A Full-Disk Solar Magnetograph at Mitaka

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A full-disk solar magnetograph was constructed at the Mitaka campus of the National Astronomical Observatory of Japan, in support of the STEP project. The basic principle of magnetic field measurement and the configuration of the instrument are presented.

1. Introduction

The magnetic field plays an important role in a variety of activities seen in the solar atmosphere, and therefore the measurement of magnetic field is of fundamental importance in studying the solar activity. The magnetic field on the solar surface is derived by measuring the polarization of spectral lines due to the Zeeman effect. At the National Astronomical Observatory of Japan (NAOJ), observations of the solar magnetic fields in active region scales have been carried out at Okayama (Makita et al., 1993) and Mitaka (Sakurai et al., 1995). The aim of these observations is to study the build-up of magnetic stress in active regions which leads to explosive release of stored magnetic energy known as solar flares.

Large-scale magnetic field distributions on the solar surface determine the magnetic field structures in the corona and in the solar wind. In order to study the influence of solar magnetic fields on interplanetary and magnetospheric environments, an instrument which measures global magnetic field distributions on the sun is of vital importance. Such full-disk or synoptic observations of the solar global magnetic fields have been carried out only in the United States so far, at Mt. Wilson, Kitt Peak, and Stanford. In order to increase the data coverage, similar kind of observations should be conducted at the complimentary longitudes.

As part of the NAOJ’s contribution to the Solar-Terrestrial Energy Program (STEP project), we have constructed a full-disk solar magnetograph at Mitaka. This instrument is capable of measuring the line-of-sight (longitudinal) component of the magnetic field, and the Doppler shift of the plasma on the solar surface. Although the previous three full-disk magnetographs are all based on spectrographs, we adopted the so-called video magnetograph which utilizes a narrow-band filter instead of a spectrograph. A similar project was initiated nearly simultaneously at Beijing Observatory (Liu et al., 1994).

2. Overall Design of the Instrument

Our instrument is made of a heliostat mirror system, imaging optics, a birefringent filter, a CCD camera, and an image analysis system based on a personal computer (Fig. 1). The heliostat has a mirror of 20 cm in diameter. The first mirror tracks the sun by a clock mechanism, and the second fixed mirror feeds the sun light into the observing room. Optical benches were set up on a block of concrete in the observing room, and the imaging optical elements were arranged on the benches.

The imaging optics is made of an objective lens of 6.5 cm diameter (F/12), a field lens at the primary solar image, a relay lens which makes an F/24 telecentric light beam, and an imaging lens which makes the image of the sun on a CCD camera. The final solar image has the diameter of 6 mm. The CCD in the camera (SONY XC-77) has a size of 8.8 mm x 6.6 mm, covering the full solar disk. The measurement of
the magnetic field is made by using the spectral line of Fe I at 5324.2 Å, which has the Landé factor of 1.5. Polarimetric characters of this line were studied by Ai et al. (1982).

The passband of the birefringent filter is a function of the angle of light beam with respect to the optical axis. We adopted the telecentric optics, so that all of the points in the image plane receive cones of incident beam whose axes are parallel to the optical axis and whose opening angles are all identical. Therefore, all the points in the field of view have the same characteristics in wavelength transmission.

For precise measurement of polarizations, it is necessary to accurately correct for sensitivity nonuniformity of the CCD pixels. This can be made by taking dark frames and flat field images. The dark frames are taken by using a mechanical shutter in front of the CCD. The flat fields are taken by inserting a calibration optics into the beam. This calibration optics makes an image of a space near the entrance aperture, uniformly illuminated by the sun, onto the CCD. The calibration optics is so designed that the tilt and the spread of the beam with respect to the optical axis are the same as in the observing condition, when the calibration is done.

The output from the CCD camera is digitized and accumulated with an image processing unit with
the format of 512 (horizontal) \times 480 (vertical) pixels. The data acquisition is controlled by a personal computer. The accumulated data are sent to a workstation via ethernet, and are processed and archived.

