# A Comparison of Co-temporal Vector Magnetograms Obtained with HMI/SDO and SP/Hinode (Postprint)

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## Abstract

Accurate measurement of magnetic fields is essential for understanding the formation and evolution of solar magnetic fields. Currently, two types of instruments are employed for solar magnetic field measurements: filter-based magnetographs and Stokes polarimeters. The former yields magnetograms with high temporal resolution, whereas the latter provides more accurate magnetic field measurements. Calibrating magnetograms obtained by filter-based magnetographs against those acquired by Stokes polarimeters constitutes an effective approach to combine the advantages of both instrument types. Our previous studies have demonstrated that, compared to magnetograms from the Spectro-Polarimeter (SP) onboard Hinode, magnetograms from both the filter-based Solar Magnetic Field Telescope (SMFT) at the Huairou Solar Observing Station and the filter-based Michelson Doppler Imager (MDI) onboard SOHO exhibit underestimation of flux densities and systematic center-to-limb variations. Here, utilizing a sample of 75 vector magnetograms of stable alpha sunspots, we compare vector magnetograms obtained by the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO) with co-temporal vector magnetograms acquired by SP/Hinode. Our analysis indicates that both the longitudinal and transverse flux densities in HMI/SDO magnetograms are in close agreement with those in SP/Hinode magnetograms, and that systematic center-to-limb variations in HMI/SDO magnetograms are minimal. Our study suggests that employing a filter-based magnetograph to construct low spectral resolution Stokes profiles, as implemented by HMI/SDO, can largely eliminate the disadvantages of filter-based measurements while preserving the advantage of high temporal resolution.

# Full Text

## Preamble

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### A Comparison of Co-temporal Vector Magnetograms Obtained with HMI/SDO and SP/Hinode

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## Abstract

Accurate measurement of magnetic fields is crucial for understanding the formation and evolution of solar magnetic fields. Currently, there are two types of solar magnetic field measurement instruments: filter-based magnetographs and Stokes polarimeters. The former provides high temporal resolution magnetograms, while the latter yields more accurate magnetic field measurements. Calibrating magnetograms obtained by filter-based magnetographs with those from Stokes polarimeters offers an effective way to combine the advantages of both approaches. Our previous studies have shown that, compared to magnetograms from the Spectro-Polarimeter (SP) on board Hinode, both the filter-based Solar Magnetic Field Telescope (SMFT) of the Huairou Solar Observing Station and the filter-based Michelson Doppler Imager (MDI) aboard SOHO underestimate flux densities in their magnetograms, and systematic center-to-limb variations are present in both instruments.

Here, using a sample of 75 vector magnetograms of stable alpha sunspots, we compare vector magnetograms obtained by the Helioseismic and Magnetic Imager (HMI) aboard the Solar Dynamics Observatory (SDO) with co-temporal vector magnetograms acquired by SP/Hinode. Our analysis shows that both the longitudinal and transverse flux densities in the HMI/SDO magnetograms are very close to those in the SP/Hinode magnetograms, and the systematic center-to-limb variations in the HMI/SDO magnetograms are very minor. Our study suggests that using a filter-based magnetograph to construct a low spectral resolution Stokes profile, as implemented by HMI/SDO, can largely eliminate the disadvantages of filter-type measurements while retaining the advantage of high temporal resolution.

**Key words:** The Sun – Sun: magnetic fields – Sun: photosphere – (Sun:) sunspots

## 1. Introduction

It is well known that the Sun's magnetic field plays an important role in controlling solar activities such as coronal mass ejections (Zhang & Low 2005). Understanding how solar magnetic fields are produced (Charbonneau 2014) and evolve is thus essential. For this purpose, accurate measurement of the magnetic field (Stenflo 1994) with good spatial and temporal resolution becomes vital.

Photospheric magnetic field measurements are primarily based on two types of solar magnetic field telescopes: filter-based magnetographs and Stokes polarimeters. Both utilize the Zeeman effect to measure magnetic fields but employ different approaches, each with distinct advantages and disadvantages. A Stokes polarimeter measures the full spectra of Stokes I, Q, U, and V of a spectral line. An inversion code is applied to derive the vector magnetic field together with other thermal parameters. Since the full spectrum (with high spectral resolution in most cases) is used in the inversion, the derived magnetic field is usually more accurate. Additionally, a parameter called the filling factor (f) can be obtained, providing a more accurate measurement of the true field strength, particularly for magnetic fields outside active regions where filling factors are usually significantly less than 1. However, because the polarimeter must scan the field of view step by step to obtain a magnetogram, the temporal resolution of the observation is typically low. For example, the Spectro-Polarimeter (SP) on board Hinode requires 40–60 minutes to scan an area covering a typical active region.

