Making global map of the solar surface $B_r$ from the HMI vector magnetic field observations

K Hayashi$^1$, Y Liu$^1$, X Sun$^1$, J T Hoeksema$^1$, R Centeno$^2$, G Barnes$^3$, K D Leka$^3$

$^1$W.W. Hansen Experimental Physics Laboratory, Stanford University, 452 Lomita Mall, Stanford, CA 94305, USA
$^2$HAO
$^3$NWRA
E-mail: keiji@sun.stanford.edu

Abstract. The Helioseismic Magnetic Imager (HMI) has made full-disk vector magnetic field measurements of the Sun with cadence of 12 minutes. The three-component solar surface magnetic field vector data are from the HMI observations with the data process pipeline modules, VFISV (Very Fast Inversion of the Stokes Vector, Borrero et al., 2011) for Milne-Eddington inversion and the minimum-energy disambiguation algorithm (Metcalf 1994, Leka et al, 2009). The models of the global corona and solar wind, such as the PFSS (potential-field source-surface) model and the MHD simulations, often use the maps of solar surface magnetic field, especially the radial component ($B_r$) as the boundary condition. The HMI observation can provide new $B_r$ data for these model. Because of weak magnetic signals at the quiet regions of the Sun, the limb darkening, and geometric effects near solar poles, we need to apply an assumption to make a whole-surface map. In this paper, we tested two assumptions for determining $B_r$ at weak-field regions. The coronal structures calculated by the PFSS model with the vector-based $B_r$ are compared with those with the magnetogram-based $B_r$ and the corona observed by the SDO/AIA (Atmospheric Imaging Assembly). In the tested period, CR 2098, the vector-based $B_r$ map gives better agreements than the line-of-sight magnetogram data, though we need further investigation for evaluation.

1. Introduction

For realistically modeling the global solar corona, the models, such as the potential-field source-surface (PFSS) model [6] and MHD simulations, use the solar surface magnetic field data as the boundary conditions to specify the time of interest. Models, in general, use the magnetic field component normal to the boundary (the radial component $B_r$ in the global model constructed in the spherical coordinates system), and the $B_r$ synoptic maps are needed for the global coronal models. Earlier, with the line-of-sight (LoS) magnetogram observations, the radial method [10] is widely applied to determine the solar surface $B_r$ from the observed LoS component $B_l$, by assuming the field is radial on the photosphere, expressed as a relation, $B_r = B_l / \sin \rho$, where $\rho$ is the arc-distance from the disk center.

The HMI vector magnetic field measurement [7, 8], in principal, can provide the radial component on the solar photosphere straightforwardly. The final data of the HMI vector magnetic field are, in brief, made through the VFISV Milne-Eddington inversion for the Stokes vector [1] and the minimum energy method [3,5] for disambiguating the 180-degree ambiguity.
in the azimuth angle. For making a whole-surface map, the disambiguated vector data are projected onto the coordinate of the synoptic or synchronic frame.

For strong-field regions such as the sunspots, the disambiguated vector data are generated regularly. However, an assumption is needed to determine $B_r$ at weak-field regions, for which the disambiguation algorithm sometimes cannot determine the minimum energy state because of the weak magnetic signal. In this paper, we apply two assumptions, the potential-field acute model and the radial-acute mode, for determining the vector of the magnetic field, then apply the $B_r$ maps to PFSS model, and compare the results with those with the HMI magnetogram [4] and the solar corona observed by the AIA.

2. $B_r$ Maps
For determining one $B_r$ value at weak field regions out of two candidate answers with the 180-degree ambiguity, we tested two assumptions. The first one is the radial-acute model where a candidate that has a larger absolute value of the radial component, $|B_r|$, is selected. The second one is the potential-field acute model in which the vector of PFSS field on the surface, $\vec{B}_{pot}$, is first calculated with the LoS component then the candidate that has greater (positive) dot product with the potential field, $\vec{B} \cdot \vec{B}_{pot}$, is chosen. In Figure 1, the global $B_r$ maps obtained in these ways are shown together with the maps from the LoS magnetogram observations. It is easily noticed that the distribution of $B_r$ derived with the PFSS-acute model is different from the other three. We made a tentatively conclusion that the radial-acute model (c) is more reasonable than the PFSS-acute model (d), after preliminary test similar to that in Section 3 and others. A supplemental reason was that the polarity inversion lines, dividing the positive

