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3D MODELING OF SOLAR MAGNETIC FIELD LINES USING MAGNETOGRAM IMAGES

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Abstract

Solar images, along with other observational data, are very important for solar physicists and space weather researchers aiming to understand the way the Sun works and affects Earth. In this study a 3D modelling technique for visualizing solar magnetic field lines using solar images is presented. Photospheric magnetic field footpoints are detected from magnetogram images and using negative and positive magnetic footpoints, dipole pairs are associated according to their proximity. Then, 3D field line models are built using the calculated dipole coordinates, and mapped to detected pairs after coordinate transformations. Final 3D models are compared to extreme ultraviolet images and existing models and the results of visual comparisons are presented.

1. Introduction

Space weather research is an active area of research and importance of it increases, as we rely more and more on communications and power systems, both of which are vulnerable to space weather. Because of technological advances there are many solar images in different wavelengths produced daily by different observatories (i.e. BBSO, Meudon, Mt Wilson, etc.) and satellites (e.g. *Solar and Heliospheric Observatory* (SOHO), *Solar Terrestrial Relations Observatory* (STEREO), *Solar Dynamic Observatory* (SDO)) but it is almost impossible for researchers to investigate all these images and compare them against each other to get a more complete picture of the Sun. There is a need for automated data analysis and knowledge extraction techniques.

In this paper we present an automated system that extracts magnetic footpoints of magnetic field lines from magnetogram images and then builds 3D models of magnetic field lines using the extracted data. True magnetic field lines provide a visual description of the magnetic vector field. A field line indicates the direction of the field at a point on the line and the distance between field lines is an indication of the strength of the field, the closer they are, the stronger the field. Producing 3D models for visualizing the magnetic field lines, similar to the one introduced in this paper, can provide better understanding of the magnetic field of the Sun. It is believed that solar storms and solar flare result from changes in the structure and connections of solar magnetic fields and understanding these magnetic fields is therefore very important. Although there are limitations in current solar data that is used for modelling, such as cadence and coverage of the full solar disk, these models can still be useful to improve our understanding of solar activities and some examples of these will be provided in the conclusion section.

The use of magnetograms for inferring coronal magnetic fields has a long history. For small fields of view extrapolations are performed in Cartesian coordinates using Fourier transforms. Previous models for magnetic field lines are provided in [1] and also a detailed study of solar magnetic field in three dimensions can be found in [2]. Although, these studies focuses on modelling magnetic field lines locally such as for single active regions, there are also various applications of magnetohydrodynamic (MHD) coronal models to solar observations. For the full Sun, the potential field source surface model (PFSS) has been used for over 40 years. In the PFSS model, Carrington maps of the photospheric field are used as boundary conditions for solving Laplace's equation and are consistent with Maxwell's equations in the absence of currents [3] [4].

This paper is organized as follows: Detection of magnetic footpoints from magnetogram images are described in Sec. 2. The methodology for representing the detected magnetic footpoints in 3D is given in Sec. 3. An algorithm for associating opposite polarity magnetic footpoints is provided in Sec. 4 while the algorithms for modelling magnetic field lines and merging them with associated magnetic footpoints are introduced in Sec. 5 and Sec. 6 respectively. Results are given in Sec. 7 and the concluding remarks are given in Sec. 8.

2. Detection of Magnetic Footpoints Using Magnetograms

In order to model the magnetic field lines in 3D, first the footpoints of these lines must be detected. We use SOHO/MDI line-of-sight magnetograms which measure magnetic field strengths in the Sun's photosphere (Figure 1). On magnetogram images, dark areas indicate regions of "south" magnetic polarity (pointing into the Sun) and the white regions indicate regions of "north" magnetic polarity (pointing outward). As only 6 to 8 MDI magnetograms are available daily from SOHO, the algorithms described here can be applied to other line of sight magnetograms from other observatories.

MDI Magnetograms are available in FITS and GIF image formats. Although algorithms described in this study can be applied to both format of images, when using GIF type images an additional algorithm must be implemented in order to detect the centre and limb of the sun. These algorithms are described in [5].

