

A comparison of co-temporal magnetograms obtained with the Huairou magnetograph and the Spectro-Polarimeter on board Hinode

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We have compared a set of co-temporal magnetograms obtained with the Solar Magnetic Field Telescope (SMFT) of the Huairou Solar Observing Station (HSOS) and with the Spectro-Polarimeter of the Solar Optical Telescope (SP/SOT) on board Hinode to check the linear calibrations of SMFT vector magnetograms. The comparison shows that the currently used calibration coefficients of the SMFT have under-estimated the flux density and that a center-to-limb variation of the calibration coefficients was not taken into account by previous calibrations.

atmosphere, magnetic fields, magnetic fields

The Solar Magnetic Field Telescope (SMFT) of the Huairou Solar Observing Station (HSOS) of the National Astronomical Observatory (NAOC) is a ground-based telescope used to observe the photospheric and chromospheric magnetic fields^[1]. It has been working for more than 20 years since the year 1986. For photospheric observations, it uses the FeI 5324.19 Å spectral line. The Stokes (IQUV) polarization images are obtained through a birefringent filter which has a 125 mÅ bandpass. When the longitudinal magnetic field is measured, the passband of the filter is tuned to -75 mÅ away from the line center. When the transverse field is measured, the passband of the filter is placed at the line center for the best sensitivity and the least cross-talk.

Note that the magneto-optical effect may influence the transverse field measurement^[2-4]. However, we will not consider this effect here, for this study focuses only on the strength of the transversal field, rather than the angle of the transverse field that is affected by the magneto-optical effect. The typical field of view of the observation is 6' × 4'.

Following Jefferies et al.^[5] and the calibration method of many other similar filter-type magnetographs, we use the following linear relationship to calibrate our magnetograms:

$$B_L = C_L \frac{V}{I},$$

$$B_T = C_T \sqrt[4]{\left(\frac{Q}{I}\right)^2 + \left(\frac{U}{I}\right)^2}, \quad (1)$$

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where I, Q, U, V are the measured Stokes parameters, B_L and B_T longitudinal and transversal components of the vector magnetic fields, and C_L and C_T their corresponding calibration coefficients.

Several studies have been made on calibrating the magnetograms obtained by SMFT. Ai, Li and Zhang^[6] gave the first, theoretical calibration of the FeI 5324.19 Å line. Their calibration coefficients are 10000 for C_L and 9730 for C_T , respectively. Wang et al.^[7] have tried to use empirical and observational methods to calibrate the longitudinal magnetic field. The coefficients are 8900 for the former and 9600 for the latter, respectively. Su and Zhang^[8] measured the magnetic fields over a sunspot and obtained the calibration coefficients by using an inversion technique and nonlinear least-squares fitting. Based on these results, currently the coefficients commonly used are 10000 for C_L and 6626 for C_T , respectively.

Recently, another approach has been taken to calibrate filter-based magnetographs, that is, to compare the magnetograms obtained by filter-based magnetographs with those obtained by spectro-polarimeters. Berger and Lites^[9,10] compared co-temporal magnetograms obtained with the Advanced Stokes Polarimeter (ASP) with the full-disk magnetograms obtained with the Michelson Doppler Imager (MDI) on aboard SOHO and found that the previous calibration of MDI magnetograms has underestimated the flux density by a factor of about 1.6. Tran et al.^[11] made a detailed cross-correlational study between sets of magnetograms simultaneously obtained by the Mount Wilson Observatory (WMO) and by MDI/SOHO. They divided the solar disk into 10 regions and found 10 different ratios of MWO FeI5250 Å magnetograms over the MDI magnetograms. Following this approach, we used a set of co-temporal magnetograms obtained with SMFT/HSOS and SP/SOT to check the calibration of SMFT.

