

The Big Bear Solar Observatory's Digital Vector Magnetograph

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Abstract. During the past three years the Big Bear Solar Observatory (BBSO) has begun an aggressive program to upgrade the observatory's instrumentation. In the forefront of this effort are the development of several magnetographs. The first of these systems, the Digital Vector Magnetograph (DVMG), which is being integrated into the observatory's routine observations, is a highly sensitive, high cadence, filter based magnetograph for the observatory's 25 cm vacuum refractor to replace the Video Magnetograph (VMG) to improve our measurements of the Ca I line at 630.1 nm. The hardware is being replaced by a 512×512 pixel, 12-bit, 30 frames per second CCD camera and high quality polarization optics. In addition, software tools are being implemented to aid instrument development by quickly evaluating images (bias, cross talk, etc.) and to generate near real-time vector magnetograms which will aid space weather forecasting and predictions. In this paper we discuss data acquisition, data calibration and flat fielding methods and present quiet sun and active region magnetograms. Lessons learned from the development of the DVMG will be applied to the development of the Imaging Vector Magnetograph which will be a Fabry-Pérot based system implemented on the observatory's 65 cm vacuum reflector.

1. Introduction

Solar magnetographs measure the polarization of light from the Sun, as explained by the Zeeman effect for light emitted by a hot gas immersed in a magnetic field. Four measurements are required to completely describe the polarization of light. Intensity (Stokes-I'), circular polarization (Stokes-V) and two linear polarizations (Stokes-Q and Stokes-U) that are at an angle of 45° to each other. Two types of magnetograms are obtained at BBSO: longitudinal magnetograms which measure the line-of-sight magnetic fields (Stokes-I', and -V), and vector magnetograms which measure the line-of-sight and transverse magnetic fields (the full Stokes vector: Stokes-I', -V, -Q and -U).

The DVMG, which was originally tested on the observatory's 65 cm vacuum reflector (Wang et al., 1998), is being integrated into the observatory's observations on the 25 cm vacuum refractor. The DVMG will replace BBSO's VMG which has been in operation, in various forms, since 1971 (Zirin, 1985) and will

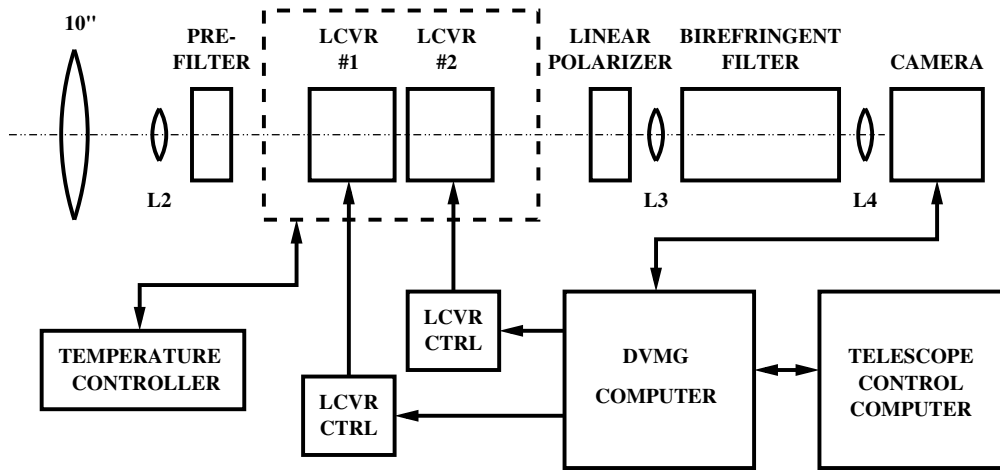


Figure 1. Schematic diagram of the Digital Vector Magnetograph.

operate in the 25 cm vacuum refractor's routine observing cycle along with two Lyot filters (Ca II K and either He D₃ or H α), which are permanently mounted on the telescope. The VMG originally used a KDP as the polarization modulator and, subsequently, a ferro-electric crystal. VMG data are recorded as 8-bit digitized video. For the DVMG, the video camera is replaced with a 12-bit, 30 frames per second CCD camera and the polarization optics are replaced with high quality liquid crystal variable retarders.