Detection of magnetic field footpoints from magnetograms is carried out using intensity filtering method, in a manner similar to [5]. The intensity filtering threshold value (T_f) is found automatically using Equation (1), where, μ is the mean, σ represents the standard deviation, and α is a constant that is determined empirically based on the polarity of the magnetic footpoint to be detected.

$$T_f = \mu \pm (\sigma \times \alpha) \tag{1}$$

Two thresholds have to be determined in order to detect magnetic field line footpoints in magnetograms. The first threshold is used for detecting footpoints with "north" magnetic polarity and the second is used for detecting footpoints with "south" magnetic polarity. The value of the first threshold is determined using Equation (1) with a plus (+) sign and α equals two. All pixels that have intensity values larger than this threshold are marked as magnetic field footpoints with "north" polarity. In the same manner, the second threshold is determined using Equation (1) with the minus (-) sign and α equals two. Any pixel with an intensity value less than this threshold is marked as magnetic field footpoint with "south" polarity. Figure 1 shows the detected "south" (marked with red colour) and "north" (marked with light blue colour) magnetic polarity footpoints.

3. Calculating the 3D Coordinates of Magnetic Footpoints on Photosphere

After the footpoints of the magnetic field lines have been detected, in order to model magnetic field lines first we need to represent the detected magnetic footpoints in 3D. In this study the detected magnetic field line footpoints are first converted to Carrington heliographic coordinates and finally to 3D Spherical coordinates.

3.1 CALCULATING HELIOGRAPHIC COORDINATES OF MAGNETIC FOOTPOINTS

After the footpoints of the magnetic field lines are detected, in order to represent the coordinates of these features in 3D, the first step is to calculate their Carrington heliographic coordinates [6]. In order to calculate the location of a specific point (detected pixel) on the solar disk on a solar image, heliographic coordinates of the centre of the solar disk (*Bo*, *Lo*) and the tilt of rotation axis (*P*) have to be calculated. This data is available in FITS formatted solar images but for GIF images they have to be calculated. For calculating these variables, it is sufficient to use the low accuracy equations from [7].

The heliographic coordinate system expresses the latitude (B) and longitude (L) of a point on the solar surface and the heliographic coordinates of a point on a solar disk can be calculated as follows:

$$B = arcsin[(\sin(B_o) \times \cos(p)) + (\cos(B_o) \times \sin(p) \times \cos(P - \theta))] \tag{2}$$

$$L = arcsin\left[\frac{\sin(p) \times \sin(P-\theta)}{\cos(B_o)}\right] + L_o \tag{3}$$

Where *Bo*, and *Lo* are the latitude and longitude of the centre of the solar disk respectively, *P* is the tilt of rotation axis, θ is the position angle of the point on the solar disk, and ρ is the angle between the position of the point on the solar surface, the Earth and the centre of the disk. *Bo*, *Lo*, *P* can be calculated using the equations in [7] as stated before and θ and ρ can be calculated using the equations in [8].

3.2 CALCULATING 3D COORDINATES OF MAGNETIC FOOTPOINTS

Once the heliographic coordinates of each detected pixel representing magnetic footpoints are calculated using Equation (2) and Equation (3), the latitude and longitude values of each pixel are used to calculate the 3D Cartesian coordinates of the magnetic footpoints with the help of following equations:

$$\begin{aligned} x &= r\sin(B)\cos(L) \\ y &= r\sin(B)\sin(L) \\ z &= r\cos(B) \end{aligned} \tag{4}$$

In Equation (4), *B* is the *latitude*, *L* is the *longitude* of the detected pixel and *r* is equal to the radius of the solar disk that can be determined according to the model we want to build.

For presenting footpoints of magnetic field lines in 3D, we start by searching for white and grey pixels on the previously created image showing detected footpoints like the one shown in Figure 1. When a white or grey pixel that is part of a detected footpoint is found, its *x* and *y* coordinates are stored and their latitude and longitude values are calculated using Equation (2) and Equation (3). After the latitude and longitude values are calculated, their 3D Cartesian values are calculated using Equation (4) assuming radius of the solar disk is equal to 500. By changing this radius value, the detected magnetic footpoint data can be mapped onto any spherical surface in 3D. It is important to choose a radius value closer to the radius of the original magnetogram image in order to visualize the detected footpoints in a proper way. If the difference between two radiuses is too big, there can be truncation in data. Original radius in a 1024 by 1024 MDI magnetogram image is approximately 490 pixels and choosing 500 as the radius value of the spherical surface in 3D environment is normal. After completing the calculations for all the previously detected pixels on the solar image, their 3D coordinates are stored.

