Coronal structure analysis based on the potential field source surface modeling and total solar eclipse observation

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Abstract. We constructed global coronal magnetic fields of the Sun during the Total Solar Eclipse (TSE) 9 March 2016 by using Potential Field Source Surface (PFSS) model. Synoptic photospheric magnetogram data from Helioseismic and Magnetic Imager (HMI) onboard Solar Dynamics Observatory (SDO) was used as a boundary condition to extrapolate the coronal magnetic fields of the Sun. This extrapolated structure was analyzed by comparing the alignment of the fields from the model with coronal structure from the observation. We also used observational data of coronal structure during the total solar eclipse to know how well the model agree with the observation. As a result, we could identify several coronal streamers which were produced by the large closed loops in the lower regime of the corona. This result verified that the PFSS extrapolation can be used as a tool to model the inner corona with several constraints. We also discussed how the coronal structure can be used to deduce the phase of the solar cycle.

1. Introduction
As the manifestation of the magnetic fields above the photosphere, solar coronal structure strongly depends on the magnetic fields generated from the interior of the Sun. These magnetic fields emerge to the photosphere, rise up to the corona and may extend to interplanetary space by some instabilities of its structure, which could result to the catastrophic impacts in the solar system. Therefore, one can infer solar corona as the extension of the magnetic fields dynamics on the solar surface. This should be valid for the assumption that the solar corona is force-free and plasma beta of the whole system is infinitesimal.

By using the vector magnetic field information on the photosphere, one can extrapolate magnetic fields in the corona on the base of assumption that there is no current flowing in the corona. This method, so called potential field, can give us general feature of the coronal structure and has been widely used to model the corona for variety of purposes. To generate global model of the coronal field, one boundary condition on top of the corona is needed where all magnetic fields in this spherical boundary are fully radial, which is called as source surface. This technique of modeling solar corona is known as Potential Field Source Surface (PFSS)[1].
In this paper, we generated model of the solar corona on 9 March 2016, which coincided with the total solar eclipse (TSE) happened in Indonesian archipelago. Since the structure of the corona can be observed during the total solar eclipse, observational and synthetic coronal structure from the model can be compared and studied extensively. In this preliminary results, we briefly compared and analyzed the structure of the corona generated by PFSS model and the observed corona from two different sites, which are Ternate and Penajam Paser Utara (PPU).

2. Data and methods

2.1. Vector magnetogram and PFSS model

The vector magnetic field data used in this work are derived from Helioseismic Magnetic Imager onboard Solar Dynamics Observatory (SDO). We used synoptic magnetogram data at 00:40:00 UTC in 9 March 2016 for one Carrington rotation taken from the database on the pffs_viewer module within SolarSoft SSW libraries.

PFSS method was generated by using radial component of the vector magnetogram data in the photosphere. Coronal fields were calculated as solution for the Laplace equation by using separation variable with some components derived from spherical harmonic components and associated Legendre polynomial [2]. The calculation was conducted by using PFSS module of SSW package in Interactive Data Language (IDL) environment developed by De Rosa and Schrijver with source-surface distance is 2.5 solar radius [3].

2.2. TSE observation from Ternate

The location site was in Pantai Falajawa, Ternate city, North Maluku, Indonesia, 0°47' N and 127°22' E. We used Extra Low Dispersion (ED) Apochromatic Refractor with aperture 103mm and focal ratio f/7.7 mounted in Sphinx SXD2, which were both manufactured by Vixen. The optical tube assembly was equipped with Seymour black polymer solar filter. Images were detected by 22.2 x 14.9 sized CMOS sensor with fast DIGIC 6 processor built in DSLR Canon EOS Rebel T6s, performing image size 6000x4000 and pixel size 3.7 µm. Unfortunately, the weather was cloudy that made the Sun covered with thin clouds during the peak time. Due to the initial target of the observation was to observe stellar background during the eclipse, most of the images were taken with low exposure which results to the dim corona in the images.

The chosen best images of the observation were first centered and then zoom (radially) blurred in GIMP. These blurred images were then subtracted from the original images before added each other to produce composite image. The composite image was then multiplied with the original images. Finally, these images were stacked and then some contrast and brightness adjustment were applied.

2.3. TSE observation from PPU

The observation site was at Pantai Corong (1°24'12.4" S, 116°39'14" E), 1.5 m above sea level in Kab. Penajam Paser Utara (PPU), East Kalimantan, Indonesia. The duration of totality was 1m 51s and the peak of totality was 00:34:02 UTC. The Sun was at 32.7 altitude when the peak was observed. By using William Optic Zenithstar 66SD (D=66mm, f=388mm) and Nikon D5100, we obtained 19 images. Some chosen images were processed by Adobe Photoshop CC 2015 and Adobe Lightroom.

