FABRY–PÉROT VERSUS SLIT SPECTROPOLARIMETRY OF PORES AND ACTIVE NETWORK: ANALYSIS OF IBIS AND HINODE DATA

PHILIP G. JUDGE1, ALEXANDRA TRITSCHLER2, HAN UITENBROEK2, KEVIN REARDON3, GIANNA CAUZZI1, AND ALFRED DE WIJN1

1 High Altitude Observatory, National Center for Atmospheric Research4, P.O. Box 3000, Boulder, CO 80307-3000, USA; judge@ucar.edu, dwijn@ucar.edu
2 National Solar Observatory/Sacramento Peak5, P.O. Box 62, Sunspot, NM 88349, USA; ali@nso.edu, huitenbroek@nso.edu
3 INAF—Osservatorio Astrofisico di Arcetri, I-50125 Firenze, Italy; kreardon@arcetri.astro.it, gcauzzi@arcetri.astro.it

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ABSTRACT

We discuss spectropolarimetric measurements of photospheric (Fe i 630.25 nm) and chromospheric (Ca ii 854.21 nm) spectral lines in and around small magnetic flux concentrations, including a pore. Our long-term goal is to diagnose properties of the magnetic field near the base of the corona. We compare ground-based two-dimensional spectropolarimetric measurements with (almost) simultaneous space-based slit spectropolarimetry. We address the question of noise and crosstalk in the measurements and attempt to determine the suitability of Ca ii measurements with imaging spectropolarimeters for the determination of chromospheric magnetic fields. The ground-based observations were obtained 2008 May 20, with the Interferometric Bidimensional Spectrometer (IBIS) in spectropolarimetric mode operated at the Dunn Solar Telescope at Sunspot, NM. The space observations were obtained with the Spectro-Polarimeter of the Solar Optical Telescope aboard the Japanese Hinode satellite. The agreement between the near-simultaneous co-spatial IBIS and Hinode Stokes-V profiles at 630.25 nm is excellent, with $V/I$ amplitudes compatible to within 1%. The IBIS QU measurements are affected by residual crosstalk from V, arising from calibration inaccuracies, not from any inherent limitation of imaging spectroscopy. We use a Principal Component Analysis to quantify the detected crosstalk. QU profiles with V crosstalk subtracted are in good agreement with the Hinode measurements, but are noisier owing to fewer collected photons. Chromospheric magnetic fields are notoriously difficult to constrain by polarization of Ca ii lines alone. However, we demonstrate that high cadence, high angular resolution monochromatic images of fibrils in Ca ii and Hα, seen clearly in IBIS observations, can be used to improve the magnetic field constraints, under conditions of high electrical conductivity. Such work is possible only with time series data sets from two-dimensional spectroscopic instruments such as IBIS, under conditions of good seeing.

Key words: instrumentation: interferometers – instrumentation: polarimeters – Sun: chromosphere – Sun: photosphere – Sun: surface magnetism

1. INTRODUCTION

This is the first of several planned papers attempting to derive chromospheric magnetic structure using imaging spectropolarimetry, a new tool with considerable potential. Our motivation is to constrain the magnetic free energy in the solar atmosphere, the cause of many of the Sun’s most interesting observable phenomena, yet measurements of this free energy are notoriously difficult to obtain. Line-of-sight (LOS) components of photospheric magnetic fields have been measured using circularly polarized light routinely for over 50 years. Such measurements set no constraints on the free magnetic energy. It was not until credible measurements of the full polarization vector became available (Baur et al. 1980) that the free component of the magnetic energy became something amenable to observation.

But several difficulties arise. The magnetic virial theorem relates the total magnetic free energy in a volume overlying a surface to the vector field measured at that surface, provided the surface is in a force-free state (e.g., Low & Lou 1990). Most vector field measurements are made in photospheric lines where, outside of sunspot umbrae, the fields are far from force-free. Thus, one must either extrapolate the field into the overlying atmosphere, or make measurements higher in the atmosphere where the field is close to force-free (the ratio of gas-to-magnetic pressure, plasma $\beta$, $\ll 1$). The first option has been pursued by many researchers with mixed success (Schrijver et al. 2008; Wiegelmann et al. 2008; De Rosa et al. 2009), in essence because the problem is non-linear (Sakurai 1979), is usually cast into force-free form incompatible with photospheric conditions, and is also ill-posed (sensitive to boundary conditions, Low & Lou 1990).

In this paper, we begin pursuit of the second option using an imaging spectropolarimeter to observe chromospheric lines. Previous polarimetric studies of chromospheric lines have been successful in recovering magnetic fields (e.g., Metcalf et al. 1995; Solanki et al. 2003; Socas-Navarro 2005; Harvey 2006; Centeno et al. 2006; Pietarila et al. 2007), but are based on slit spectroscopy. As we will show, imaging spectropolarimetry is especially suited for studying the chromosphere because it has the spatial coverage and high temporal cadence needed to follow dynamic fibril motions which mostly dominate the upper chromosphere (e.g., Judge 2006). Such work is difficult with conventional slit spectrographs. Outside of very quiet regions of the Sun, the plasma $\beta$ is certainly $<1$ in the upper chromosphere, as can be seen by inspection of Hα spectroheliograms (e.g., Kiepenheuer 1953; Athay 1976) dominated by fibril structures resulting from the entrainment of plasma by strong magnetic fields. By using measurements of the chromospheric vector field

1. the magnetic free energy in the overlying corona follows directly from the virial theorem;
2. extrapolations into the overlying atmosphere can be made using a boundary condition which is itself force-free, unlike the photospheric case; and

3. the change in regime from a forced (photospheric) to force-free state (upper chromosphere and corona) can be probed.

The third point is of more than academic interest. Recent work by Leake & Arber (2006); Arber et al. (2007) has shown that ion-neutral collisions damp components of the current density $j = \text{curl} \mathbf{B}$ which are perpendicular to the magnetic field $\mathbf{B}$. A significant component of the free energy is thus dissipated in the chromosphere before it reaches the corona.