On Figure 2, snapshots of 3D representation of detected magnetic field line footpoints from the MDI Magnetogram taken on 28/10/2003 at 01:35 are shown. These images are snapshots from our 3D visualization tool 3DSolarView. These snapshots are taken while rotating the 3D model. More information about this tool and the 3D representation will be provided in the latter parts of the text.

4. Finding the closest opposite polarity magnetic footpoints

Magnetic field lines form loops between opposite polarities and magnetograms show line-of-sight magnetic fields. The magnetic field lines move outward from the whiter regions of north polarity to be connected with their nearby darker regions of south magnetic polarity.

After calculating the 3D coordinates of the detected magnetic footpoints, we created an algorithm to determine the north and south polarities of the footpoints that are related (connected) to each other. This algorithm associates the opposite polarity magnetic footprints according to their proximity and each footpoint is associated to only one opposite polarity footpoint. This routing algorithm is based on sorting the magnetic footpoints into dipoles according to closest distance. The algorithm starts by region growing positive/negative magnetic footpoints within a sphere by increasing the radius of the sphere incrementally. Once a region grown positive/negative footpoint intersects with a negative/positive footpoint, those opposite polarity footpoints are marked as closest to each other and the algorithm continues running while omitting the previous associated footpoint pairs (Figure 3).

This algorithm is tested for correctness on 10 randomly created data sets which include 3D points representing negative and positive footpoints. On each data set, the algorithm was executed 10 times while changing the order of the data and every time same association results were achieved. Pseudo code of this algorithm is provided below.

4.1 PSEUDO CODE OF THE ALGORITHM

If positive magnetic footpoints are represented by $P(i)=P(x_i, y_i, z_i)$ and negative magnetic footpoints are represented by $N(j)=N(x_j, y_j, z_j)$, where *i* and *j* are the number of the positive and negative magnetic footpoints respectively. Assuming *i* is smaller than *j*.

S01: Place imaginary spheres around all the positive footpoints and set initial radius of the spheres *R* to zero.
S02: Increase *R* one by one until it all the positive footpoints are associated with negative footpoints.
S03: Check if there are any negative footpoints within each sphere every time R is increased.
S04: If there is just one negative footpoint within the sphere, mark the positive footpoint that is on the centre of the sphere and negative footpoint as associated, and remove these footpoints from the further calculations.

If there is more than one negative footpoint within the sphere, mark the positive footpoint that is on the centre of the sphere and negative footpoint that is closer to it, as associated, and remove these footpoints from the further calculations.

If there is more than one negative footpoint within the sphere and the closest two or more of them are same distance away from the centre of the sphere or if two spheres are intersecting and the closest negative footpoint is equal distance away from the centre of the both spheres, move to next step otherwise continue from S02.

S05: For every same distanced footpoint pairs calculate the possible total distance for the later stages, sort them and decide the final pair in the way described below.

Assuming there are *n* number of equally distanced negative footpoints from one or more, *m* number of positive footpoints, start simulations for every combination of these footpoints. In each simulation, first randomly mark one positive and one negative footpoint as associated (within n negative and m positive footpoints) and continue the routing algorithm starting from S02 until the remaining footpoints (within n negative and m positive footpoints) are associated. Then, add the distances between associated footpoints and record the total distance. Return to the beginning and continue simulations for the rest of the footpoints by changing the initially associated footpoints every time until all the combinations between n and m numbers of footpoints are simulated. At the end of the simulations for all the possible combinations, compare the total distances between the associated footpoints and mark the positive and negative footpoints with the least total simulation distance as associated. Remove the associated footpoints from further calculations and continue algorithm from S02.

Using the algorithm described above all the opposite polarity magnetic footpoints that have been converted to 3D coordinates are processed and associated to each other. After association magnetic field lines are modelled and fitted on to the associated opposite polarity magnetic footpoints.

