JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
32: 65 ~ 73, 1999

CALIBRATION OF VECTOR MAGNETOGRAMS BY SOLAR FLARE TELESCOPE OF BOAO

YONG-JAE MOON[1,2], YOUNG DEUK PARK[1], AND HONG SIK YUN[2]
[1]Bohyunsan Optical Astronomical Observatory, Korea Astronomy Observatory, Kyungpook 770-820
[2]Department of Astronomy, Seoul National University, Seoul 151-742
(Received Mar. 16, 1999; Accepted Apr. 15, 1999)

ABSTRACT

In this study we present a new improved nonlinear calibration method for vector magnetograms made by the Solar Flare Telescope of BOAO. To identify Fe I 6302.5 line, we have scanned monochromatic images of the line integrated over filter passband, changing the location of the central transmission wavelength of a Lyot filter. Then we obtained a filter-convolved line profile, which is in good agreement with spectral atlas data provided by the Sacramento Peak Solar Observatory. The line profile has been used to derive calibration coefficients of longitudinal and transverse fields, employing the conventional line slope method under the weak field approximation. Our improved nonlinear calibration method has also been used to calculate theoretical Stokes polarization signals with various angles of inclination of magnetic fields. For its numerical test, we have compared input magnetic fields with the calibrated ones, which have been derived from the new improved non-linear method and the conventional method respectively. The numerical test shows that the calibrated fields obtained from the improved method are consistent with the input fields, but not with those from the conventional method. Finally, we applied our new improved method to a dipole model which characterizes a typical field configuration of a single, round sunspot. It is noted that the conventional method remarkably underestimates the transverse field component near the inner penumbra.

Key Words : Sun : magnetic fields – Sun : vector magnetogram – Sun : calibration

I. INTRODUCTION

It is generally believed that solar magnetic fields play a significant role in activating dynamical phenomena in active regions. Thus accurate measurements of solar magnetic fields are of key importance for the understanding of the solar activity (e.g. Hagyard et al. 1984). In general, there are two types (filter-based and spectrometer-based) of vector magnetographs widely in use for solar magnetic observations. Their advantages and disadvantages are well reviewed by Lites et al.(1994) and Zirin(1995).

A filter-based vector magnetograph(VMG) is attached to the Solar Flare Telescope (SOFT, Moon et al. 1996, Park et al. 1997) at Bohyunsan Optical Astronomy Observatory (BOAO), which uses a very narrow band Lyot filter and KD*P crystals for polarimetric observations. The Stokes parameters are measured by collecting spectrally integrated data over the filter passband. It has very high time resolution which is less than 1 minute with relatively large field of view (400″ × 300″). Magnetograms obtained by filter-magnetographs are subject to uncertainty due to instrumental and atmospheric effects (Chae 1996). To convert Stokes images to vector fields, we have to know some calibrations which relate the Stokes images to magnetic fields. The calibrations for filter-based magnetographs such as SOFT have often been derived by the line slope method(Landi Degl'Innocenti 1992, Varsik 1995) based on the weak field approximation (Jefferies & Mickey 1991) and by using non-linear calibration curves obtained from theoretical atmospheric models (Hagyard et al. 1988, Sakurai et al. 1995, Cho & Kim 1995, Kim 1997).

The longitudinal and transverse field components are then independently expressed as

$$B_L = K_L \frac{V}{I} \tag{1}$$

$$B_T = K_T [\frac{Q^2 + U^2}{I^2}]^{1/4}, \tag{2}$$

where K_L and K_T are calibration coefficients.

The line slope method under the weak field approximation is to derive magnetic field vector by calculating line slopes at various off-centered positions of an observed line profile. In this case, the field strengths of the two magnetic components can be derived simply by multiplying the Stokes parameters by the corresponding calibration coefficient. This method is relatively simple, but it does not hold for fields stronger than $3500/g_L$ Gauss, where g_L is the Lande g factor(See Jefferies & Mickey 1991). The non-linear calibrations are obtained by solving a set of Stokes radiative transfer equations for the solar atmosphere permeated by uniform magnetic fields. This method can be applied to non-linear regimes between Stokes polarization signals and their corresponding vector field, but it depends on the model atmosphere under consideration and other physical conditions (Ichimoto et al. 1993, Kim 1997).

As seen from equations (1) and (2), the conventional calibration for the longitudinal field is obtained by taking the angle of inclination angle $\gamma = 0^\circ$, while the calibration for the transverse field, by taking $\gamma = 90^\circ$. The resulting calibration depends on the field strength and the angle of inclination. Accordingly, the longitudinal and transverse fields can not be derived entirely independently. Recently, Hagyard & Kineke (1995) developed an iterative method for the non-linear calibration by combining circular and linear polarization signals with different inclination angles, and applied the method to the case of Fe I 5250.22 line. They showed that the non-linear method can increase the calibration accuracy.

In the present study we introduce an improved non-linear calibration method and describe how magnetic field strengths can be obtained from the improved method. In Section II, we determine the calibration coefficients of longitudinal and transverse fields by the line slope method. In Section III, we present an improved iterative non-linear calibration method with its numerical test. Finally, a brief summary and discussion will be given in Section IV.

II. CALIBRATION COEFFICIENTS BY THE LINE SLOPE METHOD

(a) Line Slope Method

When the magnetic field is relatively weak throughout the atmosphere over which the spectral line is formed, it is possible to treat the magnetic field as a perturbation, which results in a simple relation between magnetic fields and Stokes parameters. According to Jefferies & Mickey(1991), the weak field approximation can be applied to an accuracy of 20% for fields as strong as $3500/g_L$ Gauss.

