Chapter 5

Observation of Sunspot Vector Magnetic Fields

5.1 Summary

The inversion results using the ASP code modified to take the KTT Stokes profile as the input are discussed. The inversion of a bi-polar active region NOAA 8516 was carried out with this code. The total field strength results from this inversion code is compared with the total field strength derived using the Mess Solar Observatory (MSO) Stokes polarimeter and it was found that both agree quite well except for an off-set of about 200 Gauss. The disturbed V-profiles observed near the magnetic neutral line of this bi-polar active region was analysed with a two magnetic component model and was found that flows similar to siphon flow may exist in this region. The vector field map of an active region NOAA 8951 were made and shown.
5.2 Introduction

With the removal of instrumental polarisation of the Kodaikanal Tower Telescope (KTT), it is now possible to obtain vector magnetic field information of any active region on any particular day. As shown in Chapter 4, the residual polarisation left after the removal of the instrumental polarisation is about 0.5%, 0.9% and 0.2% in Q/I, U/I and V/I, respectively. The corrected profiles need to be inverted with an atmospheric model in order to get the physical parameters present in the region of observation. The observational configuration is mentioned in the previous chapter (Section 4.5). The elimination of the instrumental polarisation for these observed Stokes profiles is also mentioned in the same section. In this chapter, we will describe the inversion code which was used to invert the corrected Stokes profiles to obtain the physical parameters like the magnetic field strength, field inclination etc. of the observed region. The code used for inverting the ASP data (Skumanich and Lites, 1987; Lites et al., 1992) is modified in such a way that it can take the Stokes profile observations from KTT and invert it to get the physical parameters in the observed region. The field strength obtained from this inversion is compared with the observations obtained at Mecs Solar Observatory (MSO) of the same region in order to look for the consistency in the data. The disturbed peculiar profiles which cannot be inverted using the ASP code is fitted using a two magnetic component model. The results obtained from this fit is also discussed. The vector field map of a sunspot is given.

5.3 Inversion of Stokes Profiles

The calculation of the physical parameters particularly the vector magnetic field from the Stokes profile observations require the solution of the Radiative Transfer Equations (RTE) (del Toro Iniesta and Ruiz Cobo, 1996a). The solar atmosphere is repre-
5.3: Inversion of Stokes Profiles

sented through a set of model parameters assumed to describe completely the physical state of the system. These parameters are not directly measurable but do determine the values of the observables, in this case the Stokes profiles, \([I_\lambda, Q_\lambda, U_\lambda, V_\lambda]^T\). Two ways are possible to determine these model parameters, one is called as forward problem and the other is inverse problem.

The forward problem consists in predicting the values of the unknown Stokes pseudo vector (del Toro Iniesta and Ruiz Cobo, 1996b) by solving the RTE which are linear differential equations under the Milne-Eddington (ME) approximations. For producing the Stokes vector, arbitrary values of the model parameters are chosen. The arbitrariness in the value of the model parameters is not really arbitrary in the sense that the approximate values are obtained from the observed Stokes vector. For example, the field strength can be found out from the splitting if the line is completely split or from the magnitude of the circular polarisation. However, to get a consistent solution, the forward problem requires enormous computation time once the number of parameters required to specify the state of the atmosphere becomes large.

The inverse problem does infer the unknown model parameters from the observed Stokes profiles. In a wider sense, any inference made of a given solar parameter might be called as an inversion. For example, the classical estimation of line-of-sight velocity from the position of the line core minimum would be an inversion. In this particular example, the model atmosphere would simply consists of a constant material velocity with height. No other solar physical quantity is assumed to alter the observed line core position. When a more detailed description is sought, careful account for the many non-linear dependence of the observed spectra on the various atmospheric parameters is needed (Ruiz Cobo & del Toro Iniesta, 1994; Bellot Rubio, Ruiz Cobo and Collados, 2000). If the dependence of the Stokes vector on the various atmospheric parameters like thermodynamic, dynamic, magnetic parameters is linear, then an analytic inversion of the problem would be taken for granted. It is the non-linearities which require the use of involved numerical techniques. We used only the analytic in-
version (Skumanich and Lites, 1987; Ruiz Cobo, 1992) for the observations described in this thesis. Refer to del Toro Iniesta and Ruiz Cobo (1996b) for the numerical inversion techniques to include the non-linearities in the physical parameters. With the advent of numerous minimisation techniques, it is now possible to use the inversion code efficiently for a large amount of data with a large number of unknown free parameters.

