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A Cross-Comparison of Cotemporal Magnetograms Obtained with MDI/SOHO and SP/*Hinode*

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Abstract We compared a set of cotemporal magnetograms of active regions obtained with the Michelson Doppler Imager (MDI) aboard SOHO and the Spectro-Polarimeter (SP) of the Solar Optical Telescope (SOT) on board *Hinode*. The comparison shows that even with the recent calibration of level-1.8 data, the magnetic flux density derived from the MDI data is still lower than that obtained with SP. The average ratio between current version 2008 MDI level-1.8 data and SP magnetograms is 0.71, and is 0.82 for version 2007 MDI level-1.8 data. The comparison also shows that the most recent version 2008 calibration of MDI level-1.8 data has successfully removed the center-to-limb variation, while version 2007 level-1.8 data did not, as estimated by Ulrich *et al.* (*Solar Phys.* **255**, 53, 2009).

Keywords Active region, magnetic fields · Magnetic fields, photosphere

1. Introduction

It is well known that there are two types of instruments that measure vector magnetic fields on the solar photosphere: the Stokes polarimeters (*e.g.*, Advanced Stokes Polarimeter; Elmore *et al.*, 1992) and the magnetographs (*e.g.*, Solar Magnetic Field Telescope; Ai and Hu, 1987). Each of these instruments has their own advantages and disadvantages. A Stokes polarimeter measures the full spectra of Stokes I, Q, U, and V of a spectral line, and an inversion code is applied to derive the vector magnetic field, together with other thermal parameters. A magnetograph measures the Stokes I, Q, U, and V at one or a few fixed wavelengths, and uses precalculated calibration coefficients or calibration maps to obtain the vector magnetograms.

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The advantage of a Stokes polarimeter is that it measures the vector magnetic fields more accurately, for it uses the full information of a spectral line. The advantage of a magnetograph is that it can obtain magnetograms at much higher temporal resolutions, so with these magnetograms fast evolution of magnetic fields can be studied. It is fortunate for our solar physics community that we currently have each of these two types of instruments in space, namely, the Michelson Doppler Imager (MDI) aboard SOHO and the Spectro-Polarimeter (SP) of the Solar Optical Telescope (SOT) on board *Hinode*. A comparison and a combination usage of their data may lead us to understand the observed magnetic field better.

The SP/*Hinode* (Tsuneta *et al.*, 2008; Ichimoto *et al.*, 2008) 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 MDI instrument (Scherrer *et al.*, 1995) is a combination of a birefringent filter and a dual Michelson interferometer fed by a 12.5 cm refractive telescope. The spectral passband FWHM is 9.4 pm and is tunable in a ± 38 pm range around the Ni I 676.78 nm spectral line. The spectral images are recorded every 3 s by a 1024×1024 pixel^2 CCD camera and processed by an on-board image processor before transmission to the SOHO satellite telemetry system. The plate scale of the instrument is variable between 1.98 arcsec per pixel (resulting in a 34×34 arcmin^2 "full-disk" FOV) and the "high-resolution mode" 0.605 arcsec per pixel (resulting in a 10.5×10.5 arcmin^2 FOV). In this work we only consider 5-min-integrated full-disk magnetograms.

It is also well know that accurate calibrations of magnetograms obtained by magnetographs is a difficult task. The MDI team has calibrated and recalibrated their data a few times (*e.g.*, Liu, Zhao, and Hoeksema, 2004; Liu, Norton, and Scherrer, 2007). The original calibration (Scherrer *et al.*, 1995) used the standard center-of-gravity method (Rees and Semel, 1979). Later on, Berger and Lites (2003) compared cotemporal magnetograms obtained with the Advanced Stokes Polarimeter (ASP) with those obtained with MDI/SOHO and found that the previous calibration of MDI magnetograms underestimated the flux density by a factor about 1.6. Then Tran *et al.* (2005) made a detailed cross-correlation between sets of magnetograms simultaneously obtained by the Mount Wilson Observatory (MWO) and by MDI/SOHO. They divided the solar disk into ten regions and found ten different ratios of MWO Fe I 525.0 nm magnetograms over the MDI magnetograms. According to their results, the MDI team recalibrated all of the full-disk MDI magnetograms in October 2007. These data will hereafter be referred to as "version 2007 level-1.8 data" in this article.

Most recently, Ulrich *et al.* (2009) recommended a new calibration of MDI data. Their recommended new correction multiplies the previous calibration map (Tran *et al.*, 2005) by a factor that depends on the distance from disk center. The factor is $(4.15-2.82\sin^2\rho)/(4.5-2.5\sin^2\rho)$, where ρ is the heliocentric angle. This correction was applied to MDI data in December 2008. We will hereafter refer to them as "version 2008 MDI level-1.8 data."