In the limit of the weak field approximation, the Stokes V parameter is given by (Landi Degl'Innocenti 1992)

$$V/I = -\mu B_L \frac{dlnI}{d\lambda}, \qquad (3)$$

where B_L is the longitudinal magnetic field and μ is the magnetic moment of transition for a spectral line :

$$\mu = \frac{e\lambda^2 g_L}{4\pi mc^2} = 4.67 \times 10^{-13} g_L \lambda^2, \qquad (4)$$

where λ is the wavelength of the line center in Å. To derive the magnetic field strength from equation (3), we have to know Stokes ratio V/I and the slope of the intensity profile.

For this study, let us define observational signals as follows:

$$I_{obs} = I * P(\lambda - \lambda_1), \quad V_{obs} = V * P(\lambda - \lambda_1), \qquad (5)$$

where $P(\lambda - \lambda_1)$ is a response function of VMG Lyot filter at an off-center(λ_1) of Fe I 6302.5 spectral line. The observational signal S_L for longitudinal field is given by

$$S_L = \frac{V_{obs}}{I_{obs}} = -\mu B_L \frac{dI/d\lambda * P}{I * P} = \frac{V(\lambda_1)}{\varepsilon_1(\lambda_1) I(\lambda_1)}, \qquad (6)$$

where $\varepsilon_1(\lambda_1)$ is a coefficient relating the observational signal S_L to V/I :

$$\varepsilon_1(\lambda_1) = \frac{I * P}{dI/d\lambda * P} \frac{dlnI}{d\lambda}. \qquad (7)$$

Finally, the longitudinal magnetic field is given by

$$B_L = K_L S_L \qquad (8)$$

where K_L is a calibration coefficient for longitudinal magnetic field :

$$K_L = -\varepsilon_1(\lambda_1)(\frac{d\lambda}{dlnI})/\mu. \qquad (9)$$

Under the weak field approximation, the total linear polarization can be approximated as (Jefferies & Mickey 1991)

$$\sqrt{Q^2 + U^2} = (\frac{\mu B_T}{2})^2 (\frac{dI}{d\lambda})(\frac{H''(a,v)}{H'(a,v)}), \qquad (10)$$

where $H(a,v)$ is the Voigt profile which is a function of the damping constant a and the dimensionless variable $v = \Delta\lambda/\lambda_D$. In order to relate $L = \sqrt{(Q^2 + U^2)/I^2}$ to the observational signal S_T, we introduce a simple coefficient ε_2 given by

$$L = \varepsilon_2(\lambda_1) S_T = \varepsilon_2(\lambda_1) \frac{\sqrt{(Q * P)^2 + (U * P)^2}}{I * P}. \qquad (11)$$

Then we can get

$$B_T = K_T \sqrt{S_T}, \qquad (12)$$

where K_T is a calibration coefficient for transverse field given by

$$K_T = \sqrt{\frac{4K_L\varepsilon_2}{\mu\varepsilon_1}} \sqrt{\frac{H'(a,v)}{H''(a,v)}}. \qquad (13)$$

For numerical calculations, Jefferies & Mickey (1991) introduced a frequency factor given by

$$G(a,v) = vH''(a,v)/H'(a,v). \qquad (14)$$

Using this frequency factor, the coefficient K_T can be expressed as

$$K_T = \sqrt{\frac{4K_L\varepsilon_2\Delta\lambda}{G(a,v)\varepsilon_1\mu}}. \qquad (15)$$

where $\Delta\lambda$ is the difference between an off-centered position and the line center. According to the numerical calculation of $G(a,v)$ for a and v (Jefferies & Mickey 1991), its value is found to be ~ 3 for line wings satisfied with $v \geq 2$ for most of the solar spectra ($a = 0.5$). In this study $G(a,v)$ is taken from Jefferies & Mickey(1991). If we assume that $\sqrt{(Q * P)^2 + (U * P)^2}$ is equal to $\sqrt{Q^2 + U^2} * P$, the coefficient ε_2 becomes ε_1. Finally the calibration coefficient K_T is given by

$$K_T = \sqrt{\frac{4K_L\Delta\lambda}{G(a,v)\mu}}. \qquad (16)$$

(b) Determination of Calibration Coefficients

To derive the calibration coefficients of longitudinal and transverse fields, we have to know the intensity gradient over wavelength. The observed intensity is convolved by the filter response function together with some unknown other effects.

In the present study, first we made a line identification of Fe I 6302.5 line by changing the central transmission wavelength of the VMG Lyot filter. The central transmission wavelength is varied from $-1\AA$ to $1\AA$ so that we can measure the intensity profile over the wavelength. In observing the line profile, the field of view of VMG system was placed on the solar disk center by operating auto-tracking program in the control software (Moon et al. 1997) of the SOFT to minimize the effect of rotational broadening. Then the average has been taken after integrating every 16 frames to obtain a clean profile intensity, covering over 512 × 480pixels. The resulting intensity profile was obtained with a step size of $0.02\AA$. Figure 1 shows an intensity profile acquired from the VMG system on Oct. 10, 1998. We have compared the observed line profile with the profile in the solar spectral atlas of Beckers et al. (1976). They are found to be in good agreements if it is noted that the observed profile was filter-convolved.

Varsik (1995) made use of the line slope method to derive calibration coefficients of Ca I 6103 Å for BBSO(Big Bear Solar Observatory) magnetograph. In his work, he assumed the linear response system such that $I = \phi I_{obs}$, where ϕ is independent of wavelength. His assumption implies that the intensity gradient is equal to the observed one, that is, $d\lambda/dlnI = d\lambda/dlnI_{ob}$, i.e. $\varepsilon_1(\lambda_1) = 1$.