5.4 Methodology

The inversion methodology used here is the same as that of the one used at High Altitude Observatory (HAO) for the Advanced Stokes Polarimeter (ASP) data. This methodology is described by Skumanich & Lites (1987), Lites & Skumanich (1990), Skumanich, Grossmann-Doerth, and Lites (1992) and Skumanich, Lites, and Martinez Pillet (1994) and references therein. The methodology involves the solution of the RTE’s in a model atmosphere. Using classical approach, Jeffries, Lites, and Skumanich (1989) solved the transfer equations for the spectral line radiation in a dielectric medium permeated by a magnetic field and their solution is given by,

\[
\frac{dI}{dz} = -K_t I + J. \tag{5.1}
\]

Where, \( I = [I, Q, U, V]^T \) and \( J = K_t[S, 0, 0, 0]^T \). \( K_t \) is the 4×4 absorption matrix which characterise the effects of magnetic field and other physical parameters on the atom,
with,

\[
\kappa_I = \frac{1}{2} \left( \frac{\kappa_p + \kappa_l}{2} \right) \left( 1 + \cos^2(\gamma) \right) + \kappa_p \sin^2(\gamma)
\]

\[
\kappa_Q = \frac{1}{2} \left( \kappa_p - \frac{\kappa_r + \kappa_l}{2} \right) \sin^2(\gamma) \cos(2\chi)
\]

\[
\kappa_U = \frac{1}{2} \left( \kappa_p - \frac{\kappa_r + \kappa_l}{2} \right) \sin^2(\gamma) \sin(2\chi)
\]

\[
\kappa_V = \frac{\kappa_r - \kappa_l}{2} \cos(\gamma)
\]

\[
\kappa'_Q = \frac{1}{2} \left( \kappa'_p - \frac{\kappa'_r + \kappa'_l}{2} \right) \sin^2(\gamma) \cos(2\chi)
\]

\[
\kappa'_U = \frac{1}{2} \left( \kappa'_p - \frac{\kappa'_r + \kappa'_l}{2} \right) \sin^2(\gamma) \sin(2\chi)
\]

\[
\kappa'_V = \frac{\kappa'_r - \kappa'_l}{2} \cos(\gamma)
\]

The \( \kappa_I, \kappa_Q, \kappa_U \) and \( \kappa_V \) are called as absorption coefficients whereas \( \kappa'_Q, \kappa'_U, \kappa'_V \) are called magneto-optical coefficients. The absorption arises because of the resonant absorption when an electric field incident on a classical dielectric. The magneto-optical effect arises because of the differential absorption of the dielectric to the two orthogonal electric field vibrations (one along the vibration axis of the dielectric and the other perpendicular to it). This produces a phase-change and hence a birefringence. \( \gamma \) is the angle made by the magnetic field with the line-of-sight and \( \chi \) is the azimuthal angle of the magnetic field vector. The physical parameters of the medium, like the temperature, velocity etc., are represented via the absorption and the magneto-optic coefficients.

In the classical approach, the atom represented as a dielectric is resolved into three normal polarisation modes in the presence of a magnetic field. The absorption coefficients for these three modes are given here as \( \kappa_p, \kappa_r \) and \( \kappa_l \). They are in turn related to the basic physical properties of the dielectric medium and to the applied magnetic field strength,

\[
\kappa'(v) = \frac{\pi N e^2}{m c} \frac{1}{\sqrt{\pi \Delta \nu_D}} \Re F(a, v),
\]

\[
\kappa(v) = \frac{\pi N e^2}{m c} \frac{1}{\sqrt{\pi \Delta \nu_D}} H(a, v).
\]
\( \Delta \nu_D \) is the Doppler width (representing the thermal properties of the atmosphere in Local Thermodynamic Equilibrium (LTE)) and \( a = \Gamma / 4 \pi \Delta \nu_D \), the damping factor (representation of micro and macro turbulence). In classical analogy, ‘a’ is the damping factor for the damped classical oscillator or the dielectric. \( H(a,v) \) is the Voigt profile and \( F(a,v) \) can be represented using the Voigt profile and they are given as,

\[
H(a, v) = \frac{1}{\pi} \int \frac{(v - y)e^{-y^2}}{(v - y)^2 + a^2} \, dy \\
2F(a, v) = \frac{a}{\pi} \int \frac{e^{-y^2} dy}{(v - y)^2 + a^2}.
\]