Magnetogram data, obtained at BBSO, are used on a routine basis for monitoring active regions, high cadence flare observations (Wang et al., 1999), daily activity reports, polar magnetic field studies (Varsik et al., 1999), and the emergence and motions of small scale magnetic features in the quiet Sun (Chae et al., 2001).

At least once a day BBSO issues a Solar Activity Report, which surveys all active regions on the Sun to provide a forecast of rapidly developing sunspot groups and solar flare potential. These reports can be seen at: <http://www.bbso.njit.edu/cgi-bin/ActivityReport>. Real time high resolution magnetograms, obtained with the DVMG, are the primary observations used to chart active region evolution and changes in magnetic field complexity, which are both key to the prediction of flares.

2. Digital Vector Magnetograph System

The DVMG is a filter based magnetograph, a schematic diagram of which is shown in Figure 1. There are three optical benches on the 25 cm vacuum refractor. Light is directed to each bench by a computer controlled mirror assembly. The DVMG is mounted on the center bench, with a straight-through light path, to avoid affecting the polarization of the light with reflections. The DVMG and the instruments on the other two benches can be used in any desired sequence to fulfill the requirements of the observation.

The prefilter, from Barr Associates, has a center wavelength of 610 nm, a band width of 1.4 nm and a transmission of about 75%. The polarization selectors, from Meadowlark Optics, are nematic liquid crystal variable retarders which contain birefringent material which can be electrically tuned from zero to one wave of retardance. The specified switching time, from 10% to 90% of a desired retardance, is from 5 ms to 30 ms depending on the switching direction, temperature and total change in retardance. However, after 90% of the desired retardance is reached the instantaneous retardance approaches the final retardance value only asymptotically. Therefore, the total switching time can be much longer than 30 ms.

The filter is a Zeiss H α filter retuned to the magnetically sensitive CaI absorption line at 610.3 nm and has a bandwidth of 0.025 nm. The camera is a Silicon Mountain Design 1M15, 12-bit, 1k \times 1k pixel, CCD camera with an 18% maximum quantum efficiency. When used in the 512 \times 512 pixel mode, the camera can run at a maximum of 30 frames per second. Changes in image position between subsequent integrations, caused by seeing, will induce a false magnetic signal into the data. To minimize this seeing induced cross-talk a single-pair magnetogram should be taken within the correlation time-scale of the seeing, which is a few tens of ms. Therefore, it is important to operate the camera at its maximum rate.

Stokes	Retardance	
	LC1	LC2
I'	0 λ	0 λ
V	0 λ	$\frac{1}{4} \lambda, \frac{3}{4} \lambda$
Q	$\frac{1}{4} \lambda$	$\frac{1}{4} \lambda, \frac{3}{4} \lambda$
U	0 λ	0 $\lambda, \frac{1}{2} \lambda$

Table 1. Liquid Crystal States for the Two Crystal Scheme

2.1. Two Crystal Optical Layout

The DVMG is operated with a Windows98 based PC. The computer controls the state of the liquid crystal variable retarders, the CCD camera and communicates with the telescope control computer. In addition, the computer can perform real-time image selection on a sequence of Ca I 610.3 nm line wing filtergrams (Stokes-I'). Magnetogram images of left-hand and right-hand circular polarizations are summed, as long integers, in two memory buffers and are saved in a three dimensional Flexible Image Transport System (FITS) file when the observation is complete. Table 1 shows the states of the liquid crystal variable retarders for each image type (Stokes-I', -V, -Q and -U). A temperature controller maintains the liquid crystal variable retarders at a constant temperature.

