Chapter 4

Off-line Correction of Instrumental Polarisation

4.1 Summary

In this chapter, we present a model to calculate the Mueller matrix of the Kodaikanal tower telescope (KTT) in order to understand the polarisation properties of it. As already explained in Chapter 2, the model depends on the following three sets of parameters,

• The angle of incidence ('i') of the light on each of the three mirrors of the coolostat.

• The real ('η') and the imaginary ('κ') part of the refractive index of the aluminium coating on each mirror.

• The thickness ('t') of the oxide layer formed on the three aluminium coated mirrors assuming the value of the refractive index for the oxide layer as 1.77 (Lide, 1995)
4.2 Introduction

The angle of incidence, $i$, can be calculated precisely from the geometry of the KTT installation using spherical trigonometry. The model for the geometry of the KTT installation developed by Balasubramaniam, Venkatakrishnan and Bhattacharyya (1985), has been modified to include the initial reference co-ordinates on the sky plane. The modified model is very similar to the one developed for the Arcetri Solar Tower (Capitani et al., 1989). However, the model developed now for the KTT includes the oxide layer formed on the aluminium mirrors. The refractive indices of the mirror coatings and the oxide layer thicknesses are taken as the free parameters. To determine these free parameters, the model is fitted with the observed daily variation of the instrumental polarisation produced by the telescope and the polarimeter when it is illuminated by an unpolarised light.

Once these free parameters are estimated, the Mueller matrix of the KTT can be calculated and then be inverted from the observed Stokes profiles in order to get the unmodified profiles. The error in the estimated free parameters will introduce an error in the correction of the instrumental polarisation. These errors will generate a spurious polarisation signal in the corrected Stokes profiles. The maximum spurious polarisation signal in these corrected profiles are estimated to be about 0.5% in $Q$, 0.9% in $U$, and 0.2% in $V$.

Any oblique reflecting surface will change the polarisation state of the input beam. Hence the study and the measurement of the telescope instrumental polarisation is essential, particularly for the case of oblique reflecting telescopes like KTT. As discussed in Chapter 2, the complete Mueller matrix of the telescope can be obtained by measuring the refractive indices of the mirror coatings with the oxide layer thicknesses if the geometry of the telescope installation is known. An ellipsometric method is implemented at the KTT in order to measure the refractive indices of the three
mirror coatings and the thicknesses of the oxide layer formed on it (see Chapter 2 of this thesis and Sankararubramanian, K., Samson, J. P. A., and Venkatakrishnan, P., 1999 for details). The main result from the ellipsometric measurement is that the model for the reflecting mirrors of the coelostat should include the oxide layer formed on it in order to minimise the error in the inversion of the instrumental polarisation. It is practically difficult to do the ellipsometric measurement before or after each observations. Another method using the polarisation observation of unpolarised light is implemented in order to verify the ellipsometric measurement as well as the telescope model.

The principle of the method is simple. The continuum spectra at the disc center in the red wavelength region is practically unpolarised (< 0.01%, Fluri and Stenflo, 1999a; Fluri and Stenflo, 1999b). Hence the polarisation observed in the continuum is produced by the telescope and the associated instrument used for the polarisation measurement. If 'M' is the combined Mueller matrix of the KTT and the polarimeter, then the measured Stokes vector is given by,

\[ [I_p, Q_p, U_p, V_p]^T = M[I, 0, 0, 0]^T = [M_{11}, M_{21}, M_{31}, M_{41}]^T I. \] (4.1)

where the superscript 'T' represents a transpose operation. It is obvious from the above equation that the observed continuum polarisation at the disk center in the red wavelength is the first column of the combined Mueller matrix of KTT and the Stokes polarimeter. It will be shown in this chapter that the first column of this combined Mueller matrix is a function of the refractive indices of the three mirror coatings, the oxide layer thicknesses and the angles of incidence of the unpolarised light on the three mirrors. On any day, the observed continuum polarisation will change with time although the variation of the refractive indices and the thicknesses of the oxide layer is practically zero. The reason for this variation is that the angles of incidence on the three mirrors are different for different observing time. By fitting the observed polar-
4.3.1 Geometry of the coelostat system

Isation variation with time to that of the model, the free parameters, the refractive indices and the thicknesses of the oxide layer can be found out with the assumption that the model gives a very accurate value for the angles of incidence. Similar kind of measurements have already been developed for other telescopes, particularly for the Mc Math-Pierce Telescope (Bernosconi, 1997) and the Dunn Solar Telescope (Elmore et al., 1992).