The dimensionless variable ‘\( v \)’ is equal to \( (\nu_0 - \nu)/\Delta \nu_D \) for the unshifted plane-polarised component \( (\kappa_p, \kappa'_p) \) while for the circular polarised pair \( (\kappa_r, \kappa_i, \kappa'_r, \kappa'_i) \), it is given as,

\[
v = \frac{(\nu_0 \mp \nu_L - \nu)}{\Delta \nu_D}
\]

\( \nu_L \) is the Larmor frequency whose value is decided by the field strength and atomic parameters.

In this methodology, the thermal, magnetic and dynamic state along the observed line-of-sight (LOS) is represented by the lowest order variation or representation possible. Thus all atmospheric parameters are considered to be constant along the LOS except for the line source function, \( S \) which is represented as a linear function of continuum optical path along the LOS,

\[
i.e., \ S = B'_0 + B'_1 \tau_c,
\]

with \( B'_1 = \beta \mu \) for plane parallel atmosphere (\( \beta \) represents the vertical gradient). Such an approximation was studied by Holt (1972) in the field free situation and shown to yield physically meaningful results. In the case of Fe I lines used by us and ASP, Bruls, Lites, and Murphy (1991) has shown that this low order approximation is a good description of realistic solar conditions.

These approximations lead to a Milne-Eddington (ME) atmosphere and hence the polarised radiative transfer equation for the emerged Stokes vector is studied for the
ME atmosphere. The emergent Stokes vector in the ME atmosphere can be written as (Skumanich, Lites, and Seagraves, 1997),

\[ I_\lambda = B'_0 u + B'_1 (\hat{I} + \eta_0 \phi_\lambda)^{-1} u. \] (5.3)

Where \( I_\lambda \) is the emergent Stokes vector \([I_\lambda, Q_\lambda, U_\lambda, V_\lambda]^T\) and \( u \) is the unpolarised Stokes vector representing the unpolarised light \([1,0,0,0]^T\), \( \eta_0 = \kappa_0 / \kappa_c \) where \( \kappa_0 \) is the line center & continuum opacity respectively with \( H(a, \Delta \lambda) \), Voigt function. \( \kappa_\lambda = \kappa_{00} \phi_\lambda(B, \psi, \phi, \Delta \lambda_D, \alpha, \lambda_0^m) \) is the absorption matrix. The above equation depends non-linearly on the magnetic field strength \( B \), inclination angle \( \psi \) to the LOS and the azimuthal angle \( \phi \) in the observers frame. Also, it depends non-linearly on the Doppler width \( \Delta \lambda_D \), damping factor \( a(=\Gamma / 4\pi \Delta \lambda_D) \) and line center position \( \lambda_0^m \) (LOS measure). Thus, nine atmospheric parameters,

\[ \text{viz., } p = (B, \psi, \phi, \eta_0, \Delta \lambda_D, \alpha, \lambda_0^m, B'_0, B'_1) \]
determines the emergent vector.

In fitting this model to the data an inconsistency between the source function coefficient \( B'_1 \) appearing in the polarisation parameters, \( Q_\lambda, U_\lambda, V_\lambda \) and that in the intensity parameter, \( I_\lambda \) has been included. This inconsistency is due to varieties of causes. It may be because of the scattered light or the lack of spatial resolution where a non-magnetic region is included in a pixel resolution or to the effects such as canopy condition (Skumanich, Grossmann-Doerth, and Lites, 1992). To reduce the number of unknowns, the fill factor is incorporated into the source function parameter without any loss of generality.

The HAO code differs from the AHH routine in incorporating the magneto-optical effect, taking the gradient of the source function \( B'_1 \) as a free parameter and including the damping parameter \( 'a' \). This allows the intensity profile to decouple from the polarisation profiles and hence an option of fitting any weighted combination of the four Stokes profiles. When the polarisation profiles are fitted by themselves (zero weight for \( I_\lambda \)), \( B'_1 \) is determined solely from the magnetic regions in the field of view.
that contribute to the polarisation. When I-profile is included in the fit, an optional additional parameter, 'f', representing scattered light and fill factor is included.

