

# Imaging Magnetographs for High-Resolution Solar Observations in the Visible and Near-Infrared Wavelength Region

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**Abstract.** The Coudé feed of the vacuum telescope (aperture  $D = 65$  cm) at the Big Bear Solar Observatory (BBSO) is currently completely remodelled to accommodate a correlation tracker and a high-order Adaptive Optics (AO) system. The AO system serves two imaging magnetograph systems located at a new optical laboratory on the observatory's 2<sup>nd</sup> floor. The InfraRed Imaging Magnetograph (IRIM) is an innovative magnetograph system for near-infrared (NIR) observations in the wavelength region from  $1.0 \mu\text{m}$  to  $1.6 \mu\text{m}$ . The Visible-light Imaging Magnetograph (VIM) is basically a twin of IRIM for observations in the wavelength range from 550 nm to 700 nm. Both instruments were designed for high spatial and high temporal observations of the solar photosphere and chromosphere. Real-time data processing is an integral part of the instruments and will enhance BBSO's capabilities in monitoring solar activity and predicting and forecasting space weather.

**Key words:** instrumentation: polarimeters, instrumentation: spectrographs, stars: magnetic fields, Sun

## 1. Introduction

To advance our understanding of small-scale magnetic fields, higher light gathering capacity and spatial resolution are essential, which started several initiatives for a new generation of solar telescopes with 1-meter apertures and beyond. Major efforts are undertaken in the solar physics community to upgrade existing or build new ground-based observing facilities. These efforts include the 1-meter New Swedish Solar Telescope (NSST), the 1.5-meter GREGOR telescope, and the 4-meter Advanced Technology Solar Telescope (ATST).

High spatial, temporal, and spectral resolution are competing factors in precision spectro-polarimetry, which leads to the question, how to slice the multi-dimensional data set? The design goals of VIM and IRIM are high temporal and spatial resolution observations while maintaining moderate spectral resolution  $\lambda/\delta\lambda$ . Both instrument operate close to the diffraction limit  $\alpha = \lambda/D$  of a telescope and are prototypes for the post-focus instrumentation of next generation of solar telescopes. A detailed description of IRIM is presented by Denker et al. (2002). The imaging magnetographs use single

Fabry-Pérot etalons as the passband defining elements and have a similar instrumental arrangement as the imaging magnetograph at the Mees Solar Observatory, Haleakala, Maui (Mickey et al. 1996). A correlation tracker and a high-order AO system with 97 actuators (Didkovsky et al. 2002) provide full compensation of wavefront errors assuming fair seeing conditions with a Fried-parameter  $r_0 > 6$  cm.

## 2. Imaging Magnetographs

IRIM will be one of the first imaging spectro-polarimeters for the NIR. Higher magnetic sensitivity (Zeeman splitting  $\Delta\lambda_B \sim g\lambda^2 B$  and better seeing conditions  $r_0 \sim \lambda^{6/5}$ ) are some of the advantages driving the development of NIR instrumentation. IRIM benefits from a larger isoplanatic angle  $\theta_0 \sim \lambda^{6/5}$  and a higher Strehl ratio in the NIR, especially when operated in combination with the AO system. Diffraction limited observations over an extended field-of-view (FOV) can be achieved in the NIR. Even for visible-light observations, the seeing induced cross-talk is minimized beyond the isoplanatic patch, since the tilt isoplanatic angle is substantially larger than the isoplanatic angle associated with higher order deformations.

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**Table 1.** Characteristic parameters of the imaging magnetographs.

	VIM	IRIM
FOV	180'' × 180''	170'' (circular)
$s$	0.18'' pixel <sup>-1</sup>	0.17'' pixel <sup>-1</sup>
$\alpha$	0.20'' @ 630 nm	0.50'' @ 1565 nm
$\lambda$	Fe I ( $g=1.66$ ) 630.15 nm	Fe I ( $g=3$ ) 1,564.85 nm
	Fe I ( $g=2.5$ ) 630.28 nm	Fe I ( $g=1.53$ ) 1,565.29 nm
	H $\alpha$ 656.28 nm	He I 1,083.03 nm
$d$	496 $\mu$ m	2,226 $\mu$ m
$p$	136	100
$R$	0.968	0.951
$A$	$3.4 \times 10^{-3}$	$2.9 \times 10^{-3}$
$\tau_{\max}$	0.799	0.885
$F_{\text{eff}}$	55.6	39.0
$\delta\lambda$	7.2 pm	14.1 pm
$\lambda/\delta\lambda$	87,500	111,000
$\Delta\lambda$	0.40 nm	0.55 nm

Nematic liquid crystals manufactured by Medowlark Optics are used as variable retarders to alter the polarization of the light. To measure the full Stokes vector, the polarization state of two variable retarders is changed between line scans.  $I$ :  $0\lambda|0\lambda$ ,  $V$ :  $0\lambda|\frac{1}{4}\lambda \leftrightarrow \frac{3}{4}\lambda$ ,  $Q$ :  $\frac{1}{4}\lambda|\frac{1}{4}\lambda \leftrightarrow \frac{3}{4}\lambda$ , and  $U$ :  $0\lambda|0\lambda \leftrightarrow \frac{1}{2}\lambda$ , where the  $\leftrightarrow$  indicates that two line scans are required to obtain the degree of polarization  $V/I$ ,  $Q/I$ , and  $U/I$ . The sensitivity goal for the imaging magnetographs is in the order of 0.1 mT for the line-of-sight component and 5 mT for the transverse component of the magnetic field.