As a first step, we apply Varsik(1995)'s method to the observed profile. In order to minimize the observational error, we have fitted a line profile near the center of Fe I 6302.5 line to a Gaussian function and a quadratic polynomial :

$$I(x) = A_0 \exp(-(x-A_1)^2/A_2)+A_3+A_4x+A_5x^2. \quad (17)$$

From the fitted line profile, we measured the gradient of the logarithmic intensity at $-100m\AA$, $-80m\AA$, $-60m\AA$, $-40m\AA$ by taking intensities at $+0.01\AA$ and $-0.01\AA$ for each selected off-centered locations. Under the Varsik's assumption, we have derived the calibration coefficients with four different off-centered locations, which are listed in the first row of Table 1.

In general, the observed intensity profile is smoothed by various factors such as filter passband and other instrumental effects. Thus the response function may not be independent of wavelength. In this work we take into account the filter response effect on the calibration coefficients. The observed intensity can be expressed as

$$I_{ob}(\lambda_1) = I_{in} * P(\lambda - \lambda_1), \quad (18)$$

where $I_{in}(\lambda_1)$ is the incoming intensity just before the Lyot filter of VMG system. In the case of VMG, $P(\lambda -$

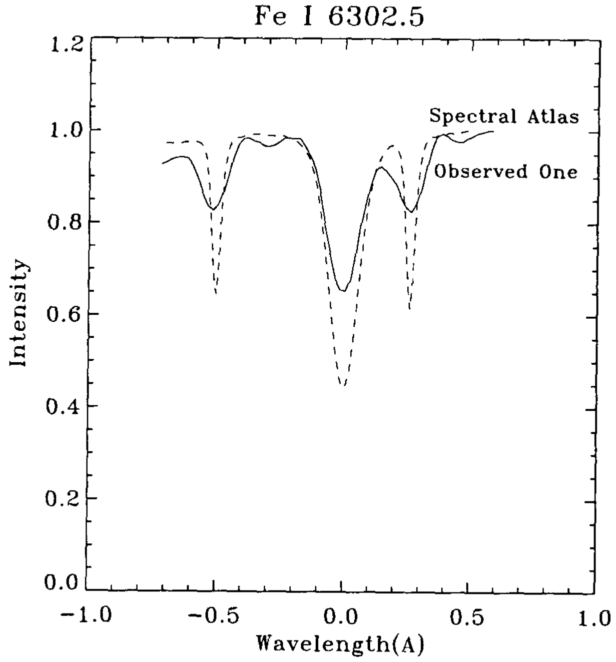

Fig. 1.— Comparison of observed Fe I 6302.5 profile and spectral atlas data provided by Sacramento Peak Solar Observatory. The observed profile was obtained by scanning monochromatic images of the line by varying the location of the the central transmission wavelength of the VMG Lyot filter.

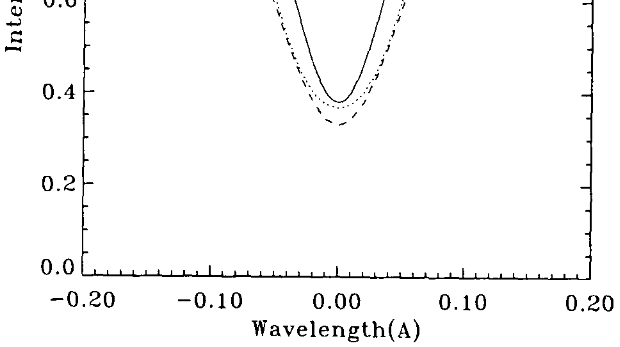

Fig. 2.— Comparison of the incoming intensity I_{in} deconvolved from the observed intensity profile with the considered two spectral line profiles. In the figure I_{qs} and I_{th} correspond to an observed spectral line profile of the quiet region (Lites et al. 1991) and a theoretically calculated profile(Ichimoto 1997), respectively.

Table 1. Calibration coefficients ($K_L : \times 10^4$) of longitudinal magnetic fields. The values in parentheses are $\varepsilon_1(\lambda_1)$

Profile	Off-center($m\AA$) -100	-80	-60	-40	Method	Data
I_{ob}	0.78	0.59	0.52	0.56	Varsik(1995)'s	SOFT
I_{in}	0.72(0.43)	0.56(1.01)	0.50(2.06)	0.55(3.86)	Present	SOFT
I_{qs}	0.50(0.98)	0.42(1.46)	0.39(2.10)	0.44(3.00)	Present	Lites et al.(1991)
I_{pen}	0.53(1.25)	0.48(1.51)	0.49(1.78)	0.58(2.05)	Present	Lites et al.(1993)
I_{sp}	0.61(1.04)	0.52(1.49)	0.50(2.06)	0.58(2.76)	Present	Beckers et al.(1976)
I_{th}	0.55(0.91)	0.45(1.42)	0.42(2.12)	0.47(3.10)	Present	Ichimoto(1997)

λ_1) is a response function of the VMG Lyot filter with FWHM=0.125$\AA$, which is approximated as a Gaussian profile given by

$$P(\lambda - \lambda_1) = \frac{1}{\sqrt{\pi}\beta} \exp(-(\lambda - \lambda_1)^2/\beta^2), \quad (19)$$

where β is $FWHM/2/\sqrt{ln2}$. This response profile was estimated for Fe I 6302.5 line by a spectrograph at NAIRC (Nanjing Astronomical Instruments Research Center). After taking a Fourier transform, the response function can be analytically described as

$$P(\sigma) = \exp(-(\pi\beta\sigma)^2), \quad (20)$$

since Fourier transform of a Gaussian profile results in another gaussian. Thus, the calculation of I_{in} can be analytically made so that it becomes free from high frequency noise. After some mathematical manipulations, the incoming intensity is given by

$$I_{in}(\lambda-\lambda_c) = A_3 + A_0\sqrt{\frac{A_2}{A_2 - \beta^2}} \exp(-(\lambda-\lambda_c)^2/(A_2-\beta^2)), \quad (21)$$

where λ_c is the central wavelength of Fe I 6302.5 line. In this calculation, the first and second order terms of equation (17) are neglected.