It is essential to have a good initial guess for any least squares regression analysis. For line center, the equivalent width bi-sector is used as a first approximation. The central depth of the I-profile provides an estimate of $B'$, and for $\Delta \lambda D$, a and $\eta_0$, a starting value of 25 mÅ, 0.2 and 3 is used respectively. The fractional contribution of the stray light profile, 'f' is initiated with a value zero. If the magnetic field is strong enough to produce a splitting in the I-profile, the separation of these split features provides an initial estimate of the magnetic field strength. If no splitting is observed an initial value of 500 G is adopted.

The inversion code tested for the ASP data, is modified to take the input Stokes spectra from KTT rather than the ASP data. The main disadvantage of this inversion code is that it cannot reproduce any asymmetries which are observed in the Stokes profiles. Also, peculiar profiles observed in the sunspot, particularly in the penumbral region cannot be reproduced. To reproduce such profiles, the gradients in the physical parameters need to be included in the atmospheric model and also the atmosphere should include three or more components rather than the two component model (one magnetic and the other non-magnetic).

5.5 Inversion Results

The ASP inversion code was run with the Stokes profile data for the KTT polarimeter. The results of the ASP inversion is the output of nine physical parameters at each point on the spatial position along the slit as well as at different slit positions used. The nine physical parameters derived are, (i) The magnetic field strength, $B$, (ii) Magnetic field inclination from the line of sight (LOS), $\psi$, (iii) Azimuthal angle of the magnetic field vector, $\chi$, (iv) LOS velocity represented as the line core position, $\lambda_c^m$. (v) Line depth. $\eta_0$. (vi) Doppler width. $\Delta \lambda_D$. (vii) Damping factor, a, (viii)
5.5 Inversion Results

Constant background source function, $B_0$, (ix) The slope of the source function, $B_1$. The tenth parameter, scattered light 'f' is taken as another parameter if the inversion includes the total intensity. The ASP code also derives the errors in each of the fitted parameters.

Figure 5.1: The four Stokes profiles of a spatial position which showed significant signals in all the profiles in the active region NOAA 8516. The data points are marked as '+' and the solid line is the best fit.

Figure 5.1 shows a typical fit of the Stokes profiles with the ME atmospheric model. The Stokes profiles were taken from a point in a region where all the Stokes profiles showed considerable signal for the active region NOAA 8516. The fit is reasonably good. The excess scatter in the U-fit originates due to the low signal to noise level compared to $Q$ and $V$. This is because of the extra polaroid inserted during $U$-measurement. While fitting, instead of using the whole wavelength region of observations, a band of data points around the line $\lambda 6301.5$Å and $\lambda 6302.5$Å are used to fit in order to reduce the noise level in the fit. Table 5.1 lists the atomic parameters of these lines (Sigwarth et al., 1999). Table 5.2 lists the observational
parameters for the active region NOAA 8516. This line is used extensively for the magnetic field measurement since the atomic parameters are very similar for these two lines except for the difference in the Lande 'g' factor which characterises the sensitivity of the line to the magnetic field. The line 6302.5Å has a larger Lande factor compared to the line 6301.5Å.

Figure 5.2: A plot between the total field strength obtained with the MSO and with the KTT. The results agree reasonably well except for an offset of about 200 Gauss.

The total field strength calculated using the ASP inversion for the active region NOAA 8516 is compared with the results from the Mees Solar Observatory (MSO). The slit positions used for the observation is marked in the Figure 4.11. Figure 5.2 shows the plot between the total field strength obtained using the MSO stokes polarimeter and the KTT Stokes polarimeter. It can be seen that both the results are agreeing quiet well with a small off-set value of about 200 G. Figure 5.3 shows a typical vector field results for the slit position '4' (See Figure 4.11) from this inversion code. This figure shows that the total field strength, LOS inclination in the observers co-ordinate and the azimuthal angle of the field. These three quantities
Table 5.1: The atomic parameters for the line $\lambda\lambda6301.5\AA$ and $\lambda\lambda6302.5\AA$.