The purpose of this article is to check how good these recent calibrations of MDI data are (version 2007 and version 2008 level-1.8 data) by comparing a set of co-temporal magnetograms obtained with MDI/SOHO and SP/*Hinode*. The underlying consideration is that SP/*Hinode* provides the most up-to-date, accurate measurements of magnetic fields. Using its magnetograms for calibrating magnetograph observations should be a good and reasonable approach. We describe our data and analysis in the following section (Section 2), and present our results and summary in Section 3.

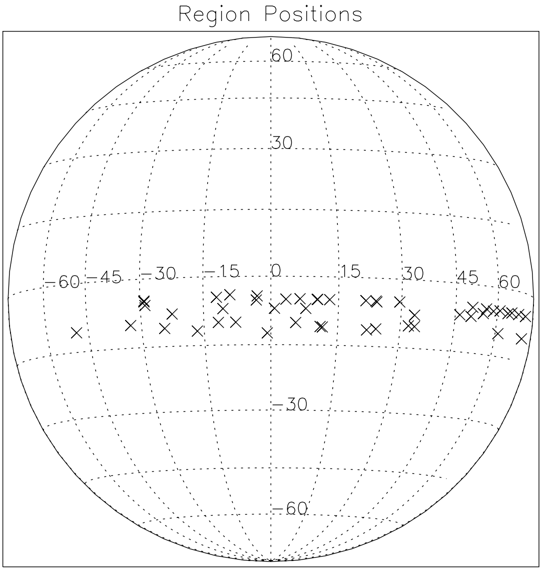

Figure 1 Positions of the 48 active regions in the sample.

2. Data and Analysis

2.1. The Sample

The sample used in this article consists of 48 pairs of solar active regions observed by both SP/*Hinode* and MDI/SOHO. In forming the sample, we first select 48 SP observations of active regions. These 48 magnetograms belong to nine different active regions observed in 42 days. Figure 1 shows the positions of these active regions. Table 1 lists some details of these active regions, such as observational date, latitude (θ), longitude (ϕ), heliocentric angle (ρ, $\cos\rho = \cos\theta\cos\phi$), and the field-of-view (FOV). Note that all of these active regions are in the Southern Hemisphere and are characterized by dominant negative polarity in the preceding sunspots. We do not know whether this will influence the results of this work. In the future when SP observes more active regions in the Northern Hemisphere, it would be worth repeating this investigation with a larger sample to see whether there is a hemisphere dependence.

The SP magnetograms have spatial resolutions of either $0.16''$/pixel (normal maps) or $0.32''$/pixel (fast maps), and their duration are usually several tens of minutes. To retrieve the vector magnetic fields, we used the nonlinear least-squares method based on the Miline-Eddington atmosphere model following Skumanick and Lites (1987). Then for each SP observation we search for one or two MDI full-disk magnetograms that has the observational time closest to the SP central observation time. By SP central observation time we mean the time in the middle of the starting and ending times of the SP scan. For most regions, we select two MDI magnetograms, one before the SP central observation time and one after. But for a few regions, only one MDI magnetogram is selected to avoid a too large time difference between the MDI observation and SP scan. We then cut the selected full-disk MDI magnetogram to make its FOV roughly the same as that of the corresponding SP magnetogram.

Table 1 List of samples.

	Date (yy/mm/dd)	SP time	MDI time	Latitude	Longitude (degrees)	ρ	FOV (arcsec^2)
1	2006/11/07	13:52 – 14:55	12:51 14:27	−6.9	46.4	46.79	296 × 163
2	2006/11/08	02:57 – 03:41	01:39 03:15	−6.1	54.4	54.63	296 × 163
3	2006/11/12	04:43 – 05:58	03:15 04:51	−4.8	−29.0	29.36	101 × 163
4	2006/11/13	21:30 – 22:25	20:51 22:27	−4.0	−9.0	9.84	95 × 163
5	2006/11/14	07:15 – 08:13	06:27 08:03	−4.3	−3.0	5.24	101 × 163
6	2006/11/15	11:10 – 12:27	09:39 11:15	−5.0	13.0	13.91	101 × 163
7	2006/11/16	22:37 – 23:35	20:51 22:27	−5.0	29.5	29.88	101 × 163
8	2006/11/18	22:20 – 23:18	20:51 22:27	−5.0	55.5	55.65	101 × 163
9	2006/11/20	03:58 – 04:57	03:15 04:51	−5.0	71.2	71.27	68 × 143
10	2006/12/09	03:40 – 04:43	03:15 04:51	−5.8	−28.8	29.33	296 × 163
11	2006/12/10	10:55 – 13:58	09:39 11:15	−4.5	−12.0	12.80	296 × 163
12	2006/12/11	20:00 – 21:03	19:15 20:51	−4.9	6.4	8.05	296 × 163
13	2006/12/12	03:50 – 04:57	03:15 04:51	−5.0	10.2	11.35	296 × 163
14	2006/12/13	04:30 – 05:34	03:15 04:51	−5.2	23.9	24.43	296 × 163
15	2006/12/15	05:45 – 06:48	04:51 06:27	−5.0	50.5	50.68	296 × 163
16	2006/12/16	07:50 – 08:53	06:27 08:03	−5.3	65.0	65.11	220 × 163
17	2007/04/29	03:30 – 04:02	01:39 03:15	−10.0	−32.8	34.13	151 × 163
18	2007/04/30	18:35 – 19:39	17:39 19:15	−10.0	−11.7	15.35	113 × 163
19	2007/05/01	01:50 – 02:22	00:03 01:39	−10.0	−7.8	12.66	151 × 163
20	2007/05/02	00:15 – 00:47	00:03 01:39	−10.1	5.5	11.49	151 × 163
21	2007/05/02	11:15 – 12:40	09:39 11:15	−11.0	11.5	15.86	147 × 163