In order to measure the coefficient $\varepsilon_1(\lambda_1)$, we need a synthetic profile of V/I. In the present work, simply we made use of equation (3) by assuming an appropriate longitudinal magnetic field, e.g., B_L = 100Gauss. It is noted that under the weak field approximation the magnetic field strength does not affect the shape of the synthetic profile and the value of $\varepsilon_1(\lambda_1)$. By replacing I by I_{in} and substituting equation (21) into equation (3), we obtained a synthetic profile V/I over wavelength. Then, we tuned the filter passband to the considered off-centered positions to estimate the value of $\varepsilon_1(\lambda_1)$ given by equation (7). Finally, the calibration coefficients are calculated with the use of equation (16), which are tabulated in the second row of Table 1. The values in parentheses correspond to $\varepsilon_1(\lambda_1)$. As seen in the Table 1, our estimates are a little smaller than those given by the Varsik's method, demonstrating that the linear response assumption for the SOFT holds within an accuracy of 10 %.

To assess the incoming intensity of VMG system we consider four different line profiles. First, we choose a profile observed by Lites et al. (1991) with a spectral resolution of 25$m\AA$ and a spatial resolution approaching 0.3″. These data were obtained at the Swedish Vacuum Solar Telescope at La Palma, Canary Island under excellent seeing. The observed intensity profile I_{qs} can be approximated as

$$I_{qs} = 1 - r_0 \exp(-(\lambda - \lambda_1)^2/\beta^2), \quad (22)$$

where a central depression r_0 is 0.67 and a Gaussian width β is $0.12\AA/2/\sqrt{ln2}$. Secondly, we take an intensity profile I_{pen} observed at the penumbral spines of AR7111 by Lites et al.(1993) who made use of HAO/NSO Advance Stokes Polarimeter. This instrument yields highly accurate polarimetric measurement better than 10^{-3} in Stokes V/I, Q/I, U/I with a good spatial resolution less than 1″. The observed profile(the lowest figure in Fig. 8 of their paper) can be approximated by equation (22) with r_0=0.56 and $\beta = 0.13\AA/2/\sqrt{ln2}$. Thirdly, we make use of the spectral data obtained with the coelostat-horizontal Littrow spectrograph at the Sacramento Peak Observatory (Beckers et al. 1976). These data have a very good spectral resolution of 0.02$\AA$ and a fine sampling size 0.01$\AA$. They are all corrected for the effect of rotational broadening. The rotational broadening function (Beckers et al. 1976) is approximated as

$$R(\lambda) = (\lambda + \lambda_0)(\lambda - \lambda_0)/\lambda_0^2 \quad (23)$$

where λ_0 is $\lambda/168000\AA$. Finally, we select a theoretical line profile calculated by solving Stokes radiative transfer equations (Ichimoto 1997).

Figure 2 shows the comparison of the incoming intensity I_{in} deconvolved from the observed profile with the adopted two line profiles I_{qs} and I_{th}. As seen from the figure, the line profile of the incoming intensity is little narrower than other line profiles under consideration. Making use of these line profiles, we have also estimated calibration coefficients by calculating the intensity gradients at each selected off-centered locations as described above. The derived calibration coefficients are tabulated from the third to the sixth rows in Table 1.

The longitudinal calibration coefficient derived from the incoming intensity is about 20% larger than those from the four selected profiles, but it is thought to be meaningful in that it reflects the effect of observing system. The derived calibration coefficients from the four different profiles are very similar to one another and also in good agreement with the non-linear calibration curves generated from the theoretical Stokes profiles (Sakurai et al. 1995, Cho & Kim 1995). The calibration coefficients listed in Table 1 depend on the location of the off-centered position at which the VMG Lyot filter is tuned. The sensitivity of observed polarization signals should be inversely proportional to the corresponding calibration coefficients. Thus, the observed circular polarization signals for longitudinal fields should be peaked near $-60m\AA$.

We have also derived the calibration coefficients of transverse fields for five different cases, which are tabulated in Table 2. In the table, all the calibration coefficients are very similar to one another except for the case of $-40m\AA$. As seen from the table, the observed linear polarization signals for transverse fields should be peaked near $-80m\AA$, which is in agreement with Sakurai et al.(1995).

III. IMPROVEMENT OF NON-LINEAR CALIBRATIONS

In this section we present an improved non-linear iterative calibration method applicable for Fe I 6302.5 line, following Hagyard & Kineke (1995). For this work we made use of the model calculations made by Ichimoto (1997). He adopted the model atmosphere of Holweger & Muller (1974) with uniform magnetic fields with various field strengths. Then he generated the emergent Stokes profiles and deduced the polarization signals by integrating them over the filter passband under the LTE assumption. Finally he derived non-linear calibration curves which relate the Stokes polarization signals to the field strengths. As can be seen from Hagyard & Kineke(1995), the calibration curves depend on inclination angles. To examine the angle dependency, we plot the calibration curves of longitudinal and transverse fields estimated at an off-centered position of $-80m\AA$ in Figure 3, where three different angles of inclination are considered. As seen from the figure, the calibration curves with $\gamma = 30^o$ and $\gamma = 60^o$ deviate from the calibration curves with $\gamma = 0^o$ (upper panel) and $\gamma = 90^o$ (lower panel) more and more as the field strength increases.