Longitudinal magnetograms (Stokes-V) typically require 100 integrations for an active region and 1000 integrations for the quiet Sun. The two transverse

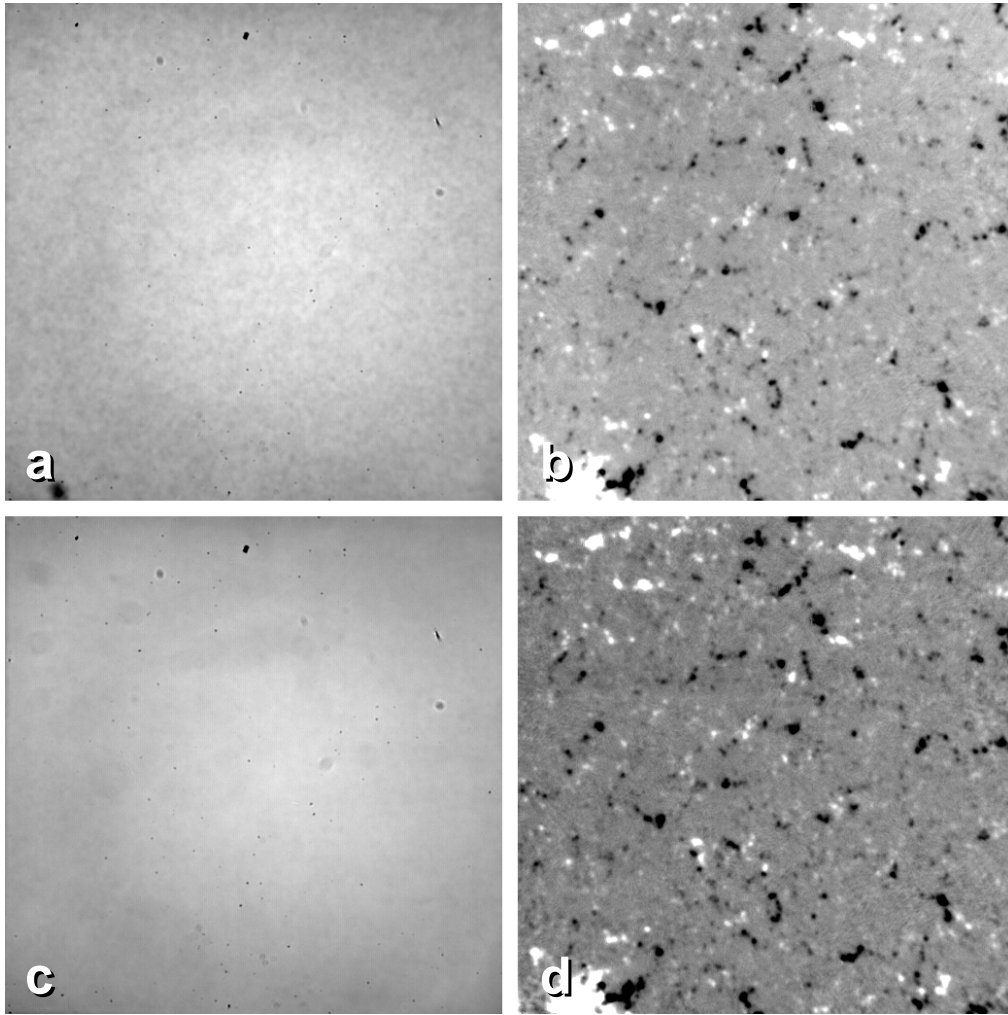


Figure 2. Data calibration. (a) raw Stokes- I' image, (b) raw Stokes- V image, (c) flat field frame obtained with the Kuhn-Lin algorithm, and (d) flat field corrected Stokes- V frame. Note the change of the bias in the magnetograms from (b) to (c).

components of a vector magnetogram (Stokes- Q and $-U$) typically require 500 to 1000 integrations each. The number of integrations required is determined by the noise level desired in each observation. The CCD camera can take images at up to 30 Hz. Taking into account the time required to wait for the liquid crystals to settle to the proper retardance values and to write the files to disk, the cadence can be as short as 5 seconds for an active region with longitudinal magnetograms only and as long as 100 seconds to acquire the full Stokes vector.

On the 25 cm vacuum refractor, the DVMG uses a field of view of approximately $300'' \times 300''$. When the detector runs in the 2×2 binning mode, producing a 512×512 pixel array which is standard for the DVMG, the re-

sulting scale is approximately $0.6''$ per pixel. This image is intentionally under sampled to increase the light level on each pixel, partially due to the camera's low quantum efficiency and to take better advantage of the camera's 12-bit dynamic range. With a sampling frequency of 30 Hz, which is also standard, the exposure is approximately 30 ms.

