INFRARED ARRAY MEASUREMENTS OF SUNSPOT
MAGNETIC FIELDS

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Abstract. We have used a 128 × 128 format HgCdTl infrared array with the Sacramento Peak Observatory Vacuum Telescope (VTT) and Echelle spectrograph to obtain two-dimensional observations of the true magnetic field strength in a sunspot. The system we describe retains all of the spectral information contained in the unpolarized IR Fraunhofer line profile with time resolution of about a minute (depending on the scan area and spatial resolution). Unlike previous optical observations (cf. Adam, 1990), infrared observations readily allow direct field strength measurements out to the outer edge of the penumbra. Our data suggest that the magnetic flux density in the outer penumbra is not well described by an extrapolation of the quadratic polynomial, in normalized central distance, that describes the umbra field. We measure a relatively high field strength of 800 G at the penumbra–quiet-Sun boundary, which is consistent with the 'return-flux' model of Osherovich and Garcia (1989).

1. Introduction

The potential for measuring solar magnetic fields in the infrared has been demonstrated by several groups (cf. Brault and Noyes, 1983; Stenflo, Solanki, and Harvey, 1987; Deming et al., 1991; Rabin et al., 1991). The advantage of using Fraunhofer lines in the IR to measure Zeeman-splitting results from the wavelength dependence of the classical Zeeman effect. This splitting is

$$\delta \lambda = 4.7 \times 10^{-12} g \lambda^2 H,$$

where $\delta \lambda$ is the wavelength difference between the $\pi$ and the $\sigma$ peaks in nanometers, $g$ is the Landé factor, $\lambda$ is the line wavelength in nm, and $H$ is the magnetic flux density in Gauss. The quadratic wavelength dependence of the splitting increases faster with $\lambda$ than the linear increase in the Doppler linewidth, so that magnetically sensitive infrared line profiles may be resolved into $\pi$ and $\sigma$ components at field strengths below 1 kG. Unlike conventional visible-band magnetographs, which generally measure the magnetic flux, IR observations may be used to directly infer magnetic field strength.

Until recently most solar IR observations have been obtained using scanning, single element, detectors (cf. Brault and Noyes, 1983; Stenflo, Solanki, and Harvey, 1987). Rabin et al. (1991) described some IR array observations aimed at mapping the two-dimensional magnetic field in plage regions. As a first test of our multipurpose IR array camera we have begun a program to measure the magnetic field near and in a sunspot with the high spatial and spectral resolution that is available using the Sacramento Peak Observatory Vacuum Tower Telescope (VTT) and Echelle spectrograph.


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2. Instrumentation

2.1. The IR Camera Hardware

The IR camera was built at Michigan State University around an array detector (type TCM1000C) fabricated by Rockwell Inc. at the Rockwell Science Center. This device uses a HgCdTl photosensitive layer grown on a 60 μ thick sapphire substrate. Light reaches the HgCdTl layer through the transparent sapphire base. The readout electronics uses a matrix of transistors (FETs) on a silicon wafer that are pressure bonded to the HgCdTl by indium beads. This device has 128 × 128 60 μ square pixels and has a high quantum efficiency (QE) at wavelengths between 1 and 2.5 μ. The average QE is about 70%, but there is a large (50%) pixel-pixel variation. The saturation well capacity of a pixel is about 3 × 10⁷ electrons while the total readout noise is about 1500 electrons.

Each pixel of the array is electronically shuttered by shunt FETs which are clocked by the external electronics. On-chip logic elements control most of the pixel sequencing during readout. This device is easily controlled by three external clock signals that are largely insensitive to voltage level (unlike conventional CCDs). The device has two independent readout amplifiers which yield a full-scale output voltage range of about 1.5 V. Each amplifier provides output for one half of the 128 pixel columns. Output voltages are brought directly out of the dewar to warm preamplifiers. Aside from double-pole passive filters on all incoming voltage and clock signals, no external cold electronics is required for the TCM1000C.

