Recent Results from the San Fernando Observatory

Video Spectra–Spectroheliograph

by

G.A. Chapman and S.R. Walton

San Fernando Observatory, Department of Physics and Astronomy
California State University, Northridge
Northridge, CA 91330 USA

Abstract. Results are presented from VSSHG observations of an extensive sunspot group, NOAA 5669, that transited disk center on 4 September 1989. The data are presently processed to obtain four images: a saturation-free longitudinal magnetogram, a Dopplergram, a continuum image, and a line core spectroheliogram. All images are from two-dimensional spectral data with a spectral window of about 1 Å, centered on the 6302.5 Å line of neutral iron. The images show the well-known “fringing” of sunspot fields, the “unsymmetrical” Evershed flow, as well as large-scale flow patterns within the active region. The results presented here are preliminary and will be improved by Fourier filtering of the original video spectra, after digitizing from video tape. Velocities in the Dopplergram are referred to laboratory wavelengths, using nearby telluric O₂ lines.

1. Introduction

In the past, measurements of the magnetic field intensity in the solar photosphere have been made by the “Babcock” method (or the Leighton photographic method). These methods convert Zeeman or Doppler line shifts into intensity variations in photometric detectors. However, the conversion of these intensity variations into magnetic or velocity signals becomes non-linear and saturates within sunspots. Furthermore, the shape of the solar absorption line changes in sunspots and non-spot magnetic regions, altering the calibration of these “Babcock” intensity variations.

The only way past these difficulties is to measure the entire line profile for each solar surface element in all of the desired polarizations. Such observations can be carried out in one of two ways: either by a sequence of images at different wavelengths and polarization, or a sequence of spectra at different positions and polarizations. The former is the basis of the Lockhead group’s use of a rapidly tunable filter (SOUP); the latter is derived from the spectra-enregistreur (Rayrole 1967) or the Spectra-Spectroheliograph (SSHG) (Title and Andelin 1971). However, the technique at the SFO utilizes video technology, hence the designation VSSHG.

The filter scheme is clearly preferable for balloon- and space-borne instruments, due to size and weight considerations. However, at ground-based locations, the filter scheme mixes image distortions into the spectral domain. To achieve high a signal-to-noise ratio, the images at different wavelengths must have seeing distortions removed (“drestretching”).

We have adopted the second approach in the VSSHG. This has the advantage that all spectral elements for one line on the sun are obtained at the same time. Thus, there is no mixing of spectral and spatial information. The spatial resolution of the images may
be lower than for the filter method, although this will depend on scanning speed, image stability, and selection of raw spectra.

We obtain pairs of spectra of opposite polarization side-by-side on a single video image. In order to maximize speed in obtaining image and reduce cost of storage, we recorded the spectral image directly from our Cohu CCD camera onto 3/4 inch, U-matic VCR magnetic tape. These data are recorded at the standard NTSC rate of 30 frames per second and are later processed to produce digital images of the solar magnetic and velocity field as well as core and continuum images. The regions are scanned with an interval of $1\frac{1}{4}$ minutes or less in order to filter out the 5-minute p-mode oscillations. (We are looking for "steady" flows associated with active region evolution.)

2. Observing Scheme

The vacuum spectroheliograph is scanned mechanically at a speed determined by the number of video frames to be summed during subsequent processing for noise reduction. For the images shown here, five video frames were summed. The scan speed during this period was higher than it should have been, resulting in a north-south compression of the images by a factor of about 2.4. More recently, the scan speed using the 28 cm vacuum telescope is typically 1.56 arc-sec per second; with our image scale, this results in undistorted images with a six-frame sum. This scanning speed appears to be a useful compromise between speed, to improve spatial resolution, and signal-to-noise ratio in the derived images. A higher signal-to-noise ratio would require more video frames to be summed for each line of the output images, and a correspondingly slower scanning speed.

3. Data Analysis

The recorded spectra are digitized by a Matrox MVP video digitizer and processor operated in a PC-AT clone that also controls a JVC model 600 U-matic VCR. The video data are digitized from the tape while the tape is in play mode, as commanded from the PC: the tape is backed up 60 frames (two seconds) before the next desired digitization to allow the playback to stabilize. The summed video spectra are corrected for the dark and flat-field response of the CCD, and a Gaussian fit is used to remove the blend with the telluric O$_2$ line at 6302.7 Å. Finally, the desired processing schemes are applied to each line of the spectrum, and the processed data are written to magnetic disk as a set of digital images generated one line at a time. The pixel size in the digitized spectra corresponds to 0.46 arc sec in the spatial direction and 9 mÅ in the spectral direction. (The spectral resolution of about 20 mÅ is set by the entrance slit width.)

