A First Look At Magnetic Field Data Products From HMI/SDO

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Abstract.

The Helioseismic and Magnetic Imager (HMI) (Scherrer & Schou 2010) is one of the three instruments aboard the Solar Dynamics Observatory (SDO) that was launched on 11 February 2010 from Cape Canaveral, Florida. The instrument began to acquire science data on March 24. The regular operations started on May 1. HMI measures the
Doppler velocity and line-of-sight magnetic field in the photosphere at a cadence of 45 seconds, and vector magnetic field at a 135-second cadence, with a 4096×4096 pixels full disk coverage. Vector magnetic field data is usually averaged over 720 seconds to suppress the p-modes and increase the signal-to-noise ratio. The spatial sampling is about 0.5 arcsec per pixel. The spectral line of HMI is the FeI 6173 Å absorption line with a Landé factor of 2.5. These data are further used to produce higher level data products through the pipeline at the HMI-AIA Joint Science Operations Center (JSOC)-Science Data Processing (Scherrer et al. 2010) at Stanford University. In this paper, we briefly describe these data products, and demonstrate the performance of the HMI instrument. We conclude that the HMI is working extremely well.

1. Introduction

The HMI instrument (Schou et al. 2010a) is a filtergraph with a full disk coverage at 4096×4096 pixels. The spatial resolution is about 1” with a 0.5” pixel size. The width of the filter profiles is 76 mÅ. The spectral line of HMI is the FeI 6173Å absorption line formed in the photosphere (Norton et al. 2006). There are two CCD cameras in the instrument, the “front camera” and the “side camera” (Schou et al. 2010a). The front camera acquires the filtergrams at 6 wavelengths along the line FeI 6173Å in two polarization states with 3.75 seconds between the images. It takes 45 seconds to acquire a set of 12 filtergrams. This set of data is used to derive the Dopplergrams and the line-of-sight magnetograms. The side camera is dedicated to measuring the vector magnetic field. It takes 135 seconds to obtain the filtergrams in 6 polarization states at 6 wavelengths positions. The Stokes parameters IQUV are computed from those measurements, and are further inverted to retrieve the vector magnetic field. Intensity, line depth and line width are also derived from the filtergrams. Higher level data products are further produced from these data automatically through the HMI-AIA Joint Science Operations Center (JSOC)-Science Data Processing (SDP) at Stanford University (Scherrer et al. 2010). Detailed information, description and calibration of the HMI instrument can be found in Schou et al. (2010a,b), Couvidat et al. (2010a), and Wachter et al. (2010). In this paper, we present HMI data products and instrument performance. In Section 2, we briefly describe HMI data and the higher level magnetic field data products. A detailed description of HMI magnetic field data products is given by Hoeksema et al. (2010). In Section 3, we demonstrate the performance of the HMI instrument. We summarize our results in Section 4. Details of other data products, especially those from the Dopplergrams with the helioseismology techniques, are published elsewhere (Bogart et al. 2010; Couvidat et al. 2010b; Larson et al. 2010; Parchevsky et al. 2010; Zhao et al. 2010), and will not be a focus in this paper.

2. Data products

Shown in Fig. 1 is the HMI data processing in the JSOC pipeline. The observed filtergrams, at left, produce the Stokes I and V, Stokes I, Q, U, V, and the continuum brightness. The Stokes I and V, obtained from the front camera, are used to compute the Doppler velocity (green rectangle) and the line-of-sight magnetic field (white rectangle). Similar to the MDI magnetograms (Scherrer et al. 1995), the line-of-sight magnetic field is computed from the difference of two Doppler velocities measured from the
Figure 1. The diagram of the HMI data processing in the JSOC pipeline. The Stokes parameters $I$ and $V$, and Stokes parameters $I$, $Q$, $U$, $V$, are directly derived from the observed filtergrams. The continuum brightness is calculated from the filtergrams. The Dopplergrams and the line-of-sight magnetograms are computed from the Stokes $I$ and $V$, and the full disk vector magnetic field is derived from the Stokes $I$, $Q$, $U$, $V$. These data are further processed to produce the high level data products, which are listed in the right column.