A magnetograph measures Stokes I, Q, U, and V maps at only one or at most several fixed wavelengths. Pre-calculated calibration coefficients or calibration maps are typically used to obtain vector magnetograms. The advantage of magnetograph measurements is their high temporal resolution—while it may take tens of minutes or even hours for a Stokes polarimeter to generate a vector magnetogram of a typical solar active region, a filter-based magnetograph can obtain a full-disk vector magnetogram in only a few minutes. However, accurate calibration is not an easy undertaking (Su & Zhang 2004), and many other parameters may influence the calibration.

The difficulty in obtaining accurate calibration for filter-based magnetographs is evident from the fact that Michelson Doppler Imager (MDI) data aboard SOHO have been recalibrated multiple times. The original calibration (Scherrer et al. 1995) used the standard center-of-gravity method. Later, Berger & Lites (2003) compared MDI magnetograms with co-temporal magnetograms from the Advanced Stokes Polarimeter (ASP) and found that MDI magnetograms underestimated flux density by a factor of about 1.6. Subsequently, based on detailed cross-correlation between magnetograms simultaneously obtained by the Mount Wilson Observatory and MDI/SOHO (Tran et al. 2005), the MDI team recalibrated all full-disk MDI magnetograms in October 2007, referring to these data as "version 2007 MDI level-1.8 data." However, Ulrich et al. (2009) later recommended a new calibration that multiplies the previous calibration map (Tran et al. 2005) by a factor dependent on distance from disk center. This correction was applied to MDI data in December 2008, resulting in "version 2008 MDI level-1.8 data."

Since Berger & Lites (2003) first compared MDI magnetograms with co-temporal ASP magnetograms to calibrate MDI data, comparing magnetograms from filter-based magnetographs with those from Stokes polarimeters has become a popular approach. On September 22, 2006, the Hinode satellite (Kosugi et al. 2007) was launched. The Stokes polarimeter SP/Hinode began providing what are possibly the most accurate vector magnetograms to date. It is therefore prudent to use SP/Hinode magnetograms to calibrate various filter-based magnetograph data.

Wang et al. (2009a) compared co-temporal magnetograms from SP/Hinode with those from the Solar Magnetic Field Telescope (SMFT) of the Huairou Solar Observing Station to check the linear calibrations of SMFT vector magnetograms. They found that the calibration coefficients used for SMFT (Su & Zhang 2004) underestimated flux density and that a strong center-to-limb variation in the calibration coefficients had not been accounted for.

Using the same approach, Wang et al. (2009b) compared co-temporal active region magnetograms from MDI/SOHO and SP/Hinode. They found that although the most recent calibration of "version 2008 MDI level-1.8 data" had largely removed the center-to-limb variation that was severe in "version 2007 MDI level-1.8 data," the magnetic flux density in "version 2008 MDI level-1.8 data" remained lower than that in SP/Hinode magnetograms. The average ratio between "version 2008 MDI level-1.8 data" and SP/Hinode magnetograms is 0.71, and 0.82 for "version 2007 MDI level-1.8 data."

In early 2010, the Solar Dynamics Observatory (SDO) was launched. The Helioseismic and Magnetic Imager (HMI) on board SDO began providing continuous observations of full-disk vector magnetograms from space. In this paper, we carry out a cross-calibration between HMI/SDO and SP/Hinode vector magnetograms. The data and sample are described in Section 2, analysis and results presented in Section 3, and a brief conclusion and discussion given in Section 4.

## 2. The Data and the Samples

HMI (Scherrer et al. 2012) aboard SDO is designed to study photospheric magnetic fields and solar oscillations. Two 4096 × 4096 pixel CCD cameras on HMI provide full-polarimetric filtergrams at six carefully selected spectral points of the Fe I 6173 Å line. With a spatial resolution of about 0.5 × 0.5 per pixel, observations at the six spectral points form a low-resolution spectrum at each pixel. Unlike other filter-based magnetographs where magnetograms are obtained using pre-calculated calibration coefficients or calibration maps, HMI vector magnetograms are derived using a Milne–Eddington-based inversion code (Borrero et al. 2011), where the filling factor has been taken into account. As we will see throughout this paper, this inversion approach has successfully removed most disadvantages of filter-type instruments caused by rough pre-calibrations.