Table 1 (*Continued*)

	Date (yy/mm/dd)	SP time	MDI time	Latitude	Longitude (degrees)	ρ	FOV (arcsec^2)
22	2007/05/03	06:14 – 06:46	04:51 06:27	−11.4	21.8	24.47	147 × 163
23	2007/05/03	10:15 – 11:39	09:39 11:15	−11.1	24.0	26.30	147 × 163
24	2007/05/04	01:25 – 01:57	00:03 01:39	−10.1	32.1	33.49	147 × 163
25	2007/05/04	04:40 – 05:12	03:15 04:51	−10.2	33.7	35.03	147 × 163
26	2007/05/06	05:00 – 05:32	03:15 04:51	−10.0	61.3	61.78	147 × 163
27	2007/05/07	08:48 – 09:20	08:03 09:39	−10.0	75.5	75.73	88 × 123
28	2007/06/06	02:39 – 03:41	01:39 03:15	−7.9	−22.3	23.59	292 × 163
29	2007/06/06	22:21 – 23:23	20:51 22:27	−7.0	−10.6	12.68	240 × 163
30	2007/06/07	19:45 – 20:42	19:15 20:51	−7.0	0.8	7.05	260 × 163
31	2007/06/08	07:10 – 08:13	06:27 08:03	−7.0	7.7	10.39	292 × 163
32	2007/06/10	03:26 – 04:29	03:15 04:51	−7.7	33.5	34.27	297 × 163
33	2007/06/12	01:26 – 02:29	00:03 01:39	−5.0	61.1	61.22	297 × 163
34	2007/06/12	12:55 – 13:53	11:15 12:51	−5.0	67.0	67.09	101 × 163
35	2007/06/13	06:57 – 07:56	06:27 08:03	−5.0	76.5	76.55	73 × 143
36	2007/06/27	19:10 – 19:43	17:39 19:15	−10.7	−48.8	49.67	151 × 163
37	2007/06/29	01:00 – 01:32	00:03 01:39	−11.0	−24.3	26.54	151 × 163
38	2007/06/30	09:47 – 10:18	08:03 09:39	−11.8	−16.6	20.27	147 × 163
39	2007/07/01	13:32 – 14:14	12:51 14:27	−12.4	−0.8	12.43	185 × 163
40	2007/07/02	12:17 – 12:56	11:15 12:51	−10.9	11.0	15.44	185 × 163
41	2007/07/13	19:07 – 20:11	17:39 19:15	−5.2	−3.2	6.10	296 × 163
42	2007/07/18	07:28 – 08:31	06:27 08:03	−5.3	58.3	58.45	260 × 163

Table 1 (*Continued*)

	Date (yy/mm/dd)	SP time	MDI time	Latitude	Longitude (degrees)	ρ	FOV (arcsec^2)
43	2007/08/25	07:57 – 08:29	05:51 09:39	−5.0	−29.0	29.39	151 × 163
44	2007/08/27	07:34 – 08:06	04:51	−5.0	3.3	5.99	151 × 163
45	2007/08/28	07:06 – 07:38	08:03	−5.0	10.3	11.44	151 × 163
46	2007/08/29	03:57 – 04:29	08:03	−5.0	21.3	21.85	151 × 163
47	2007/08/29	07:12 – 07:44	08:03	−5.0	23.7	24.19	151 × 163
48	2007/09/05	04:00 – 04:32	03:15 04:51	−7.0	50.1	50.46	151 × 163

2.2. Alignment and Analysis

Pixel-to-pixel comparison of the MDI magnetograms to the SP maps requires an alignment and image scaling. Because there is a large difference between the spatial resolutions of SP and MDI magnetograms (0.1476″ × 0.1585″/pixel for SP normal maps, 0.2952″ × 0.3170″/pixel for SP fast maps, and 1.9857″ × 1.9857″/pixel for MDI magnetograms), we used two methods to scale the SP or MDI magnetograms to make them comparable. A similar approach was taken in Berger and Lites (2002, 2003). The first one (hereafter referred to as "Method 1") is to change SP magnetograms to have the same spatial resolution of MDI full-disk magnetograms. We first use the SMOOTH function in IDL to change their spatial resolutions. Then we use the CONGRID function in IDL to reform the smoothed SP maps to be of 1.9857″/pixel. The second method (hereafter referred to as "Method 2") is to change each MDI magnetogram to have the same spatial resolution of corresponding SP magnetograms, using the CONGRID (with /interp keywords) function in IDL.