4.3 Model for the KTT

The imaging system at the KTT is a three mirror coelostat system and an achromatic refractor (Bappu, 1967). The sunlight from the first mirror is reflected on to a secondary mirror which in turn reflects the light vertically down to a third mirror. The third mirror reflects the light horizontally on to a 38 cm lens which images the sun on to the slit of a Littrow mount spectrograph. The first mirror revolves around the polar axis with a frequency which can be set for the particular day of observation in order to compensate for the earth's rotation. The second mirror faces the first and the third mirror. This mirror can be moved in two axis in order to focus a particular region on the sun on to the slit of the spectrograph. The two axis of the second mirror can be controlled using a hand set which has both coarser and finer movement control switch.

The first mirror in turn can be moved along the earth's N-S direction for different declinations of the sun in order to reflect the sunlight on to the second mirror since the center of the second mirror is fixed. When the sun is at certain declinations, the mount of the second mirror can cast a shadow on the first mirror when the sun is around noon. This disadvantage is typical of this mounting and can be avoided by displacing the first mirror towards west.
4.3.1 Geometry of the coelostat system

The three mirrors of the coelostat system is projected on to the celestial sphere in order to calculate the angles of incidence of sunlight on each mirror. Consider a right handed, orthogonal co-ordinate system \((e_1, e_2, e_3)\) to be associated with each light beam with the unit vector \(e_3\) pointing along the ray direction. The polarisation properties of the beam is specified by the Stokes vector \([I, Q, U, V]^T\). The direction of \(e_1\) specifies the positive-Q direction.

Figure 4.1(a) shows the geometrical considerations of the KTT. \(C_1, C_2\) and \(C_3\) are the centers of first (M1), second (M2) and third mirror (M3), projected on to the celestial sphere, respectively. \(C_1\) is taken as the origin for the celestial sphere and \(C_2\) is the point where the direction joining M1 with M2 meets the celestial sphere. \(S\) is the position of the sun on the celestial sphere. \(N_1\) is the direction perpendicular to M1 and it lies on the celestial equator since M1 revolves around the polar axis. \(\phi\) is the latitude of KTT.

The geometric configuration given in Figure 4.1(a) corresponds to M1 displaced towards east during morning which is the usual configuration for the solar observations at KTT. However, some of the observations carried out for this thesis is taken with M1 placed in the west. Nevertheless, the model developed in this chapter can be used for both configurations.

Let \(I_s\) be the uncorrupted Stokes vector of light emerging from the sun, mainly due to the physical processes happening in the region of observation. Let \(I_s\) be defined in the right-handed reference system \((e_1, e_2, e_3)\), where \(e_3\) points towards \(C_1\) and \(e_1\) is tangent to the celestial meridian through the center of the sun and points towards the north celestial pole \(P\). Hence, the positive-Q is measured along the celestial meridian. The conversion from the celestial meridian to the heliospheric co-ordinates can be done using the data given in the Astronomical Almanac, through a rotation matrix with an angle \(\theta_0\), the angle between the direction of celestial meridian from the sun and the north pole direction of the sun. The angle \(\theta_0\) varies with the declination of
Figure 4.1: (a) The geometrical representation of KTT. The celestial sphere is centered on M1 (see text for details). (b) Spherical triangle PSN₁ is used for the calculation of the angles $\theta₁$ & $i₁$. (c) Spherical triangle PZC₂ is used to calculate the hour angle of M₂. (d) Spherical triangle SC₂N is used to calculate the angle $\theta₂$.

