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NEW IZMIRAN SOLAR SPECTROMAGNETOGRAPH

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ABSTRACT

A new solar spectromagnetograph for measuring the full magnetic-field vector and line-of-sight velocities is described. A new version of a polarization analyzer ensuring parallel measurements of six polarization components of spectral lines is considered. The spectromagnetograph allows the use of any algorithms for obtaining the magnetic fields vector, in particular, the Babcock algorithm and the Fourier transform technique. The sensitivity of the instrument for the longitudinal and transverse magnetic field is 5-10 and 30-50 G, respectively, and ~10 m/s for the line-of-sight velocities.

INTRODUCTION

The magnetic field vector can be determined by various methods, but the most reliable and precise data are obtained from observations of the Zeeman effect in solar spectral lines. In this case in order to determine the magnetic field vector, it is necessary to measure all polarization parameters of the radiation at a single or several wavelengths of the magnetically sensitive lines. Measurements must be performed at each spatial point of the sun disc under study in a time comparable to the time scale of the developing solar processes.

Here we compare the magnetographs based on filter-based and spectrographical schemes. Then a new version of the polarization analyzer, which ensures simultaneous measurements of six polarization components of a spectral line, is considered.

COMPARISON OF SCHEMES FOR MAGNETIC FIELD MEASUREMENTS

In order to investigate the dynamics of magnetic processes, we need a four-dimensional data array (file) including two spatial, one spectral, and one time coordinate in six versions corresponding to six states of the polarization analyzer. The absence of sufficient resources for parallel measurements of the entire data array leads to the necessity of sacrificing the simultaneousness for one or several measured parameters.

One of the widespread schemes for magnetic fields measurements includes an tunable optical filter, an adjustable polarization analyzer, and a two-dimensional CCD array placed in the solar image plane, see, for example [Wang et al, 1998; Mickey et al, 1996]. The main advantage of this system is that data are obtained simultaneously for all points of the image. However, it is necessary to use sequential procedure to measure the different polarization states. In result in the accuracy of the determination of the line-of-sight velocity and magnetic field is decreased.In addition, observations are often restricted to measurements only in two spectrum regions of a line wing. Because of this, data can be unambiguously interpreted only within the framework of the simplest models of the solar atmosphere, which hardly conforms with the reality.

Another type of magnetograph scheme uses a diffraction spectrograph with a long entrance slit as a selective spectral element, see for example [Jones et al, 1992; Lites et al,1992]. In this case, the receiving CCD array is located in the spectrum image plane. Such a scheme has a high spectral resolution and ensures simultaneous recording of the intensity over the entire spectrum and along one of the spatial coordinates, allowing us to unambiguously interpret the measurement data. However, since the spectrum fluctuations in slit spectrographs are usually higher than those for the filters, this advantage hardly translates into a gain in the accuracy. In addition, the factor of simultaneousness is lost both for the second spatial coordinate because of the necessity for scanning the solar image along it. Nevertheless, the situation can still be corrected. As a rule, the maximum number of resolved spectral elements over a line profile is within 20–30. This means that no more than 3–5% of the CCD array resolution along one coordinate is used. An obvious conclusion is to design a device for parallel analysis, which makes possible to simultaneously record six polarization components of a spectrum. In this case, the time instability of the spectrum

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loses all it's significance, because the measurements corresponding to all of the spectrum points are strictly simultaneous for all polarization components. Moreover, this solution reduces the duration of the analysis.

The comparison of two design versions allows us to conclude that, at the current technological level, the spectromagnetograph is somewhat more suitable for practical implementations than the filter magnetograph design.

GENERAL OPTICAL LAYOUT OF THE SPECTROMAGNETOGRAPH

The spectromagnetograph for parallel measurement of the spectral and polarization characteristics of magnetically active lines was designed on the basis of the IZMIRAN optical solar telescope. Its block diagram is shown in Fig. 1. The general system includes a tower solar telescope *(TST)*, a grating spectrograph, a polarization analyzer, two CCD cameras, two controllers, a scanning unit, an Hα filter, and three personal computers *(P*C).

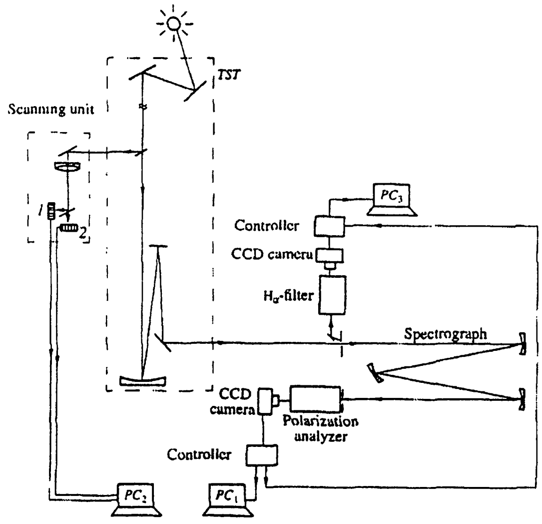

Figure 1: Functional diagram of the spectromagnetograph installed on the TST.