Stokes	Retardance		
	LC1	LC2	FLC
I'	0λ	0λ	$\frac{1}{2} \lambda$ at 0°
V	0λ	$\frac{1}{4} \lambda$	$\frac{1}{2} \lambda$ at $0^\circ, 45^\circ$
Q	0λ	0λ	$\frac{1}{2} \lambda$ at $0^\circ, 45^\circ$
U	$\frac{1}{4} \lambda$	$\frac{1}{4} \lambda$	$\frac{1}{2} \lambda$ at $0^\circ, 45^\circ$

Table 2. Liquid Crystal States for the Three Crystal Scheme

2.2. Three Crystal Optical Layout

As an improvement to the current DVMG system, we are currently developing a new optical layout which will use three crystals, two nematic and one ferro-electric. This scheme will take advantage of the desirable characteristics of both types of crystals. The two nematic liquid crystals, which can be tuned to any retardance between zero and one wave but have a switching time longer than 30 ms, will be used to select which type of image will be taken (Stokes-I', -V, -Q, or -U). The ferro-electric crystal, which is a fixed $\frac{1}{2}$ wave retarder that rotates 45° depending on the polarity of the applied voltage and has the very fast switching time of $40 \mu\text{s}$, will be used as the system's fast modulator. Table 2 shows the states of the crystals for this system. Preliminary results indicate that the three crystal system works much better than the two crystal scheme.

3. Observations and Data Reduction

The DVMG data are calibrated with dark and flat-field frames. The flat-field images are calculated, using the Kuhn-Lin algorithm (Kuhn et al., 1991), from a series of images taken at slightly different positions of the quiet Sun. A flat field frame is generated for each component of a magnetogram (I', I \pm V, I \pm Q, I \pm U) to compensate for the slight change in transmission of the liquid crystals at different retardance settings. Figure 2 shows a typical flat-field image and the improvements gained by its application to a raw image. We see that a properly calculated flat-field image is quite successful in removing any bias and/or background nonuniformity caused by the liquid crystals and birefringent filter.