In order to evaluate how the polarisation changes in reflection on the first mirror, a preliminary rotation of the reference system ($\mathbf{e}_₁, \mathbf{e}_₂, \mathbf{e}_₃$) has to be performed. The rotation is done to bring the unit vector $\mathbf{e}_₁$ which corresponds to $+Q$ direction, to the incidence plane $SC₁C₂$. This can be done through a rotation around the unit vector $\mathbf{e}_₁$ of the angle $\theta₁$ as shown in Figure 4.1(a). The modified Stokes vector $I'ₙ$ after the
first mirror reflection is then given by,

\[ I'_s = M(i_1)R(\theta_1)I_s \]

where \( M(i_1) \) and \( R(\theta_1) \) are the reflection and rotation matrix defined by,

\[
[M] = \frac{1}{2} \begin{pmatrix}
1 + X^2 & 1 - X^2 & 0 & 0 \\
1 - X^2 & 1 + X^2 & 0 & 0 \\
0 & 0 & 2X \cos(\tau) & 2X \sin(\tau) \\
0 & 0 & -2X \sin(\tau) & 2X \cos(\tau)
\end{pmatrix}
\]

\[
[R] = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(2 \theta_1) & \sin(2 \theta_1) & 0 \\
0 & -\sin(2 \theta_1) & \cos(2 \theta_1) & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\]

where,

\[
\tan(\tau) = \frac{2 \sin(i_1) \tan(i_1)}{\sin^2 i_1 \tan^2 i_1 - (\alpha^2 + b^2)},
\]

\[
X^2 = \frac{a^2 + b^2 - 2a \sin(i_1) \tan(i_1) + \sin^2 i_1 \tan^2 i_1}{a^2 + b^2 + 2a \sin(i_1) \tan(i_1) + \sin^2 i_1 \tan^2 i_1},
\]

and,

\[
a^2 = \frac{1}{2} \left[ \eta^2 - \kappa^2 - \sin^2 i_1 + \sqrt{(\eta^2 - \kappa^2 - \sin^2 i_1)^2 + 4 \eta^2 \kappa^2} \right],
\]

\[
b^2 = \frac{1}{2} \left[ -\eta^2 + \kappa^2 + \sin^2 i_1 + \sqrt{(\eta^2 - \kappa^2 - \sin^2 i_1)^2 + 4 \eta^2 \kappa^2} \right].
\]

Here \( \eta \) and \( \kappa \) are the real and imaginary part of the refractive index of aluminium coating. Similarly, the Stokes vector after reflection from the second and third mirror is obtained using a rotation matrix with rotation angle \( \theta_2 \) & \( \theta_3 \) and a reflection matrix with an angle of incidence \( i_2 \) & \( i_3 \) respectively. Finally, the combined Mueller matrix of the three mirror coelostat system can be written as,

\[
I'_s = M I_s = R(\theta_1)M(i_1)R(\theta_3)M(i_2)R(\theta_2)M(i_1)R(\theta_1)I_s.
\]
Where \( I_s \) is the Stokes vector of the radiation falling on the input side of the polarimeter whose Mueller matrix is defined in Chapter 3. The polarisation effects due to the refractor present in the imaging system is not considered since it is a symmetric optics and will produce very little polarisation compared to the reflecting mirrors of the coelostat (atleast one to two order less, Chipman, 1995; Sanchez Almeida and Martinez Pillet, 1992). The rotation angles \( \theta_1, \theta_2, \theta_3 \) and the incidence angles \( i_1, i_2, i_3 \) can be calculated from the spherical trigonometry and is related to the position of the sun (declination \( \delta_\odot \), hour angle \( H_\odot \)) and the geometric parameters of the coelostat. The combined Mueller matrix will have sixteen non-zero elements and all of them will depend on \( i_1, i_2, i_3 \) & \( \eta, \kappa \). The inclusion of oxide layer will change the values of \( X^2 \) and \( \tau \) (Equations 4.2 and 4.3) as explained in Chapter 2. This new \( X^2 \) and \( \tau \) values, which includes the oxide layer are taken in this model instead of using Equations 4.2 and 4.3.

From the laws of reflection,

\[
i.e., \ C_2 \hat{C}_1 N_1 = \frac{1}{2} SC_1 C_2, \tag{4.5}
\]

the following relation can be derived,

\[
\delta_{C_2} = -\delta_{\odot}, \tag{4.6}
\]
\[
H_{N_1} = \frac{1}{2}(H_{C_2} + H_\odot). \tag{4.7}
\]

Where \( H \) and \( \delta \) denotes the hour angle and the declination respectively. The subscript \( C_2 \) and \( \odot \) represents the mirror M2 and the sun (i.e., \( H_{C_2} \) is the hour angle of M2 etc.).