3. The Birefringent Filter

Video magnetographs are made of a narrow band filter as a wavelength selector, a polarization modulator, and a video camera. In our system, a birefringent filter is used as the wavelength selector, and a KD\*P is used as the polarization modulator. The KD\*P modulator is made of KD\*P crystals sandwiched between two transparent electrodes. When high electric voltages are applied, the modulator yields retardation which is proportional to the applied voltage. Our system has two KD\*P modulators; KD\*P1 at the front which is for polarization analysis, and KD\*P2 which is for Doppler analysis.

The internal configuration of our birefringent filter is shown in Fig. 2. When the KD\*P2 is switched off, the filter has a double-peaked passband centered at 5324.2 Å, and each peak is 0.16 Å wide (FWHM) (Fig. 3(a)). The parameters of optical elements are summarized in Table 1. The transmission half width \( w \) and the retardation order \( n \) are related as

\[
\frac{\lambda}{2w} = n \left( 1 - \frac{\lambda}{\mu} \frac{\partial \mu}{\partial \lambda} \right)
\]

![Diagram](image-url)

**Fig. 2.** The internal structure of the birefringent filter used in the magnetograph. “IF” at the entrance of the filter stands for an interference filter. Orientations of optical axes are shown by bars under each element. “H” and “Q” respectively denote half and quarter-wave plates. “C” are rotatable half-wave plates. Polaroids are represented by hatching.

<table>
<thead>
<tr>
<th>Half width ( w ) (Å)</th>
<th>Thickness ( d ) (mm)</th>
<th>Retardation order ( n )</th>
<th>Material</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>2 x 17.675</td>
<td>2 x 5788</td>
<td>calcite</td>
<td>wide field, tunable</td>
</tr>
<tr>
<td>0.4</td>
<td>2 x 8.847</td>
<td>2 x 2894</td>
<td>calcite</td>
<td>wide field, tunable</td>
</tr>
<tr>
<td>0.8</td>
<td>2 x 4.424</td>
<td>2 x 2447</td>
<td>calcite</td>
<td>wide field, tunable</td>
</tr>
<tr>
<td>1.6</td>
<td>2 x 2.212</td>
<td>2 x 723.5</td>
<td>calcite</td>
<td>wide field, tunable</td>
</tr>
<tr>
<td>3.2</td>
<td>2 x 21.823</td>
<td>2 x 376</td>
<td>quartz</td>
<td>wide field, tunable</td>
</tr>
<tr>
<td>6.4</td>
<td>2 x 10.911</td>
<td>2 x 188</td>
<td>quartz</td>
<td>wide field</td>
</tr>
<tr>
<td>12.8</td>
<td>2 x 5.456</td>
<td>2 x 94</td>
<td>quartz</td>
<td>wide field</td>
</tr>
<tr>
<td>25.6</td>
<td>2 x 2.728</td>
<td>2 x 47</td>
<td>quartz</td>
<td>blocking filter</td>
</tr>
</tbody>
</table>
where $\lambda$ is the observing wavelength and $\mu = n_e - n_o$ is the degree of birefringence. The thickness $d$ of an element is given by

$$d = \frac{n\lambda}{\mu}. \quad (2)$$

All of the elements are wide-fielded by inserting half-wave plates at the middle (Evans, 1949). The two KD*Ps are also wide-fielded. For slow wavelength shifting, the five thickest elements are equipped with rotatable half-wave plates and the transmission peak can be manually shifted up to ±0.6 Å from the center of the 5324.2 Å line.

In contrast to the usual birefringent filter which has a single passband peak, the thickest element (the 0.2 Å element) in our filter is given a half-wave retardation offset, and makes the double-peaked passband of this filter. The second thickest element in the filter, the 0.4 Å element, is located at the entrance of the filter, and it works together with the KD*P2. By giving a quarter-wave retardation in the KD*P2, either the blue or the red side peak is suppressed while the other peak remains. Therefore we can place the transmission peak of the filter at either blue (b) or red (r) wing of the spectral line. (Figs. 4(a) and 4(b)). In our another video magnetograph which has a field of view of active region scales (Sakurai et al., 1995),
Fig. 4. The measured transmission of the filter when the KD*P2 is active, giving the red-ward (a) and blue-ward (b) passband shifts.

the thickest calcite element is modulated with a KD*P. In that system, the filter has a single passband peak when the KD*P is switched off. When the KD*P is switched on, the peak is shifted to the blue side while a large sidelobe remains on the red side, and vice versa. The present scheme provides a cleaner transmission pattern at the wings of the spectral line when the KD*P2 is active.