The images produced are: a continuum image, formed from an average of a few pixels at a wavelength of 6302.25 Å; a line core image, formed from the minimum intensity within several pixels of the center of the solar line—we allow for the Doppler shift of the line; and a line-of-sight magnetogram and line-of-sight velocity field map, both calculated using a center of gravity technique. That is, $B_\|$, $v_\|$ are given by:

$$B_\| = k_B \times \frac{\int \lambda V(\lambda) d\lambda}{\int [I_c - I(\lambda)] d\lambda} \quad (1)$$
and

\[ v_{\parallel} = k_v \times \frac{\int \lambda [I_c - I(\lambda)]d\lambda}{\int [I_c - I(\lambda)]d\lambda} \]  

(2)

where \( I(\lambda) \) and \( V(\lambda) \) are the Stokes profiles, \( I_c \) is the continuum intensity, and \( k_B \) and \( k_v \) are the appropriate constants to convert from splitting in pixels to longitudinal field and velocity, respectively. That is, the ratio of the above integrals, calculated as simple sums in the digitized spectra, give essentially the line-of-sight magnetic field and the shift of the line center in pixels; the known dispersion and Landé \( g \) factor are used to convert to \( B_{\parallel} \) and \( v_{\parallel} \).

The integrals in equations 1 and 2 are calculated only over that wavelength range for which \( I(\lambda) \) is less than 90% of \( I_c \), as a means of reducing noise (Brants 1985). Some noise in spot umbrae, visible in these images, will be reduced in the future by Fourier smoothing the spectra before calculating the quantities indicated in equations 1 and 2.

The resulting images are both simultaneous and perfectly co-registered, essentially by definition. Seeing-induced image motion changes the spatial relationship between lines, but not within a single line of the images.

Much of the data from August, 1989 (NOAA Region 5643) have been processed, as have some of the data from September 1989 (NOAA Region 5669). An analysis of the relationship between non-spot magnetic fields and their continuum contrast has been carried out by Lawrence et. al. (1990) for the August 1989 data. The video data have been processed with a preliminary version of the software, without Fourier smoothing and without use of floating point arithmetic in the processing. Test runs of new software, which use a DSP Point-1 array processor to both Fourier smooth the data and calculate the above integrals using floating-point arithmetic, produce significantly better results, with reduced streaking and random noise, particularly in sunspot umbrae. The noise outside of spots for the magnetic image is approximately 30G RMS, and for the Doppler image is about 40 m/s RMS.
4. Results

Figure 1 shows the leader spot for NOAA 5669 at 18:59UT on 2 September 1989. These images have been magnified in the computer so that individual pixels can be seen. This spot shows an interesting opposite (South, black) polarity feature in the north part of the penumbra. There is no obvious darkening in the continuum image, but there is a curious bipolar Doppler feature with a strong red-shifted feature at the same position as the black magnetic flux. There is a curved light bridge dividing the main part of the spot into two umbrae. The mean line-of-sight magnetic field for these two umbrae was 1873G. The field strength in the light bridge was 1432G, a difference of 440G or over 20 standard deviations. It is possible that there is a directional change to the magnetic fields in this region. Since each scan takes only about 1 minute, we can repeat scans at $1\frac{1}{4}$ or $2\frac{1}{2}$ minute intervals and sum and difference the Doppler images so as to enhance either the steady flows or the oscillatory velocities.

Figure 2 shows the entire active region from which Figure 1 was taken. Figure 2(a) shows the continuum image, 2(b) shows the sum of two Dopplergrams separated by $2\frac{1}{4}$ minutes, and 2(c) shows the difference of these same two Dopplergrams. There are some interesting flow patterns in Figure 2(b), especially at the trailing (right) side of the main spot, where a two-pronged downflow is adjacent to a large region of upflow associated with opposite polarity magnetic fields in the penumbral region between the two large umbrae. There is some suggestion of weaker p-mode waves in 2(c) in parts of the active region with a strong magnetic field. The horizontal streaks in 2(b) and 2(c) have been found to be caused by the use of integer arithmetic, and have been eliminated in a new version of the processing software.

In Figure 3, we see NOAA 5669 on 4 September 1989 at 20:00UT. (The magnetic polarities are shown reversed.) Figure 3(a) and (b) are images of the continuum and line-of-sight magnetic field, respectively. In Figure 3(c), a single Dopplergram, one can see that the northern parts of the active region are blue shifted and the southern parts are red shifted with maximum velocities of approximately $-0.49$ km/s and $+1.48$ km/s, respectively. The peak line-of-sight magnetic field in the leader spot (left side) is $2684 \pm 59$ G. A small "satellite" magnetic feature to the northeast of the main spot is more closely seen in Figure 4.

In Figures 4(a) through (c), we have magnified views of the corresponding Figures 3. One of the interesting features to note is the "satellite" magnetic feature (white) near the center of the figure. The peak magnetic field strength of this feature seems to be at the right edge of the penumbra of the lead spot. The magnetic feature, which has a peak field strength of $319 \pm 23$ G, corresponds to a strong downflow (white) to the west (left) of a large region of upflow (black) in the Dopplergram of Figure 4(c). This may correspond to a westward plasma flow in a magnetic loop rather than the loop rising or falling.