(a) Calibration Method

Here we summarize how to calibrate vector magnetic fields from observed polarization signals. The iterative calibration method developed by Hagyard and Kineke (1995) makes use of the dependence of circular and linear polarization signals on magnetic field strength and its inclination angle. While Hagyard & Kineke (1995) uses sixth order polynomials to approximate the relations between polarization signals and magnetic fields, we use only the first three order terms, which give us sufficient accuracy for the present work.

(1) We obtain the observed polarization signals by using the solutions of Stokes radiative transfer equations (Ichimoto 1997) for $\gamma = 0^o$ and $\gamma = 90^o$ with the VMG filter response being taken into account. Then we take a first set of trial values of longitudinal and transverse fields to fit the following polynomials :

$$B_L^{(0)} = a_0 + a_1 S_L + a_2 S_L^2 + a_3 S_L^3 \qquad (24)$$

and

$$B_T^{(0)} = b_0 + b_1 S_T + b_2 S_T^2 + b_3 S_T^3, \qquad (25)$$

where S_L and S_T are circular and linear polarization signals convolved over the filter passband, respectively. The above equations correspond to a conventional calibration method given by equations (1) and (2) (Cho & Kim 1995, Ichimoto 1997).

(2) We compute the observed circular and linear polarization signals for a set of inclination angles $\gamma = 0^o$, 10^o, 20^o, ... , 90^o. Then the observed polarization signals are approximated as

$$S_L(\gamma) = c_0 + c_1 B + c_2 B^2 + c_3 B^3 \qquad (26)$$

and

$$\sqrt{S_T(\gamma)} = d_0 + d_1 B + d_2 B^2 + d_3 B^3. \qquad (27)$$

(3) By noting that the dependence of polarization signals on the inclination angle is given by equations (8) and (12), we estimate interpolated polarization signals by using

$$S_L^{(0)} = S_L(\gamma_2) + [S_L(\gamma_1) - S_L(\gamma_2)] \times [(cos\gamma_0 - cos\gamma_2)/(cos\gamma_1 - cos\gamma_2)] \qquad (28)$$

and

$$S_T^{(0)} = S_T(\gamma_1) + [S_T(\gamma_2) - S_T(\gamma_1)] \times [(sin^2\gamma_0 - sin^2\gamma_1)/(sin^2\gamma_2 - sin^2\gamma_1)], \qquad (29)$$

where $\gamma_0 = \text{atan}\,(B_T^{(0)}/B_L^{(0)})$ for $\gamma_1 \le \gamma_0 \le \gamma_2$. Here γ_1 and γ_2 are a couple of consecutive inclination angles.

(4) We calculate the variations δS_L, δS_T from the relations:

$$\delta S_L = S_L - S_L^{(0)},\ \delta S_T = S_T - S_T^{(0)}. \qquad (30)$$

(5) We derive corrected vector fields such as

$$B_L^{(1)} = B_L^{(0)} + \delta B_L,\ B_T^{(1)} = B_T^{(0)} + \delta B_T, \qquad (31)$$

Table 2. Calibration coefficients (K_T : $\times 10^4$) of transverse magnetic fields

Profile	Off-center($m\AA$) -100	-80	-60	-40	Method	Data
I_{ob}	0.42	0.37	0.42	0.80	Varsik(1995)'s	SOFT
I_{in}	0.42	0.36	0.42	0.78	Present	SOFT
I_{qs}	0.34	0.31	0.37	0.71	Present	Lites et al.(1991)
I_{pen}	0.35	0.33	0.41	0.82	Present	Lites et al.(1993)
I_{sp}	0.38	0.35	0.42	0.82	Present	Beckers et al.(1976)
I_{th}	0.36	0.32	0.38	0.74	Present	Ichimoto(1997)

where δB_L and δB_T are calculated from derivatives of equations (24) and (25). Equation (31) corresponds to the first set of corrections for the initial trial values. Then, the corrected vector fields $B_L^{(1)}$ and $B_T^{(1)}$ become a new set of trial values. The same process is repeated until the iterated values converge.

(b) Numerical test

For numerical tests of the present algorithm, we consider two kinds of magnetic field configurations to examine the difference between the present method and the conventional method ($B_L^{(0)}$ and $B_T^{(0)}$) given by equations (24) and (25).

(1) We considered input fields having fifteen different field strengths (100, 200, ... 1500 Gauss) with two inclination angles ($\gamma = 30^o, 60^o$). Then we have derived filter convolved polarization signals for each given set of input field strength and angle of inclination by using the solution of Stokes radiative equations (Ichimoto 1997) with the filter response being taken into account. Then we derive the calibrated magnetic fields by applying both the present method and the conventional method for the observed polarization signals. The calibrated fields are compared with the input fields as shown in Figures 4 and 5, where the dotted lines refer to the conventional method and the solid lines to the present one. As seen from the figures, the calibrated vector fields (solid lines) given by the present method are almost completely reduced to the input fields, but not by the conventional method (dotted lines). In particular, it is noted that the transverse fields for smaller inclination angles are considerably underestimated. Such deviation increases with the field strength.