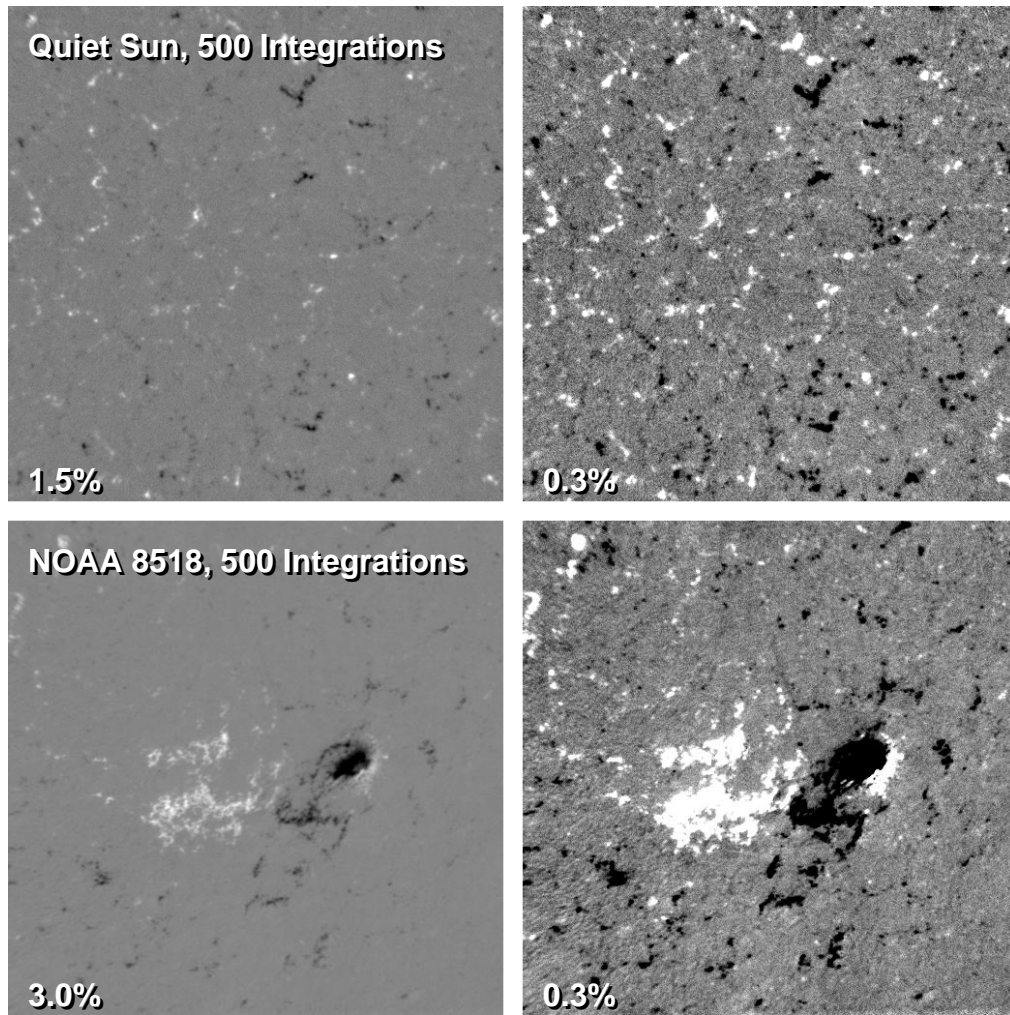


Figure 3. Magnetograms obtained with the BBSO Digital Vector Magnetograph system on 26 April 1999. The field of view is $235'' \times 235''$ and the cadence is 1 minute. The images are scaled between a degree of polarization of $\pm 3.0\%$, $\pm 1.5\%$ and $\pm 0.3\%$, respectively, to show the weak intra-network fields more clearly.

4. Results

Figure 3 shows two typical longitudinal magnetograms (Stokes-V). The upper set was obtained with 500 integrations of the quiet sun while the lower set was obtained with 500 integrations of an active region. The scaling of the images was set to $\pm 1.5\%$ and $\pm 3.0\%$ to show the details in the strong fields on the left side of the figure. The scaling was set to $\pm 0.3\%$ to show the weak fields on the right. The weak intra-network fields can clearly be seen in the images on the right. Polarization levels on the order of 1×10^{-4} can be obtained in 1000 integrations with the DVMG. It would require the VMG 4096 integrations to

obtain that level. Since both systems acquire frames at 30 Hz, the DVMG can reach a given signal noise level four times faster than the VMG.

A typical vector magnetogram is shown in Figure 4. The Stokes-I' image was obtained using real-time image selection to choose the image with the highest contrast out of a set of 100 images taken at 30 Hz. The Stokes-V image is the sum of 100 integrations while the Stokes-Q and -U images are the sum of 1000 integrations each. This image set can be repeated with a cadence of 100 seconds, faster if fewer integrations are required.

5. Concluding Remarks

While the DVMG is still being tested and optimized it has yielded satisfactory results thus far. Typically, we find that 5% to 10% of the longitudinal signal bleeds through into the transverse images. This value should be reduced with more careful tuning (rotation angle and retardance) and better temperature control of the crystals. To implement these improvements, we are currently developing a compact, portable box which will contain the polarization optics in a thermally stable environment and allow easy tuning of the nematic and ferroelectric crystals. This polarimetric package, when placed in front of any Lyot filter, tuned to a magnetically sensitive line, will allow vector magnetograph observations. We also find that careful image calibration with dark frames and flat-fields is very important in removing the bias and background non-uniformity caused by the liquid crystals and non-uniformity of the birefringent filter.

Due to the 12-bit digitization of the Silicon Mountain Design 1M15 CCD camera, used on the DVMG as an improvement over the VMG's 8-bit digitized video, we find that the DVMG can reach polarization levels that would require the VMG four times more integrations to detect. The DVMG also has the potential for real-time image processing, such as image selection, alignment and destretching, to further improve the vector magnetograms (Wang et al., 1998). Additional improvements that are either currently under development or planned for the near future are a user-friendly graphical user interface (GUI), better integration into the telescope control system, on-line data calibration and the calculation of vector magnetograms in near real-time. The full set of calibrated data from the 25 cm vacuum refractor (Ca II K and either He D₃ or H α , longitudinal and vector magnetograms) will be publicly available on BBSO's www page and FTP archive.