Below, we present vector polarimetry of the photosphere ($\text{Fe}$ i 630.25 nm) and chromosphere (Ca ii 854.21 nm) using the Interferometric Bidimensional Spectrometer (IBIS; Cavallini 2006; Reardon & Cavallini 2008). However, while proven for earlier instruments (e.g., the Imaging Vector Magnetograph (IVM); Mickey et al. 1996), the technique needs to be proven for IBIS, and so we combine the IBIS data with (nearly) simultaneous measurements of the same Fe i line from the slit spectropolarimeter aboard the Hinode satellite, to assess the spectropolarimetric capabilities of IBIS. Later work will present a physical analysis of these data together with Hα, EUV, X-ray, and G-band data obtained simultaneously.

### 2. OBSERVATIONS

Joint observations with the Dunn Solar Telescope (DST), Hinode, and TRACE were obtained from 2008 May 13 to 21. Only data from 2008 May 20 were of sufficient quality to merit further study and are reported here. We targeted the strongest magnetic features on the solar disk, but only small pores were observed. Two regions were observed: the first (NOAA 10996), centered near solar latitude and longitude N8.7, E10.2, was also observed by Hinode. The second (NOAA 10994, S12.4, W46.1) was observed only at the DST.

Table 1 summarizes the observations. The heliographic pointings, listed between instruments, were determined from a SOLIS full disk magnetogram. The SOLIS scan was obtained between 15:11:27 and 15:23:23 UT, the region shown in Figure 1 being observed by SOLIS near 15:16:15 UT over a period of 1 minute. The figure shows the context of the NOAA 10996 IBIS and Hinode spectropolarimetric measurements, in a SOLIS 630.2 nm magnetogram and a TRACE 19.5 nm image.
There is some 19.5 nm “moss” emission associated with the photospheric field concentrations. Moss is the bright footpoint emission at the base of an overlying hotter corona (Fletcher & de Pontieu 1999; Berger et al. 1999).

2.1. Spectropolarimetric Observations from IBIS

The IBIS observations reported here were obtained between 14:29 and 15:19 UT. IBIS is a Fabry–Pérot-based filtergraph in a classical mount with a circular FOV of diameter 80″, rapidly tunable in wavelength (Cavallini 2006; Readon & Cavallini 2008). IBIS was operated in dual-beam spectropolarimetric mode (A. Tritschler et al. 2010, in preparation) in which two liquid crystal variable retarders (LCVRs) are placed in a collimated beam in front of the instrument, and a polarizing beam splitter is inserted in front of the detector. The FOV is then reduced to ≈40″×80″, because the beam splitter produces a pair of simultaneous I+S and I−S images with S = Stokes Q, U, or V. At each wavelength six modulation states were acquired sequentially, with the first beam acquired in the following order: I+Q, I−V, I−Q, I+V, I−U, and I+U. This sampling order was chosen to maximize the efficiency of the LCVR modulation. The Fe i, Ca ii, and Hα lines were sampled with 14, 21, and 22 non-equidistant wavelength points, respectively. In Hα only unpolarized measurements were acquired. Thus, a full sequence consists of (14+21)×6+22 = 232 exposures, requiring 70 s in total. For the Fe i 630.2 nm and Ca ii 854.2 nm lines, the scanning was performed by jumping sequentially between the blue and red sides of the line. To avoid detector saturation, the exposure time for each individual image was set to 50 ms, which limits the polarimetric sensitivity obtainable. The instrument performed electronic 2 × 2 binning prior to writing to disk which resulted in a detector image scale of 0.16 arcsec pixel⁻¹.

The narrowband observations are supplemented with simultaneous wide band (WB) data (721 nm), covering the same FOV with a detector image scale of ~0.08 pixel⁻¹. The WB data were used for alignment purposes and the correction of the effects of anisoplanatism (to first order) during scanning via a de-stretch algorithm using speckle reconstructed WB images as reference images. The speckle reconstructions were calculated from bursts of 77 images each (burst durations of 23 s) using the implementation by Wöger et al. (2008). G-band data covering a FOV of twice the width but the same height as the WB data were also obtained at a cadence of 0.2 s on a 1024 × 1024 detector with ≈0.09″ pixel⁻¹. These data are not discussed here. All observations were performed in conjunction with the high-order adaptive optics (AO) system (Rimmele 2004). Seeing conditions were good but variable. Full calibration data sets including flats, darks, resolution targets, and polarization calibration measurements were obtained before and after science observations.

The IBIS I ± S data frames were reduced following procedures described by Cauzzi et al. (2008), including dark subtraction, flat fielding, co-alignment with WB images, a blueshift correction needed because of the classical etalon mountings, de-stretching, and co-registration of all images in each sequence. The reduced I ± S frames were then combined and corrected for instrumental polarization to determine the solar Stokes vector S. The telescope calibration data used were from 2007 February. A more recent calibration data set was acquired in 2008 October, but the results were not ready at the time of writing.

The measured S is in a frame of reference defined by the elevation mirror of the telescope (see, e.g., Skumanich et al. 1997; Beck et al. 2005). In the solar reference frame (Q positive in the E–W direction on the Sun), a final rotation in the Q–U plane is required. However, prior to this rotation some care is needed because residual crosstalk from V to Q and U is evident in the data. Thus, an empirical correction to QU using the V data was applied, as described below, to try to derive the actual QU entering the telescope, before applying the rotation. The Appendix describes the different origins of crosstalk in IBIS and the Hinode SP.

For the first target, 30 IBIS scans of 70 s each were completed, for the second, just five scans were obtained before clouds intervened. Figure 2 shows typical IBIS filtergrams of NOAA 10996 taken in the blue wing of Fe i, Ca ii, and Hα, at the nominal line core position of Ca ii and Hα, and a magnetogram constructed by subtracting V(+56 mÅ) from V(−74 mÅ) for the Fe i line. The seeing was examined using a 10″ square region centered near (−150″, 120″), free of measurable magnetic influences. Figure 3 shows the rms intensity contrast measured with IBIS and the Hinode SP in the continuum near 630 nm, as a fraction of the mean intensity. Also shown is the 630 nm continuum rms contrast corresponding to 1″ resolution derived by Lites (2002). The AO-corrected rms contrast was variable, and so was not dominated by stray light. The seeing was clearly worse during the first and 16th–24th IBIS scans. The seeing-limited resolution of these IBIS observations, at best, corresponds to somewhere between 1″ and the resolution of Hinode SP. (Note that “resolution” of Hinode here refers to the characteristic width of the point spread function (PSF) modified by the pixel size. In terms of granular contrast statistics, the smaller Hinode SP PSF corresponds to an effective resolution close to 0′′315.)