<table>
<thead>
<tr>
<th>Species</th>
<th>Wavelength in $\AA$</th>
<th>Lande factor</th>
<th>Excitation Potential</th>
<th>Mult. No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe I</td>
<td>6301.5091</td>
<td>1.5</td>
<td>3.64 5.60</td>
<td>816</td>
</tr>
<tr>
<td>Atm.O$_2$</td>
<td>6302.0005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe I</td>
<td>6302.5017</td>
<td>2.5</td>
<td>3.67 5.63</td>
<td>816</td>
</tr>
<tr>
<td>Atm.O$_2$</td>
<td>6302.7629</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

specify the vector field of the magnetic region. The errors in the derived parameter are shown as the error bars with the length of the error bar equal to three times the error derived from the fit (i.e., 3$\sigma$). The ambiguity of 180° present in the azimuth measurement is removed manually by looking at the spurious jumps present. This ambiguity arises because the transverse Zeeman effect is insensitive to the 180° changes in the azimuthal orientation of the magnetic field vector.

5.6 Peculiar Profiles around Magnetic Neutral Line

The Stokes profile observations done for the active region NOAA 8516 showed peculiar V-profiles. Figure 4.11 shows the slit positions used to observe the region with the polarimeter at KTT. Figure 5.4 shows the same region but the gray scale image is the line of sight field map taken using the MSO Stokes polarimeter.

The sunspot NOAA 8516 is a bipolar region as seen in the MSO line of sight magnetic field map (Gray image in Figure 5.4). The negative and positive polarity is mapped as dark and bright respectively. It can be seen from Figure 5.4 that the slit position marked '5' crosses the neutral line region. Magnetic neutral line is a region where the field is fully transverse. However, if there are flows present in those regions, the cancelation of the V profiles from adjacent regions is not exact and can
produce peculiar V-profiles. This can be used as a sensitive diagnostic of the line-of-sight velocity difference between the opposite polarity regions (Skumanich and Lites, 1991). Figure 5.5 shows the line-of-sight magnetic field strength (longitudinal field strength) along the slit position number '5'. The line-of-sight field was calculated using the results from the ASP code modified to take the KTT Stokes profiles as input. The result of the total field strength and the line-of-sight angle derived with the ASP code is used to calculate the line-of-sight field strength using the relation,

\[ B_{\text{lon}} = B_{\text{tot}} \cos(\psi) \]  

where \( B_{\text{lon}} \) is the longitudinal field strength and \( B_{\text{tot}} \) is the total field strength. \( \psi \) is the line-of-sight inclination of the magnetic field vector in the observers co-ordinate.
Figure 5.3: Vector field calculated using the ASP code along the slit position marked as '4' in the Figure 4.11. The error bars for the derived parameters are plotted. The length of the error bar is equal to three times the error value derived from the inversion code.

It can be seen from this figure that two opposite polarity regions exist within the field of view and Figure 5.6 shows the total field strength along the same slit position.

By comparing these two figures (Figure 5.5 and 5.6), it can be seen that the positive polarity has slightly more field strength than the negative polarity near the neutral line. Along the neutral line, the magnetic flux of positive and negative polarity cancels each other if there are no other dynamics involved like the velocity etc. An examination of the Stokes profile around the neutral line indicated that the V-profiles were disturbed and showed multiple reversal. A simple two magnetic component model is generated by taking the profile from the positive and negative polarity (pixel position 11 for the positive polarity and pixel position 103 for the negative polarity). The neutral line lies around the pixel position 76. From the positive and negative polarity profile, a composite profile was made using two free parameters, one is the
5.6: Peculiar Profiles around Magnetic Neutral Line

Figure 5.4: The observed slit position over plotted on the line-of-sight magnetic field observed using the MSO Stokes Polarimeter. This active region NOAA 8516 is bipolar as seen in the figure and the slit position number ‘5’ passes through the neutral line region.

The fill factor, ‘f’ and the other is the relative velocity, ‘Δλv’. The composite profile is represented as,

$$CP(\lambda) = f . P_1(\lambda) + (1 - f) . P_2(\lambda - \Delta \lambda_v).$$

Where, CP(\lambda) represents the composite profile. P_1 and P_2 refers to the positive and negative polarity profile respectively and ‘f’ is the fill factor which represents the weightage of these two profiles in the composite profile. By varying ‘f’ and Δλ_v, the observed profile near the neutral line (pixel number 76) is fitted. Figure 5.7 shows a typical profile near the neutral line and the best fit using the composite profile. About eight profiles around the neutral line is fitted with the above composite profile equation. Table 5.2 lists the results of these fittings.

