Infrared Stokes Spectro-Polarimeter at the National Astronomical Observatory of Japan

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Abstract. We are now constructing an infrared spectro-polarimeter for the Solar Flare Telescope of NAOJ. It observes the full Sun in two wavelength bands, one near 1.56 μ for highly Zeeman-sensitive spectral lines of Fe I and the other near 10830 Å for He I and Si I lines. The instrument records full Stokes profiles, and a Stokes inversion process will give information on the strength and orientation of the magnetic field vector for both of the photosphere and the chromosphere. The infrared detector we are using is an InGaAs camera manufactured by a Belgian company Xenics. Its format is 640×512 pixels and its read-out speed is 90 frames s⁻¹. The solar disk will be covered by two swaths (the northern and southern hemispheres) of 640 pixels each. The final magnetic maps will be made of 1200×1200 pixels with a pixel size of 1.8 arcsec. Now we are operating regular observations and generate full-disk, full-Stokes maps (a few maps per day). Our ultimate goal is to derive the distribution of magnetic helicity over the whole surface of the Sun, not only in sunspots and active regions.

1. Introduction

Synoptic solar observations are required not only from the solar physics community but also from the geophysics community particularly for the space weather study. The long-term evolution of the global magnetic activity of the sun is the major scientific target of the synoptic observations, and therefore, advanced polarimetric observations are getting more important.

We constructed an infrared Stokes spectro-polarimeter for next generation synoptic solar observations. It regularly observes the full disk of the Sun in near infrared wavelengths, aiming at studying the evolution of the solar magnetic filed with long-time operation. It was installed into the Solar Flare Telescope (Sakurai et al. 1995), which has been mainly used to take vector magnetograms with the Fe I 6303 Å line and images and polarizations with the Hα line. There are two observing wavelength bands for the infrared spectro-polarimeter; one includes the He I 10830 Å and Si I 10827 Å lines, which give chromospheric and photospheric magnetic field information, respectively. Another one includes Fe I 15648 Å and 15653 Å line pair. They also give photospheric magnetic field information, but the large Zeeman splitting of these lines (particularly of the Fe I 15648 line) enables us to do direct measurement of the magnetic field strengths.
We carry out daily observations with this instrument. A full-disk map with about 1200×1200 pixels can be obtained by raster-scannings and it takes about 1.5 hours to scan the whole disk. Several full-disk maps are regularly taken every day. While some full-disk Stokes observations in the visible wavelengths are now being operated by, e.g., SOLIS of National Solar Observatory, Kitt Peak, and HMI of Solar Dynamics Observatory, this instrument gives us unique full-Stokes data of the photosphere and the chromosphere taken in the infrared wavelengths.

In this paper, we will describe the instrument briefly in Section 2, and present some observational results in Section 3, and a summary is given in Section 4.

2. Instrument

Here we describe the instrument. A detailed description will be given in a separate paper (Sakurai et al. in preparation). Basically, this instrument is designed as a single-beam spectropolarimeter. For this reason, fast polarization modulation is required to reduce the seeing-induced crosstalk, and therefore, we adopted a polarization modulator consisting of ferroelectric liquid crystals (FLCs; see e.g. Gandorfer 1999; Hanaoka 2004) and a rather high-speed infrared camera to realize a fast polarization modulation. Figure 1 shows the telescope and the spectropolarimeter. We present brief descriptions of various parts of the instrument below.
As shown in Figure 1(a), the telescope has four refractor tubes, and an infrared objective lens with a diameter of 15 cm, which is achromatic at 10830 Å and 1.6 μ, was installed in one of them (the uppermost tube in Figure 1(a)).

Figure 1(b) shows the spectro-polarimeter installed behind the telescope tubes (the cover is removed). After the objective lens there is a pre-filter. It consists of two interference filter elements, and has two transmission bands, one around 10830 Å and another around 1.6 μ. Thus most of unnecessary light is blocked before the FLC modulator to avoid heat input to the FLCs, because the polarization characteristics of the FLCs are sensitive to the temperature.

The polarization calibration optics and the polarization modulator are placed just after the pre-filter before the first mirror. The polarization calibrator contains a polarizer and several λ/4 plates, and produces some kinds of completely polarized light. The polarization modulator consists of two FLCs, which have retardations of λ/2 and λ/4 at λ = 1.3 μ. We have some experiences to construct polarization modulators with FLCs (e.g. Hanaoka 2006). The FLCs were made by Displaytech, and has a clear aperture as large as 45 mm. However, the light reaching the spectrograph slit always passes through the same small area at the center of the aperture of the FLCs. This is to avoid the effect due to the possible non-uniformity of the FLCs and keep the polarization modulation characteristics to be constant during the scans. The large diameter of the FLCs is necessary to pass images of the entire disk for the position sensor of the sun described below.

The temperature of the FLCs is kept to be 45°C, because the polarization characteristics of the FLCs is sensitive to the temperature. The FLCs can be modulated with a speed up to ~kHz, and the high speed modulation contributes to reduce the seeing-induced crosstalk. Now the modulation frequency is limited by the frame rate of the camera (30-50Hz). In the current typical operation, data taken during 24 repetitions of the polarization modulation with four polarization states produced by the two FLCs are integrated for one slit position. The exposure time is 20 ms, and the total integration for a slit position is about three seconds. Such integration realizes the RMS polarization noise to be less than 1 × 10^−3.