In the visible wavelength region, interference filters with a passband of a few tenths of a nanometer can be used as order sorting filters for Fabry-Pérot etalons. However, NIR interference filters with similar passbands are not available. Therefore, a custom narrow-band NIR Lyot-filter with a FWHM of 0.25 nm was developed at NJIT (Wang et al. 2000) and is currently assembled at Cambridge Research Instruments.

We use ET-70-FS Fabry-Pérot etalons and a CS100 controllers manufactured by SDL Queensgate. The peak transmission  $\tau_{\max}$  of the etalons is given by

$$\tau_{\max} = \left(1 - \frac{A}{1 - R}\right)^2, \quad (1)$$

where  $R$  and  $A$  are the reflectivity and absorption of the mirror coating. The effective finesse  $F_{\text{eff}}$  is given by

$$F_{\text{eff}} = \left(\frac{(1 - R)^2}{R\pi^2} + \frac{4}{p^2}\right)^{-1/2}. \quad (2)$$

VIM and IRIM both use a modified telecentric set-up, i. e., the etalons are not directly located at a focal plane but close to it, to limit the impact of coating non-uniformities. In the case of a telecentric configuration, the passband  $\delta\lambda$  across the FOV is given by

$$\delta\lambda = \left[ \left(\frac{\lambda^2(1 - R)}{2\pi nd\sqrt{R}}\right)^2 + \left(\frac{\lambda^2}{ndp}\right)^2 + \left(\frac{\lambda\theta^2}{8n}\right)^2 \right]^{1/2}, \quad (3)$$

where  $n$  is the refractive index of the medium inside the cavity,  $d$  is the plate separation,  $\lambda/p$  is the flatness error of the etalon plates after coating, and  $\theta$  is the angular size of the accepted beam. The third term in Equation 3 indicates that

the  $f$ -ratio of the accepted beam has to be larger ( $< 100$ ) to avoid an unacceptable broadening of the passband at the periphery of the FOV. The spectral resolution and free spectral range can be computed according to

$$\frac{\lambda}{\delta\lambda} = \frac{2ndF_{\text{eff}}}{\lambda} \quad \text{and} \quad \Delta\lambda = \frac{\lambda^2}{2nd} = \delta\lambda F_{\text{eff}}. \quad (4)$$

The two-dimensional spectral line profiles are recorded by a 1024 × 1024 pixel detectors – a 12-bit CCD camera manufactured by Silicon Mountain Design/Dalsa for VIM and a 14-bit Hg Cd Te/Al<sub>2</sub>O<sub>3</sub> Complex Metal Oxide Semiconductor (CMOS) focal plane array manufactured by Rockwell Scientific Imaging for IRIM. Comparing image scale  $s$  and diffraction limited resolution  $\alpha$  shows that VIM data is under-sampled by a factor 1.8 whereas IRIM data is over-sampled by a factor of 1.5. Typical exposure times are in the range from 100 to 250 ms. The characteristic parameters for VIM and IRIM are summarized in Table 1.

### 3. Real-Time Data Reduction

Imaging magnetographs record multi-dimensional data sets, i. e., two spatial dimensions, wavelength, polarization state, and time. A scan across the spectral line profile takes about 5 s for 20 wavelength points. The procedure is repeated six times to obtain the full Stokes vector, which results in about 250 MByte data every 30 s assuming the data to be 16-bit. Processing the data off-line requires large data storage capacity and the time-lag between observations and data analysis becomes far too long for any sort of rapid response, which is needed for space weather warnings and flare forecasting. Furthermore, the time-lag renders the whole scientific enterprise less efficient than it needs to be, considering today's computer technology. Parallel processing has been applied to real-time image reconstruction (Denker et al. 2001) and a 32-node parallel computer (Linux Beowulf cluster) with 1.8 GHz AMD Athlon processors is available for real-time data processing. The final data products include vector magnetograms from two-dimensional Stokes-polarimetry, accurate photometric intensity maps, charts of Doppler velocities or of velocities derived from the zero-crossing of the Stokes- $V$  profile, and transverse flows measured with Local Correlation Tracking (LCT) or Feature Tracking (FT).

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