by a computer controlled digitiser. The data sets yield simultaneous measurements of Stokes parameters over a narrow spectral range all along the Zeeman broadened lines, for a narrow rectangular strip over the solar disc. The method of analysis below yields the distribution of the magnetic field strength and direction over the strip delinated by the entrance slit to the spectrograph.

We now discuss in some detail the concept of measuring the vector magnetic fields using the polarisation content of the Zeeman broadened spectral lines. The spectral lines are formed in absorption at the photosphere of the Sun and hence their profile will be affected by the ambient magnetic field. The lines with a sufficiently good value of the Lande's g factor will split with their components separated by $\Delta\lambda$, given by

$$\Delta\lambda = \frac{e}{4\pi mc^2} \cdot \lambda^2 \cdot g.H \tag{1}$$

where e, m are charge and mass of the electron, c is the velocity of light and H is the magnetic field.

Since the lines are generally broadened due to thermal motions considerably, the split compnnents are not distinguishable, but a wavelength dependent polarisation is noticed along the line profile.

The state of polarisation of light at every point can be fully described the Stokes parameters, I, Q, U, V. In terms of an electromagnetic beam propagating along the positive z-direction, these can be defined as:

$$\begin{aligned} I &= \langle E_{x_0}^2 + E_{y_0}^2 \rangle \\ Q &= \langle E_{x_0}^2 - E_{y_0}^2 \rangle \\ U &= \langle 2E_{x_0}E_{y_0} \cos(\delta_y - \delta_x) \rangle \\ V &= \langle 2E_{x_0}E_{y_0} \sin(\delta_y - \delta_x) \rangle \end{aligned} \tag{2}$$

where the electrical vector variations of the beam in two orthogonal directions are given by

$$\begin{aligned} E_x &= E_{x_0} \cos(wt - \delta_x) \\ E_y &= E_{y_0} \cos(wt - \delta_y) \end{aligned}$$

and < > denotes the time average.

An optical component can be described by a 4x4 matrix, the Mueller matrix (which takes into account all forms of fresh polarisation, retardation and extinction introduced by it). If $(I,Q,U,V)^T$ is the Stokes parameter of an incoming beam of light, then on passing through the optical component it transforms into the Stokes parameter $(I',Q',U',V')^T$ as

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

where m_{ij} represents the elements of the Mueller matrix. This is the basic principle for the measurement of the polarisation profile of any Zeeman broadened spectral line.

The actual experimental set-up for the measurement, at Kodaikanal, consists of a three-mirror coelostat system feeding a 38 cm F/90 achromat (Balasubramaniam et al, 1985) coupled to a spectrograph of high dispersion and resolution.

As the radiation from the Sun passes through this three-mirror coelostat system (Figure 1), each of these mirrors introduces changes in the beam which can be represented by individual Mueller matrices. Each of these matrices are characterised by the angle of incidence (which depends on the geometry of the telescope and the coordinates of the Sun), and the complex refractive indices of the mirror surface which can be derived from the Fresnel's law of reflection for a metallic surface (Makita and Nishi, 1970).

If $[M_1]$, $[M_2]$, $[M_3]$ are the Mueller matrices of mirrors 1, 2 and 3 respectively, then an incident Stokes vector $[I] = (I,Q,U,V)^T$ on the first mirror emerges from the third mirror as $[I'] = (I',Q',U',V')^T$

$$[I'] = [M_3][R_2][M_2][R_1][M_1][I] \tag{4}$$

where

$$[M] = \frac{1}{2}\begin{bmatrix} 1+X^2 & 1-X^2 & 0 & \\ 1-X^2 & 1-X^2 & 0 & \\ 0 & 0 & 2X\cos\tau & 2X\sin\tau \\ 0 & 0 & -2X\sin\tau & 2X\cos\tau \end{bmatrix} \tag{5}$$

X is the ratio of the reflection coefficients and τ the phase difference between the electric vectors orthogonal to and in the plane of reflection, respectively, for each of the three mirrors. R_1 and R_2 are rotation matrices to account for changes in the planes of incidence from mirrors 1 to 2 and 2 to 3 respectively. These are represented by:

$$[R] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\theta) & \sin(2\theta) & 0 \\ 0 & -\sin(2\theta) & \cos(2\theta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where θ is the rotation angle which is a function of the geometry of the telescope and the coordinates of the Sun.