1 Data and analysis

The Hinode satellite^[12] was launched on 2006 September 22. The Solar Optical Telescope (SOT) on board Hinode consists of the main 50 cm aperture telescope (Optical Telescope Assembly, OTA)

and focal plane package (FPP). The combined SOT system is optimized for accurate measurement of the vector magnetic field in the photosphere and dynamics of both the photosphere and chromosphere associated with the magnetic fields. The SP obtains line profiles of two magnetically sensitive Fe lines at 630.15 and 630.25 nm and nearby continuum. Spectra are exposed and read out continuously 16 times per rotation of the polarization modulator, and the raw spectra are added and subtracted onboard in real time to demodulate, generating Stokes IQUV spectral images. The SP magnetograms we use in this work have spatial resolutions of either 0.16"/pixel (normal maps) or 0.32"/pixel (fast maps), and their duration is usually several tens minutes. To retrieve the vector magnetic fields, we use the non-linear least-squares method based on the Milne-Eddington atmosphere model following Skumanich and Lites^[13].

To create the sample used in this paper, we first produce 17 SP magnetograms of 16 days which we know SMFT also has the observations (see Table 1 also). Then we select SMFT magnetograms to pair with each of these 17 SP magnetograms if the observation time of the SMFT magnetogram lies in the range of SP observations. Because the temporal interval of SMFT magnetograms is only 3 minutes, much shorter than the scanning time of SP magnetograms, we usually find more than one SMFT magnetograms to pair with each SP magnetogram.

A pixel-to-pixel comparison of the SMFT image to the SP maps requires a common alignment and image scaling. We doubt the observing condition in Huairou may have smeared the structures much more than the instrument's point spread function does. Out of this consideration we have chosen to smooth both SMFT and SP magnetograms to a large spatial resolution, that is, 2" per pixel, so that the magnetograms become comparable without being over-sampled. That will also offer a better signal-to-noise ratio for SMFT magnetograms. The original spatial resolution of SMFT magnetograms is 0.352"/pixel. When doing smoothing, we have used the SMOOTH and CONGRID (with /interp keywords) functions in IDL to reform the

magnetograms to be of $2''/\text{pixel}$. For example, for a SP magnetogram that has a size of 1000×512 pixels and resolution of $0.3''/\text{pixel}$, we convert it into $2''/\text{pixel}$ with a new size of 150×77 pixels ($1000 \times 0.3/2=150$, $512 \times 0.3/2 \approx 77$).

Our next step is to co-align each pair of SMFT and SP magnetograms and compare the SP longitudinal and transversal magnetograms with those of SMFT. By SP longitudinal (B_L^{SP}) and transversal (B_T^{SP}) magnetograms, we mean the following quantities that are calculated from the retrieved SP vector magnetic fields:

$$\begin{aligned} B_L^{\text{SP}} &= (B f \cos \psi)^{\text{SP}}, \\ B_T^{\text{SP}} &= (B \sin \psi \sqrt{f})^{\text{SP}}, \end{aligned} \quad (2)$$

where B is the retrieved SP field strength, ψ the angle of the magnetic field vector to the line of sight and f the filling factor. By taking into account the filling factor, the B_L^{SP} and B_T^{SP} maps are actually flux density maps, ready to be compared with those obtained with filter-based magnetographs.

Figure 1 gives an example of such a cross comparison between one pair of SP and SMFT magnetograms which were observed on January 28, 2007. In the left panel, the x -axis is the strength of the longitudinal magnetic field (B_L^{SP}) from SP, and the y -axis is the strength of the longitudinal magnetic field (B_L^{HR}) from SMFT. In the right panel, the x -axis is the strength of the transverse magnetic field (B_T^{SP}) from SP, and the y -axis is the strength of the