Array timing, readout sequencing, and other camera functions are controlled by two circuits mounted on the dewar. A microcontroller (Dallas Semiconductor DS5000) handles all communication functions between the array and the data acquisition system. A separate analog board contains the 14 bit 100 kHz A/D, amplifiers, and multiplexor that sample and digitize the array signals. The microcontroller is a modified, industry standard, 8051 controller which contains 32 K of internal non-volatile RAM and numerous timing and I/O functions. Array clocking is generated from a program in the controller that sequences output I/O pins on the controller. The readout pixel rate is limited by the A/D to about 50 K pixel s⁻¹. The microcontroller also controls two stepper motors and their encoders, a high speed UART, and logic to control the operating mode of a duplex optical fiber link between the camera electronics and the data acquisition system. A simple 8-bit bus in this system allows many future I/O expansion options.

The camera and electronics are electrically isolated from the PC-based data acquisition system by a duplex fiber optic cable. The fiber operates in the usual duplex mode for sending and receiving camera commands at 9600 Baud and for downloading machine code for operating the DS5000. During a picture read sequence the outgoing fiber from the PC becomes a 1 MHz synchronous clock line and the incoming line transmits digitized pixel data at a rate of 1 Mbit s⁻¹. Except for the fiber control board, the data acquisition system hardware is commercially available. Images are viewing
using VGA hardware and stored using an Exabyte 8 mm tape drive. Our software is written primarily in Fortran and machine code. Data written on the PC system is readable on our Unix-based workstation Exabyte drive.

Our 8-inch diameter dewar is a modified Infrared Labs Inc. dewar. The cold plate is 8 inches from the face plate of the up- or down-looking outer surface. The camera may also be used for night-time observing on several telescopes. Our provisions for internal optics requires a larger dewar than would be necessary for a single application. The front window is 2.75 inches in diameter. The internal filter wheel uses 1 inch round filters and is driven by an external stepper/vacuum-gland combination. A second cold stepper has been used in the dewar for internal focus adjustments when additional (cold) optics were used. Mechanical magnet proximity switches are used for encoding the filter wheel position. We use platinum resistance thermometers for measuring temperatures within the dewar. The array is thermally contacted to the dewar cold plate by a subassembly which includes a printed circuit board which holds cold electronic filter components for the TCM1000C.

2.2. OBTAINING SPECTRAL DATA

The IR camera was used with the VTT Echelle spectrograph at the National Solar Observatory’s Sacramento Peak Observatory during several days in October 1990. It was operated with no internal cold optics except for a standard astronomical H (1.6 μ) filter. It was mounted horizontally on a side port of the lower optics box of the Echelle, with a bench-mounted relay lens in the box to provide a useful dispersion and image scale for the 0.76 cm detector. In this configuration the image plane is 10 cm into the dewar and the filter is about 4 cm above the focal plane. We used a 79 lines mm⁻¹ grating (turned backwards to improve the 'blaze' efficiency) and the prism monochromator was tilted out of its normal position to get light from the 14th order (near a wavelength of 1.57 μ) to the detector. The grating angle was 66.8 deg. In this configuration the spectral resolution was about 2 × 10⁵ and the dispersion was 33 mÅ pixel⁻¹. The image scale along the slit was 0.32 arc sec pixel⁻¹ after demagnifying by a factor of 1.5. The data was obtained with a slit width of 100 μ (0.6 pixels) and the exposure time was 1.6 s. The slit was oriented perpendicular to the horizon.

The data described here were obtained on October 12 by repeatedly scanning an isolated sunspot (NSO 8795C) across the slit while obtaining IR spectra. This spot was located at a projected radius of 0.54. We observed the same position on the disk relative to the limb during the 2-hour observation, i.e., solar rotation caused the spot to move with respect to the scan area. The control computer for the Tower telescope was synchronized with the IR camera acquisition computer by a single duplex RS232 line. The telescope moved the image perpendicular to the slit in 1 arc sec steps then sent a read command to the camera control system. A complete sequence of 55 steps required 3.7 min. A series of 33 cycles was obtained during a 2-hour observing sequence that started at 2:30 MDT.