A fill fraction of 0.8 means the weight for the positive polarity (profile 1) is 80%
Figure 5.5: The line-of-sight magnetic field strength calculated using the ASP inversion code along the slit position '5'. The polarity reversal is clearly seen in this picture.

in the composite profile and for the negative polarity (profile 2), it is 20%. It can be seen from Table 5.2 that the results for the velocity is mostly negative around the neutral line. This means that the profile 2 is shifted towards blue compared to the profile 1. Hence, the flow in the negative polarity is towards the observer (upflow) compared to the flow in the positive polarity. It has been observed that there are flows in the outer edges of sunspots (Evershed, 1909). These flows start in the penumbral region. The end points of these flows are shown to be in the photosphere around the active region or the sunspot (Westendorp Plaza et al., 1997a). The possibility of this Evershed flow as siphon flow is also been studied (Montesinos and Thomas, 1997). Siphon flow occurs along a magnetic flux tube. The flow will occur only when there is a field difference between the two foot points of the magnetic flux tube. The flow goes from the foot point which has lower field strength to the higher field strength
Figure 5.6: Total field strength calculated using the ASP code modified to take the KTT Stokes profiles along the slit position marked as '5'. By comparing with the Figure 5.5, it can be said that the total field strength in the negative polarity (field lines going away from the observer) is less than in the positive polarity (field lines pointing towards the observer).

foot point. The pressure balance equation for a bi-polar region can be written as,

$$ P_{gas}^+ + \frac{B_+^2}{8\pi} = P_{gas}^- + \frac{B_-^2}{8\pi}, $$

where, $P_{gas}^+$ and $B_+$ represents the gas pressure and the total magnetic field strength respectively. The ' +' sign refers to the positive polarity. Similarly, $P_{gas}^-$ and $B_-$ refers to the gas pressure and total field strength for the negative polarity. It can be seen that the gas pressure will be higher in the low field strength foot point compared to the high field strength foot point and hence a flow from the low field strength foot point to the high field strength foot point, is expected. However, the observed Evershed effect is from the penumbral region to the photosphere and observationally the photosphere around a sunspot has less field strength compared to the penumbral region and hence
Figure 5.7: A typical observed disturbed V-profile around the neutral line shown as solid line and the best fit using the composite profile shown as dashed line.

the flow was expected from the photosphere to the penumbral region, if the flow is a siphon flow. However, this difference can be attributed to the difference in the atmospheric height for the photosphere and the penumbral region. In the penumbra the observed profile originates from the deeper layer compared to the photosphere and hence the reduction in the field strength in the photosphere (Montesinos and Thomas, 1997). In the case of a bi-polar region, the observed height on the atmosphere will be approximately same if the field strength of these two regions are similar.

From the Table 5.2, the flow seems to be from the negative polarity to the positive polarity and from Figure 5.5 and 5.6, it can be seen that the field strength in the negative polarity is less than the field strength in the positive polarity around the neutral line by about 300 Gauss. Hence, the derived flows well matches with the predicted siphon flow (flow from the lower field strength to the higher field strength). However, to map the flow over the observed region, a high resolution Stokes polarimetry is needed. The flow speed derived about the neutral line is 1 to 1.5 km/sec.
Table 5.3: Results from the fit of the composite profile for V-profiles taken from eight positions around the neutral line

<table>
<thead>
<tr>
<th>Pixel number</th>
<th>fill fraction</th>
<th>Velocity (km/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>66</td>
<td>0.8</td>
<td>1.44</td>
</tr>
<tr>
<td>70</td>
<td>0.7</td>
<td>-0.48</td>
</tr>
<tr>
<td>72</td>
<td>0.6</td>
<td>-0.48</td>
</tr>
<tr>
<td>74</td>
<td>0.6</td>
<td>-1.44</td>
</tr>
<tr>
<td>76</td>
<td>0.5</td>
<td>-1.44</td>
</tr>
<tr>
<td>78</td>
<td>0.4</td>
<td>-0.48</td>
</tr>
<tr>
<td>80</td>
<td>0.3</td>
<td>-0.48</td>
</tr>
<tr>
<td>84</td>
<td>0.2</td>
<td>-0.48</td>
</tr>
</tbody>
</table>