transverse magnetic field (B_T^{HR}) from SMFT. Each plus symbol in the plots represents a point in the magnetograms and each diamond symbol in the plots represents a median value in the bin of every 50 Gauss of B_L^{SP} or B_T^{SP} . We have excluded those points whose magnitude of B_L^{SP} or B_T^{SP} are larger than 1000 Gauss because these points may be influenced by the saturation effect in SMFT magnetograms. We have also excluded those points whose B_L^{SP} are smaller than 100 Gauss or B_T^{HR} are smaller than 250 Gauss because these points are largely influenced by the noise level in SMFT magnetograms. Then, using these diamond points we find an average of the ratio $R_L = B_L^{\text{SP}}/B_L^{\text{HR}}$ or $R_T = B_T^{\text{SP}}/B_T^{\text{HR}}$. These numbers are listed in the fifth ($\overline{R_L}$) and seventh ($\overline{R_T}$) columns of Table 1. For the pair showed in Figure 1, $\overline{R_L} = 2.14334$ and $\overline{R_T} = 1.30671$. The solid line in the left panel of Figure 1 shows $y = x/\overline{R_L}$, and the solid line in the right panel of Figure 1 gives $y = x/\overline{R_T}$.

Table 1 shows that these numbers are all larger than 1. This means that compared to the SP/SOT measurements, our previous calibrations have underestimated the flux density. The new calibration coefficients, according to this work, should be larger, as listed in the sixth (“New C_L ”) and ninth (“New C_T ”) columns of Table 1.

As we have made an intentional choice, the magnetograms analyzed here are located at different

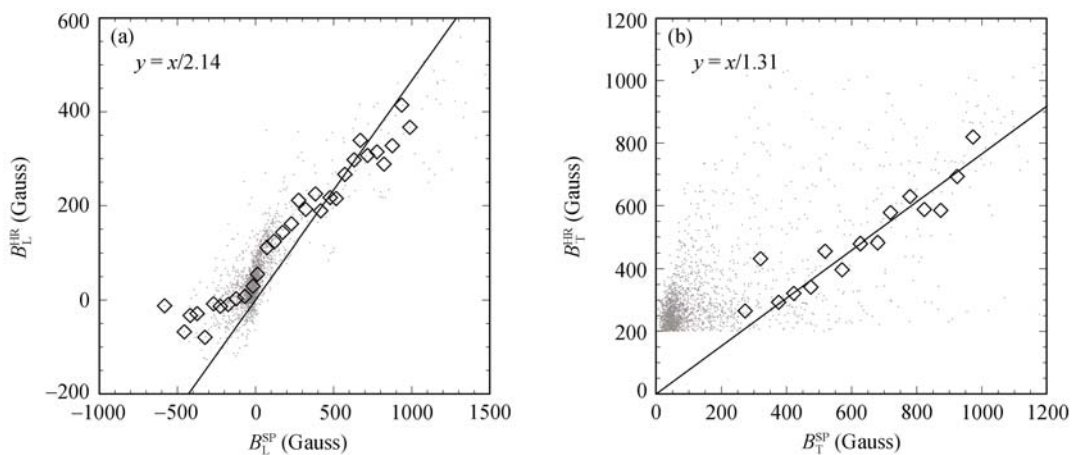


Figure 1 An example of the cross comparison between a pair of SP and SMFT magnetograms on January 28, 2007. (a) The relationship between the longitudinal field strengths of SP and SMFT; (b) the relationship between the transversal field strengths of SP and SMFT. See the text for details.