The monochromatic illumination of the layered structure of the detector produced interference fringes which were visible in the raw data. There was approximately one
complete fringe across the array that produced an intensity modulation of about 30%. Unfortunately the fringe pattern was not stable, probably because of drift in the Echelle. Our best flat-fields were obtained by using an incandescent lamp to illuminate a 200 μ wide slit. While this yielded reasonable calibration along the dispersion, it lead to significant spatial direction calibration errors (of order 10%). Our future observations will combine more frequent lamp observations with ‘moving telescope’ flats to obtain better calibration in both the spatial and wavelength directions.

2.3. Spectral line

Stenflo, Solanki, and Harvey (1987) clearly demonstrated the potential for measuring solar magnetic structure using the infrared Fe I λ1564.854 nm. They obtained high spectral resolution Stokes profiles of sunspot and plage regions using the National Solar Observatory Fourier-Transform Spectrometer. This line is unblended in quiet photosphere and has a large normal Zeeman effect Landé factor (g = 3, cf. Solanki, Piemont, and Murset, 1990). The line has a comparatively low height of formation (probably about 100 km above t500 = 1) which may explain why they measured magnetic field strengths that were about 20% higher than visible line determinations.

We also used this line, although we found that it is not ideal for measuring magnetic fields in the cooler sunspot umbra. Figures 1(a–c) show examples of the resolved line profiles and model fit we obtain in the quiet photosphere, penumbra, and sunspot umbra. Figure 2 shows a greyscale image of a spectrum obtained for a slit oriented

![Figure 1a - Quiet photosphere](image)
through the center of the sunspot. The spatial direction is horizontal in this figure and the umbral line that appears near the top of this figure is the CN 0–1 transition (laboratory 6389.51 cm\(^{-1}\)). Bluer wavelengths are at the top. The deeper umbral line that appears near the blue sigma peaks coincides with an Fe line (laboratory 6389.09 cm\(^{-1}\)) also identified by Livingston and Wallace (1991). The noise in these observations prevents us from observing these non-magnetic lines outside of the umbra.

These data show a large asymmetry between the red and blue \(\sigma\) peak heights in the sunspot umbra. We obtained similar spectra of spots using this camera and the Sacramento Peak Evans Facility Littrow spectrograph. These data also show a larger blue \(\sigma\) line depth in the umbra. The Littrow data are not scanned but the noise spike problem was eliminated so that we do see a weak photospheric line (identified by Livingston and Wallace, 1991; as an ironline at 6389.09 cm\(^{-1}\)) which coincides with the umbra blue \(\sigma\) peak – although it must be much stronger in the umbra to explain the observed asymmetry. Because we have seen the asymmetry with two different telescopes, it is difficult to understand this as an effect of telescope polarization sensi-
tivity or order "leakage". This contamination in the blue component of the line is treated in the analysis described below by deweighting the spectrum shortward of the π peak.

3. Analysis

We discovered intermittent random noise spikes in dark- and gain-corrected data obtained from the October observations. Because the width of the noise peaks was small compared to the spectral signal, we were able to effectively filter out the noise by fitting a 40th-order cubic spline to each of the 127-point spectra. Much of our analysis was performed using the Image Reduction Analysis Facility (IRAF). We used the 'fit1d' routine in IRAF (Tody, 1986) to do spline fitting. This also served to remove the effect of bad pixels in the array. The fitted spectra were then normalized and detrended using the 'continuum' routine in IRAF.

These fitted and normalized spectra served as the input to a routine which attempts to fit a sum of Lorentzians to determine the Zeeman splitting, the Doppler shift, the height of the π and σ components of the triplet, and the width of the three components. We fit the following expression to the data:

\[ -\frac{A^2_\sigma}{(\lambda + B - D)^2 + 1} - \frac{A^2_\pi}{(\lambda - B - D)^2 + 1} - \frac{A^2}{(A - D)^2 + 1} + C, \]  

where \( A^2_\sigma \) is the height of the σ peaks, \( A^2_\pi \) is the height of the π peak, \( C \) is the continuum, \( D \) is the shift of the π peak relative to the first pixel of the spectrum, \( B \) is the Zeeman splitting, and \( W \) is the half-width of each of the three peaks of the triplet. The peak height coefficients were squared to avoid problems with peak heights going negative in the fitting routine. We used an implementation of the Levenberg–Marquardt fitting algorithm ("MRQMIN" from Press et al., 1989).