From the spherical triangle \( PSN_1 \) (Figure 4.1(b)) and using the trigonometric sine and cosine relations the following equations can be derived,

\[
\sin(\theta_1) \sin(i_1) = -\sin(H), \tag{4.8}
\]
\[
\sin(i_1) \cos(\theta_1) = -\sin(\delta_\odot) \cos(H), \tag{4.9}
\]
\[
\cos(i_1) = \cos(\delta_\odot) \cos(H), \tag{4.10}
\]
where $H$ is the difference between hour angle of $N_1$ and that of sun,

$$i.e., \ H = H_{N_1} - H_{\odot}.$$

If $H_{C_2}$ is the hour angle of $M_2$ then,

$$H_{C_2} = H_{\odot} + 2(H_{N_1} - H_{\odot}).$$

From the above two equations, the relation for $H$ will be,

$$H = \frac{1}{2}(H_{C_2} - H_{\odot}). \quad (4.11)$$

From Equations 4.8, 4.9 and 4.10, the following relation can be derived,

$$\sin(2\theta_1) = \frac{2 \sin(\delta_{\odot}) \sin(H) \cos(H)}{\sin^2(H) + \sin^2(\delta_{\odot}) \cos^2(H)}, \quad (4.12)$$

$$\cos(2\theta_1) = \frac{\sin^2(\delta_{\odot}) \cos^2(H) - \sin^2(H)}{\sin^2(H) + \sin^2(\delta_{\odot}) \cos^2(H)}. \quad (4.13)$$

The set of Equations 4.8, 4.9, 4.10 and 4.12, 4.13 allows the calculation of Mueller matrix $M_1 (M(i_1))$ and rotation matrix $R(\theta_1)$ for the first mirror. However, the value of $H$ which is related to hour angle of the sun and that of $M_2$, is needed. Looking at the triangle $PZC_2$ (Figure 4.2(c)), the hour angle of $M_2$ can be obtained using trigonometric relations and is given by,

$$\sin(H_{C_2}) = \frac{\cos(h_{C_2}) \sin(A_{C_2})}{\cos(\delta_{\odot})}, \quad (4.14)$$

$$\cos(H_{C_2}) = \frac{\sin(h_{C_2}) + \sin(\phi) \sin(\delta_{\odot})}{\cos(\phi) \cos(\delta_{\odot})}, \quad (4.15)$$

where $h_{C_2}$ and $A_{C_2}$ are the altitude and azimuth of the second mirror of KTT. The altitude and azimuth of $M_2$ can be derived using Figure 4.2 and is given below.

$$\cos(h_{C_2}) = \frac{\sqrt{a^2 + b^2}}{\sqrt{a^2 + b^2 + c^2}}, \quad (4.16)$$

$$\sin(h_{C_2}) = \frac{c}{\sqrt{a^2 + b^2 + c^2}}, \quad (4.17)$$

$$\cos(A_{C_2}) = \frac{b}{\sqrt{a^2 + b^2}}, \quad (4.18)$$

$$\sin(A_{C_2}) = \frac{a}{\sqrt{a^2 + b^2}}, \quad (4.19)$$
where ‘a’ and ‘b’ are the distances from the center of M1 to that of M2 measured along the east and south respectively. In figure 4.2, M1 is kept towards east of M2. The sign of ‘a’ is positive if M1 is in east and negative if it is in west. The height from the center of M1 to that of M2 is represented as ‘c’. In practice, the value of ‘c’ and ‘a’ is fixed at once. The day to day variation of the declination of sun is reflected in the value of ‘b’. For a given declination, the value of ‘b’ is unique so that the light from the first mirror is always reflected into the second mirror. The value of ‘b’ can be calculated by knowing the declination of sun and the latitude of the place and is given by (Balasubramaniam, Venkatakriahnan, and Bhattacharyya (1985)),

$$b = r_2 \tan(\beta).$$

Where,

$$\beta = A + \sin^{-1}\left(\frac{\delta_\odot}{B}\right),$$

$$A = \tan^{-1}\left(\frac{c}{a} \tan(\phi)\right),$$

$$= (\cos^2(\phi) + \sin^2(\phi)(\frac{c}{a})^2),$$

$$r_2 = (a^2 + c^2)^{1/2}$$

The angle of incidence at the second mirror can be obtained from the triangle $C_1C_2V$ as,