2.2. Spectropolarimetric Observations from Hinode

The Spectro-Polarimeter (SP; Lites et al. 2001) aboard Hinode (Kosugi et al. 2007) obtained “fast maps” of the 630 nm region. In typical operation mode, 112 wavelength samples of the SP CCD detector are read, each pixel having a spectral width of 0.00215 nm and a width along the slit of 0′′16 (Centeno et al. 2010). The 12 μm wide SP slit presents an effective width of 0′′16 to the solar image. The fast map mode reduces telemetry volume via an effective 2 × 2 binning of the image produced by the SP mapping process: the image pixel wells are binned in the direction along the slit during each read of the spectral/spatial CCD image, then successive integrations of one full rotation (1.6 s) of the retarder polarization modulator are summed onboard. Successive integrations correspond to one step of the image perpendicular to the CCD slit: an average step size of 0′′149. To further reduce the overall SP data rate for these coordinated observations as a consequence of the failure in late 2007 of the Hinode onboard X-band telemetry system (Shimizu 2010), one of the two CCD polarimetry images was not downlinked, and for the remaining data, we retained only the central half of the full 164″ length of the SP CCD along the slit. The resulting SP fast maps for these observations were then 335 × 256 pixels, or approximately 99′′6 × 81′′9. These maps required ≈21 minutes to execute, and have an effective (square) pixel aperture of about 0′′3. With the Hinode rotating retarder modulator, demodulation was accomplished via onboard summing of images corresponding to four phases over a half-rotation of the modulator. The Stokes...
Figure 2. Typical IBIS data of NOAA 10996 observed on 2008 May 20 from scan number 11. Almost the entire IBIS FOV is shown. The “magnetogram” is simply $V(-74 \text{ mÅ})$ minus $V(+56 \text{ mÅ})$ for the Fe line.

vector was derived using the level 1 data product from the Hinode project, which includes the 630.15 nm and 630.25 nm lines of Fe.

While the SP observations are seeing-free, they do experience spacecraft jitter. The amplitude of the jitter is remarkably small ($1\sigma < 0.01$; Shimizu et al. 2008), which has two implications. First, the images are far more stable than can be obtained from the ground. Second, the influence of jitter on the spectropolarimetry is small, when we understand jitter to have the same effect as “seeing” in the sense modeled by Lites (1987); Judge et al. (2004). This issue is reviewed in the Appendix.

3. ANALYSIS

IBIS obtains narrowband two-dimensional images but must scan through multiple wavelengths to build up the spectra; the SP obtains spectra along the slit but must scan spatially perpendicular to the slit, to build up maps of the solar surface. The instruments also differ in the way the polarimetry is performed. IBIS is a “Stokes definition polarimeter,” i.e., during the IBIS integrations only $I + S_i$ for $S_i = QU$ or $V$ is acquired. Other than inevitable $I \rightarrow S_i$ crosstalk, which is mostly removed by the dual beam, there is no other “seeing-induced
crosstalk.” The combined modulation/demodulation matrices \( \hat{H}_{ij}(v) \) of Lites (1987) are diagonal. Yet such a polarimeter is still susceptible to crosstalk because the telescope mixes the four polarization states prior to entering the polarimeter in a fashion which may be imperfectly calibrated, and the modulation/demodulation is not perfect. Crosstalk induced by calibration errors varies far more slowly than seeing, and could be “calibrated out” if accurate calibration data were available. Difficulties arise because the calibration matrices are imprecisely known. Below, we will apply a simple correction for the \( V \rightarrow QU \) crosstalk by simply requiring the average \( QU \) profiles to be symmetric around line center. The SP data show this to be a good assumption.

Every SP exposure is a linear combination of \( I \) and at least two other Stokes parameters. Such measurements have significant off-diagonal \( \hat{H}_{ij}(v) \) terms. The SP is therefore subject to the systematic errors induced by “seeing-induced crosstalk” (again, for the SP, “image motion” means jitter). But the residual image motion is very small: the factor \( \beta_i \) in Lites’ (1987) formula (15) is far less than it would have been if observing with the SP through the atmosphere. It is in this sense that we can use the SP data as fiducial values against which we compare the data from IBIS.

\[ \beta_i \]

### 3.1. Polarization of Fe i 630.2 nm

In Figure 4, direct comparisons of Stokes parameters between IBIS and Hinode SP are shown. These data are typical of the entire data set. The intensity images and magnetograms show the context of the Stokes parameters shown in the rightmost panels, which for the IBIS data shown were extracted from the near-vertical line representing the position of the SP slit. First, consider the Stokes \( I \) profiles. The spatial variation of Stokes \( I \) profiles along the SP slit position is remarkably similar in the two instruments. The higher angular and spectral resolution of the Hinode observations is evident. Closer scrutiny reveals that Stokes \( V \) to continuum intensity ratios, \( V/I_c \), measured by Hinode are larger than those from IBIS, by a factor of typically 2.4. These differences can arise primarily because the magnetic field is spatially intermittent and not fully resolved. Consider \( V/I_c \) which measures the net LOS flux per unit area in each resolution element, in the weak field limit of the Zeeman effect (e.g., Lites 2000). This approximation not wildly incorrect for these data. Consider just one magnetic element of area \( A \) and LOS field strength \( B_{los} \). The magnetic field generates an intrinsic \( V_{actual} \). But when measured by an instrument \( i \) integrating over area \( A_i \), the Stokes \( V \) is diluted by the (instrument-dependent) “filling factor” \( f_i = a/A_i \leq 1 \). Then for instrument \( i \), \( V/I_c \) is

\[ V_i/I_c \propto f_i B_{los}. \]