Figure 5 shows some details of NOAA 5643 on 17 August 1989 at 22:59UT. Figure 5(a) gives an overview of the region (all images are compressed by about a factor of 2 in the N-S [vertical] direction). In Figures 5(b) and (c) the leader spot is magnified. In Figure 5(b) the continuum image is shown with two squares, located off the umbra where the line-of-sight
Figure 1: Lead spot, NOAA no. 5669, 2 September, 18:50 U.T. (a) continuum image, (b) longitudinal magnetogram, and (c) Dopplergram. All 3 images obtained simultaneously. North is up, West is to the left. Width of image is 50 arc sec.
Figure 2 Complete image of data of Figure 1. (a) continuum, (b) sum of 2 Dopplergrams with 2½ minute time separation to eliminate most of the p-mode oscillations, and (c) difference of same 2 Dopplergrams to enhance p-mode and eliminate slowly varying velocities.
Figure 3 NOAA no. 5669 on 4 September 1989, 20:00 UT. (a) continuum image, (b) longitudinal magnetogram, and (c) Dopplergram. The northern part of the region shows preferentially blue shifts and the southern part red shifts, with maximum velocities of approximately -0.49 km/s and +1.48 km/s, respectively. The peak magnetic field strength in the leader spot is 2684 ± 59G. The small white region (arrow) has $B = 319 \pm 23$G. Black is positive and white is negative in this view.
Figure 4 Magnified views of leader spot of Figure 3. (a) continuum, (b) magnetogram of white features, and (c) Dopplergram showing strong change in velocity to the right (east) of the white feature. Noise in the spot umbra can be reduced by reprocessing the original video data with Fourier noise removal.
Figure 5 Images of NOAA no. 5643 on 17 August 1989 at 22:59 UT. (a) continuum image at $\lambda = 6302.2\,\text{Å}$. The contrast has been enhanced with respect to the photospheric intensity. The white square yields a photospheric intensity of 1773 in machine units, with a standard deviation of 17.8 or 1.0% per pixel. (b) Continuum image, (c) line-of-sight magnetic field, and (d) line-of-sight velocity. See text for discussion of boxed regions. West is toward the left.
field is still strong. Within the left box we find the following quantities on images (b) and (c), respectively: $I/I_{ph} = 0.26$, $B_\parallel = 1552 \pm 87$G, $v_\parallel = -280 \pm 110$ m/s. For the right box we find, for the same quantities: $I/I_{ph} = 0.32$, $B_\parallel = 2406 \pm 57$G, and $v_\parallel = 433 \pm 110$ m/s. The uncertainties are the standard error. The rectangles are 8 by 8 pixels (measured in units where the N-S direction is compressed by a factor of about 2.)

For the leader sunspot of NOAA 5643 we find a peak magnetic field strength of about 2400G. Near the center of the disk, there is a faint ring of opposite polarity flux outside the penumbra, perhaps representing the outer edge of the "superpenumbra" (Figure 5(c)). We find a peak Evershed velocity of approximately 2.2 km/s near the penumbra-photosphere boundary. The spatial character of the Evershed flow is highly structured. The nature of the flow on the disk side is different than that on the limbward side. Individual elements show Doppler shifts corresponding to velocities of about 2.5 km/s, near $\mu \approx 0.7$. Flow patterns can be seen persisting for most of the day. Some of the larger follower magnetic elements show no Doppler signal.

5. Summary

We have presented preliminary results from the SFO VSSHG that show it to be a promising instrument. The data acquisition technique is relatively fast and inexpensive. Raw data are stored in analog form and can be processed by increasingly sophisticated software.

With the present software we can produce images showing interesting relationships between the magnetic, velocity, and intensity fields. For example, in NOAA 5669, over several consecutive days, we see a strong N-S asymmetry in the velocity images, suggesting opposite flow patterns in solar radius or solar longitude or a combination of the two. Detailed analysis of proper motions will help resolve this ambiguity. It is important to note that this N-S Doppler asymmetry was not seen in NOAA 5643. An important question is whether these different Doppler patterns relate to any differences in the evolution of the magnetic field or intensity configurations; e.g., umbral versus penumbral areas.

We hope to address some of these fundamental questions in the near future while making incremental improvements to the processing software. In addition, we have added the ability to measure Stokes Q and U spectra. These data should help us better understand the evolution of the total magnetic field.

This work has been partly supported by California state funds and partly by NSF grant number AST-8603009. We thank Dr. J.K. Lawrence for suggesting improvements to this paper.

REFERENCES


Discussion

S. Koutchmy: Outside the core of sunspots, do you have any method to calculate the strength of the magnetic field by introducing the filling factor for example?

G. Chapman: No, we don't yet know the filling factor in non-spot field regions.

S. Koutchmy: What is the contrast you measure for "faint" fields at the disc center?

G. Chapman: The contrast depends on the magnetic flux measured in the feature (to be published by Lawrence et al.).

E. Landi: How is the $\Delta_\lambda$ appearing in your equations defined?

G. Chapman: The line center is determined from the nominal line position relative to the telluric $O_2$ lines.