As a next step after the Digital Vector Magnetograph a Fabry-Pérot based Imaging Vector Magnetograph is currently being developed to be a permanent instrument on the 65 cm vacuum reflector at BBSO. The Fabry-Pérot, purchased from Queensgate Instruments, has a center wavelength of 630.1 nm, a transmission of 70%, a finesse of 46 and a free spectral range of 0.37 nm. The field of view of the instrument will be 140" \times 140" which is sufficient to cover sunspots and active regions. The cadence for a full Stokes vector is expected to be approximately 4 minutes.

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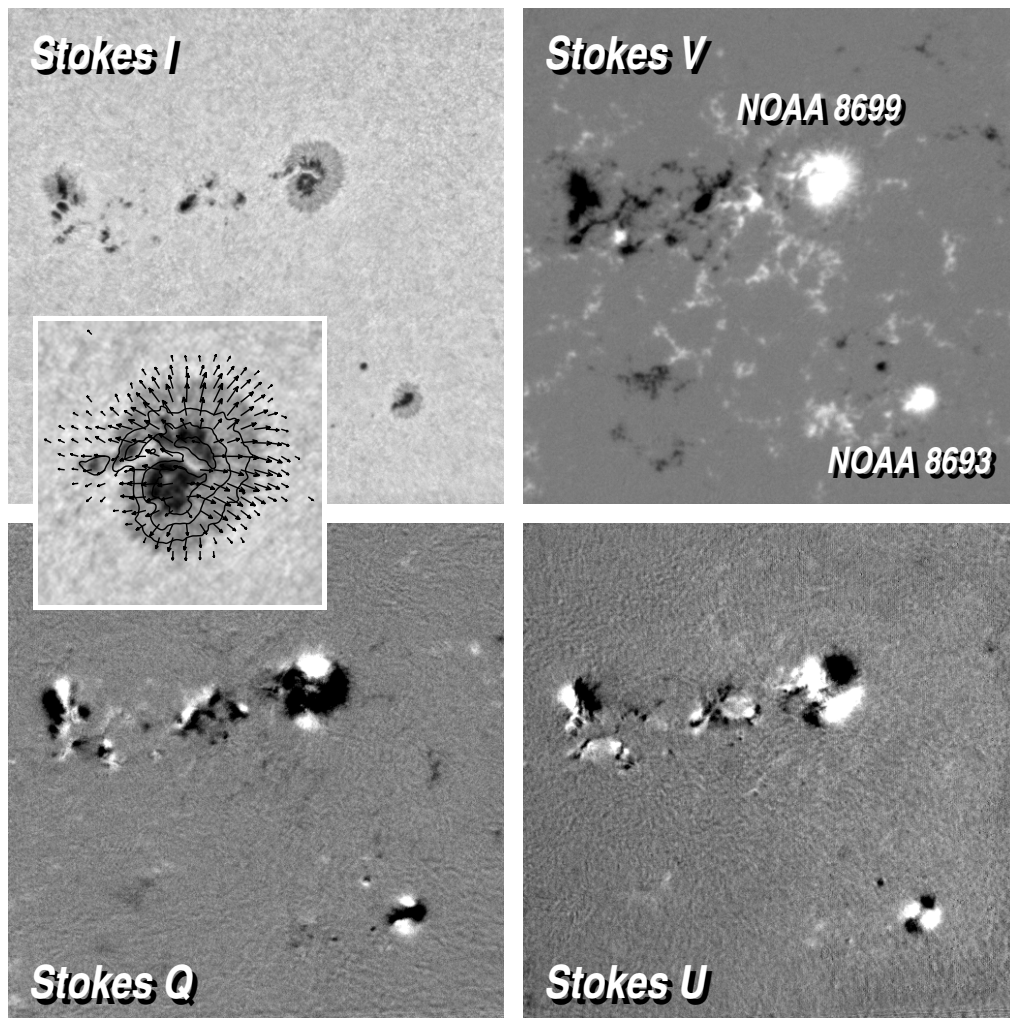


Figure 4. Vector magnetograms observed with the 25 cm vacuum refractor at BBSO on 13 September 1999. The inset shows the line-of-sight field in contours and the transverse field with arrows.

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