We then use the simple cross-correlation algorithm to align each pair of MDI and SP magnetograms and compare the SP longitudinal magnetogram with the MDI magnetogram. By SP longitudinal (B_L^{SP}) magnetogram, we mean the following quantity that is calculated from the retrieved SP vector magnetic field:

$$B_L^{SP} = (Bf \cos\psi)^{SP}, \tag{1}$$

where B is the retrieved SP field strength, ψ is the angle of the magnetic field vector to the line of sight, and f is the filling factor. By taking into account the filling factor, the B_L^{SP} maps are actually Flux-density maps, ready to be compared with MDI magnetograms (B_L^{MDI}). Then, for each pair of SP and MDI magnetograms, we will evaluate an average ratio (R) between the MDI flux density and that of SP. That is,

$$R = \overline{B_L^{MDI}/B_L^{SP}}. \tag{2}$$

We denote $R = R_1$ if version 2007 MDI level-1.8 data are used and $R = R_2$ if version 2008 MDI level-1.8 data are used.

Figure 2 gives an example of how we get R_2 for an active region observed on 11 December 2006. It is a near disk-center region, whose latitude is 4.9° and longitude 6.4°. Its field-of-view (FOV) is 296 × 163 arcsec^2. It is the 12th region listed in Tables 1 and 2.

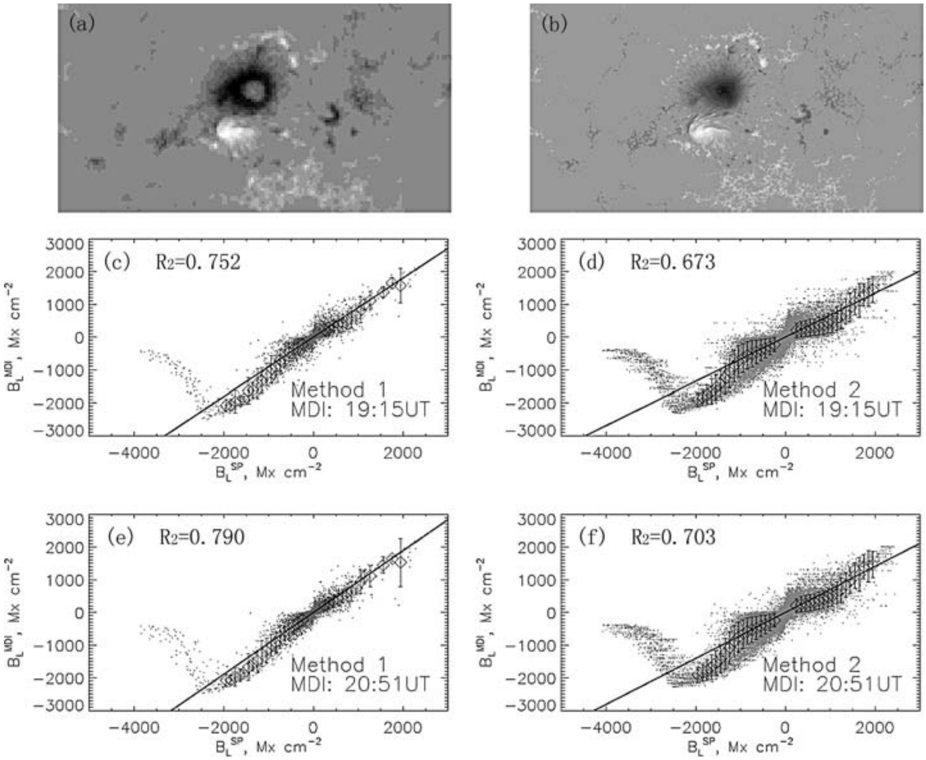

Figure 2 An example of a near disk-center active region AR 10930, observed on 11 December 2006. Its FOV is 296 × 163 arcsec^2. (a): The version 2008 MDI magnetogram observed at 20:51 UT. (b): The longitudinal magnetogram of SP observed between 20:00 UT and 21:03 UT. (c): Correlation between the longitudinal flux densities of SP and MDI. The MDI data used are the version 2008 level 1.8 data. The MDI magnetogram is observed at 19:15 UT. Here the SP magnetogram was rescaled using "Method 1." (d): Same as panel (c), but here the MDI magnetogram was rescaled using "Method 2." (e): Same as panel (c), but here the MDI magnetogram is observed at 20:51 UT. (f): Same as panel (d), but here the MDI magnetogram is observed at 20:51 UT.