For scientific investigations, the HMI team provides a multitude of data products. In this paper, we use the hmi.B_{720s} data series. The "720s" indicates that a tapered temporal average is performed every 720 seconds using 360 filtergrams collected over a 1350-second interval. The vector magnetograms in this series are in native coordinates, i.e., a 2D array as measured at each CCD pixel. Since our study focuses on field strengths of longitudinal and transverse fields, the 180° disambiguation solution becomes irrelevant, even though three different solutions have been provided by the HMI team.

SP/Hinode obtains two magnetically sensitive Fe lines at 630.15 and 630.25 nm and nearby continuum using a 0.16 × 164 slit. The SP/Hinode data are calibrated (Lites & Ichimoto 2013) and inverted at the CSAC (Community Spectro-polarimetric Analysis Center, http://www.csac.hao.ucar.edu/). The inversion is based on the assumption of a Milne–Eddington atmosphere model and a nonlinear least-squares fitting technique, where analytical Stokes profiles are fitted to observed profiles. The inversion yields 36 parameters including the three components of magnetic field and the filling factor. The resolution of the magnetograms is either 0.16 pixel$^{-1}$ for normal maps or 0.32 pixel$^{-1}$ for fast maps, with map durations typically lasting tens of minutes.

Our sample consists of 75 pairs of vector magnetograms, with each pair comprising one HMI magnetogram and one co-temporal SP magnetogram. These are from four alpha sunspot active regions: NOAA 11084, NOAA 11092, NOAA 11216, and NOAA 11582. Alpha sunspots were chosen because they are very stable, exhibiting minimal evolution during their passage across the solar disk. Since HMI magnetograms are taken at "one-time" (although integration time is 720 seconds) while co-temporal SP magnetograms typically require tens of minutes to scan, using stable sunspot magnetograms significantly reduces errors induced by sunspot evolution.

We first downloaded all SP magnetograms of these four sunspots, yielding 75 SP magnetograms. The on-disk positions of these 75 magnetograms are plotted in Figure 1, where different active regions are presented in different colors. These magnetograms cover a wide range of longitudes on the solar disk, from near the solar limb to near disk center. This is why these four active regions were selected—they provide multiple observations from center to limb.

After downloading these SP magnetograms, we read the FITS headers and calculated the middle times of each SP observation. We then accessed the HMI webpage (http://hmi.stanford.edu/magnetic/) and downloaded full-disk vector magnetograms whose observation times are closest to the middle times of the SP magnetograms. Information on SP observation time periods, middle times of SP observations, and HMI observation times for these 75 magnetogram pairs is listed in Tables 1 and 2. Also listed in Tables 1 and 2 are the latitudes ( ), longitudes ($\phi$), and heliocentric angles ( ) of the sunspots in these 75 magnetogram pairs.

## 3. Analysis and Results

To compare the 75 magnetogram pairs in our sample, we first perform alignment and image scaling to ensure each pair has the same field of view and pixel size for pixel-by-pixel comparison.

To accomplish this, we first cut the field of view of each downloaded SP magnetogram. Examples are given in Figure 2, which shows continuum intensity maps (Ic, left panels) and longitudinal magnetograms (BL, right panels) for the four active regions. For each active region, we present the observation taken closest to the central meridian. While each map in Figure 2 shows the full field of view of the SP observation, the red square in each panel outlines the region we cut for this study, focusing on sunspot regions while largely excluding network fields.

After cutting the 75 SP Ic, BL, and BT maps, we use the CONGRID function in IDL to reformat these maps to match the pixel size of HMI maps. For alignment, we first use the gravity center of the SP Ic map to obtain a rough position of the sunspot in the HMI full-disk Ic map. We then apply a cross-correlation algorithm to overlay the reformed SP BL map onto the HMI full-disk BL map and cut out the same field of view as the SP map to obtain the corresponding HMI BL map. The same alignment is applied to the HMI full-disk BT map to extract the studied HMI BT map. For the HMI data, the transverse field component is calculated as BT = B sin $\gamma$, where B is the inversion-derived field strength and $\gamma$ is the field inclination. The filling factor is omitted here because in HMI inversion it has been set to 1. Also noteworthy is that latitudes, longitudes, and heliocentric angles presented in Tables 1 and 2 are estimated using the gravity center of the sunspot in the HMI full-disk Ic map. We did not use pointing information from the SP FITS header because it can be incorrect by dozens of arcseconds, as noted by Fouhey et al. (2023).