$$i_2 = \frac{1}{2}(90^\circ - h_{C_2}) \quad (4.20)$$

The spherical triangle $SC_2N$ (Figure 4.1(d)) will give the rotation angle $\theta_2$,

$$\sin(\theta_2) = -\frac{\cos(h_\odot) \sin(A)}{\sin(2i_1)} \quad (4.21)$$

$$\cos(\theta_2) = \frac{\sin(h_{C_2}) \cos(2i_1) - \sin(h_\odot)}{\cos(h_{C_2}) \sin(2i_1)} \quad (4.22)$$

where $h_\odot$ and $h_{C_2}$ denotes the altitude of the sun and the mirror, M2 respectively. ‘A’ is the difference between the azimuth of M2 and that of the sun. From Equations
4.3.1: Geometry of the coelostat system

Figure 4.2: The geometrical representation of first two mirrors of the coelostat system (represented as $C_1$ and $C_2$). The azimuth and altitude of the second mirror can be calculated from this configuration as described in the text. The values of $a$, $b$, and $c$ are measured for the KTT installation and used in the calculation of the instrumental polarisation.

4.20, 4.21 and 4.22, the reflection and the rotation Mueller matrix for $M2$ can be obtained.

For $M3$, the angle of incidence is fixed at $45^\circ$ and the rotation angle $\theta_3$ is given by,

$$\theta_3 = 360^\circ - A_{C_3}$$

(4.23)

These two angles are used to find the reflection and the rotation Mueller matrix of $M3$. The altitude and azimuth of sun can be obtained from its declination and
hour angle. These relations are given by (Green, 1984),

\[
\begin{align*}
\cos(h_\odot) \sin(A_\odot) &= \sin(H_\odot) \cos(\delta_\odot) \\
\cos(h_\odot) \cos(A_\odot) &= \cos(\delta_\odot) \cos(H_\odot) \sin(\phi) - \sin(\delta_\odot) \cos(\phi) \\
\sin(h_\odot) &= \cos(\delta_\odot) \cos(H_\odot) \cos(\phi) + \sin(\delta_\odot) \sin(\phi)
\end{align*}
\]

(4.24) (4.25) (4.26)

The rotation angle \(\theta_4\) is fixed at 45° since the +Q is measured at 45° from the slit direction.

4.3.2 Elements of the Mueller matrix

The complete Mueller matrix ‘M’ of the system can be obtained using Equation 4.4 by calculating the values of angles of incidence and rotation angle of the plane of reflections. In order to understand the variation of the elements of this combined Mueller matrix, ‘M’, the values of each element are calculated at different hour angle of the source. These variations are plotted in Figures 4.3 to 4.5. These values are calculated for the day, 16 April 1999. The first mirror was kept in west and hence the value of ‘a’ is negative. The values for a and c are measured for actual positions of the coelostat mounting and is given in the figure caption. In Figure 4.3, variations of the diagonal elements of the Mueller matrix is plotted. These diagonal elements represent the efficiency of the coelostat system to the input polarised light. Even a 100% input polarised light will be detected as 75% because of these reflections. The variation of these efficiency values over half day of observations is about 0.5%.

Figure 4.4 shows some of the off-diagonal elements which is responsible for the cross-talk from the intensity to the polarisation and vice versa, i.e., these elements represent the polarisation and depolarisation produced by KTT. The critical parameters for us is the talk from I to Q, U and V, since the value of I will be atleast an order of magnitude more than that of Q, U and V for a typical measurement of sunspot magnetic field. The talk from I to the linear components Q and U has a typical value of few percent and the variation of these parameters within half day of observation
4.3.2: Elements of the Mueller matrix

Figure 4.3: The diagonal elements of the Mueller matrix of KTT installation at different hour angle on 16 April 1999. These elements show the efficiency of the instrument to input polarised light and which changes very little with time for that particular day. The values of the positions of M1 are, \( a = -83 \) cm, \( c = 74 \) cm (see text for the details of \( a \) and \( c \))

is also few percent. This is the main reason for calculating the complete Mueller matrix at the particular time of observation, otherwise the inversion of these matrices will have few percent residual error left. However, the talk from I to the circular component V is an order less than that of the linear component which makes the longitudinal magnetic field measurement more accurate than the transverse magnetic field. The main conclusion from Figure 4.4 is that even if the input is unpolarised the coelostat produces linear polarisation of few percent and circular polarisation of about fraction of a percent. If the instantaneous Mueller matrix is not known at the
Figure 4.4: The cross-talk (off diagonal) elements of the Mueller matrix of KTT installation at different hour angle on the same day as in Figure 4.3. These elements give the talk from I to Q, U, V and vice versa time of observation and if the inversion is carried out with a Mueller matrix calculated at different time, then the residual error in the inversion will be of few percent.