In the middle and bottom panels of Figure 2, the abscissa is the longitudinal flux density ($B_{\mathrm{L}}^{\mathrm{SP}}$) in SP magnetogram and the ordinate is the longitudinal flux density ($B_{\mathrm{L}}^{\mathrm{MDI}}$) of version 2008 MDI level 1.8 data. Dots represent raw data points and diamonds indicate mean values calculated for bins of 100 Mx cm^{-2} width. We excluded those points whose magnitude of $B_{\mathrm{L}}^{\mathrm{SP}}$ are larger than 2000 Mx cm^{-2} to make sure that no points selected will be influenced by the saturation effect in MDI magnetograms. We also excluded those points whose $B_{\mathrm{L}}^{\mathrm{SP}}$ are smaller than 200 Mx cm^{-2} to ensure that our points are those with good accuracy of measurements. Then, using these diamond points, we find an average of the ratios between $B_{\mathrm{L}}^{\mathrm{MDI}}$ and $B_{\mathrm{L}}^{\mathrm{SP}}$. This number is $R_2 = 0.752$ for this active region, by comparing the version 2008 MDI level 1.8 data observed at 19:15 UT (before the SP central observation time) and SP magnetogram using Method 1 (panel (c)) and is $R_2 = 0.673$ for the same pair of MDI and SP magnetograms, but using Method 2 (panel (d)). Similarly, by comparing the version 2008 MDI level 1.8 data observed at 20:51 UT (after the SP central observation time) and SP magnetogram, we get the numbers of 0.790 using Method 1 (panel (e)) and 0.703 using Method 2 (panel (f)). These numbers are also listed in Table 2, labeled as R_2^{M1} and R_2^{M2}, respectively. We see here that by using MDI magnetograms observed at different times and

Table 2 Results.

	Date (yy/mm/dd)	SP time	MDI time	R_1^{M1}	R_1^{M2}	$\overline{R_1}$	R_2^{M1}	R_2^{M2}	$\overline{R_2}$
1	2006/11/07	13:52 – 14:55	12:51	0.96	0.82	0.86	0.80	0.69	0.72
			14:27	0.91	0.74		0.76	0.61	
2	2006/11/08	02:57 – 03:41	01:39	0.89	0.83	0.89	0.71	0.67	0.71
			03:15	0.95	0.89		0.76	0.72	
3	2006/11/12	04:43 – 05:58	03:15	0.52	0.46	0.55	0.46	0.40	0.49
			04:51	0.65	0.58		0.58	0.51	
4	2006/11/13	21:30 – 22:25	20:51	0.71	0.60	0.67	0.65	0.55	0.62
			22:27	0.73	0.64		0.67	0.59	
5	2006/11/14	07:15 – 08:13	06:27	0.63	0.60	0.64	0.58	0.55	0.59
			08:03	0.65	0.68		0.60	0.62	
6	2006/11/15	11:10 – 12:27	09:39	0.72	0.42	0.65	0.66	0.38	0.59
			11:15	0.78	0.67		0.72	0.61	
7	2006/11/16	22:37 – 23:35	20:51	0.76	0.69	0.76	0.67	0.60	0.66
			22:27	0.80	0.77		0.70	0.67	
8	2006/11/18	22:20 – 23:18	20:51	0.98	1.05	1.02	0.76	0.82	0.79
			22:27	0.99	1.05		0.76	0.81	
9	2006/11/20	03:58 – 04:57	03:15	0.91	0.92	0.91	0.62	0.65	0.63
			04:51	0.85	0.96		0.58	0.67	
10	2006/12/09	03:40 – 04:43	03:15	0.74	0.77	0.78	0.66	0.68	0.69
			04:51	0.85	0.78		0.75	0.69	
11	2006/12/10	10:55 – 13:58	09:39	0.61	0.64	0.66	0.56	0.59	0.60
			11:15	0.67	0.70		0.62	0.64	
12	2006/12/11	20:00 – 21:03	19:15	0.81	0.73	0.79	0.75	0.67	0.73
			20:51	0.85	0.76		0.79	0.70	
13	2006/12/12	03:50 – 04:57	03:15	0.84	0.77	0.81	0.77	0.71	0.75
			04:51	0.85	0.80		0.78	0.73	
14	2006/12/13	04:30 – 05:34	03:15	0.89	0.84	0.88	0.81	0.76	0.79
			04:51	0.92	0.87		0.83	0.78	
15	2006/12/15	05:45 – 06:48	04:51	1.05	1.04	1.05	0.87	0.86	0.86
			06:27	1.06	1.04		0.87	0.86	
16	2006/12/16	07:50 – 08:53	06:27	1.08	1.07	1.07	0.81	0.82	0.81
			08:03	1.07	1.07		0.80	0.81	
17	2007/04/29	03:30 – 04:02	01:39	0.93	0.84	0.89	0.81	0.73	0.78
			03:15	0.94	0.87		0.82	0.76	
18	2007/04/30	18:35 – 19:39	17:39	0.74	0.74	0.75	0.68	0.68	0.69
			19:15	0.80	0.73		0.73	0.67	
19	2007/05/01	01:50 – 02:22	00:03	0.85	0.73	0.80	0.79	0.67	0.73
			01:39	0.89	0.71		0.82	0.65	
20	2007/05/02	00:15 – 00:47	00:03	0.62	0.79	0.64	0.57	0.72	0.59
			01:39	0.61	0.55		0.56	0.51	
21	2007/05/02	11:15 – 12:40	09:39	0.90	0.54	0.72	0.83	0.49	0.66
			11:15	0.90	0.56		0.83	0.51	