5. Magnetic Field Line Modelling

After determining the associated magnetic footpoints we can model the magnetic field lines that are connecting them. In this study we used bipolar coordinate system (Figure 4.A) to model the magnetic field lines between selected footpoints [9]. Bipolar coordinate system is a two-dimensional coordinate system defined by the family of circles that pass through two common points and if we assume that there is a radial line passing through each associated opposite polarity footpoint then bipolar coordinate system will be easier way to model each magnetic field line. To calculate each segment of the loop that is forming any magnetic field line, the following equation has to be solved:

$$x^2 + (y - a.\cot(\gamma))^2 = \frac{a^2}{sin^2(\gamma)} \quad (5)$$

For any point (x, y) in the *xy* plane, *a* represents half the distance between the magnetically connected footpoints, and γ is the angle subtended at (x, y) by the two poles (-a,0) and (a,0).

If we solve Equation (5), we would have two equations representing y coordinates for the given x coordinate:

$$y_{1,2} = \pm \sqrt[2]{\frac{a^2}{sin^2(\gamma)} - x^2} - a.\cot(\gamma) \quad (6)$$

Where x is changing between –R and +R. R is equal to the radius of the circle passing through poles (opposite polarity magnetic footpoints) and can be calculated by using:

$$R = \frac{a}{sin(\gamma)} \quad (7)$$

Which is derived by calculating the maximum and minimum values of y coordinates of the model (When x coordinate is equal to zero) and halving their differences.

By using the Equation (6), we can model any field line between opposite polarity magnetic footpoints in any number of segments we want while changing the number of x coordinate values between –R and +R and storing the y coordinate values. Calculating the model in segments can allow us to change the shape of each line by changing the coordinates of each segment. By keeping the distance between the magnetically connected footpoints and changing the angle γ, the height of the magnetic field loop can also be changed. In Figure 4.B. four different simulated magnetic field line loops are shown. Each loop has 12 segments and all loops are assumed to have originated from the same magnetic footpoints.

6. Fitting the Model to Magnetic Poles on Solar Disk.

In order to fit the modelled magnetic field lines to the associated opposite polarity magnetic footpoints, first we need to calculate the distance between them. Using half of the calculated distance as "a" in Equation (6) and assigning one for the angle γ, we created models for all associated footpoints in 3D while assuming the z coordinates of the segments to be zero. We then fit the models onto each associated magnetic footpoint pair after 3D rotations and translations. The Pseudo code of this algorithm is provided below.

5.1 PSEUDO CODE OF THE ALGORITHM

If positive polarity and negative polarity magnetic footpoints are represented with P(x, y, z) and N(x, y, z) respectively in 3D, and their distance is equal to *d*. Using half of *d* as "a" value in Equation (6) build a model between two imaginary points A(x, y, z) and B(x, y, z) while setting the z coordinate value as zero for both points. In this case A(x, y, z) will be equal to A(-d/2,0,0) and B(x, y, z) will be equal to B(d/2,0,0) (Figure 5.A). In order to fit this model on to the magnetic footpoints those are represented in 3D:

S01: Define a vector between P and N, |PN| and A and B, |AB| like seen in Figure 5.B. Repeat all the calculation applied to vector |AB| in the later stages also to all the nodes of the segments of the model between A and B.

S02: Translate the origin of the vector |PN| and |AB| to origin of the Cartesian coordinate system (x=0, y=0,z=0) by subtracting starting node of the vectors (P(x,y,z) and A(x,y,z)) from the starting and ending nodes of the vectors (Figure 5.C). Name the new vectors |PN|' and |AB|'.

S03: Calculate the angle α which is between |PN|' and |AB|' in the xy-plane and the angle β which is between |PN|' and |AB|' in the xz-plane (Figure 5.C).