The results of alignment and image scaling are demonstrated in the examples shown in Figures 3 and 4. The top panels of Figure 3 display SP BL, HMI BL, SP BT, and HMI BT maps (left to right) for active region NOAA 11582 when observed near disk center (No. 61 pair in Table 2). The alignment works well, as also evident in the top panels of Figure 4, which show the same maps for NOAA 11582 when observed near the solar limb (No. 75 pair in Table 2).

After successful alignment and image scaling, we perform linear fitting between SP BL data points and HMI BL data points. An example is given in the bottom left panel of Figure 3 for the No. 61 pair. Blue plus symbols represent BL values, with the x-axis showing SP values and the y-axis showing HMI values. The red thick line shows the linear fitting result, y = RL ·x, where data points with |BL| < 100 G have been excluded. The fitting yields y = 0.964x, meaning the flux density in the HMI BL map is about 96.4% of that in the SP BL map—already very close to 1. Note that on average, the flux density in version 2008 MDI data is only 71% of that in SP (Wang et al. 2009b).

Similarly, we perform linear fitting between SP BT data points and HMI BT data points. The bottom right panel of Figure 3 shows the fitting result between the SP BT map and HMI BT map. Blue plus symbols represent BT values, with the x-axis indicating SP values and the y-axis indicating HMI values. The red thick line shows the linear fitting result, y = RT ·x, where data points with |BT| < 200 G (approximately the 2$\sigma$ noise level for transverse fields) have been excluded. The fitting yields y = 1.001x, meaning the flux density in the HMI BT map is very close to that in the SP BT map—closer even than the HMI BL map relative to the SP BL map.

The bottom panels in Figure 4 show fitting results for the No. 75 pair, giving RL = 0.984 and RT = 1.002. The same trend is evident: flux densities in both HMI BL and BT maps are very close to those in SP maps, indicating that the problem of flux density underestimation present in previous SMFT and MDI data has been largely overcome.

The fitting results for all 75 RL and RT values are listed in Tables 1 and 2 and plotted in Figure 5. Red filled circles represent the 75 RL values, while blue filled circles represent the 75 RT values, with heliocentric angle ( ) on the x-axis. The solid red line shows the linear fitting result for the 75 RL values: RL = 0.91 + 0.05 sin . The solid blue line shows the linear fitting result for the 75 RT values: RT = 0.99 − 0.007 sin . All RL and RT values are close to 1, and the center-to-limb variation (dependence on sin ) is small. The mean RL value is 0.932 and the mean RT value is 0.984.

For comparison, the average ratio between "version 2008 MDI level-1.8 data" and SP/Hinode magnetograms is 0.71, and 0.82 for "version 2007 MDI level-1.8 data." A similar linear fitting (Wang et al. 2009b) yields y = 0.68 + 0.06 sin for version 2008 MDI level-1.8 data and y = 0.68 + 0.29 sin for version 2007 MDI level-1.8 data. These two MDI fitting results are also plotted in Figure 5 as purple (2007 version) and black (2008 version) lines. Comparing the four solid lines reveals that HMI data have largely overcome both the flux density underestimation and center-to-limb variation problems present in previous MDI magnetograms.

## 4. Conclusion and Discussion

In this paper we compared co-temporal alpha sunspot magnetograms obtained by HMI/SDO and SP/Hinode. A pixel-by-pixel comparison shows that the flux density in HMI/SDO longitudinal magnetograms is about 0.93 that of SP/Hinode, and the flux density in HMI/SDO transverse magnetograms is about 0.98 that of SP/Hinode. Moreover, the center-to-limb variation, which was severe in previous filter-type magnetograph data, is very minor in HMI/SDO data. We conclude that HMI/SDO has largely overcome the problems found in previous filter-type data: underestimation of flux density and severe center-to-limb variation. Our investigation indicates that using a filter-based magnetograph to scan a few spectral points to form a low spectral resolution Stokes profile, as implemented in HMI/SDO, can largely remove the disadvantages of filter-type magnetograph measurements while retaining the advantage of high temporal resolution.

With this conclusion, a few clarifications are in order. First, there are situations that low spectral resolution measurements cannot address. Specifically, in complicated magnetic field configurations, complex circular polarization profiles with central reversal cannot be detected by low spectral resolution observations like HMI/SDO. Second, with large-aperture telescopes such as DKIST and EST becoming available, the temporal resolutions of magnetograms obtained by Stokes polarimeters are improving significantly. Finally, it should be noted that both instrument types share the limitation that true 3D (two spatial dimensions plus one dispersion dimension) polarimetric data cannot be obtained simultaneously. Real-time 3D polarimetric data will be obtained by future instruments based on integral field units like those to be mounted in FASOT (Qu 2011; Qu et al. 2017, 2022).

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