Table 1 Sample information and new calibration coefficients obtained

Date	Latitude N(+),S(-)	Longitude E(-),W(+)	Wavelength shift (mÅ)	$\overline{R_L}$	New C_L	$\overline{R_T}$	Average $\overline{R_T}$ of the day	New C_T						
070128	-6	-59.25	-32.1647	2.14334	2.69688	2.75752	25325.8	1.30671	1.37065	1.37982	1.35239	8960.94		
070201	-4	-6.0	-3.12972	1.69306	1.79693	1.49787	16626.2	1.12535	1.16478	1.08423	1.12479	7452.86		
070202	-4	6.56	4.27738	1.79518	1.73775	1.69386	17422.6	1.36344	1.13765	1.22358	1.24156	8226.58		
070501	-10	-7.54	-4.58467	1.55210	1.62102	1.38379	14991.8	1.05017	1.14877	1.05922	1.06391	7145.68		
070502	-10.08	5.54	3.13237	1.66089	1.31237	1.05089	109760	1.05089	1.09760			7442.39		
070503	-11.42	21.79	12.0415	1.58358	1.47781	1.35061	14911.4	1.03425	1.13141	1.10438	1.10025	1.12321	7529.12	
070504	-10.23	33.98	18.1284	1.52273	1.48789	1.78761	17801.3	1.04484	1.32416	1.29099	1.12476	1.13630	8401.77	
070505	-10.96	44.58	24.5200	1.83013	2.06565	1.78761	167325	1.11946	1.10163	1.29099	1.12476	1.13630	7529.12	
				1.54403				1.04465						
				1.97059	1.86162	1.93690	19260.4	1.52938	1.12164	1.15297	1.26800	8401.77		
				1.83814	2.26386	1.88529	2.10187	19910.3	1.12263	1.24802	1.20289	1.13750	7624.34	
				1.85591	2.34372	1.90678	1.97794	1.14467	1.20916	1.09135	1.09630			
				1.74575				1.10351						
				2.94360	2.04359	2.42510	2.94810	25901.0	1.29231	1.10170	1.11678	1.08442	1.14880	7611.95
				2.07689	1.81694	1.22043	2.16619	18081.4	1.49290	1.51088	1.45916	1.44125	1.47292	9759.57
				1.76321	2.25890	1.40878	1.75378	1.48905	1.28171	1.48243	1.62601			
				1.85671	1.81366	1.88310	1.89842	19365.1	1.52935	1.55688	1.55584	1.59142	1.56143	10346.0
				2.18733	1.97985			1.57367						
				1.83814	1.43682	2.73578	2.69713	21089.6	1.12263	1.99119	1.75578	1.85786	1.61284	10686.7
				1.83695				1.33672						
				1.64749				1.18674						
				1.80669	1.75383	1.79149	17840.0	1.22494	1.14023	1.25358	1.20625	7992.61		
				1.54738				1.07186						
				1.10639	1.24825	1.16460	1.18709	12086.8	1.12506	1.09341	1.05195	1.01567	1.16440	7715.31
				1.16133	1.32743	1.26570		1.77175	1.05140	1.04154				
				1.73084	1.77101	1.65241	1.32164	16189.8	1.65492	1.44860	1.47552	1.42832	1.48226	9821.46
				1.40394										

positions on the solar disk. It is known that the Sun has a differential rotation velocity. The longitudinal component of the velocity will vary with the different positions on the solar disk. We suspect that this will shift the actual filter position relative to the line center and change the calibration coefficients. To verify this hypothesis, we have plotted Figure 2, where the x -axis is the actual wavelength shift (relative to the line center, in units of $\text{m}\text{\AA}$) of each observed region and the y -axis is the obtained new calibration coefficients as listed in the sixth and ninth columns of Table 1. Each observed region has a different position, so a different doppler velocity is caused by the solar rotation and hence a different wavelength shift. These data are also listed in the first four columns of Table 1.

Since the calibration coefficients do show a disk-position dependence we went further to fit these coefficients with a fourth-order curve as $C = a_0x^4 + a_1x^2 + a_2x + a_3$, where x is the wavelength shift and C is either new C_L or new C_T . Let $A = [a_0, a_1, a_2, a_3]$, our fitting gives $A = [2.35005 \times 10^{-5}, 7.08605, 1059.09, 54522.7]$ for the solid line in the top panel, and $A = [8.03991 \times 10^{-6}, 2.41208, 454.625, 30053.0]$ for the solid line in the bottom panel.