Since the angles of incidence and the planes of incidence vary continuously as the Sun changes in hour angle and declination, the mirrors are likely to introduce varying extinction and polarisation in the beam. These have been estimated for various hour angles and declinations. The results showed that, when the incident light is totally unpolarised, the percentage polarisation is a maximum of about 12% during extreme hour angles and declinations of the Sun, and falling to about 2% during noon. The composite Mueller matrix elements of the three mirrors have also been calculated, so that the instrumental polarisation can be compensated for.

A polarisation analyser consisting of a quater wave plate followed by a polaroid is placed just ahead of the entrance slit of the spectrograph (Figure 2), the spectral lines chosen are FeI 6301.5 Å and 6302.5 Å with Lande' factors g=1.5 and 2.5, respectively. Since instrumental polarisation is also introduced in the set up, the uncertainty in the measured values need be estimated.

The composite Mueller matrix of the polarimeter can be written as:

$$[M] = [P][\alpha_2][R][\alpha_1]$$

hence the errors in the measurement of Stokes parameters is given by the Mueller error matrix

$$\partial [M] = [P]\frac{\partial[\alpha_2]}{\partial\alpha_2}\,\partial\alpha_2[R][\alpha_1] + [P][\alpha_2][R]\frac{\partial[\alpha_1]}{\partial\alpha_1}\,\partial\alpha_1$$

where

$$[P] = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

is the matrix due to the polaroid,

and

$$R = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta_r & \sin\delta_r \\ 0 & 0 & -\sin\delta_r & \cos\delta_r \end{bmatrix}$$

is the matrix due to the retarder. Here δ_r is the retardance: for a quater wave plate $\delta_r=90^\circ$. $[\alpha_1]$ and $[\alpha_2]$ are the rotation matrices required to transform from the reference frame denoted by XOY (Figure 2) to the retarder frame (denoted by F and S), and from the retarder frame to the polaroid frame (denoted by the transmission direction T), respectively.

We have evaluated these errors and find that, for a positioning error of $\pm 1/2^\circ$, the maximum errors ΔQ, ΔU and ΔV for the different orientations do not exceed 2% of the Q, U and V signals.

Once the spectra are digitised and the various known sources of error removed, the Stokes profiles will have to be compared with the numerically solved profiles derived from the polarised radiative transfer equations (Landi Degl' Innocenti & Landi Degl' Innocenti, 1972, Wittman, 1974). This will have to be done for a grid of values of the optical depth, inclination and azimuth of the magnetic field. Model solar atmospheres will have to be assumed and the vector magnetic field solutions will be iteratively determined.

The computer programs for calculating the transfer of polarised radiation are under development. Further measurements of the complex refractive index of the mirror surface will also be done. The method described thus far will, in the first instance, be employed in the measurement of relatively strong fields over active areas. The experience gained will help us in designing a total vector solar magnetograph using panoramic solid state detectors.

Table I

Methods of solar magnetic field measurements

Methods	Effect	Remarks
Direct Methods		
1. Zeeman effect	Splitting of spectral lines into polarized components.	Sensitive for high magnetic fields in solar active regions. Good for polar fields in photospheric levels.
2. Hanle effect	Changes of polarization of spectral lines.	Suitable for chromospheric measurements and to some extent in corona.
3. Gyrosynchroton radiation.	Emission of polarized radiation.	Emission in microwave or longer wavelengths — suitable for coronal fields.
4. Faraday Rotation	Change of plane of polarization during transmission.	Measurements require special conditions. Suitable for coronal fields.
5. Razin effect	Low frequency cut off of radiation during transmission.	Measurements need special conditions; used for confirmation of results obtained by other methods.
Indirect Methods		
1. Alignment of features	Alignment of brightness inhomogeneities along field lines.	Qualitative measurements possible.
2. Local thermodynamic changes	Intensity changes in spectroheliograms.	Convenient qualitative method for obtaining field patterns.
3. Dark H_α filaments	Demarcates boundary between opposite field polarities.	Provides information about large scale field pattern.