The dispersion of the spectrograph in the second-order spectrum, which is used during the magnetograph's operation, is 0.8 Å/mm. The spectrograph has mirror-type jaws at the entrance slit. The size of the output slit, which is also the entrance slit of the polarization analyzer, is 20 x 0.15 mm (about 200"× 1.5"). The polarization analyzer is described in detail in Section 4. Commercial CCD cameras (Proscan, Germany) are used in the system as photodetectors. The number of pixels in the CCD array is 1024 × 1024, and their size is 14 × 14 μm. The readout rate is 6–10 frame/s. The dark noise and the maximum signal levels correspond to 430 and 16384 units, respectively. The controller ensures signal recording in a digital 16-bit format. A possibility of mutual synchronization of CCD cameras is provided. The wide-band guide of the telescope [Kozhevatov et al, 2000;.Kozhevatov et al, 2000a] serves as a scanning unit. The Hα filter used in the optical arrangement is an interference–polarization filter (Halle, Germany) transmitting the solar radiation at a wavelength of 6562.8 Å (Hα).

The TST forms an image of the solar disc 168 mm in diameter on the entrance slit of the spectrograph. The solar radiation transmitted through the spectrograph is directed to the polarization analyzer, which forms six bands of the spectrum region selected corresponding to six polarization states. The intensity of all these bands is recorded by the first CCD camera. Subsequent data recording is performed with the help of a personal computer, PC1. Scanning along one of the spatial coordinates of the active area is carried out by the help of the scanning unit, whose operation is controlled with a personal computer, PC2. The program developed ensures an absolute referencing of the coordinate system, which is fixed to the guide's photosensors, to solar coordinate systems. Moreover, as a result of the action of the wide-band guide in a frequency band of 1–100 Hz, the total value of the solar image motion decreases by a factor of 3–5, and the component related to microseisms is suppressed to the noise level of the tracking system.

The solar radiation reflected by the mirror-like jaws of the spectrograph entrance slit passes through the filter used for constructing a solar image in the Hα. line. It gives the possibility to have more precise referencing of the observation data to spatial solar coordinates. It also allows us to take into consideration the displacements caused by the sun image motion in the subsequent data analysis. The image is read out by the second CCD camera and stored by the PC3.

PARALLEL-TYPE POLARIZATION ANALYZER

In Section 2, we noted the high importance of designing a parallel-type polarization analyzer. This device is necessary, when a spectrograph and a low-frequency camera are used as a spectral element and a detector, respectively. If a step-by-step analyzer (with time modulation) is used in this case, then a spectral line may be appreciably shifted in a time required for running all

2002ESASP.506..951K

six polarization positions, directly resulting in errors in Zeeman effect measurements.

Figure 2 shows the optical diagram of an entirely parallel–type polarization analyzer. The system contains a slit, a beamsplitter, two quarter-wavelength plates, a polarization beam splitter, a unit of matching lenses, and an objective lens. In accordance with the spectrograph's dispersion and slit dimensions, a spectrum band with a height of 20 mm and a spectral width of ~1.2 Å is incident on the front plane of the beamsplitter.

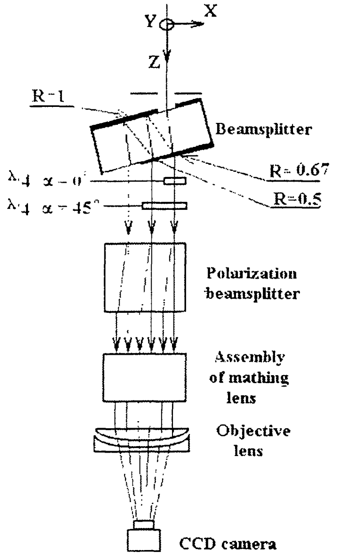

Figure 2: Optical diagram of the parallel-type polarization analyzer

The spatial beamsplitter is designed for forming three maximally identical beams with minimal distortion of the initial polarization. Is is oriented at a 1/8 angle to the optical axis. The directions of the polarization axes of the first quarter-wavelength plate coincide with the axes of the coordinate system. The directions of the polarization axes of the second λ/4 plate are turned with respect to those of the first plate clockwise by an angle of 45 ° in the XY-plane. The polarization beamsplitter made of spar is a beam-separating crystal element, from which beams with orthogonal linear polarizations emerge in parallel to each other. The polarizations of the ordinary and extraordinary waves are directed along the Y and X axes, respectively.