left and right circular polarizations. As an input, the Doppler velocity further produces higher level data products that are listed in the orange and purple rectangles in the right column (rows 1-7). These data products are normally used for the research purposes of helioseismology. The line-of-sight magnetograms are mapped on various coordinates systems for further uses that are described later in Section 2.1. The Stokes $I$, $Q$, $U$, $V$ from the side camera (pink rectangle in the second column) are derived from the filtergrams at a cadence of 135 seconds, or from the filtergrams averaged over a certain time interval (currently a 720-second average) to suppress the p-modes and increase the signal-to-noise ratio. This average needs extra filtergrams before and after the expected temporal window because the filtergrams need to be interpolated onto a regular and finer grid before averaging. For the 720-second average, the temporal window used is actually 1215 seconds. The weights for the extra data are different from the rest of the data. These Stokes parameters are inverted to obtain the vector magnetic field. The vector magnetic field data further produce higher level data products that are listed in the pink rectangles in the right column (rows 9-11), which are described in Section 2.2. Usually the Doppler velocity and line-of-sight magnetic field are also computed from the averaged Stokes $I$ and $V$ using the same algorithm as that for the front camera data. The continuum brightness (“brightness images”) in the yellow rectangle at the bottom is a derived product computed from the filtergrams, since true continuum is not sampled in the standard filtergram sets from either camera.
Figure 2. The data processing map for the line-of-sight magnetic field data products. The white and green rectangles represent the temporary and archived data products, respectively. The pink rectangles with black shadow denote the names of the JSOC modules that produce the products. The parenthetical abbreviations here refer to the institutions developing the codes. The diagram at the left shows the definitive data products; at the right are the near-real-time (NRT) data products (or the quick-look data products).

Figure 3. Same as Fig. 2, but for the vector magnetic field data products.

There are two categories for the HMI data, the near-real-time (NRT) data (quick-look data) and the definitive data. The NRT data are usually available within minutes after the data are acquired. The main purposes of the NRT data are monitoring the
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Figure 4. The active regions are automatically identified in the JSOC. Left: A line-of-sight magnetogram taken on March 29, 2010. The active region, AR11057, was identified, and bounded by a rectangle. Right: The vector magnetic field of this active region derived by VFISV. From top to bottom are inclination, azimuth, and strength of the vector magnetic field. The $180^\circ$ degree ambiguity of the azimuth is solved. The scale of x- and y-axis is 0.5" per pixel.

instrument and providing information for space weather forecast. Most NRT data are temporary and will be removed later. The definitive data will be archived. They consist of three different types of data products: the standard, the on-demand, and the on-request. The standard data products are completed on regular cadence about one day after the data are acquired; the on-demand data products are completed for a small fraction of data when interesting things such as flares happen or whenever requested by a user; the on-request data products will be generated as resources allow, and completed when the system resources allow. In the following sections, we describe the line-of-sight magnetic field data products (Section 2.1), the vector magnetic field data products (Section 2.2), and show examples of the data products (Section 2.3).

Figure 5. Left: The vector magnetic field of AR11057 deprojected to the heliographic coordinates with the Mercator projection method. The image is the vertical magnetic field, and the arrow represents the horizontal field. Only the field with the vertical component greater than 100 G is plotted here. Right: The non-linear force-free field modeling of the active region AR11060 at 02:00 UT of April 8, 2010 computed from the HMI vector magnetic field data. The algorithm used here was developed by Wheatland et al. (2000); Wiegelmann (2004); Wiegelmann et al. (2006). The vector field data was pre-processed, as proposed by Wiegelmann et al. (2006).
Figure 6. First test run result of the DAVE4VM (Schuck 2008) module on an HMI vector field data series. **Left**: One of the input vector magnetic field data of the active region AR11084 on July 1, 2010. The background image is the vertical component of magnetic field with negative field in black and positive field in white. The blue arrows denote the horizontal field. **Right**: The derived horizontal flow velocity in orange arrows. The background image is again the vertical magnetic field.