After the filter was delivered to Japan, its transmission characteristics were measured by using a spectrograph at Hida Observatory, Kyoto University. A slide projector was used as the light source, and the spectra were recorded with a CCD camera with exposures ranging 30–60 s. The wavelength scale was determined by using the solar spectrum.

Figure 3(b) shows the measured transmission profile when the KD*P2 was not active. The reason why the central dip did not reach zero intensity is because the beam going through the filter is too fast and the transmission peaks were slightly broadened. The measured passband widths were 0.19 Å while their true widths should be 0.16 Å. The change in the center wavelength against temperature change is $-0.3$ Å K$^{-1}$, in agreement with the design value. The wavelength shift of the filter by the application of high voltage on the KD*P2 is shown in Figs. 4(a) and 4(b). Since the application of high voltage for more than a few seconds may damage the KD*P, the exposure was limited to 2 s and the profile data were noisy. The applied voltage was also restricted to 900 V, although the quarter-wave retardation is generated at 1200 V.
4. Magnetic Field and Doppler Measurements

If the KD*P1 generates a quarter-wave retardation, a circularly polarized light is converted into a linearly polarized light after passing through the KD*P1. This linearly polarized light is either transmitted or blocked at the entrance polaroid of the birefringent filter, depending on the handedness of the incoming circular polarization. By switching the sign of the voltage applied to the KD*P1, we can alternatively select left (L) or right (R) hand circular polarization that goes through the filter system. The output images are taken with a CCD camera, and are digitized in 8 bits and are accumulated onto two sets of 16-bit buffer memory M1 and M2.

Usually 128 frames are accumulated on M1 and M2. The contents of the memories are mixtures of L and R images taken at the wavelength \( r \) or \( b \). In the magnetograph mode, memory M1 accumulates 64 frames each of R(b) and L(r), while memory M2 accumulates 64 frames each of L(b) and R(r). The circular polarization degree is obtained from \( C = (M1 - M2) / (M1 + M2) \). The longitudinal field strength is given as \( B_l = 2.0 \times 10^4 C \) gauss under the so-called weak field approximation (Jefferies et al., 1989). In the Doppler mode, memory M1 accumulates 64 frames each of R(r) and L(r), while memory M2 accumulates 64 frames each of R(b) and L(b). The Doppler velocity is given as \( (M1 - M2) / (M1 + M2) \times 22.3 \text{ km s}^{-1} \). Photometric accuracy in each measurement was estimated by comparing two flat field frames. The inferred accuracy is 0.06% which is consistent with the photon number statistics and the estimated full-well capacity of the CCD used. In terms of the longitudinal field strength, this number corresponds to 12 gauss. It also corresponds to 13 m sec\(^{-1}\) in Doppler shifts.

One sequence of observation, which takes one of each of the magnetogram and the Dopplergram, is completed in approximately 75 seconds including the time for data transmission via network.

5. Example of Observation

From June 1993 we started test observations of full disk magnetograms. Currently we are taking a few magnetograms per day. An example shown in Fig. 5 was taken on August 11, 1993. White and black

![Fig. 5. Magnetogram of 1993 August 11. White and black indicate positive and negative magnetic fields.](image-url)
indicate positive and negative polarities, respectively.

When the solar tracker which is under construction is completed, we will start continuous observations. We are aiming at a sensitivity better than one gauss, by summing up many magnetograms in the computer.

So far the data coverage is about 30%. This low coverage is mostly due to interruption for instrumental adjustment. The number of fine days (days with sunshine for more than one hour) per year at Mitaka averaged over these 30 years is about 75%, and the observing coverage should be close to this value after the instrument is stably operated.

The heliostat system and the birefringent filter were constructed by Nanjing Astronomical Instrument Research Center, Academia Sinica. Other optical components were built by Nikon. The assistance of Drs. H. Kurokawa, R. Kitai, and Mr. Y. Funakoshi of Hida Observatory, Kyoto University, is appreciated during the test of the birefringent filter. Observations by using the present instrument have been carried out by the staff of the solar physics division and Norikura Observatory of NAOJ. Contributions from these people are cordially acknowledged.

REFERENCES