In order to reduce the entire image to a size corresponding to the CCD array, an assembly of matching lenses and an exit objective lens are introduced into the optical system. With their help three pairs of reduced images are brought to the plane surface of CCD camera.

After passing through the beamsplitter, the light beam is divided into three beams of equal intensities. The first one passes through two quarter-wavelength plates, the second beam, through one plate, and the third beam is transmitted unimpeded.

Subsequently, all three beams fall onto the polarization beam splitter, where they are transformed into six parallel beams corresponding to different linear polarization states and shifted with respect to each other in the X-direction. Figure 3 shows the spectrum images in six different polarizations in the vicinity of the Fe I solar line (λ 6302.5 Å, the Lande factor is 2.5) and the line of atmospheric oxygen (λ 6302.8 Å). The latter serves as a reference line in line-of-sight velocity measurements.

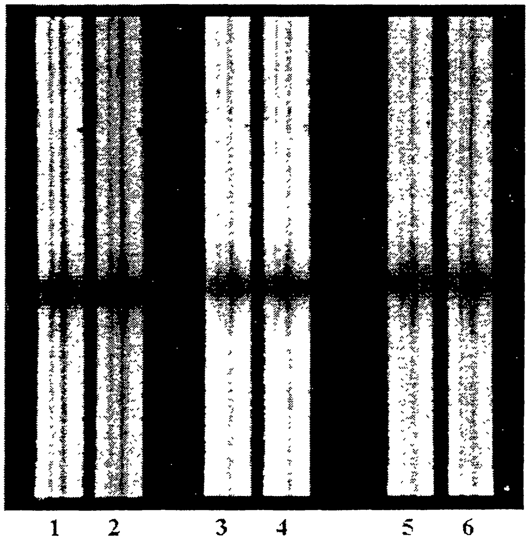

Figure 3: Radiation intensity of the solar spectrum in six different polarizations in the vicinity of the solar spectral line FeI6302.5A (on the right) and telluric oxigen line6302.8A.

With the perfectly manufactured quarterwavelength plates, the intensity values in each of the six beams are described by the expressions

$$J+\mathrm{Q} \quad (1) \qquad J-\mathrm{V} \quad (4)$$
$$J-\mathrm{Q} \quad (2) \qquad J+\mathrm{U} \quad (5)$$
$$J+\mathrm{V} \quad (3) \qquad J-\mathrm{U} \quad (6)$$

As known, four independent linear equations are sufficient for calculating four parameters. Nevertheless, it is preferable to have these six relations. First, the greater part of the array area of CCD is unutilized. On the other hand, the three most important Stokes parameters (Q, V, U) can be easily derived from relations (1)–(6) by appropriate subtractions, making it possible to eliminate any possible additive errors (interferences, noises). This error elimination technique is similar to the modulation method for noise suppression, which is widely used in the sequential analysis.

In the actual system, the reflection coefficients of the elements of the spatial beamsplitter differ from the specified values, and distortions of the polarization characteristic of the radiation introduced by the optics of both the polarization analyzer and the spectrograph exist. Moreover, the light transmission efficiency of the system may be different for different pixels, since it depends on the it's individual sensitivity and on the presence of dust and contaminations on optical elements. As a result each pixel has its own polarization matrix.

Hence, the general problem of calibration of magnetographs and, especially, that of the type under consideration, is at least as important as the development and creation of the optico–electronic system itself. However, this part of the problem is so wide in scope and topical that it deserves special consideration.

CONCLUSIONS AND OUTLOOKS

The spectromagnetograph with parallel spectral and polarization analysis of radiation described in this paper was mounted on the IZMIRAN tower solar telescope and is test-operated. The spectromagnetograph proposed to give a sensitivity of 5 -10 G in measurements of the longitudinal magnetic field, 30 -50 G for the transverse field, ~10 m/s for line-of-sight velocities and, in addition, permits the use of any algorithms for measurements of the magnetic field vector, such as the Babcock algorithm and the Fourier transform method [Ioshpa et al, 1996].

An important feature of the parallel polarization analyzer designed for the spectromagnetograph is that it is entirely static. It contains no controllable elements implying mechanical movements and feeding of electric signals. Therefore, it is much more stable as compared to mechanical and electro-optic modulators and has an almost unlimited service life.

The spectromagnetograph will be used in permanent observations of the full vector of the magnetic field and line-of-sight velocities in the solar atmosphere.

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