Table 2 (*Continued*)

	Date (yy/mm/dd)	SP time	MDI time	R_1^{M1}	R_1^{M2}	$\overline{R_1}$	R_2^{M1}	R_2^{M2}	$\overline{R_2}$
22	2007/05/03	06:14 – 06:46	04:51	1.01	0.85	0.94	0.91	0.77	0.86
			06:27	1.04	0.88		0.94	0.80	
23	2007/05/03	10:15 – 11:39	09:39	0.71	0.65	0.67	0.65	0.59	0.60
			11:15	0.68	0.63		0.62	0.57	
24	2007/05/04	01:25 – 01:57	00:03	1.07	0.92	1.00	0.95	0.82	0.89
			01:39	1.07	0.94		0.95	0.83	
25	2007/05/04	04:40 – 05:12	03:15	1.06	0.92	1.00	0.93	0.82	0.88
			04:51	1.06	0.95		0.94	0.83	
26	2007/05/06	05:00 – 05:32	03:15	1.10	1.03	1.06	0.86	0.81	0.83
			04:51	1.10	1.02		0.85	0.80	
27	2007/05/07	08:48 – 09:20	08:03	1.03	0.98	0.98	0.71	0.69	0.68
			09:39	0.95	0.94		0.65	0.66	
28	2007/06/06	02:39 – 03:41	01:39	0.93	0.85	0.89	0.84	0.77	0.80
			03:15	0.93	0.85		0.84	0.77	
29	2007/06/06	22:21 – 23:23	20:51	0.71	0.75	0.74	0.65	0.68	0.68
			22:27	0.74	0.77		0.68	0.70	
30	2007/06/07	19:45 – 20:42	19:15	0.69	0.66	0.68	0.63	0.61	0.62
			20:51	0.69	0.68		0.64	0.61	
31	2007/06/08	07:10 – 08:13	06:27	0.78	0.67	0.73	0.72	0.62	0.67
			08:03	0.79	0.68		0.73	0.63	
32	2007/06/10	03:26 – 04:29	03:15	0.86	0.76	0.81	0.76	0.68	0.71
			04:51	0.86	0.76		0.76	0.67	
33	2007/06/12	01:26 – 02:29	00:03	0.95	0.90	0.90	0.75	0.72	0.72
			01:39	0.89	0.85		0.71	0.68	
34	2007/06/12	12:55 – 13:53	11:15	0.88	0.89	0.88	0.66	0.68	0.67
			12:51	0.85	0.90		0.63	0.68	
35	2007/06/13	06:57 – 07:56	06:27	0.76	0.82	0.80	0.53	0.58	0.56
			08:03	0.83	0.80		0.58	0.56	
36	2007/06/27	19:10 – 19:43	17:39	0.93	0.83	0.92	0.75	0.67	0.74
			19:15	1.05	0.88		0.85	0.71	
37	2007/06/29	01:00 – 01:32	00:03	1.00	0.91	0.97	0.87	0.79	0.85
			01:39	1.05	0.93		0.92	0.81	
38	2007/06/30	09:47 – 10:18	08:03	0.86	0.77	0.84	0.78	0.70	0.76
			09:39	0.91	0.81		0.83	0.73	
39	2007/07/01	13:32 – 14:14	12:51	0.84	0.73	0.78	0.78	0.66	0.72
			14:27	0.82	0.73		0.75	0.67	
40	2007/07/02	12:17 – 12:56	11:15	0.83	0.70	0.78	0.76	0.64	0.71
			12:51	0.86	0.73		0.78	0.66	
41	2007/07/13	19:07 – 20:11	17:39	0.86	0.80	0.85	0.80	0.73	0.78
			19:15	0.90	0.82		0.83	0.75	
42	2007/07/18	07:28 – 08:31	06:27	0.88	0.78	0.88	0.67	0.62	0.68
			08:03	0.98	0.89		0.74	0.69	

Table 2 (*Continued*)