Thus, the lower the resolution (larger \( A_i \)), the smaller the \( V/I_c \) signal, when the magnetic field is not resolved. The presence of unpolarized stray light can also reduce \( V/I_c \), but this effect is clearly smaller judging by the measured granular contrast variations. Similar arguments apply to \( QU \) data. The data then suggest that the IBIS \( V \) profiles sample areas \( \lesssim 2.4 \) times those sampled by the Hinode SP instrument, thus the effective resolution of these observations is \( \lesssim 1.5 \) worse than that of Hinode. Taking, as noted above, the latter to be \( 0.3 \) (not twice this which is the Nyquist limit), we get \( 0.49 \) for IBIS. This number is compatible with the seeing-limited resolution derived independently from Figure 3. Furthermore, the Stokes \( V/I_c \) integrated over unipolar areas of several \( \text{Mm}^2 \) observed by IBIS and Hinode SP give the same LOS magnetic flux (not flux density) to within 1\%, validating the above analysis, no unresolved flux of opposite sign being significant. Below, we will show that the IBIS and Hinode Stokes \( V \) data, as reduced into principal components (PCs), have very similar leading order eigenvectors.

IBIS \( QU \) profiles are shown twice in Figure 4. Those marked “Orig.” are profiles obtained in the telescope reference frame. These data are clearly not symmetric about line center, and appear \( V \)-like throughout. Rotation of these profiles alone to the solar reference frame only involves linear combinations of the \( QU \) data, which will yield similar profiles with large asymmetric, \( V \)-like components. The entire data set is similarly contaminated by \( V \)-like profiles. Some extra retardance has not been accounted for in the telescope calibration which converts incoming \( V \) to \( QU \) before entering the polarimeter. Requiring that \( QU \) be symmetric about the (Doppler-shifted) line centers, we found that the sign and amount of \( V \rightarrow QU \) crosstalk is not a strong function of time, position on the detector etc. Thus, this crosstalk can be accounted for by a fixed Mueller matrix, of which the important components lead to the corrections:

\[ Q = Q_{\text{Orig}} - (0.085 \pm 0.004)V \]

\[ U = U_{\text{Orig}} - (0.051 \pm 0.003)V, \]

using 1σ statistical uncertainties. Figure 4 shows these corrected \( QU \) profiles also rotated to the solar reference frame. The agreement with Hinode SP data for \( QU \) is now remarkable. These corrections are just the largest terms arising from extra retardance \( 6^\circ \) oriented at about \( 30^\circ \) to the IBIS reference direction, in which \( QUV \) become mixed via the Mueller algebra (e.g., Seagraves & Elmore 1994). This retardance appears to arise from a thin film of oil noted on the exit port of the telescope. The corrections above were applied to the lines of both Fe and Ca.

The Hinode SP data for \( QU \) in the magnetic network and pore are significantly above the designed sensitivity limit of the instrument. They have essentially the symmetric profiles expected from the Zeeman effect. The heritage of Hinode’s SP is in the Advanced Stokes Polarimeter (Elmore et al. 1992; Skumanich et al. 1994) and Diffraction Limited Polarimeter (Sankarasubramanian et al. 2006). Such profiles are clearly of
3.2. Polarization of \( \text{Ca} \, \text{ii} \) 854.2 nm

Figure 5 shows a comparison of Fe\( \text{i} \) and Ca\( \text{ii} \) profiles for NOAA 10996, plotted as in Figure 4, and from the same pixels. At the peak of the \( V \) profile near \( y = 179'' \), the signal-to-noise ratio of \( V \) is \( \sim 7 \) for the Ca\( \text{ii} \) data shown. No significant \( QU \) signal was detected in the Ca\( \text{ii} \) data. These data differ qualitatively from those of Fe\( \text{i} \), as found from the analysis of Fe\( \text{i} \) 849.7 and 853.8 nm lines observed with SPINOR by Pietarila et al. (2007). Beyond 0.04 nm from line center, i.e., at wavelengths where at least the intensity is formed in the upper photosphere (Cauzzi et al. 2008), the Ca\( \text{ii} \) \( V \) profiles are similar to those of Fe\( \text{i} \) in their signs and spatial distribution along the slit. Thus, the nominal calibration of IBIS leads to credible Stokes \( V \) signals in the parts of the Ca\( \text{ii} \) line profiles whose intensities originate in the upper photosphere.

Hence, the (stronger) Stokes \( V \) signals in the cores are also credible signals, formed in the chromosphere. Within 0.04 nm of the line core, the profiles are spatially much more diffuse, reflecting an expansion of magnetic flux with height, but the core profiles themselves are more complex than their photospheric counterparts.

The “magnetograms” in the second column are constructed by subtracting the blue lobes of each line’s \( V \) profile from the red lobes, taking no account of Doppler shifts, at \( \pm 0.0064 \) and \( \pm 0.017 \) nm from line center for Fe\( \text{i} \) and Ca\( \text{ii} \), respectively. \( V \) profiles show that Ca\( \text{ii} \) “magnetograms” are a mix of Doppler, thermal and magnetic signals which cannot be interpreted straightforwardly in terms of LOS components of the chromospheric magnetic field. Nevertheless, chromospheric magnetic fields are the origin of Stokes \( V \) in Ca\( \text{ii} \) in this region, but there are also large influences from non-local thermodynamic equilibrium (NLTE) radiative transfer and chromospheric dynamics (Pietarila et al. 2007). In particular, the Ca\( \text{ii} \) line intensity forms over many scale heights (e.g., see Figure 5 of Cauzzi et al. 2008). Hence, the inner wings form in the up-
per photosphere where the magnetic field is relatively strong (compare the Fe I line core data with the Ca II line wing data in Figure 2). But the core (within roughly \( \pm 0.02 \) nm of line center) forms some 1 Mm (6–7 pressure scale heights) higher, in the middle to upper chromosphere. The core intensity data (see also Figure 4 of Cauzzi et al. 2008) are dominated by magnetically dominated fibril structures, over concentrations of photospheric magnetic flux. The question of the formation heights of Stokes V for the Ca II 854.2 nm line in such regions is complex, and will be addressed in later work. For now, we simply note that contributions to V can arise from the bulk of the chromosphere, spanning several pressure scale heights and including the plasma \( \beta = 1 \) surface. Also, the V profiles below \( y = 178 \) have two peaks and are correlated with strong line core emission, but that from \( y = 179 \) to 184 the V profile is simpler and the cores are dark. Evidently, the relationship between bright Ca II emission and magnetic field is not linear in our data. Similar results have been reported elsewhere (e.g., Socas-Navarro et al. 2006).