For each spectrum in the dataset, the algorithm begins by setting the Zeeman splitting and σ amplitude to zero, then attempting to fit a single peak, while allowing all other parameters to vary. If a fit is achieved, the resulting parameters and r.m.s. variance are saved for future reference. The worst case fits occur in the umbra where the r.m.s. variance between the model and data could be as large as 9% of the continuum. Note, as Figure 1(c) shows (and see below), that there are some points in the spot umbra where this fit matches the mean red-blue σ peak depth (because of the red-blue line-depth asymmetry) without matching the individual σ peak line-depths.

We now attempt to fit a triplet while allowing all parameters to vary. First, all parameters except the magnetic flux density are held fixed while a series of models of increasing field strength are fit to the spectrum. This grid of models is chosen so that the increment in field is approximately equal to the half-width of the σ peaks. If a minimum in the r.m.s. variance is detected then the minimizing field strength is used as the guess for a fit of the full model to the spectrum. The fitting procedure is not very sensitive to the initial choice of the line center position and peak heights – the first guess
for these values is estimated from the local minima in the spectrum. If this fit fails then a second attempt is made after deweighting all data points bluer than the \( \pi \) peak center position plus half the halfwidth, thus reducing the contribution of the contaminant peak to the solution. The center position of this deweighted fit is constrained to the mean linecenter position off the spot. If either of these attempts to fit a triplet succeeds then the resulting r.m.s. variance is compared to that saved for the single peak fit (if any) using the F probability test at a confidence level of 90\% (Bevington, 1969). A no-fit flag is stored for the magnetic field value if no triplet fit was possible, or if a single peak fit was the best fit obtained; otherwise, the field strength computed using Equation (1) is stored. In addition, the r.m.s. variance and all the parameters of the best fit for each spectrum are written to separate IRAF data files for later examination.

4. Results

Our code successfully fits the triplet model to virtually all locations sampled inside the boundaries of the penumbra. A few points in the umbra cannot be fit without deweighting the blue part of the spectrum. At each point, we measured the magnetic field strength, the \( \pi \) to \( \sigma \) peak height ratio, and the Doppler shift along the line of sight. Figure 3 shows these results from the model as it was fit to data obtained at the beginning of the observing sequence. An infrared continuum intensity image, derived from the spectra, is also displayed here. Unfortunately we found that spectra that were obtained later in the observing sequence were more contaminated by noise spikes. This degraded our ability to measure the umbral magnetic field strength in the later time steps.

These unpolarized IR spectra are most useful for measuring the true magnetic field strength, although information on the flux and line-of-sight inclination angle of the field is also contained in the \( \pi \) and \( \sigma \) peak heights. Since we do not observe separate linear and circular polarized light components this information is not uniquely contained in the resolved spectra. In addition, at small field values and low magnetic flux values we may expect large errors in our field measurements. To quantify these errors we simulated a grid of spectra of increasing flux and field strength. Each spectrum had a white noise component added to it which had an amplitude comparable to the noise in the actual IR array data. The algorithm was applied to these spectra to compute the field strength. In this grid of spectra the actual input field value increased from 95 to 3100 G while we took the \( \sigma \) peak height to vary from 0 to 20\% of the continuum intensity. The derived magnetic field strength is computed for each combination of input field and flux. For pixels with field strengths above 570 G and peak heights greater than 0.025 our algorithm recovers the correct field strength with an r.m.s. error of 15 G. Thus the field maps in the uppermost panels of Figure 3 have been clipped so that all pixels with spectra having a \( \sigma \) peak height less than 0.03 appear as black regions in this figure. At smaller field and flux values polarized observations are needed to measure the magnetic field.