Figure 1. Synoptic maps of $B_r$, for October 2012. Top row: (a) daily-updated synoptic map of the magnetogram observation and the radial method, and (b) a standard synoptic map of the magnetogram observation for a Carrington rotation (CR) 2128. Bottom row: Synoptic map of vector-based $B_r$ with (c) radial-acute assumption, and (d) PFSS-acute assumption. Vertical dashed lines in plots (a), (c), and (d) approximate the longitudes 60 degrees east and west from the central meridian viewed from Earth, on 2012 October 19. In plot (a) regions between the two dashed lines are the part updated. We extended the sampling window about 2 days to make vector-based $B_r$ maps, (c) and (d).
Figure 2. The four synoptic maps of $B_r$, around CR 2098, used for the PFSS calculations shown in Figure 3. The vector-based $B_r$ maps, with the last full-disk observation data at (a) 2010/06/30, (b) 2010/07/14, and (c) 2010/07/30, are shown. The end time of the 27.3-day window are chosen so that the times of comparison in Figure 3 will be well near the center. The synoptic map of $B_r$, with the radial method applied to the LoS magnetogram data, for CR 2098 is shown in plot (d).

and negative $B_r$, of the map (d) did not coincide with the filaments observed in the period.

3. Comparisons
We use the $B_r$ maps in the PFSS calculation and compare the bases of the open-field lines with the low-intensity regions of AIA 193. We chose a period, CR 2098, because the solar corona had the coronal holes (CHs) of various types of shape during this period.

As the input to the PFSS, we use the maps of the radial-acute vector $B_r$ and those of the magnetogram-based $B_r$. Figure 2 shows the data. An additional choice, whether or not to adjust values of $B_r$ to make the whole-surface integration, $\int B_r dS$ will be zero, is also critically important in the PFSS model and other coronal models. In this study, the adjustment is made by offsetting the $B_r$ on whole surface uniformly. We run four PFSS calculations with iterative direct Laplace solver, determine the base of the open-field region by tracing the field lines, and compare with the AIA data at each instant.

Figure 3 is the comparison plots: The AIA 193 images are in the leftmost column, and the other four columns are for the base of the open field lines in the potential field viewed from the position of the Earth at instants of the AIA observation. The rectangles, circles, diamond and triangle boxes emphasize the differences of the base of the open field lines among the four calculations.

Here we briefly summarize comparisons: (1) In the parts marked with rectangles at the topmost row, we can see that the north-south (trans-equatorial) stretched coronal hole is better reproduced with the vector-based $B_r$, with or without $B_r$ offset, than those with the magnetogram data. (2) In the parts marked with the circles, the stretched narrow coronal holes are well reproduced with the vector-based $B_r$ with the offset, while the magnetogram-based $B_r$ maps without offset gives best agreements. (3) The northern polar coronal hole marked with
Figure 3. Comparison of the base of the PFSS open-field lines with the AIA 193 observations, at the Carrington longitudes 45 degrees apart, over a period of CR 2098. Time of the AIA observations and the point of view of open-field base of the PFSS model (darker grays) are denoted at the left. From the left, the AIA observation, the base of the open field derived from the PFSS model using the "monopole-offset" radial-acute vector $B_r$, the offset magnetogram-based $B_r$ with the radial method, and the radial-acute $B_r$ without the offset correction, and the magnetogram-based $B_r$ without the offset correction. For each three of nine rows, one vector-based synoptic map is made from dataset with a different 27.3-day window of the HMI observations.
diamonds is best reproduced with the vector-based \( B_r \) with the offset. (4) The open field region at the southern polar region marked with the triangles is not well seen in the AIA image data. Probably this is because the Earth was at about 4 degrees north of the solar equatorial plane.

4. Summary
We test two types of the assumptions to solve the 180-degree ambiguities at the weak field regions, and select one (the radial-acute) to compare with the standard LoS magnetogram and the AIA data. The vector-based \( B_r \) map with the offset gives overall better agreements with the AIA images than the magnetogram-based one; however, the advantage of vector-based \( B_r \) over the \( B_r \) maps from the magnetogram with the radial method is not sufficiently outstanding at this time.

As seen in the differences between the second and forth column, and between the third and fifth (rightmost) column of Figure 3, the treatment of the surplus of the magnetic field is critically important. The apparent ”monopole” (the surface integration of \( B_r \)) may come from the fact that the synoptic maps are made by collecting solar-disk observation data at various instants over 27.3 days. In addition, if a synoptic map has one of two active-region polarities (i.e., the boundary line of longitude happens to split an active region), then the unbalance of \( B_r \) will be substantial [2]. For better determining the magnetic field in the polar regions, the polar field correction [9] is a method to apply. We continue to examine these factors to make ”best” global map of \( B_r \).

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