	Date (yy/mm/dd)	SP time	MDI time	R_1^{M1}	R_1^{M2}	$\overline{R_1}$	R_2^{M1}	R_2^{M2}	$\overline{R_2}$
43	2007/08/25	07:57 – 08:29	05:51	0.87	0.80	0.87	0.77	0.70	0.77
			09:39	0.96	0.86		0.85	0.76	
44	2007/08/27	07:34 – 08:06	04:51	0.75	0.70	0.73	0.69	0.64	0.67
45	2007/08/28	07:06 – 07:38	08:03	0.82	0.71	0.76	0.75	0.65	0.70
46	2007/08/29	03:57 – 04:29	08:03	0.69	0.58	0.64	0.62	0.52	0.57
47	2007/08/29	07:12 – 07:44	08:03	0.82	0.71	0.77	0.74	0.65	0.69
48	2007/09/05	04:00 – 04:32	03:15	0.86	0.75	0.82	0.69	0.61	0.67
			04:51	0.92	0.77		0.74	0.63	

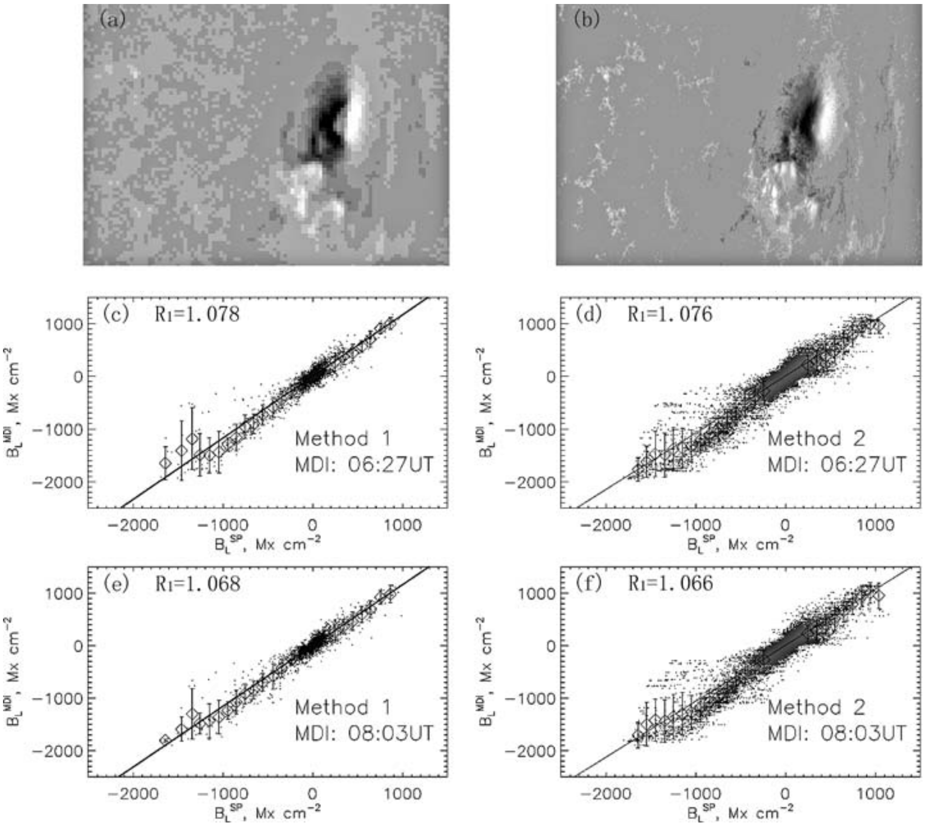

Figure 3 An example of a near disk-limb active region AR 10930, observed on 16 December 2006. Its FOV is 220 × 163 arcsec^2. (a): The version 2007 MDI magnetogram observed at 08:03 UT. (b): The longitudinal magnetogram of SP observed between 07:50 UT and 08:53 UT. (c): Correlation between the longitudinal flux densities of SP and MDI. The MDI data used are the version 2007 level 1.8 data. The MDI magnetogram is observed at 06:27 UT. Here the SP magnetogram was rescaled using "Method 1." (d): Same as panel (c), but here the MDI magnetogram was rescaled using "Method 2." (e): Same as panel (c), but here the MDI magnetogram is observed at 08:03 UT. (f): Same as panel (d), but here the MDI magnetogram is observed at 08:03 UT.

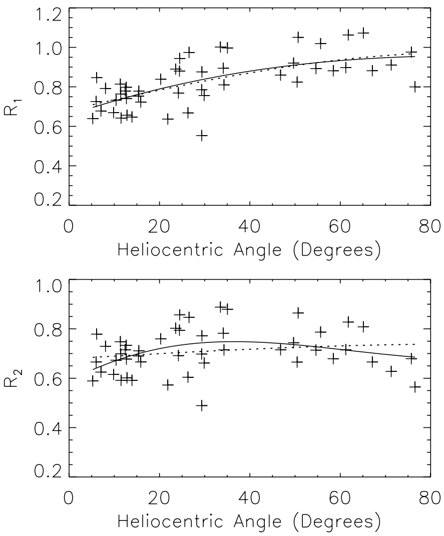

Figure 4 Top: The variation of $\overline{R_1}$ with the heliocentric angle (ρ). The solid line shows the result of the second-order polynomial fitting: $y = 0.66 + 0.43x - 0.13x^2$ and the dotted line shows the result of the first-order polynomial fitting: $y = 0.68 + 0.29x$. Bottom: Same as the top panel, but for $\overline{R_2}$ values. Solid line gives $y = 0.59 + 0.53x - 0.45x^2$ and dotted line gives $y = 0.68 + 0.06x$.