(2) We consider Skumanich(1992)'s dipole fields to characterize the field configuration of a single round sunspot. The radial variation of the dipole field configuration is given by

$$B_L = \frac{1}{2} B_o \frac{(2-\alpha^2)}{(1+\alpha^2)^{5/2}} \tag{32}$$

and

$$B_T = \frac{3}{2} B_o \frac{\alpha}{(1+\alpha^2)^{5/2}} , \tag{33}$$

where B_o refers to the photospheric magnetic field strength at the sunspot center and α is a fractional radius of the sunspot (Moon et al. 1998). In the present study B_o in equations (32) and (33) is set to 2500 Gauss.

To avoid saturation effects for umbral magnetic fields (See Fig.3), we only consider field configurations of sunspot penumbra, larger than $r/R \geq 0.5$. Figure 6 shows the comparison of (1) the input field (solid line), (2) the field calculated by the conventional method (dashed line) and (3) the field by the present method (dotted line). The present method yields the field strength consistent with the input field, implying that our method works satisfactorily. Both of the calibration methods are in fairly good agreement with each other within 10 % for longitudinal fields, but not for transverse fields. It is interesting to note that the conventional method remarkably underestimates the transverse field in the inner penumbra.

IV. SUMMARY AND DISCUSSION

In this work we have developed calibration tools for vector magnetograms made by the SOFT. To assess the capability of the VMG Lyot filter, we scanned monochromatic images integrated over filter passband to obtain a line profile, varying the location of the central transmission wavelength of the Lyot filter. The calibration coefficients of longitudinal and transverse fields have been derived by using the line slope method in which the filter response effect is taken into account. We have also developed an improved iterative calibration method by using theoretical Stokes polarization signals calculated with various inclination angles of magnetic fields. Then we have made numerical tests by considering magnetic field configurations with different inclination angles and by applying the present method to a dipole model to characterize a typical field configurations of a single round sunspot.

The main results in this study can be summarized

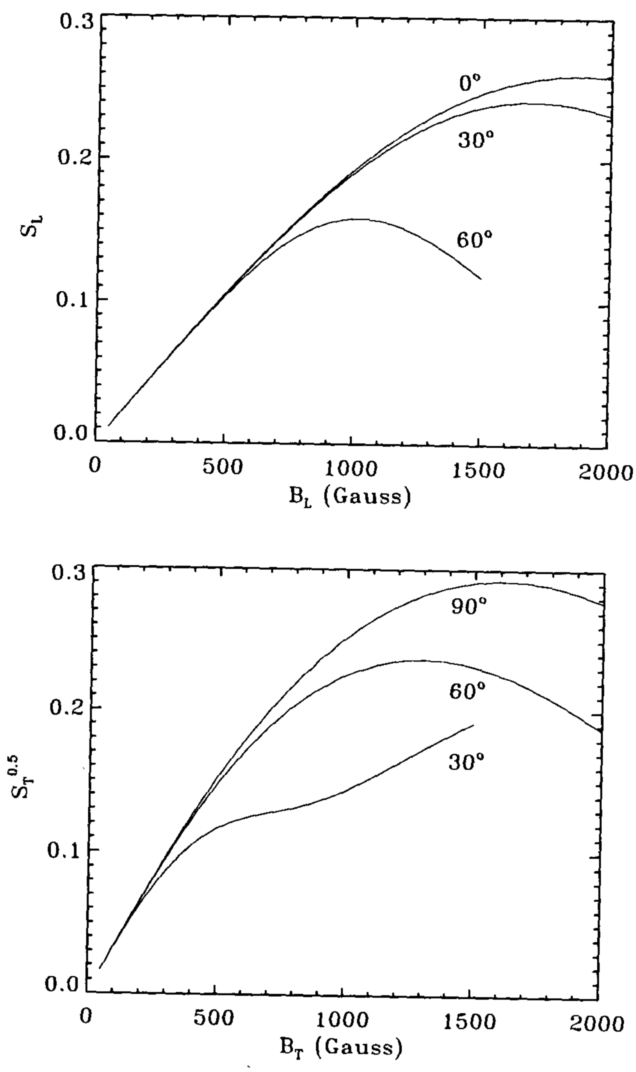

Fig. 3.— Comparison of calibration curves for longitudinal and transverse fields with three different inclination angles.