Calibrated data for NOAA 10994 are shown in Figure 6, including profiles extracted from two columns (“a” and “b”). The local vertical of this region is at \( 47^\circ \) to the LOS, thus strong vertical fields are seen partially as QU signals from the transverse Zeeman effect, as well as V. Credible QU profiles are observed in the Ca II 854.2 nm line as well as the Fe I 630.2 nm line. These show perhaps some residual V to QU crosstalk. This is not surprising given the difference in wavelength between the Fe I and Ca II lines, and the unknown optical properties of the oil film.

3.3. Principal Components

Principal Component Analysis (PCA), a pattern/shape recognition method, is useful in application to solar Stokes profiles because PCs are often directly related to underlying atmospheric parameters (Skumanich & López Ariste 2002), for example to magnetic field strength, direction, line-of-sight motions, and thermal properties. Here, we use it also to quantify crosstalk. PCs are the eigenvectors of the covariance matrix with components defined as

\[
C_{ij} = \langle S_i S_j \rangle_{x,t},
\]

where \( S_i \) is the Stokes vector component (one of IQUV) at wavelength \( i \), and the angle brackets imply an average over all spatial pixels \( x \) and/or time \( t \). Denoting \( e_i \) as the \( i \)th eigenvalue and \( v_{i,j} \) as the \( j \)th component of the eigenvector belonging to \( e_i \), any data point \( d_{k,j} \), \( k = \) spatial and/or temporal index, is represented by

\[
d_{k,j} = \sum_{i=1}^{n_{\lambda}} c_{k,i} v_{i,j},
\]

where \( n_{\lambda} \) is the number of wavelengths, and

\[
c_{k,j} = \sum_{j=1}^{n_{\lambda}} d_{k,j} v_{i,j}.
\]

Assume that the eigenvalues/vectors are ordered in decreasing magnitude. When the eigenvalues \( e_i \) drop steeply with increasing \( i \), then most properties of the data are described by...
the first few eigenvectors in the sum. The data points across the line profiles are not completely independent of one another, and so the data can be represented by truncating the sum to values smaller than $n_\lambda$. If however, the spectrum is shallow, there is much independence between data points and a larger number of vectors are needed. In our IBIS data, Stokes $IV$ have steep spectra, but $Q$ and $U$ are shallower. This is because $QU$ are noisy. Noise introduces linear independence between the different wavelengths across the lines, thereby flattening the eigenvalue spectrum.

Figure 7 shows the first three eigenvectors derived for SP and the IBIS data set obtained near 14:43 UT, covering the FOV shown in Figure 4. The IBIS $QU$ data shown are calibrated but uncorrected for crosstalk because our aim is to quantify the crosstalk here using PCA. Consider first the $Hinode$ $Q$ and $U$ are almost symmetric around the line center and resemble the second derivative of the intensity profile, the principal $V$ component being antisymmetric. This is as expected because the $Hinode$ $V$ and $QU$ profiles arise from the first and second order Zeeman effect, respectively. While the IBIS principal $V$ component is asymmetric, too are the PCs of $QU$. PCA has thus revealed the previously identified crosstalk in $QU$ as the principal signal, but it is to be noted that the more symmetric second and third eigenvectors have eigenvalues just 0.6 and 0.2 dex below the PC’s eigenvalue. There is therefore significant signal of the appropriate symmetry in these IBIS data: the second PCs of IBIS $QU$ resemble those seen with SP.

Using PCA, $V \to QU$ crosstalk can be quantified by projection of profiles onto the leading order PCs. Figure 8 shows scatter plots of leading order coefficients $c_{k1}$ for $Q$ and $U$ with those for $V$, for typical observations $k$ from both instruments. There is no significant correlation for the $Hinode$ SP data, but the IBIS coefficients are correlated, the figure lists Spearman rank correlation coefficients. The dashed lines show $c_{k1}(Q) = 0.085c_{k1}(V)$ and $c_{k1}(U) = 0.051c_{k1}(V)$, the numerical coefficients being those of Section 3.1. If the $QU$ data were pure crosstalk from an antisymmetric $V$, then all points would be distributed along the plotted lines. The actual distributions show significant scatter, data for $U$ having a broader, skewed distribution. This behavior, arising from an unknown source of systematic error, highlights the limitation of the simple post-facto corrections of Section 3.1. The corrected $U$ profiles are probably reliable to at best $\pm 50\%$, given the plotted scatter. Nevertheless, the PCA lends support for our empirical corrections.

PCA should also help disentangle the complex Ca ii $QUV$ profiles, in terms of identifying the physical parameters most directly related to the Stokes profiles (Skumanich & López Ariste 2002). Figure 9 shows the eigenvalue spectra and first few eigenvectors of the PCA expansion, for a $10'' \times 10''$ area centered on NOAA 10994 (see Figure 6), a region chosen because it has measurable linear polarization in the Ca ii 854.2 nm line. The $QU$ profiles are mostly dominated by noise (as shown by the shallow gradient in the eigenvalue spectrum, and noisy first eigenvector). But the other eigenvectors show that genuine $QU$ signals are present for this small pore. Stokes $V$ contains real signal because the first eigenvector is predominantly of asymmetric form, and the eigenvalue spectrum is steeper than $Q$ and $U$. This $V$ component has no obvious net amplitude or area asymmetry, in contrast with Pietarila et al. (2007), who
Figure 7. First three eigenvectors in the PCA expansion for each of the four Stokes parameters of the FeI 630.2 nm line are shown, for the IBIS data from 14:43 UT on 2008 May 20, and the corresponding *Hinode* SP data. The first row is the eigenvector with the largest eigenvalue, the second and third show the eigenvectors for the second and third largest eigenvalues. The second and third rows list \( \log_{10} \) of the modulus of the eigenvalue (the largest is set to 1). The columns are labeled with the instrument and Stokes parameter. The abscissa is wavelength index.