Figure 3 shows the \( \sigma \) peak height. If the magnetic filling factor is approximately 1.0 for both the penumbral and umbral regions the larger ("lighter") umbral \( \sigma \) peak height
Fig. 3. Results of the model fit to the sunspot. The upper left panel shows the magnetic field strength where the scale from black to white corresponds to magnetic field values between 0 and 4300 G. The upper right panel shows the amplitude of the \( \sigma \) peak. The scale from dark to light here corresponds to 0 to 0.2 of the continuum intensity. The center left image shows the log of the ratio of the \( \pi \) to \( \sigma \) peak height, where dark to light corresponds to values between \(-10.0\) to \(2.0\). The center right panel shows the Doppler shift, where the scale from dark to light corresponds to a velocity difference of \(5.3\, \text{km s}^{-1}\), where dark regions are blue-shifted. The last panel shows an IR continuum intensity image of the sunspot.

is presumably due to the effect of variations in the inclination of the magnetic field. The ratio of the \( \sigma \) and \( \pi \) peaks is also displayed in Figure 3. The ‘dark’ umbra in the ratio figure corresponds to small \( \pi \) to \( \sigma \) peak ratios, and a more vertical field inclination. Of course the full vector magnetic field would be more directly obtained from polarized observations.
Fig. 4.  (a) Radial variation in the true magnetic flux density plotted versus the distance from the mean spot position normalized by the mean spot semi-diameter. The error flags show the standard deviation of the distribution of field measurements at a fixed radius for all position angles through the spot. The dashed line shows mean field measurements from Adam (1990) extended to the penumbral-photosphere boundary.

(b) Same as (a) but now plotting the $\sigma$ peak line depth versus normalized central distance.
The lowermost panel in the figure is effectively a narrow-band continuum IR image of the spot. As in visible images it shows the well-defined dark umbra and brighter penumbra of the spot, but from a slightly deeper height-of-formation (about 50 km) than the visible continuum.

The IR Doppler data clearly show a penumbral Evershed effect (cf. Foukal, 1990) with a velocity difference between the limbward and centermost penumbral regions of 2.2 km s\(^{-1}\). The limbward penumbra shows an apparent redshift. There is some evidence of an umbral Evershed flow, although we need better (spike-free) data to explore this further.

Figures 4(a) and 4(b) show the radial variation in the magnetic field and the line-depth of the \(\sigma\)-component of the Zeeman-split iron line. The horizontal axis shows the fractional radius (where this radius is normalized by the measured mean outer penumbral semi-diameter). The dotted curve in Figure 4(a) shows the radial variation that Adam (1990) found from her observations of a similar circular spot. Because she obtained the field strength from visible-band observations, her data actually extends only to a fractional radius of about 0.6. They are also in reasonable agreement with other observations (Wittmann, 1974). The error flags in our data on these figures represent the gaussian-width of the measured distribution of points at a fixed fractional radius over all position angles through the spot. Figure 4(b) shows the radial variation in the measured line-depth in units of the continuum intensity. The error flags here also show the observed width of the distribution of line-depth at the indicated fractional radius.

The polynomial dependence of the field strength versus radius that has been obtained for the umbra does not appear to extend into the penumbra, i.e., the penumbral field is not well-characterized by the Wittmann or Adam polynomial. Consequently we find that the outer penumbral field is actually much larger at the quiet photosphere boundary (about 800 G) than the earlier central field extrapolations imply. There is also a rapid change in the \(\sigma\) line-depth at the umbra-penumbra boundary. Further polarization sensitive observations will be needed to distinguish this effect as a change in the field direction from the effect of spatial variation in the magnetic filling factor. Both of these observations are consistent with the return-flux model of Osherovich and Garcia (1989). The higher penumbral boundary field we see would tend to support this model over, for example, the Schlüter and Temesvary (1958) model, although it is not clear that either explains the radial dependence of the penumbral field we observe.

5. Future Prospects

The VTT/IR camera system described here clearly works well out to wavelengths beyond 1.6 \(\mu\). The noise spike problem has been corrected and will simplify any future analysis from that described above. We have shown that magnetic field strength values below 1 kG can be measured even in unpolarized light down to flux levels at least as low as the magnetic flux in a single pixel of our penumbral observations of this spot (6 \(\times\) 10\(^9\) Weber). The addition of a polarizer to this system will make a very attractive full vector magnetograph.
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