using different scaling methods the ratios we obtained do not differ a lot. This indicates that the ratios we obtained are not largely influenced by the evolution of the magnetic field during the SP scan as well as the scaling methods we used. We then average these four numbers to get a number of 0.73 and use this number ($\overline{R_2}$ in Table 2) as the result of the comparison for this active region.

Figure 3 gives an example of how we get R_1 for the same active region, but observed on 16 December 2006 near the solar limb. Its latitude is 5.3° and longitude 65.0°. Its FOV is 220 × 163 arcsec^2 and it is the 16th region listed in Table 1. The analysis processes are similar to those described above, except that here we used the version 2007 MDI level 1.8 data. The four ratios we obtained are 1.078 (panel (c)), 1.076 (panel (d)), 1.068 (panel (e)), and 1.066 (panel (f)) for this region. The average value of these four ratios is $\overline{R_1} = 1.07$, as listed in Table 2.

3. Results and Summary

Table 2 lists the obtained $\overline{R_1}$ and $\overline{R_2}$ for the 48 regions in the sample. From Table 2, we see that most of $\overline{R_1}$ and all of $\overline{R_2}$ are smaller than 1. This means that compared to the SP measurements, MDI calibrations still underestimate the flux density. The average value of $\overline{R_1}$ is 0.82 ± 0.13 and the average value of $\overline{R_2}$ is 0.71 ± 0.09.

As we intentionally chose, the magnetograms we analyzed here are located at different positions on the solar disk. Figure 4 shows the variation of $\overline{R_1}$ and $\overline{R_2}$ with the heliocentric angle (ρ). We see that the $\overline{R_1}$ values show a clear disk-position dependence, whereas this disk-position dependence is very weak for $\overline{R_2}$ values. To show this, we fit these ratios using both first-order and second-order polynomial functions. The results are plotted in Figure 4. The fitting results do show that $\overline{R_1}$ is more dependent on ρ.

In summary, by comparing cotemporal SP and MDI magnetograms, we find that current version 2008 MDI level 1.8 data may still underestimate the flux density. The average ratio between version 2008 MDI level 1.8 magnetograms and SP magnetograms is 0.68. Our comparison also shows that version 2008 MDI level 1.8 data have successfully removed the center-to-limb variation that appeared in the version 2007 MDI level 1.8 data, as estimated by Ulrich *et al.* (2009).

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References

Ai, G.X., Hu, Y.: 1987, *Acta Astron. Sin.* **27**, 173.
Berger, T.E., Lites, B.W.: 2002, *Solar Phys.* **208**, 181.
Berger, T.E., Lites, B.W.: 2003, *Solar Phys.* **213**, 213.
Elmore, D.F., Lites, B.W., Tomczyk, S., Skumanich, A.P., Dunn, R.B., Schuenke, J.A., Streander, K.V., Leach, T.W., Chambellan, C.W., Hull, H.K.: 1992, In: Goldstein, D.H., Chipman, R.A. (eds.) *Polarization Analysis and Measurement*, *Proc. SPIE* **1746**, 22.
Ichimoto, K., Lites, B., Elmore, D., Suematsu, Y., Tsuneta, S., Katsukawa, Y., *et al.*: 2008, *Solar Phys.* **249**, 233.
Liu, Y., Zhao, X.P., Hoeksema, J.T.: 2004, *Solar Phys.* **219**, 39.
Liu, Y., Norton, A.A., Scherrer, P.H.: 2007, *Solar Phys.* **241**, 185.
Rees, D.E., Semel, M.D.: 1979, *Astron. Astrophys.* **74**, 1.
Scherrer, P.H., Bogart, R.S., Bush, R.I., Hoeksema, J.T., Kosovichev, A.G., Schou, J., *et al.*: 1995, *Solar Phys.* **162**, 129.
Skumanick, A., Lites, B.W.: 1987, *Astrophys. J.* **322**, 473.
Tran, T., Bertello, L., Ulrich, R.K., Evans, S.: 2005, *Astrophys. J. Suppl.* **156**, 295.
Tsuneta, S., Ichimoto, K., Katsukawa, Y., Nagata, S., Otsubo, M., Shimizu, T., *et al.*: 2008, *Solar Phys.* **249**, 167.
Ulrich, R.K., Bertello, L., Boyden, J.E., Webster, L.: 2009, *Solar Phys.* **255**, 53.