Figure 8. Scatter plot of the leading coefficients in the principal component expansion for Stokes \( Q \) and \( V \). The dashed lines show the relations \( c_1(Q) = 0.085c_1(V) \) and \( c_1(U) = 0.051c_1(V) \) derived empirically using the symmetry properties discussed in the text.

found a net red-asymmetry in the 854.2 nm line for some active network.

3.4. Fibrils and their Motions Constrain the Magnetic Field

Figure 5 also shows core and wing intensities of the H\( \alpha \) line from IBIS. The wing and core behavior is similar to the 854.2 nm line of Ca\( \text{ii} \), reflecting conditions at deeper layers of the photosphere and top of the chromosphere, respectively, consistent with the picture of line formation of Athay (1976). The fibril structures in the core intensity images are similar to, not identical with, those for the 854.2 nm Ca\( \text{ii} \) line. H\( \alpha \) images at a given wavelength setting of IBIS are remarkably structured. The motions of “blobs” of emission or absorption seem to trace the fibril and hence magnetic field line orientations. Curiously, on the red side of H\( \alpha \), blobs appear to converge on the underlying photospheric flux concentrations. On the blue side, they diverge from them. To try to determine if these “blobs” correspond to real material motion, we show in Figure 10 H\( \alpha \) data from three snapshots in the time series. The leftmost panel is the line core intensity image of the middle snapshot. The three other panels show data using PCA. The particular eigenvector which corresponds to line-of-sight Doppler shift, i.e., having a profile corresponding to the first derivative of the intensity profile with respect to wavelength, was identified. This component was then projected onto the data themselves at each point and time and images displayed, yielding Doppler maps. (These Doppler velocities are similar to those derived from the first wavelength moment of the profiles.) Darker (lighter) profiles correspond to blue (red) shifted components. Examining the region between the two plotted circles, several dark blobs of material move away from the circle centers with time. The Doppler shifts of these blobs are toward the observer (\( v_{\text{los}} < 0 \)). (While less clear, movies of the red-shifted material show components converging onto the circle centers.) This behavior is compatible with simple flows of absorbing material which diverge from or converge to a magnetic structure originating from the photospheric flux concentration and expanding outward, perhaps into the corona. Hence, using proper motions (determined by eye in this case) and Doppler shifts, one can trace out the three-dimensional vector velocity field of the entrained fibril material. In the particular blobs shown, the vector velocity has components \( (v_x, v_y, v_z) \approx (-7, -7, -3) \) km s\(^{-1}\), i.e., the velocity is inclined at 17° to the plane of the sky, only 16° from the local solar horizontal plane.

These measurements are more than a curiosity. Given the strong collisional coupling between the neutral and ionized components, and the high electrical conductivity, the three-
Figure 9. Eigenvalues and the first three eigenvectors from a PCA of the 854.2 nm line of Ca II. The data are constructed from the central 10′′ × 10′′ area of the pore, NOAA 10994, where significant linear polarization was measured.

Figure 10. Hα data shown for NOAA 10996. The leftmost image is a simple intensity image, the others show the time sequence of three snapshots taken roughly 70 s apart, of Doppler shifts derived using the PCA technique. Bright features are redshifted, dark features blue shifted. The dark blobs near 8 o’clock (see the arrow) propagate roughly outward from the centers of the circles marking a bright concentration of magnetic flux. These data are qualitatively compatible with magnetic field directed flows along the magnetic fields originating from the flux concentration and expanding into the overlying corona. The velocity vectors can, in principle, yield the direction of the magnetic field.

dimensional velocity field traces out the direction of the vector magnetic field, which is therefore also only ≈16° to the horizontal plane. Such observations offer observers the important opportunity to augment spectropolarimetric measurements of chromospheric vector magnetic fields, which will always suffer from weak Zeeman-induced QU signals. Measurement of the LOS component of the magnetic field from Stokes V, coupled with kinematic fluid velocities, determines the vector magnetic field. Chromospheric fibril observations in Ca II or Hα are thus far richer than suggested by inspection of Figure 5. They will be discussed in the context of constraining the chromospheric magnetic fields elsewhere.
4. DISCUSSION

We have demonstrated the fidelity of a two-dimensional filtergraph instrument, IBIS for accurate Stokes $V$ measurements at high angular resolution, by verification through almost simultaneous measurements from the Spectro-Polarimeter on board the Hinode satellite. IBIS measurements of Stokes $QU$ profiles of the Fe $\text{I}$ 630.2 nm line are subject, as expected, to systematic errors (crosstalk), which we have quantified both empirically and using PCA. IBIS is a Stokes Definition Polarimeter so that just one polarization state is measured during each camera integration. Therefore, the crosstalk among $QU$ and $V$ is of a slowly varying character, originating from errors in the telescope calibration data. An empirical correction yields $QU$ profiles in remarkable agreement with the SP data, yielding credible $QU$ profiles both in the Fe $\text{I}$ 630.2 nm line, and, for a pore far from disk center at a viewing angle of $47^\circ$, credible observations of Stokes $QU$ in the chromospheric Ca $\text{II}$ 854.2 nm line.

We believe this is the first time that a direct comparison of spectropolarimetry has been made between slit and two-dimensional filtergraph instruments using data of the same region obtained within a few seconds of each other. (The Advanced Stokes Polarimeter had this capability by use of a slit-jaw but the results were not very good—B. W. Lites 2009, private communication.) Given the intrinsic difficulty of making spectropolarimetric measurements from the ground, the excellent agreement of Stokes profiles found with near-simultaneous observations from IBIS and the Hinode SP provides strong support for the credibility of measurements made with an IBIS-like instrument. We note that the magnetic features observed here are rather weak compared with strong sunspots, and the IBIS camera is to be updated to permit a larger duty cycle and increased signal to noise.