Figure 7. The synoptic chart of the line-of-sight magnetic field for the Carrington rotation CR2096. The X-axis denotes longitude in degree, and the Y-axis is in Sin(latitude). The image is scaled to \( \pm 50 Mx/cm^2 \)

2.1. Line-of-sight magnetic field data products

Fig. 2 shows the data processing flow of the line-of-sight magnetograms. The line-of-sight magnetograms are either derived from the *front camera* Stokes I and V at a 45-second cadence, or from the *side camera* averaged Stokes I and V. Currently the average is done over 720 seconds. We use "45-s magnetogram" to refer to the *front camera* magnetograms, and "720-s magnetogram" to the *side camera* magnetograms derived from the 720-second averaged Stokes I and V hereafter. Since the *side camera* measures 6 polarizations, only one third of this 720-second average window is spent for measuring the left and right circular polarizations that are used to derive the line-of-sight magnetograms. The white rectangles represent temporary data, while the green
rectangles represent archived data that include the standard, the on-demand and the on-request data products. The pink rectangles with black shadow denote the pipeline modules that produce the products. The parenthetical abbreviations here refer to the institutions developing the codes. On the left are the definitive line-of-sight field data products, and on the right are the NRT data products. The definitive data products include various synoptic maps and magnetogram movies. Also included are the coronal and heliospheric structures modeled by a Potential Field Source Surface (PFSS) model (Schatten et al. 1969; Altschuler & Newkirk 1969; Hoeksema et al. 1982), or a 3D MHD simulation (Hayashi 2005). Solar wind speed and the polarity of the interplanetary magnetic field computed from synoptic maps using the empirical Wang-Sheeley-Arge (WSA) model (Wang & Sheeley 1990; Arge & Pizzo 2000), surface flow inferred from time-series magnetograms using the algorithm FLCT (Fisher & Welsch 2008), and patches of the active regions identified and bounded by a feature recognition model (Turmon et al. 2002), are also given here. The NRT data products include synoptic maps and magnetogram movies. More NRT data products, such as corona and heliosphere modeling and solar wind speed, may also be produced.

![Image](image1)

Figure 8.  
**Left:** The open field lines computed from the synoptic chart shown in Fig. 7 based on the Potential Field Source Surface (PFSS) model. The blue and red lines represent the open fields with positive and negative polarities, respectively. The yellow lines denote the open field from a large coronal hole that is a source of the fast wind. The source surface is set at 2.5 solar radius.  
**Right:** The field lines of the magnetic field computed from the synoptic chart using a 3D MHD simulation (Hayashi 2005). The blue and red areas on solar surface represent the positive and negative fields, respectively.

### 2.2. Vector magnetic field data products

Fig. 3 shows the data flow for the vector magnetic field. A 720-second average of the Stokes parameters I, Q, U, V, taken by the side camera, are inverted to produce the vector magnetic field using an inversion algorithm Very Fast Inversion of the Stokes Vector (VFISV). VFISV is a Milne-Eddington (ME) based approach developed at HAO (Borrero et al. 2010). The 180° degree ambiguity of the azimuth is solved based on the “minimum energy” algorithm (Metcalf 1994; Metcalf et al. 2006; Leka et al. 2009).
Figure 9. **Left:** The solar wind speed in the Carrington Rotation CR2096 calculated from the Wang-Sheeley-Arge (WSA) model (Wang & Sheeley 1990; Arge & Pizzo 2000). From top to bottom are the solar wind speeds on the source surface and solar surface, respectively. The source surface is set at 2.5 solar radius. The vertical lines indicate a high speed stream event. **Right:** Comparison of the in-situ observation and prediction of the solar wind speed (top panel) and the polarity of the interplanetary magnetic field (bottom panel). The black curves are from ACE observation, and the red curves are from the WSA model.