Figure 4.5 visualises the cross-talk between different states of polarisation. Physically this represents the change in the form of elliptically polarised input to an elliptically polarised output with different ellipticity and orientation. In these plots, the cross-talk varies from few percent to few tens. The major source of cross-talk is from circular to the linear and vice versa. These cross-talk too varies about a few percent within half day of observations.
4.4 Measurement & Elimination of Telescope Instrumental Polarisation

In order to test the model in actual observational geometry, the telescope instrumental polarisation is measured by illuminating the telescope with unpolarised light. It is well known that the continuum spectra at disk center of the sun in longer wavelength region is practically unpolarised (Fluri and Stenflo, 1999a). So, the observations are carried out at disk center of the sun around the wavelength 6302Å which is the spectral region of interest for the actual polarisation measurement of sunspot. These observations are carried out during the afternoon of 16 April 1999. About 22
polarisation observations are carried out at different hour a.

Figure 4.6: The schematic diagram of the optical setup used for the observations.

Figure 4.6 shows a schematic diagram of the observational setup used. The converging beam from the telescope is passed through the polarimeter described in Chapter 3 of this thesis. The image plane of the telescope is the slit plane of the spectrograph. A portion of the sun's image is sent through the slit and dispersed using a grating. The spectrum is imaged onto the CCD chip. A portion of the disk center of the sun is used for the measurement of the instrumental polarisation. A region which does not show any activity is chosen so that the polarisation produced at the sun will be very minimum. Figure 4.7 shows the plot of the continuum polarisation variation with local hour angle. The error bars shown are the rms variation of these continuum polarisation values. These are calculated by taking a region of interest containing the continuum wavelength and spatial position. The data points are obtained by taking the mean values of the polarisation in this region. The Mueller matrix derived from the model explained above and the Mueller matrix of the Stokes polarimeter discussed in Chapter 3, is combined to get the overall Mueller matrix of the system. This when combined with the input unpolarised light gives the theoretically expected
continuum polarisation shown as solid line in Figure 4.7. The free parameters used to fit the data with the model, are the real and imaginary part of the refractive indices of the three mirrors of KTT and the thicknesses of the oxide layer formed on these three mirrors. The best fit for the observed continuum polarisation variation will give the optimised value for these free parameters. The free parameters derived from the best fit are, $\eta = 1.31$, $\kappa = 7.80$ and $t = 0.0$ for all the three mirrors. These observations are carried out just after the realuminisation of all the mirrors and hence we do not expect any formidable oxide layer formed on these mirrors. The value for the refractive index derived matched well with bulk aluminium value. However, the accuracies of these derived values are about few percent since the error bars in these data points are about a percent. These can be improved in the future by improving the polarimetric accuracy.

Since the fit is not exact, the rms deviation will produce a residual error in the calculation of the theoretical Mueller matrix. These residual errors can be found out from the inaccuracies in the fitted parameters. Matrix $\Delta M$ given below shows the calculated maximum residual error in the elements of Mueller matrix which when multiplied with uncorrupted Stokes parameters will give the spurious Stokes profiles produced because of these inaccuracies.

$$
\begin{pmatrix}
0.0500 & 0.0040 & 0.0030 & 0.0005 \\
0.0030 & 0.0015 & 0.0040 & 0.0100 \\
0.0040 & 0.0500 & 0.0030 & 0.0050 \\
0.0006 & 0.0050 & 0.0100 & 0.0050
\end{pmatrix}
$$

By assuming three different cases with case(i) as $Q = 0$, $U = 0$ & $V = 20\%$, case(ii) as $Q = 10\%$, $U = 0$ & $V = 0$ and case(iii) as $Q = 0$, $U = 10\%$ & $V = 0$, the maximum residual errors in the inverted Stokes profiles are calculated. Table 4.1 shows a comparison between the maximum amplitude of spurious Stokes profiles produced without and with instrumental polarisation correction.
Figure 4.7: The measured polarisation at disk center in the continuum for different observing time given in Indian Standard Time (IST). The asterisk symbol is for Q/I, diamond is for U/I and triangle is for V/I. The solid line is the best-fit model. The refractive index calculated matches well with bulk aluminium value.