For the sake of comparison, we have also plotted

the results from Su and Zhang^[14]. They obtained the observed Stokes profiles by tuning the filter of a full-disk vector magnetograph in HSOS (note this is not the SMFT). They also got a series of calibration coefficients with different wavelength shifts. We plotted their results in Figure 2 also. The fitting of their results gives $A = [1.20599 \times 10^{-7}, 3.49598, -9.00109, 7497.22]$ and $A = [9.27416 \times 10^{-6}, -0.0365765, -6.41906, 6206.46]$ for the dashed lines in the top and bottom panels respectively. Here again our coefficients are systematically larger than theirs.

2 Results and discussion

The calibration coefficients of SMFT we obtained, by comparing co-temporal SP and SMFT magnetograms, are systematically larger than currently used numbers and those of Su et al.^[14].

One possible reason is the spatial resolution. As discussed in Berger and Lites^[10], the spatial scale of magnetic elements may be much smaller than the spatial resolution and the flux contribution from magnetic elements with different polarity may have canceled each other. This may be particularly true for the SMFT observations because of the seeing conditions.

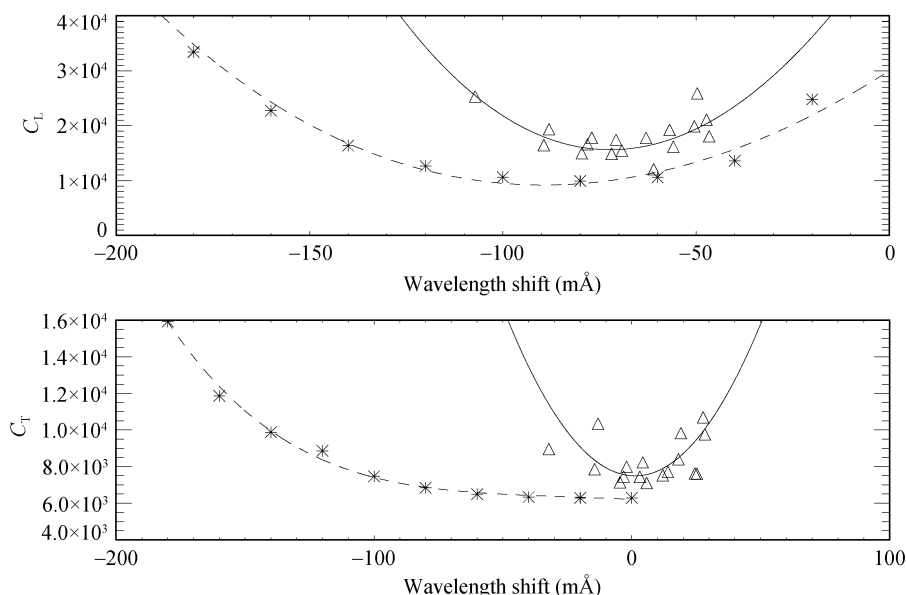


Figure 2 The dependence of calibration coefficients on the disk position. Δ —Coefficients obtained in this work. $*$ —Coefficients obtained by Su et al.^[13]. See the text for details.

Another reason may be the atmospheric thermal model. Previous calibrations, particularly those theoretical ones, usually use one or a few chosen atmospheric models for all data points. Instead of using any atmospheric model, this study uses SP data to calibrate SMFT magnetograms. This means for each pixel we have used a different atmospheric model given by the SP observations. That may make a difference.

As we mentioned before, shifting the spectral line due to differential solar rotation may produce the location-dependent coefficients among other factors. In addition to this reason, other reasons, such as different line shapes in umbrae and penumbrae,

line profile and formation height being dependent on the center-to-limb angle etc., could also influence SMFT's observation. In that sense, Figure 2 only shows that the calibration coefficients are disk-position dependent and in our fitting formula the shift of the spectral line due to differential solar rotation should only be regarded as a register of the disk position.

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