With significant improvements from the original algorithm, the disambiguation module for automatic use in JSOC is implemented at the NorthWest Research Associates (NWRA) at Boulder. Some of the salient aspects of the code are described in Leka et al. (2009). The disambiguated vector magnetic field data of active regions, shown in the left branch, are deprojected to the heliographic coordinates. This data further produce higher level data products such as the inferred velocity field (three components) from the models DAVE4VM developed by Schuck (2008) and ILCT developed by Welsch et al. (2004). The non-linear force free field modeling is another higher level data product. The module used here is based on an optimization method from Wheatland et al. (2000); Wiegelmann (2004); Wiegelmann et al. (2006) that includes weighting functions and pre-processing the input vector field data. Indices that represent non-potentiality of the active regions are also computed from the vector magnetic field data (e.g. the indices in Leka & Barnes (2003a,b); Abramento et al. (2008); Barnes & Leka (2008)). 3D MHD simulation solutions from Wu et al. (2006) may be produced under request, and the computation will be carried out externally outside of the JSOC.

The full disk disambiguated vector field data, shown in the right branch, are used to produce various synoptic maps of the radial magnetic field. Those maps further produce higher level products such as coronal, heliospheric, and the interplanetary (denoted by IP_dynamics in the diagram) structures from the PFSS model and 3D MHD simulations from the models by Hayashi (2005) and Linker et al. (1999); Mikić et al. (1999). Solar wind speed and the polarity of the interplanetary magnetic field (denoted by SW.IMF in the diagram) are also produced from those MHD models and the WSA model.

### 2.3. Examples of data products

To limit the length of the paper, we will not describe each data product in great detail. But instead, we show some examples of data products in Fig. 4 to Fig. 10. A brief
description for each is given in the figure caption. A detailed description of the magnetic field data production can be found in the paper of Hoeksema et al. (2010).

![Figure 10](image-url)

Figure 10. Coronal structure for CR2096 computed from a 3D MHD simulation (Hayashi 2005). From top to bottom are radial velocity, density and radial magnetic field. From left to right are these parameters at different heights: 1.010 (left), 2.516 (middle) and 10.914 solar radius (right). The contour levels are given in each panel.

### 3. Instrument performance

Performance of the HMI instrument has been well examined, and detailed results are reported in Schou et al. (2010a,b); Couvidat et al. (2010a); Wachtet al. (2010). Shown here are some comparisons between HMI data and MDI data. The curves in Fig. 11 are the spatial power spectra of a single observation of the HMI Doppler velocity (blue) and the MDI high-resolution Doppler velocity (red) integrated over azimuth, shown on a logarithmic scale. Fig. 12 shows another comparison of the power spectra of 8-hour HMI Doppler data (left) and MDI high-resolution Doppler data (middle) near the disk center. The MDI data were taken in 1996 when the instrument had not degraded very much. The ridges of spectrum of the HMI Doppler data significantly extend to higher spatial and temporal frequencies. In the right panel of Fig. 12 is the power spectrum of 8-hour HMI line-of-sight magnetic field data near the disk center. It is pretty clean, indicating that there is no significant p-modes leakage to the magnetograms, which is an issue for the MDI magnetograms. The HMI data used for these comparisons are taken by the front camera.

Following the work done with MDI magnetograms (Liu et al. 2004), we roughly estimate the noise levels of HMI line-of-sight magnetograms. We assume that the noise in the magnetograms has a Gaussian distribution, and use a Gaussian function to fit the
Figure 11. Spatial power spectra of snapshots near disk center of the HMI Doppler data and MDI high-resolution Doppler data integrated over azimuth, shown on a logarithmic scale.

distribution of the low-field pixels of the magnetograms. The stars in Fig. 13 are the distributions of the on-disk pixels of a 45-s magnetogram from the front camera (left) and a 720-s magnetogram (right) from the side camera versus magnetic field. Only the pixels with a value within -200 to 200 Mx/cm$^2$ are selected. The number of the pixels is normalized. The solid lines are the Gaussian functions that fit the distributions. The noise for the 45-s magnetogram, taken to be the sigma of the best-fit Gaussian, is 10.2 Mx/cm$^2$, and 6.3 Mx/cm$^2$ for the 720-s magnetogram. As a comparison, by using the same method, the noise for the MDI 1-minute magnetograms is 16.1 Mx/cm$^2$, and 9.7 Mx/cm$^2$ for the 5-minute magnetograms (Liu et al. 2004).