Our goal is to diagnose properties of the magnetic field near the base of the corona using, in part, the Ca $\text{II}$ chromospheric lines. At face value, the Ca $\text{II}$ data appear to be of limited use in that under many conditions the noise is dominant in the $QU$ data and corrections must be applied for inaccuracies in the telescope polarization calibration data. Other complications include difficulties concerning NLTE transfer of in the Ca $\text{II}$ lines. Yet, IBIS has some significant advantages over slit spectropolarimetric measurements. IBIS images can be corrected using image reconstruction techniques. This is important because an angular resolution of $1''$ or better, covering fields of tens of seconds of arc with a spectral resolution of some tens of mÅ is required to see clearly the fibril structure of the upper chromosphere (see Figure 2). A cadence of 70 s is barely enough to track kinematic motion along the fibrils, $\lesssim 20$ s being highly desirable. Such criteria may not be achieved using slit instruments. The observation of fibril kinematics, even in unpolarized light, appears important for diagnosing chromospheric magnetic fields because fibrils not only trace out magnetic lines of force, but the partially ionized plasma is required to flow along these lines because of the large electrical conductivity. From our IBIS data for H$\alpha$, it appears possible to measure the velocity vector of fibril “blobs” in the plane of the sky, and along the LOS, yielding the direction of the magnetic field (to within an ambiguity of $180^\circ$). Coupled with the Stokes $V$ signals which may in principle yield the LOS field strength, there is thus hope that the vector magnetic field might be constrained from such observations.

In conclusion, this data set provides, for the first time, credible imaging spectropolarimetry from photosphere through the chromosphere together with a useful time series of resolved fibril motions in the upper chromosphere. These data can be used to place observational constraints on the vector magnetic field throughout the chromosphere. In the case of NOAA 10996, we have found that the magnetic field is highly inclined to the LOS, as in a traditional magnetic “canopy” (Giovannelli 1982), and that the chromospheric heating rates are not simply related to the Stokes $V$ profiles of Ca $\text{II}$. We will explore the possibilities further using the data described here in later publications. More generally, IBIS holds promise as a tool for chromospheric vector polarimetry in the Ca $\text{II}$ 854.2 nm line, following the work on a larger sunspot by Socas-Navarro (2005).

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APPENDIX

ORIGINS OF CROSSTALK

Consider for simplicity the case of a perfect polarimeter. Let $M$ be the Mueller matrix describing the known telescope calibration parameters. The Stokes vector $S$ entering the polarimeter is $R = MS$, where $S$ is the (desired) solar Stokes vector, $R$ is inferred from the modulation and analysis of instrument $i$. Then, the estimate of the solar Stokes vector from this instrument is

$$S' = M^{-1}R.$$  

With (fictional) perfect knowledge of the Mueller matrix, the solar Stokes vector is

$$S = M_0^{-1}R.$$  

We can write $M = M_0 + E$, where the (unknown) elements of the error matrix $E$ are assumed small compared with $M_0$—the telescope calibration matrix is close to the actual matrix. Keeping first order terms only,

$$S - S' = EM^{-1}R = ES',$$

which is the error in the inferred solar Stokes vector resulting from an inaccurate telescope calibration. Off-diagonal (unknown) terms in $E$ convert the inferred $S'$ values into other Stokes components. For a stable instrument, $E$ can be considered constant or very slowly varying with time. This kind of error is present in all practical polarimeters.

In the presence of atmospheric seeing, the Stokes vector entering the telescope is a rapidly varying distortion of $S$ in which neighboring points on the solar surface are spatially smeared. Let $T_\alpha(x, y; t)$ represent the $\alpha$ component of the Stokes vector entering the telescope from apparent position ($x, y$) at time $t$.
(x, y) on the sky at time t. Then, including just the lowest order (tip/tilt) distortions at any time t, T arises from a different place on the sky (x', y') = (x + δx(t), y + δy(t)). Expand Tα(x, y; t) as a Taylor series in the solar Stokes component Sα on the sky:

\[ Tα(x, y; t) = Sα(x + δx(t), y + δy(t)) \approx Sα(x, y; t) + \nabla Sα \cdot s(t) \]

to first order (Judge et al. 2004). Here, the \( \nabla \) operator and vector s(t) are vectors in the (x, y) plane, s(t) = (δx(t), δy(t))\(^T\) is the tip-tilt component of the seeing. Let \( P_ν \) be the power spectrum of the seeing. All measurements require a finite integration time \( \tau \), during which the seeing \( s(t) \) varies. At all frequencies \( ν \) where \( P_ν, \tau \gg 1 \), seeing detrimentally affects the measurements. When integrated over time \( \tau \), detectors record energy

\[ \int_0^\tau \sum_{α=0}^3 a_α Tα(x, y; t) \, dt = \int_0^\tau \sum_{α=0}^3 a_α \langle Sα(x, y; t) \rangle \quad + \nabla Sα \cdot s(t) \rangle \, dt, \quad (A1) \]

where \( a_0 = 1 \) (\( S_0 = 1 \)) and \( a_α \neq 0 \) depends on the polarimeter’s particular modulation and integration scheme. With many realizations of the seeing, the equation becomes

\[ \sum_{α=0}^3 a_α \langle Tα \rangle = \sum_{α=0}^3 a_α \langle Sα \rangle, \quad (A2) \]

because \( \langle \nabla Sα \cdot s(t) \rangle \) averages to zero when \( s(t) \), arising from atmospheric turbulence, is statistically spatially symmetric. The \( \langle Sα \rangle \) components have variances arising from the seeing:

\[ σ^2_α = \langle \nabla Sα \cdot s(t) \rangle^2, \quad (A3) \]

which Lites (1987) has shown, can be evaluated from the seeing power spectrum using the assumption that the seeing is a random phenomenon. Equation \( (A2) \) is a linear system for the desired solar components \( Sα \) in terms of the measurements \( Tα \), subject to statistical variations described by \( σ_α \).