S04: Rotate the vector |AB|' around the y axis using Equation (8) below, where φ is equal to α (Figure 5.D) and name the resulting vector |AB|''.

$$\begin{aligned} x' &= \quad x.\cos\varphi + z.\sin\varphi \quad (8) \\ z' &= -x.\sin\varphi + z.\cos\varphi \end{aligned}$$

S05: Rotate the vector |AB|'' around the z axis using Equation (9) below, where φ is equal to β (Figure 5.E) and name the resulting vector |AB|''' which will be equal to |PN|'.

$$\begin{aligned} x' &= x.\cos\varphi - y.\sin\varphi \\ y' &= x.\sin\varphi + y.\cos\varphi \end{aligned} \tag{9}$$

S06: Translate the origins of the |AB|''' vector to the origin of the |PN| vector in its original position. This translation can be achieved by adding the starting node P(x, y, z) of the original |PN| vector to the starting and ending nodes of the |AB|''' vector (Figure 5.F).

S07: Using the steps above all the models can be fitted on to any desired nodes. Also the model can be rotated around the x-axis after it was translated to the origin of the Cartesian coordinate system by using Equation (10) and changing the angle φ. By this way the orientation of the model around |PN| vector can be determined.

$$\begin{aligned} y' &= y.\cos\varphi - z.\sin\varphi \\ z' &= y.\sin\varphi + z.\cos\varphi \end{aligned} \tag{10}$$

After all the models are built, they can be fitted on to associated opposite polarity magnetic footpoints using the algorithm described above. It is also worth mentioning here that in this study we modelled each magnetic field line using a maximum of 10 segments. Modelling these lines with more segments can slow down the modelling processes since the calculations for rotations and translations has to be repeated for every added segment times the number of associated magnetic footpoints.

7. Results and Discussions

The algorithms described in the previous sections were implemented in C++ and were executed on a PC with the Microsoft Windows operating system. Due to the complexity of magnetic structures, it takes between 5 - 15 minutes to build 3D models of magnetic field lines for each magnetogram image. Also an OPENGL based 3D visualization tool called 3DSolarView was created to visualize the solar features and models that are built. In Figure 6, the modelled magnetic field lines using the MDI Magnetogram taken on 28/10/2003 at 01:35 are shown in the visualization window of the 3DSolarView program. Using this program the 3D model can be moved, rotated, and resized.

Some magnetic field lines that have plasma frozen onto them are generally visible in EIT extreme ultraviolet images. They are mostly visible towards the solar corona; therefore we randomly chose an EIT image where some magnetic field lines are visible in the corona and built magnetic field lines in 3D with the algorithms provided in this paper using a Magnetogram captured at about the same time. In Figure 7, a comparison is shown between the modelled magnetic field lines and the visible field lines. The 3D model is built for a SOHO/MDI Magnetogram taken on 01/09/2005 at 04:51 and it is compared with a SOHO/EIT 171 image taken on 01/09/2005 at 19:00. In this figure other EIT images are provided for comparison. It can be seen from the figure and the marked red squares that the 3D modelled magnetic field line loops and real magnetic field line loops closely coincide with each other, although they are not completely identical. Generally, the same structures appear in both model and data.

In Figure 8, also the rotated and zoomed snapshots for this 3D model are provided. This 3D model allows us to see the shape and configuration of magnetic field in any desired perspective by eliminating the visibility handicaps (e.g. limb effects) caused by 2D images. It provides the user with the ability to visualize these loops from different directions and at different scales.

Also another 3D model is created using HMI magnetogram images from SDO satellite and compared to PFSS model superimposed on SDO/HMI magnetogram images like it can be seen on Figure 9. The images with PFSS models are freely available from SDO website (http://sdo.gsfc.nasa.gov/data/). PFSS model is applied to synoptic maps that are created by taking slices from the centre of solar disks over a period of 27 days and although they are very useful for driving some of the space weather models, they don't necessarily reflect all of the changes on Sun. The image on the right hand side on Figure 9 is a good example for these kinds of changes. On the upper left side of this image (marked with square) although there is strong magnetic region there are no magnetic field lines generated using PFSS model. This is probably due to this strong magnetic region being a newly formed one and doesn't exist on synoptic maps. On the other side the magnetic field on this region is successfully modelled using the algorithms described in this paper also rest of the magnetic field lines are visually very similar to the ones created using PFSS model.