HMI and MDI magnetograms have been further compared pixel by pixel. The scatter plot in the left panel of Fig. 14 shows a comparison between HMI 45-s magnetograms and 720-s magnetograms. The alignment is done based on the location of the solar disk center in the magnetograms. A 0.1 degree offset of the position angle in the 45-s magnetograms is corrected. This comparison includes 14 pairs of 45-s and 720-s magnetograms. Each pair of magnetograms was taken at the same time. The solid line in the plot is a linear fit to the data. The slope is 0.98, and the zero point offset is significantly small, only 0.013. On the right is a comparison between MDI and HMI 45-s magnetograms. The comparison was done with 24 pairs of magnetograms. Each pair of magnetograms was taken at the same time. The HMI magnetograms were degraded to the MDI resolution by convolving a 2D Gaussian function. The width of the Gaussian
Figure 12. The spectrum of 8-hour HMI Dopplergrams near the disk center (left), compared with the spectrum of 8-hour MDI high resolution Dopplergrams near the disk center (middle) taken in 1996. The ridges of HMI Doppler spectrum extends into higher temporal and spatial frequencies. In the right panel is the spectrum of 8-hour HMI line-of-sight magnetic field data near the solar disk center. It is pretty clean, indicating no significant leakage of the p-modes to the magnetograms.

is the ratio of the MDI and HMI pixel sizes. A -0.22 degree offset of the position angle in the MDI magnetograms is corrected. The offset of the position angle in the HMI 45-s magnetograms is corrected, too. The slope of a linear fit to the data, shown in the solid black line in the plot, is 1.2, implying that the line of sight pixel-averaged magnetic signal inferred from MDI data is greater than that derived from the HMI front camera data by a factor of 1.2. There is also an outstanding zero point offset between them. A comparison of 24 pairs of MDI magnetograms and HMI 720-s magnetograms (being not shown here) gives a slope of 1.2, too. A boxcar average was also tested to degrade HMI’s spatial resolution. The result is very similar.

The quality of data towards the solar disk limb is also examined. Fig. 15 shows an area of the Sun from 60 degree north to the north pole from a MDI 1-minute magnetogram (left), a HMI 45-s magnetogram (middle), and a HMI 720-s magnetogram (right). Many small-scale magnetic elements that are not visible in the MDI magnetogram are clearly seen in the HMI magnetograms.

A time series profile of the mean solar magnetic field is shown in Fig. 16. The mean field from WSO is measured with integrated sunlight in a mode of measuring the Sun-as-a-star. The WSO mean field plotted here is multiplied by a factor of 1.8 for the saturation correction (Svalgaard et al. 1978). The “mean field” from the MDI and HMI, on the other hand, is derived from the full disk line-of-sight magnetograms by simply
Figure 13. Estimate of the noise level for the line-of-sight magnetograms. Here we assume that the noise has a Gaussian distribution, and use a Gaussian function to fit the distribution of the low-field pixels of the magnetograms. Left: The stars are the distribution of the pixels selected from a 45-s magnetogram over the Sun’s disk, and the solid line is a Gaussian function that fits the distribution. The number of pixels is normalized. The sigma of the Gaussian (width) is 10.2 Mx/cm$^2$, and the shift of the Gaussian peak is 0.06 Mx/cm$^2$. Right: Same as that in the left panel, but for a 720-s magnetogram. The sigma is 6.3 Mx/cm$^2$ and the shift of the Gaussian peak is 0.08 Mx/cm$^2$.