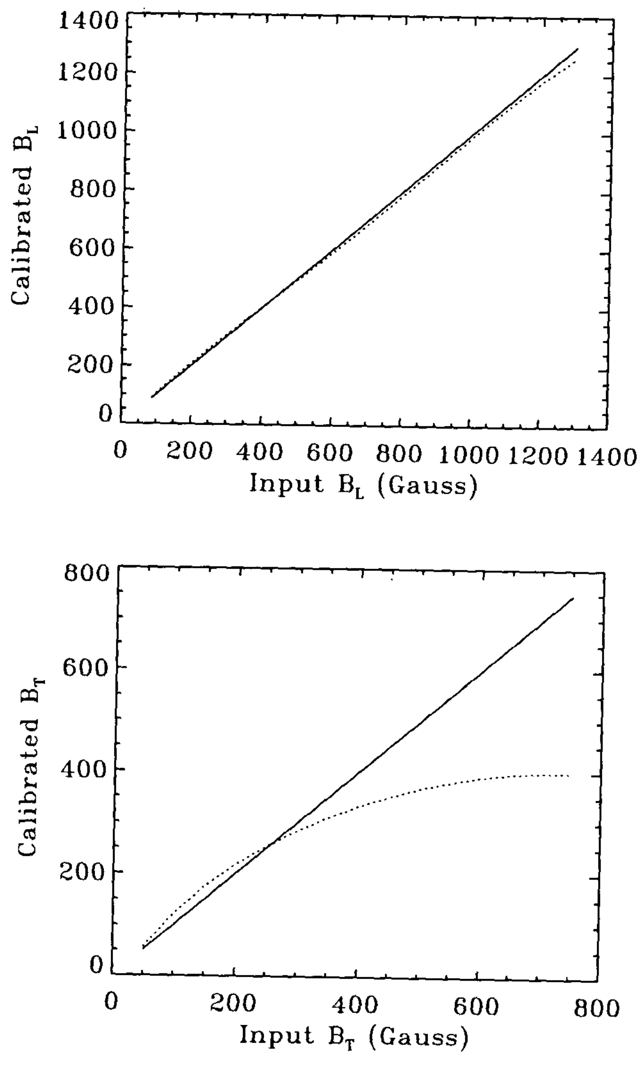

Fig. 4.— Comparison of the input magnetic fields with the calibrated ones for $\gamma = 30^o$. The solid lines are obtained by means of the present calibration method and the dotted lines, of the conventional one.

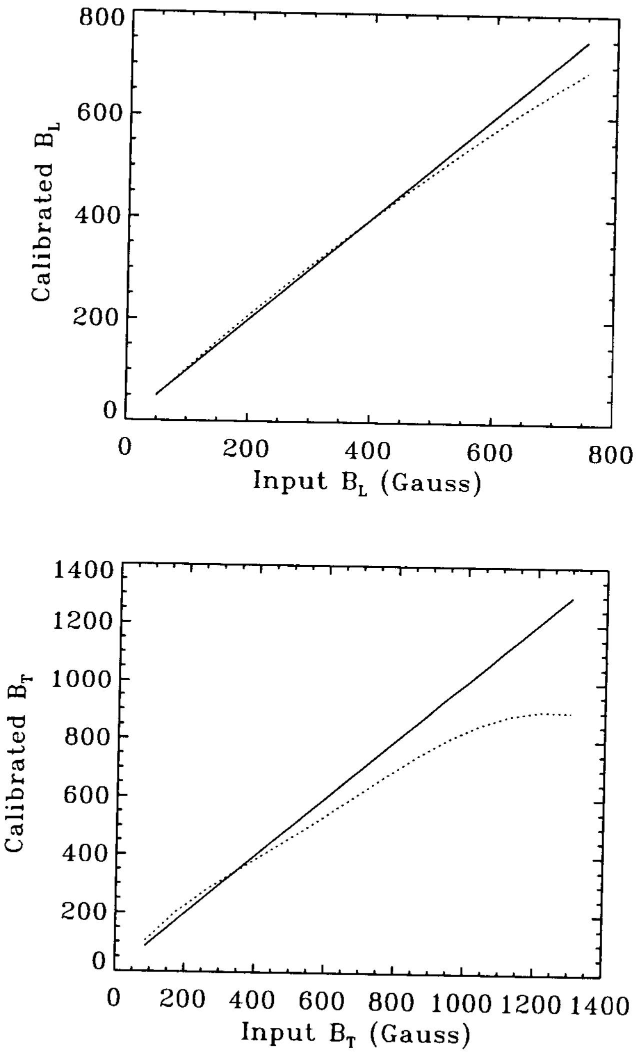

Fig. 5.— Comparison of the input magnetic fields with the calibrated ones for $\gamma = 60^o$. The solid lines refer to the present calibration method and the dotted lines to the conventional one.

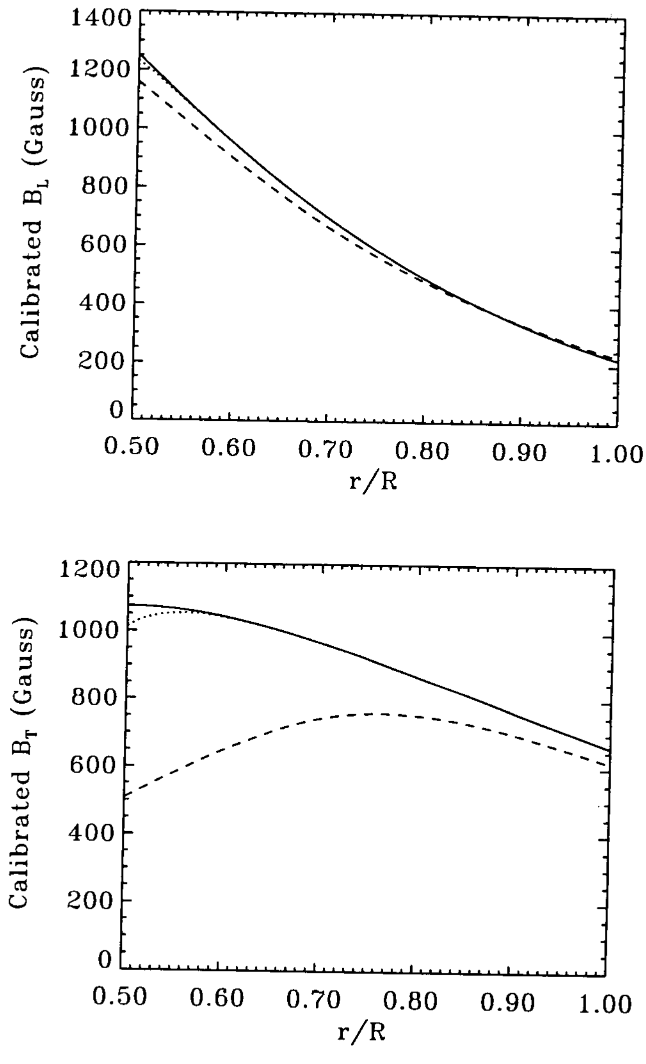

Fig. 6.— Comparison of the input magnetic fields with the calibrated fields, where Skumanich's dipole sunspot model is considered. Solid lines refer to the input magnetic fields, dotted lines to the present calibration method, and dashed lines to the conventional one.

as follows:

1) The observed intensity line profile for Fe I 6302.5 of the VMG Lyot filter is found to be in good agreement with spectral atlas data provided by Sacramento Peak Solar Observatory.