8. Conclusions and Future work

In this paper some algorithms for detecting footpoints of magnetic field lines present in the solar photosphere and representing them in 3D coordinates are presented. Also, these 3D representations of magnetic field line footpoints are used for modelling magnetic field lines in 3D. The 3D conversion algorithms presented for magnetic footpoints can also be used to calculate the 3D coordinates of other types of solar features in the chromosphere and transition regions and if necessary depth information for these features can be determined.

One of the applications of these 3D magnetic field line models is to identify source regions of solar flares or Coronal Mass Ejections (CMEs). For example in Figure 10, some SOHO LASCO and SOHO EIT 195 images taken on 7th January 2007 are provided showing the initiation of a CME at 10:24. The CME is marked with a box with black borders and active region 10537, where this CME was initiated, is marked with a box with blue borders on all the images. As it can be seen from the image in the middle, there is a brightening at the upper left corner of the active region and this is the place where the CME was initiated.

Using our algorithms, we built 3D models of magnetic field lines (Figure 11) before and after this CME using the available magnetograms on 7th January 2007 at 09:36 and at 11:15. In Figure 11, the top row shows front views of the modelled loops and the bottom row shows rotated views of the same 3D modelled magnetic field line loops. In image A, if we focus on the upper left corner of the area of the solar disk where active region 10537 is present, we can see a modelled magnetic field loop indicated by a blue arrow. The same loop is also shown with a blue arrow on the rotated version of the model presented in image C. We can see that these magnetic field lines that are modelled using the MDI magnetogram at 09:36 are not visible on image B and D which are modelled using the MDI magnetogram at 11:15. It is very clear from the magnetic field line models that there was a change in this area. The magnetic field in this region is reshaped within one and a half hours. Also, it is clear that number of magnetic field lines around this area and their complexity are reduced.

These modelled field lines can also be used to estimate the energy stored on active regions and can be used for predicting the major solar flares in a similar way to [10]. In [10], authors showed that, finding the magnetic connectivity in the active region photosphere by identifying footpoint pairs and calculating the flux committed to the connections between these pairs can be used for predicting major flares. The footpoint connections determined by the model described in this paper can be used in a similar way to predict solar flares. But in order to achieve that the modelling has to be concluded in real-time on near real-time.

The computationally most time consuming algorithm provided in this paper is used for finding the closest opposite polarity magnetic footpoints. This algorithm consumes nearly 90% of the computational time and in order to achieve near-real-time modelling this algorithm has to be significantly improved. One of the ways of improving the computational time of the algorithm is to apply it to two dimensional heliographic data before converting it to three dimensions. This is one of our aims we want to achieve in the future in order to improve modelling time.

Also in the future we are planning to research on creating images similar to different wavelength EIT images by projecting the modelled magnetic field lines onto 2D plane. By comparing the projected 2D images and EIT images the accuracy of the modelling algorithms can be judged and improved models can be developed.

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Vitae

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Figure Captions

Figure 1: SOHO/MDI magnetogram taken on 28/10/2003 at 01:35, detected opposite polarity regions are over plotted on the image.

Figure 2: Snapshots of 3D modelled magnetic field line footpoints using the MDI Magnetogram taken on 28/10/2003 at 01:35. Snapshots are taken while rotating the 3D model.

Figure 3: The evolution of the routing algorithm.

Figure 4: Bipolar Coordinate system A. Constants and variables in bipolar coordinate system, B. Constructed model examples.

Figure 5: The steps in translations and rotations needed in order to fit model to selected poles.

Figure 6: OPENGL based 3DSolarView program that allows us to rotate, move and zoom the modelled magnetic field lines.

Figure 7: Comparison of modelled magnetic field lines with SOHO EIT images.

Figure 8: Rotated and zoomed 3D Magnetic field line models for Magnetogram taken on 01/09/2005 at 04:51.

Figure 9: Modelled 3D magnetic field lines for SDO/HMI magnetogram image taken on 17/10/2011 at 15:11 using the algorithms provided on this paper on left and PFSS model on right.

Figure 10: Consecutive SOHO LASCO images and SOHO EIT 195 images on 07/01/2004.

Figure 11: Models for magnetic field lines. A. model built using MDI magnetogram on 7/01/2007 at 09:36. B. model built using MDI magnetogram on 7/01/2007 at 11:15. C. Rotated version of the model on image A. D. Rotated version of the model on image B.