Figure 4.8 shows a typical Stokes profiles at a spatial position on the disk center of the sun after correcting for the instrumental polarisation. The rms noise level in Q/I, U/I and V/I Stokes profiles are 0.27%, 0.35% and 0.16% respectively. Figure 4.8 shows only the noise level and there is no Stokes profile signal present as expected since the observations were carried out at a position where visually no magnetic activity was found.
4.5 Observations of an active region

Table 4.1: Comparison of the maximum amplitude of spurious Stokes profiles

<table>
<thead>
<tr>
<th>Polarisation</th>
<th>Without Instrumental Polarisation Correction</th>
<th>With Instrumental Polarisation Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>5.4%</td>
<td>0.5%</td>
</tr>
<tr>
<td>U</td>
<td>3.6%</td>
<td>0.9%</td>
</tr>
<tr>
<td>V</td>
<td>2.8%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

4.5 Observations of an active region

The observations of an active region sunspot KKL 21263 (NOAA 8516) are carried out at the KTT with the Stokes polarimeter and a Littrow mount spectrograph described in Chapter 3 of this thesis. The observations are done in the morning of 16 April 1999 from 9 hrs to 12 hrs Indian Standard Time (i.e., UT hours 3:30 to 6:30). Stokes profiles for the well known lines Fe I 6301.5 Å and Fe I 6302.5 Å are recorded. The optical setup used to record these profiles is similar to the one used to record the instrumental polarisation for the continuum wavelength (Figure 4.6). The slit width used is 100 μ (0.55 arcsec). The dispersion of the spectrograph is 10.1 mÅ per pixel in the second order and the spectral resolution is of 46 mÅ which gives a spectral resolving power (λ/Δλ) of about 137000. The spatial region covered along the slit direction is about 19 arcsec.

The sunspot is mapped by stepping the image in steps of 5.5 arcsec using the finer movement control of the second mirror. This resolution for the scanning is not good enough to do a mapping of the active region for its full magnetic field configuration. Due to the unavailability of a tracking system, a slit jaw picture and a proper calibration of the image motion, it is not possible to go for a stepping better than 1 arcsec. Currently, a step of 2.75 arcsec (0.5 mm in the image plane) is achieved.
Figure 4.8: A typical Stokes spectral profiles at a spatial position on the disk center of the sun. The rms noise level in the Q/I, U/I and V/I Stokes polarisation profiles are 0.27%, 0.35% and 0.16% respectively using a scale fixed in the image plane with a least count of 0.5 mm. This scanning is done manually. However, step size of better than 1 arcsec is needed to get the full high resolution (about an arcsec) mapping of active regions. This should be possible in the near future with a slit jaw picture and a spot tracker. The tracking errors for the observations carried out for this thesis is found to be within 1-2 arcsec. However, since the measurements are done using fast chopping, the spurious polarisation signal produced because of this tracking errors will be minimum.

The first mirror was kept in the west during these measurements. Dark, bias and flat-field frames are taken before and after the observations of the sunspot in order to calibrate the CCD for its DC-offset and the pixel to pixel response variations.
4.5.1 Data reduction

The recorded full Stokes profiles of the sunspot KKL 21263 (NOAA 8516) located at N18°E55° are corrected for the dark and bias. The flat field frame is recorded at disk center of the sun without changing any optical configuration. About five flat field frames are taken to make a master flat. The five flat field frames are added together and the master flat is obtained by dividing each row of this added frames with the row averaged spectra in order to remove the spectral lines present in it. The average of the five frames removes most of the spectral line shifts produced by the five minute oscillation present. Finally, the resultant frame is normalised to get a master flat which was then divided from the observed spectra. Similar procedure is done for all the six observations for a single slit position (i.e., \( I \pm Q, I \pm U \) & \( I \pm V \)). All the spectro-polarimetric measurements of a region are done with the same pixel and hence the flat field errors will be eliminated in the parameters \( Q/I, U/I \) and \( V/I \).