Figure 14. Comparison of the line-of-sight magnetograms taken by the two cameras of HMI (left) and by the HMI front camera and MDI (right). Left: Scatter plot of 14 pairs of 45-s and 720-s magnetograms taken in June-August 2010. Each pair of magnetograms was taken at the same time. The solid line is a linear fit to the data. Right: Scatter plot of 24 pairs of HMI 45-s and MDI magnetograms taken in June-August 2010. Each pair was taken at the same time. The HMI magnetograms are degraded to the MDI spatial resolution by convolving a 2D Gaussian function. The solid line is a linear fit to the data.
Figure 15. Solar north pole observed by MDI and HMI on September 11, 2010. From left to right are MDI magnetogram, HMI 45-s magnetogram, and HMI 720-s magnetogram. The region is from 60 degree north to the north pole. The images are all scaled to $\pm 50 \text{Mx/cm}^2$.

Figure 16. The mean solar magnetic field from 2010 May 1 to June 12. The “mean field” from HMI and MDI is derived by summing the line-of-sight magnetic field over the solar disk. The black crosses and the green diamonds are the “mean field” computed from the HMI 45-s and 720-s magnetograms. The blue stars are calculated from the MDI magnetograms. The red dots are the mean field measured at WSO, multiplied by a factor of 1.8.

As a demonstration of evolution of active regions, we show in Fig. 17 the snapshots of the line-of-sight magnetic field of two emerging active regions, AR11069 and AR11072. An outstanding difference between these two regions is the complexity of the magnetic field structure: there are multiple positive and negative field patches emerging in AR11069, while only two patches with opposite polarities in AR11072. The solar activities are also different: AR11069 produced 7 C-class and 1 M-class flares during...
Figure 17. Snapshots of the line-of-sight magnetic field of the active region AR11069 for a 48-hour interval during the rapidly growing phase (top panels), and the AR11072 for a 100-hour interval during the growing phase (bottom panels). The field of view of each image is 150”x120”. The images are all scaled to ±250 Mx/cm². There are multiple emerging flux patches in AR11069, which are marked by N1-3 and S1-3, while only two patches with opposite polarities emerged in AR11072.

Figure 18. The time profiles of the pseudo-fluxes for the emerging active region AR11069 from 2010 May 3 to May 8. The unsigned pseudo-flux (thick black curve), positive pseudo-flux (thin black curve), and negative pseudo-flux (red curve) are measured from the 45-s magnetograms. The blue curve shows the 5-minute averaged GOES X-ray flux. This plot shows that the active region produced its first C-class flare after 20 hours of the initial emerging, and took another 14 hours before producing three more C-class (or above) flares. After this activity, the emergence apparently stopped, and 36 hours later another C-class flare was produced. Its disk passage, while AR11072 did not produce any C-class or above flares (from http://www.swpc.noaa.gov/). To show their emerging in more detail, we plot a time series of a “pseudo-flux” of AR11069 (Fig. 18) and AR11072 (Fig. 19). The “pseudo-flux”, computed from the line-of-sight magnetograms by assuming the field is purely radial, is defined to be $\sum_i B_{los}^i \times S_i / \cos(\mu_i)$, where $B_{los}^i$ is the line-of-sight field at pixel $i$, $S_i$ is the area this pixel covers, and $\mu_i$ is the center-to-limb angle. The real magnetic
flux could be computed from the vector magnetic field data that will be available soon. It shows that both underwent a quick emerging phase, and their sizes are very similar. Continuing analysis with HMI vector magnetic field data could bring new insight to help understand why their activities are so different.

4. Conclusions

In this paper, we briefly describe the HMI magnetic field data products, and present analyses to demonstrate the performance of the HMI instrument. We conclude that the HMI is working extremely well.

Acknowledgments. We wish to thank many many others who have been making great contributions to this mission! This work was supported by NASA Contract NAS5-02139 (HMI) to Stanford University. The disambiguation module (NWRA) was improved through additional support by NASA GI contract NNH09CF22C. The research of the feature recognition described in this paper was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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