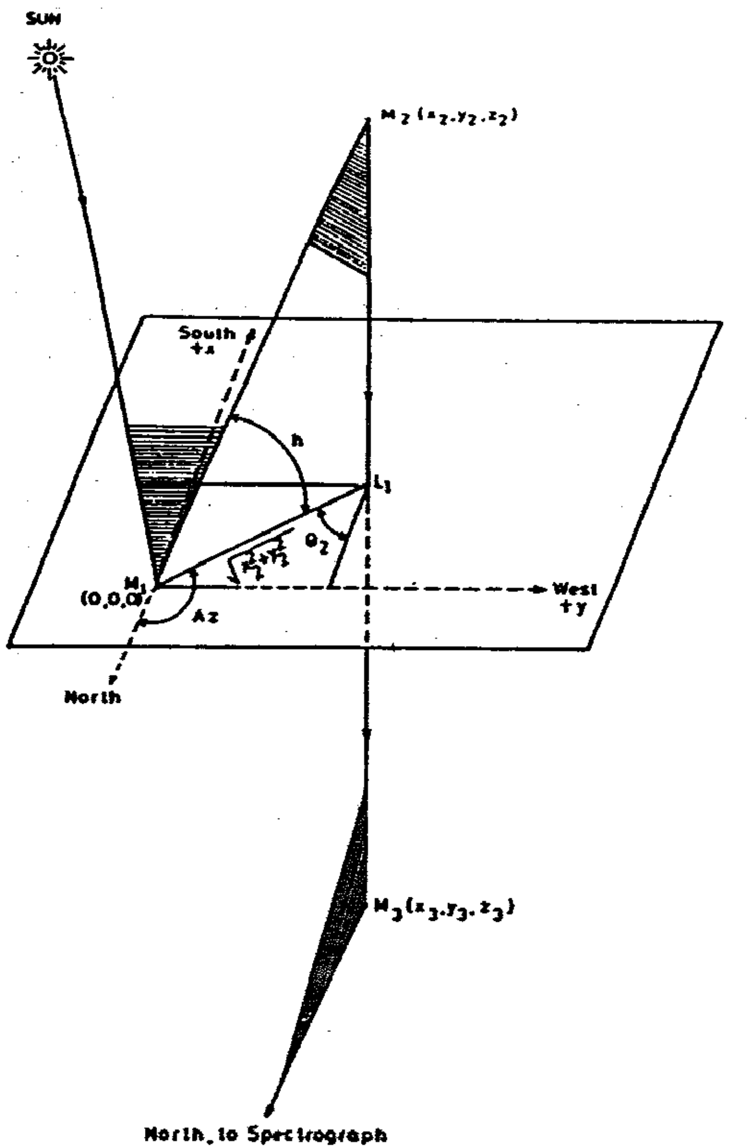

Fig.1. The 3-mirror coelostat system at Kodaikanal.

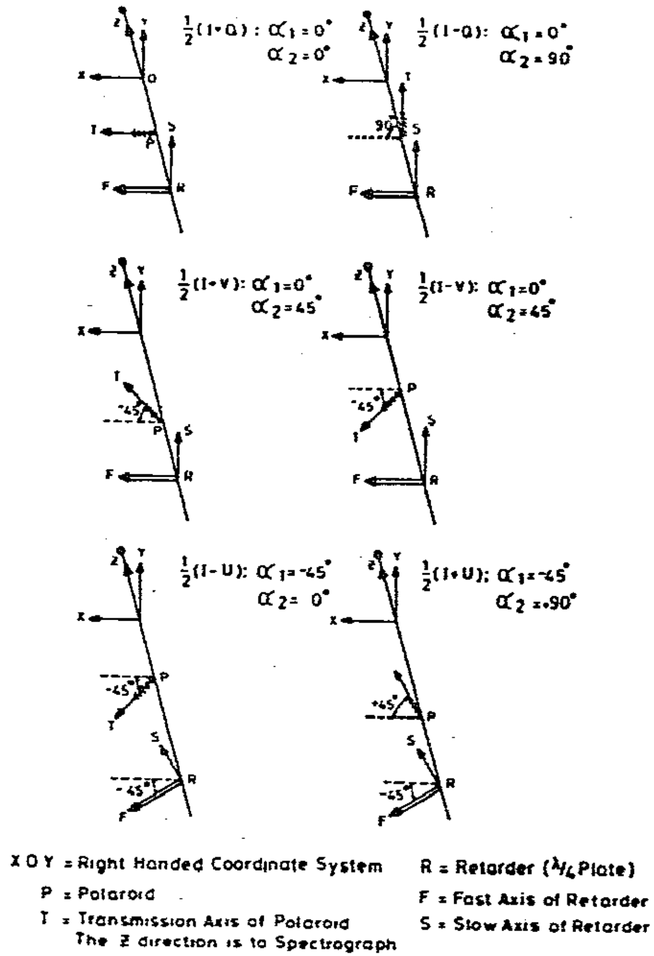

Fig.2. Arrangement of the polarimeter.

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