For a Stokes definition polarimeter like IBIS, \( a_α=1,2,3 \) is non-zero only for one Stokes parameter, \( β \) say. Then, the above equations relate \( \langle S0 \rangle + a_β \langle Sβ \rangle \) only to \( \langle T0 \rangle \) and \( a_β \langle Tβ \rangle \). The second beam yields simultaneous measurements of equation \( \langle T0 \rangle = a_β \langle Tβ \rangle \), and this two-equation system is solved for all components \( Sβ \) in terms of \( Tα \) as usual, with uncertainties propagated via \( σ_0 \) and \( σ_β \).

But for other polarimeters, like the SP on Hinode, \( a_β \) is non-zero for at least two of \( QUV \) during each measurement. The above equation becomes a system of more than two equations. After eliminating the intensity from the equation using the second beam, we see that Stokes parameter \( Sβ \) is also influenced though the terms \( σ_α \neq 0 \). If the variances \( σ_α \) (e.g., Stokes \( V \)) are larger than the desired terms \( Sβ \) (e.g., Stokes \( Q \)), then the linear system yields estimates for \( Sβ \) which are dominated in any particular realization by terms of order \( σ_α \). In words, crosstalk arises because, during the exposure for modulation state \( S0 + Sβ \), fluctuations in time occur in \( Sβ \) resulting from the motion of the solar image with contains structure. The great advantage of the SP is its remarkably small rms image motion, so that image motion induced crosstalk is practically negligible.

REFERENCES

Arber, T. D., Haynes, M., & Leake, J. E. 2007, ApJ, 666, 541
Athay, R. G. 1976, The Solar Chromosphere and Corona: Quiet Sun (Dordrecht: Reidel)
Baur, T. G., House, L. L., & Hall, H. K. 1980, Sol. Phys., 65, 111
Beck, C., Schlichenmaier, R., Collados, M., Bellot Rubio, L., & Kentischer, T. 2005, A&A, 443, 1047
Berger, T. E., De Pontieu, B., Schrijver, C. J., & Title, A. M. 1999, ApJ, 519, L97
Cauzzi, G., et al. 2008, A&A, 480, 515
Cavallini, F. 2006, Sol. Phys., 236, 415
Centeno, R., Collados, M., & Trujillo Bueno, J. 2006, ApJ, 640, 1153
Contenko, R., Lites, B. W., & de Wijn, A. G. 2010, in ASP Conf. Ser. 445, Second Hinode Science Meeting, ed. B. Lites et al. (San Francisco, CA: ASP), in press
De Rosa, M. L., et al. 2009, ApJ, 696, 1780
Elmore, D. F., et al. 1992, Proc. SPIE, 1746, 22
Fletcher, L. N., & de Pontieu, B. 1999, ApJ, 520, L135
Giovanelli, R. G. 1982, Sol. Phys., 80, 21
Harvey, J. W. 2006, in ASP Conf. Ser. 358, Solar Polarization 4, ed. R. Casini & B. W. Lites (San Francisco, CA: ASP), 419
Judge, P. 2006, in ASP Conf. Ser. 354, Solar MHD Theory and Observations: A High Spatial Resolution Perspective, ed. J. Leibacher, R. F. Stein, & H. Uitenbroek (San Francisco, CA: ASP), 259
Judge, P. G., Elmore, D. F., Lites, B. W., Keller, C. U., & Rimmele, T. 2004, Appl. Opt.: Optical Technology and Medical Optics, 43, 3817
Kiepenheuer, K. O. 1953, in The Sun, ed. G. P. Kuiper (Chicago: Chicago Univ. Press), 322
Kosugi, T., et al. 2007, Sol. Phys., 243, 3
Leake, J. E., & Arber, T. D. 2006, A&A, 450, 805
Lites, B. 2002, ApJ, 573, 431
Lites, B. W. 1987, Appl. Opt., 26, 3838
Lites, B. W. 2000, Rev. Geophys., 38, 1
Lites, B. W., Elmore, D. F., & Streamer, K. V. 2001, in ASP Conf. Ser. 236, Advanced Solar Polarimetry—Theory, Observation, and Instrumentation, ed. M. Sigwarth (San Francisco, CA: ASP), 33
Low, B. C., & Lou, Y. Q. 1990, ApJ, 352, 343
Metcalf, T. R., Jiao, L., & Uitenbroek, H. 1995, ApJ, 439, 474
Mickey, D. L., Canfield, R. C., Labonte, B. J., Waterson, M. F., & Weber, H. M. 1996, Sol. Phys., 168, 229
Pietarila, A., Socas-Navarro, H., & Bogdan, T. 2007, ApJ, 663, 1386
Reardon, K. P., & Cavallini, F. 2008, A&A, 481, 897
Rimmele, T. R. 2004, in Proc. SPIE, 5400, 34
Sakurai, T. 1979, PASJ, 31, 209
Shimizu, T. 2010, in ASP Conf. Ser. 445, Second Hinode Science Meeting, ed. B. Lites et al. (San Francisco, CA: ASP), in press
Shimizu, T., et al. 2008, Sol. Phys., 249, 221
Skumanich, A., Lites, B. W., & Martínez Pillet, V. 1994, in Proc. NATO Advanced Research Workshop, Solar Surface Magnetism, ed. R. J. Rutten & C. J. Schrijver (Dordrecht: Kluwer), 99
Skumanich, A., Lites, B. W., Martínez Pillet, V., & Seagraves, P. 1997, ApJS, 110, 357
Skumanich, A., & López Ariste, A. 2002, ApJ, 570, 379
Socas-Navarro, H. 2005, ApJ, 631, L167
Socas-Navarro, H., Elmore, D., Pietarila, A., Darnell, A., Lites, B. W., Tomczyk, S., & Hegwer, S. 2006, Sol. Phys., 235, 55
Solanki, S. K., Lagg, A., Woch, J., Krupp, N., & Collados, M. 2003, Nature, 425, 692
Wiegelmünnich, T., Thalmann, J. K., Schrijver, C. J., Derosa, M. L., & Metcalf, T. R. 2008, Sol. Phys., 247, 249
Wöger, F., von der Lühe, O., & Reardon, K. 2008, A&A, 488, 375