5.7 Vector Field Map of NOAA 8951

The sunspot KKL 21551 (NOAA 8951) is observed on 13 April 2000 using the polarimeter and the CCD detector (Det-2) described in Chapter 3 of this thesis. The observational configuration is shown in Figure 5.8. The observational parameters are listed in Table 5.3. The instrumental polarisation is removed from the observed Stokes profiles using the continuum polarisation observation as it was done for the active region NOAA 8516 and explained in the last chapter. The corrected Stokes profiles are then inverted for the physical parameters in the observed region using the inversion code explained in section 5.4 of this chapter. Figure 5.9 shows the observed and fitted Stokes profiles at a point of the observed active region. Figure 5.10 shows the total field strength, LOS inclination and the azimuthal angle of the magnetic field derived using the code for a slit position which passes through the umbra portion of the active region NOAA 8951. The error bars marked in these figures are the errors
5.8 Conclusions

The ASP code used to invert the Stokes profiles from the Advanced Stokes Polarimeter data was modified to take the Stokes profiles input from the KTT polarimeter. The results from these inversion for the active region NOAA 8516 was discussed. The inversion code used cannot reproduce the asymmetries or peculiar profiles observed since the code uses the approximation that all the atmospheric parameters are constant in the line forming region and the source function is linear with optical depth. With the polarimetric accuracy at the KTT this approximation is good enough to pro-
Figure 5.8: The schematic view of the observational setup used for the vector field measurement of the active region NOAA 8951.

duce a vector field map of active regions and get an average magnetic field strength in these regions. However, with this accuracy we found that the V-measurement shows very peculiar profiles near a magnetic neutral line. We used a two magnetic component model rather than one magnetic and one non-magnetic component and fitted these peculiar profiles. These fittings gives us the LOS velocity present in those regions. The velocity flow in the bi-polar region of NOAA 8516 has been observed near the neutral line and it shows flows similar to siphon flow. The velocity of the flow calculated is around 1 - 1.5km/sec.

Even though the step size of the slit used was 2.75 arcsec, atleast three times poorer than what is needed for a high resolution vector field map, we produced a map for active region NOAA 8951 by using these inversion results. We used a linear interpolation to fill the vector field data between the slit positions. The map produced was reasonably good and can be used for a morphological studies with a resolution of about 5 arcsec. To conclude, the polarimeter and the inversion code works fine. The vector field mapping of sunspot is possible with the existing instrument as shown by the vector field map of a single spot near the disc center.
Table 5.4: Observational parameters of the spectrograph, the Stokes polarimeter and the active region NOAA 8951.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Range covered:</td>
<td>6296.50 to 6306.85Å</td>
</tr>
<tr>
<td>Spectral Resolution:</td>
<td>138 210 at 6302Å</td>
</tr>
<tr>
<td>Dispersion:</td>
<td>20.25mÅ per pixel</td>
</tr>
<tr>
<td>Spatial Scale:</td>
<td>0.121 arcsec per pixel</td>
</tr>
<tr>
<td>Slit Width:</td>
<td>0.55 arcsec</td>
</tr>
<tr>
<td>Step Width:</td>
<td>2.75 arcsec</td>
</tr>
<tr>
<td>Integration Time:</td>
<td>200 to 500 msec</td>
</tr>
<tr>
<td>First Mirror Position:</td>
<td>East</td>
</tr>
<tr>
<td>Date of Observation:</td>
<td>13 April 2000</td>
</tr>
<tr>
<td>Time in UT Hours:</td>
<td>02:30 Hrs.</td>
</tr>
<tr>
<td>Field of View:</td>
<td>52.25 × 68.0 arcsec²</td>
</tr>
<tr>
<td>Active region:</td>
<td>NOAA 8951</td>
</tr>
<tr>
<td>Position on the sun:</td>
<td>N17°E8°</td>
</tr>
</tbody>
</table>
Figure 5.9: The observed and fitted Stokes profile at a point in the active region NOAA 8951.
Figure 5.10: Plot of the parameters which specifies the vector magnetic field at a slit position which passes through the umbra of the sunspot. The top figure shows the field strength variation (as solid line), the dashed line is the plot of the intensity to show the position of the umbra or the minimum intensity region. The middle plot is the line of sight inclination and the bottom one is for the azimuthal angle. The error bars are the errors derived from the fit and the length is five times the error derived.
Figure 5.11: Vector field map of the observed region for the active region NOAA 8951. The vertical rectangular box shown in the figure corresponds to the slit and the width corresponds to the slit width used. The grey scale represents the longitudinal field strength and the arrows represent the transverse field strength. The contour map is the intensity contour of the observed region. The data points in between the slit positions were obtained using interpolation.