2) The calibration coefficients derived by the line slope method are a little larger than those by other methods.

3) Numerical tests show that our improved non-linear calibration method yields magnetic fields very close to the input fields regardless of the strength and the angle of inclination of magnetic fields. The conventional method, however does not provide the original input field as closely as our calibration method does.

4) It is found that the conventional method remarkably underestimates the transverse field component near the inner penumbra.

In applying the present method to the actual analysis the following facts should be kept in mind. In many cases, magnetic field strengths derived from filter-based magnetographs have been underestimated relative to theoretically predicted or spectrally determined ones. To compensate this problem, an arbitrary factor, so called k-factor, has been introduced to raise the observed polarization signals so that it matches the field strength estimated from nonfilter-based magnetic observations (Gary et al. 1987, Sakurai et al. 1995, Chae 1996). For examples, Gary et al.(1987) made use of the k-factor of 8.1 for longitudinal fields to match the Mount Wilson sunspot data. Sakurai et al.(1995) used a k-factor to balance longitudinal and transverse magnetic forces, since longitudinal fields are underestimated far more than transverse fields. The empirical k-factors for Mitaka Solar Observatory were also estimated by comparing observed polarization signals with empirically predicted ones (See Table 5-2 in Chae 1996). The underestimation of the deduced field strength could be attributed to instrumental depolarization (Gary et al. 1987) and stray light effects(Chae 1996).

ACKNOWLEDGEMENTS

We wish to thank Dr. Ichimoto for allowing us to use some of his numerical routines for Stokes polarization calculations. We also thank Dr. Li Ting and his colleagues for taking good care of the VMG Lyot filter. This work has been supported in part by the Basic Research Fund (99-1-500-00 and 99-1-500-21) of Korea Astronomy Observatory and in part by the Basic Science Research Institute Program, Ministry of Education 1998 (BSRI-98-5408).

REFERENCES

Beckers, J. M., Bridges, C. A., & Gilliam L. B. 1976, in A High Resolution Atlas of the Solar Irradiance from 380 to 700 Nanometers

Chae, J.C. 1996, Ph.D. dissertation, Seoul National University

Cho, K. S. & Kim, K. S. 1995, Pub. Kor. Astron. Soc. 10, 91

Gary, G. A., Moore, R. L., & Hagyard, M. J. 1987, ApJ, 314, 782

Hagyard, M.J., Smith, Jr, J.B., Teuber, D., & West, E. A. 1984, Sol. Phys., 91, 115

Hagyard, M.J., Gary, G. A. & West, E. A. 1988, The SAMEX Vector Magnetograph, NASA Technical Memorandom 4048

Hagyard, M.J. & Kineke, 1995, Sol. Phys., 158, 11

Holweger, H., & Muller, E.A. 1974, Sol. Phys., 39, 19

Ichimoto, K., Sakurai, T. Nishino, Y., Shinoda, K., Noguchi, M., Kumagai, K., Imai, H., Irie, M., Miyashita, M., Tanaka, N., Sàno, I., Suematsu, Y., & Hiei, E. 1993, in The Magnetic and Velocity Fields of Solar Active Regions, eds. H. Zirin, G. Ai, & H. Wang, ASP Series 46, 166

Ichimoto, K. 1997, private communication

Jefferies, J. T. & Mickey, D. L. 1991, ApJ, 372, 694

Kim, K. S. 1997, Pub. Kor. Astron. Soc. 12, 1

Landi Degl'Innocenti, E. L. 1992, in Solar Observations : Techniques and Interpretation, eds. Sanchez, F., Collados, M, & Vazquez, M, p73

Lites, B.W., Thomas, A. B., Johannesson, A., & Sharmer, G. B. 1991, ApJ, 373, 683

Lites, B.W., Elmore, D. F., Seagraves, P., & Skumanich, A. 1993, ApJ, 418, 928

Lites, B.W., Martinez Pillet, V., & Skumanich, A. 1994, Sol. Phys., 155, 1

Moon, Y.-J., Park, Y.D., Jang, B.H., Sim, K. J., Yun, H. S., & Kim, J. H. 1996, Pub. Kor. Astron. Soc, 11, 243

Moon, Y.-J., Yoon, S.-Y., Park, Y.D.,& Jang, B.H. 1997, Pub. Kor. Astron. Soc, 12, 47

Moon, Y.-J., Yun, H. S., & Park, J.-S. 1998, ApJ, 494, 851

Park, Y.D., Moon, Y.-J., Jang, B-H., & Sim, K. J. 1997, Pub. Kor. Astron. Soc, 12, 35

Sakurai, T., Ichimoto, K,. Nishino, Y., Shinoda, K., Noguchi, M., Hiei, E., Li, T., He, F., Mao, W., Lu, H., Ai, G., Zhao, Z., Kawakami, S., & Chae, J. 1995, PASJ, 47, 81

Varsik, J.R. 1995, Sol. Phys., 161, 207

Skumanich, A. 1992, in Sunspots : Theory and Observations, eds. J. H. Thomas and N. O. Weiss (Dordrecht: Kluwer Academic Publishers), 121

Zirin, H. 1995, Sol. Phys., 159, 203