The basic image processing steps are: 1) The coordinates of the center of the Moon were detected with high accuracy. 2) Applying radially blur filter from the center of the Moon. 3) Subtracting centered images with its radial blurred images. 4) Multiplying centered images with subtracted images. 5) The aligned images were combined. The weights were proportional to the exposure time of each image. 6) Finally, in order to enhance the combined image, locally adaptive filters and noise reduction were applied.
3. Results and discussions

Result of the PFSS model for 9 March 2016 solar corona, TSE observation from Ternate and PPU are shown in figure 1, 2, and 3, respectively. The orientation of the Sun in figure 2 and figure 3 are rotated in order to adjust the North-South orientation of the model.

![PFSS Model](image1.png)  
**Figure 1.** PFSS Model.

![TSE observation from Ternate](image2.png)  
**Figure 2.** TSE observation from Ternate.

![TSE observation from PPU](image3.png)  
**Figure 3.** TSE observation from PPU.

TSE observation from Ternate shows only lower regime of the corona due to the combination of the cloudy sky and low exposure time of the observation. The detail structure of the corona is very difficult to be observed. However, we still can identify some small closed structures in the east limb of the Sun and at least three large loops in the western limb. Comparison for the observation image from Ternate and PPU shows that all the structures in figure 2 indeed correspond well with the larger structures of the corona shown in figure 3.

Figure 3 shows more detail structures with the extension of the corona beyond 2 solar radius from the photosphere. We can obviously identify several streamers originate from the corresponding loops of figure 2, particularly in the western side of the solar disc. More complex structures are observed in the eastern limb of the Sun with many loops overlaid each other from the line of sight of the observer.

![PFSS closed loop Model superimposed to the Ternate TSE observation](image4.png)  
**Figure 4.** PFSS closed loop Model superimposed to the Ternate TSE observation.

![PFSS Model superimposed to the PPU TSE observation](image5.png)  
**Figure 5.** PFSS Model superimposed to the PPU TSE observation.

In order to emphasize the detail comparison between model and observations, we overlaid the PFSS model of the 9 March 2016 solar corona on the TSE observation images from Ternate.
and PPU. The results of the overlaid images for Ternate and PPU observations are shown in figure 4 and figure 5, respectively. Since coronal streamer always occur on top of the closed magnetic loop structure in the corona, we can compare the position of the coronal streamers from the observation with the closed loop structures in the model. The consistency between these two features can be used to qualitatively see how well the model can reconstruct real coronal structures.

Figure 4 shows the PFSS model of corona overlaid on Ternate TSE observation where only closed loops are shown. The observation from Ternate cannot provide large loop structure and it makes the comparison becomes difficult. However, in general we still can see the agreement between the observation of the TSE and the model from the consistency of the appearance of while light corona in the low altitude with some closed loops. In figure 5, more detail comparison between TSE observation in PPU and model can be possibly done. Here we see that coronal streamers in the TSE observation obviously related with the closed loops below it. PFSS model can reproduce those closed loops in the direction of the associated streamers although further analysis should be made in order to discriminate each source for different streamer. PFSS model can also predict the location of the open field with good agreement with the observation. It suggests that PFSS model is reliable as the model of corona, which can be used to model the source of the solar wind.

PFSS model and TSE observations show that the global coronal structure on 9 March 2016 are far from simple dipole structure. From the solar dynamo theory perspective, it means that the toroidal field still dominates the solar dynamo action in the interior of the Sun. This kind of property implies that the Sun is still active in producing many active regions in the low latitude regions [4]. Therefore, the Sun was in fact still descending from its maximum phase, but perhaps was still far to reach the lowest minimum phase of this solar cycle. Although here we still cannot yet exactly determine the phase by using this method, we suggest that some parameters of the symmetrical shape of the solar corona can be good representation to determine phase of solar activity for enhancing the determination of the solar cycle phase merely by measuring the flattening index.

4. Conclusion
In this paper, we show that PFSS method can be a good tool to model the general structure of the solar corona. We have briefly compared how the PFSS model can reconstruct the closed loops associated with the streamers appear in the TSE observations. We also show that the global structure of the corona is close to spherically symmetry shape, which suggest that the Sun is still far from the lowest phase of solar cycle. The more detail comparison and analysis of coronal structure as well as the method to represent symmetrical shape of the corona will be explained elsewhere in the future.

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