Figure 4.9 shows a composite intensity picture obtained by choosing a continuum region and combining all the slit & spatial positions. It can be seen that the 5.5 arcsec (a resolution of 11 arcsec) stepping cannot produce a good intensity map of the region. However, in order to get a feel for the region of observation, spectro-polarimetric data obtained with Mees Solar Observatory (MSO) is compared with our observations (Thanks to Prof. Richard Canfield and Prof. Barry LaBonte for the data). The MSO data is obtained on 16 April 1999 during UT hours 16:42 to 18:54 which is 13 hours after our observation. Figure 4.10 shows the intensity map of the region which was observed at MSO. At KTT, before each spectro-polarimetric observation a sketch of the full region with the initial slit position is obtained. This sketch and the intensity image from the MSO is matched to calculate and correct for the rotation between these two images. After the rotation correction is done, the initial and the other slit positions are drawn on the intensity image from the MSO in order to understand the region of observation. In Figure 4.11, the vertical line marked as ‘1’ is the initial slit position of the scanning. The direction of the scan is given as increasing order of the
Figure 4.9: Composite intensity image of the sunspot KKL 21263 (NOAA 8516). The image is obtained by combining all the slit and the spatial positions of the region of observations. The scan step used is 5.5 arcsec. The step size along the x-direction is 5.5 arcsec and the y-direction is limited by seeing slit position (i.e., from 2 to 10). Each slit position is separated by 1 mm in the image plane (5.5 arcsec). The width of the rectangular box marked corresponds to the slit width used for the observation (0.55 arcsec).

The dark, bias and flat field corrected frames are in turn corrected for the instrumental polarisation. The Mueller matrix of KTT is calculated for the time of observation of the Stokes profiles with the refractive index values calculated from the last section. The inverse of this Mueller matrix is multiplied with the observed Stokes profiles in order to get the unmodified profiles. The accuracies in this inversion are 0.5% in Q, 0.9% in U and 0.2% in V. Figure 4.12 shows a typical observed Stokes profiles of a region in the sunspot observed after correcting for the instrumental polarisation.
Figure 4.10: Intensity image of the active region sunspot NOAA 8516 (AR 8516) taken with the Stokes polarimeter of the Mees Solar Observatory. This data is obtained from the MSO (Prof. Barry LaBonte and Prof. Richard Canfield) for comparison with our Spectro polarimetric data. The step size along x-direction is 2.828 arcsec and along y-direction is 2.828 arcsec.

### 4.6 Conclusions

In this chapter, the model for the KTT installation has been developed by modifying the model given by Balasubramaniam, Venkatakrishnan, and Bhattacharyya (1985) to include the initial rotation plane from the solar co-ordinates to celestial co-ordinate. The model developed with the above said modification is very similar to the model developed for the Arcetri solar tower telescope (Capitani et al., 1989). The daily variation of the instrumental polarisation was measured and fitted with the model developed. The free parameters, the real, imaginary part of the refractive indices of the three mirrors of KTT and the thicknesses of the oxide layer on these three mirrors,
Figure 4.11: Intensity image of the active region sunspot NOAA 8516 (AR 8516) taken with the Stokes polarimeter of the Mees Solar Observatory. The slit positions which are used to take the Stokes profile at the KTT is given. The initial slit position is marked as ‘1’ and the slit is stepped for every 5.5 arcsec and is marked in the figure as increasing number (from 2 to 8).

are found out from the best fit. These three best fit parameters are then used to calculate the Mueller matrix of the coelostat of KTT at any observing time on that day. The inverse of the Mueller matrix is then multiplied with the observed Stokes profiles of an active region (NOAA 8516) in order to get the unmodified Stokes profiles. The uncertainty in the free parameters found out from the fit is used to calculate the spurious polarisation signal produced after the inversion for the instrumental polarisation. It was found that the uncertainty is 0.5% in Q, 0.9% in U and 0.2% in V.
Figure 4.12: A typical Stokes spectral profiles at a spatial position on the sunspot KKL 21263 (NOAA 8516) after correcting for the instrumental polarisation. The accuracies of this inversion are 0.5% in Q, 0.9% in U and 0.2% in V.