Spectrograph is an ordinary Echelle type one, and it is a single-beam polarimetry system. The grating angle for the wavelength 10830 Å and that for 1.6 μ is different from each other, and we need to rotate the grating to change the observing wavelength band.

The raster scan is carried out by moving the image of the sun on the slit. An Offner optics is installed before the slit, and we control it to move the solar image on the slit without changing the pointing of the telescope. There is no slit-jaw monitor, but we have a sun-sensor system consisting of 4 CCD linear arrays to determine the position of the slit on the solar disk. As described above, the full disk image is always produced at the slit position. Therefore, the position of the disk can be determined with the solar limb detected by the CCD linear arrays.

The infrared camera is XEVA-CL-640 fabricated by Xenics. This has a 640×512 pixel InGaAs detector, which has high sensitivity in the wavelengths between 0.9 and 1.7μ. The detector temperature can be cooled by 40 K lower than the ambient temperature. The detector is not a large format one, so it is designed that the width (640 pixels) of the detector matches half of the solar diameter. Two slit-scans are necessary to cover the full disk, one for the northern hemisphere and another for the southern hemisphere. The sun’s disk is covered by about 1200×1200 pixels with the pixel size
Figure 2. Sample Stokes full-disk maps of Si I 10827 Å. In panels (b)(c), the range of the degree of polarization ± 0.1 % is shown. In panel (d), the range ± 0.3 % is shown.

of about 1.8″×1.8″. This is a kind of high-speed cameras, of which the frame rate is up to 90 frames sec⁻¹ (full-frame). This camera shows a significant non-linearity between the input light intensity and the output A/D count. We measured the non-linearity accurately, and obtained raw A/D counts are converted to correct values of input intensity with the derived non-linear response function.

After the installation work for a couple of years, we eventually started the regular operation of the spectropolarimeter in April 2010.

3. Preliminary Observational Results

In this section, some preliminary results of observations are presented.

Figure 2 shows an example of a set of full Stokes maps in the Si 10827 line taken on 2010 April 21. The Stokes I, Q/I and U/I maps are the summation of the blue wing image and the red wing image, and the V/I image is the difference between the red wing image and the blue wing image. The polarization maps show regular Zeeman signals. The V/I image shows the positive and negative magnetic polarities both of the quiet and
active regions distributed over the disk. We can find some linear polarization signals in active regions in the $Q/I$ and $U/I$ maps, although there is no significant sunspot.

Figure 3 shows a set of full Stokes maps of the main (red) component of the He 10830 line taken simultaneously with the maps in Si 10827 in Figure 2. The $I$, $Q/I$ and $U/I$ maps are the summation of the images taken in the wavelengths covering the absorption line, and the $V/I$ image is the difference between the red wing image and the blue wing image. We can find Zeeman polarization signals in the $V/I$ map in active regions, which are weak but similar to those in the Si 10827 $V/I$ map.

In the $Q/I$ and $U/I$ maps, besides polarized interference fringes produced by incomplete polarization calibration, real linear polarization signals originating the Sun can be found. Whereas the Zeeman polarization signals in the $Q/I$ and $U/I$ maps are very weak, filaments on the disk denoted by the arrows in panels (a)(b)(c) in Figure 3 show significant polarizations. Those polarizations are due to the Hanle effect (see e.g. Trujillo Bueno et al. 2002) under the presence of weak (several gauss) magnetic field. In such cases, linear polarizations in the blue component of the He 10830 line show opposite signs to those of the main (red) component (Trujillo Bueno et al. 2002). With the polarization maps in the blue component, we confirmed that. Magnetic field
Figure 4. Sample Stokes maps of an active region in Fe I 15648 taken on 2010 March 30. The field of view is about 6′ × 6′. The columns correspond to the wavelength offsets -0.8/-0.4/0/+0.4/+0.8 Å, respectively. Scratches in images are due to dead pixels.

in filaments is difficult to be measured by the other method than the Hanle effect. Our observation provides us with the magnetic information of all the filaments on the disk every day. It will help us to derive three-dimensional magnetic information of filaments and their evolution.

Figures 3(b) and (c) also show the globally distributed linear polarization signals. In panel (b), near the east and west limb, there are negative Q signals, and near the north and south limb, positive Q signals. In panel (c), the first and the third quadrants show negative U signals near the limb, and the second and the fourth quadrants show positive U signals. In this figure, the orientation of positive Q signals is defined to be horizontal. Therefore, these signals correspond to tangential linear polarization, which is produced by the scattering.

The second example is an active region observed in Fe I 15648 on 2010 March 30. Figure 4 shows full-Stokes maps of 6′ × 6′ field of view at five wavelengths around the Fe I 15648 line (-0.8 Å, -0.4 Å, 0 Å, +0.4 Å, +0.8 Å from the line center) and Figure 5 shows Stokes profiles of 20 pixels around the biggest sunspot. Unfortunately the images, which were taken during the test operation, are somewhat out of focus. However, in Figure 4 we can find the usually expected distribution of Stokes signals. In Figure 5 there can be find several components of magnetic atmosphere which have different magnetic field strengths and different Doppler velocities.

4. Summary

Our IR spectro-polarimeter is a unique instrument which take the full-Sun in the lines of He 10830, Si 10827, and Fe 15648/15653 polarization maps regularly. After some
adjustments, we will open the polarization maps and/or magnetograms taken in these lines on our web page.

**Acknowledgments.** The construction of the spectro-polarimeter has been financially supported by the Grant-in-Aid for Scientific Research of MEXT (category A, No. 17204014, 2005-2008).

**References**