Analysis of IMF Orientation and Pc5 Power During St. Patrick Geomagnetic Storm on 17 March 2015

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Abstract. Solar storms have a hazardous effect on the Earth, one of the most powerful is Coronal Mass Ejection (CME). St. Patrick geomagnetic storm is a severe geomagnetic storm which is caused by partial halo CME. Propagation of CME at interplanetary space is detected by solar wind parameters by speed and magnetic field. Interplanetary Magnetic Field (IMF) has orientation to determine the shift of solar wind particle. IMF orientation can be classified by IMF cone angle and IMF clock angle. Both can be used as an indicator of Kelvin-Helmholtz instability. This study aims to determine the flow of solar wind to the magnetosphere. The solar wind will enter the magnetosphere can be detected by THEMIS satellite orbits at ~100 km to ~12 Re at magnetotail and ground-based Fluxgate Magnetometer at LAPAN Pasuruan. Meanwhile, the geomagnetic storm is observed by Dst index. We combine data from interplanetary space, magnetosphere, and ground-based magnetometer and processed to Pc5 power. The results are IMF clock angle was closer to zero and IMF cone angle got wider on 15-18 March 2015, FM and FGM Pc5 power surged since March 16, 2015. Finally, a severe geomagnetic storm observed on March 17, 2015 with Dst index was -222 nT.

1. Introduction
The magnetosphere is a magnetic layer that surrounds the Earth and consists of several parts and is shaped by interaction between the Earth’s magnetic field and the solar wind. The bow shock develops in front of the magnetosphere which has function to slow down the solar wind speed by a factor of 3-4 [1]. The region behind the bow shock is magnetosheath which converts solar wind energy into thermal energy, so that in this layer, the solar wind speed reduced ~ 50 km/s [2]. In the sunward direction of the Magnetosphere is the Magnetopause while the part of anti-sunward is Magnetotail, extended by solar wind beyond 100 Re (average Earth radius, ~6367 km) [2, 3]. The magnetosphere has a region dominated by solar wind plasma in the magnetopause and ionospheric plasma in the plasmasphere [3]. Inside the plasmasphere, energetic particles are trapped in the the Van Allen Radiation Belt (Electron Radiation Belt) which has two regions. The inner region (1-3 Re) is dominated by CRAND (Cosmic Ray Albedo Neutron Decay) particles from cosmic rays. Meanwhile, the outer region (4-5 Re) is associated with solar storms, such as flares and Coronal Mass Ejection (CME), wherein the outer radiation belt condition is one of the parameters of the Space Weather [2, 3].

Space weather is the condition of the Sun, Solar Wind, Earth's Magnetosphere, Ionosphere, and Thermosphere that can affect space-borne and ground-based technology and human life and health [4].
The solar wind speed in quiet conditions is around 400 km/s, but if there is disturbance (e.g. CME, High Speed Stream) the speed ~1500 km/s [1]. The space weather parameters for the solar wind are velocity, density, temperature, and magnetic field.

Interplanetary Magnetic Field (IMF) is magnetic field in the solar wind which can be classified by its orientation: the IMF clock angle and IMF cone angle. The IMF cone angle is the angle between the x-direction magnetic field and the resultant. The IMF cone angle can detect the energy that will enter the magnetosphere by identifying the resulting angle. IMF clock angle is the angle of the y-z plane measured away from the z-direction clockwise looking from the Sun to the Earth and defined from -180° to 180° [5, 6]. The IMF orientation can be used as an indicator of Kelvin-Helmholtz instability by decreasing the IMF cone angle from ~ 90° to ~ 10° and the IMF clock angle less than 30° [5].

Solar wind conditions affect the magnetosphere. The magnetosphere has several regions that have their respective functions. If there is interference from solar activity, the part of the dayside magnetosphere will experience an increase in pressure which results in shifting of the inner region. In addition, there is an increase in density and speed resulting in deep dielectric charging on satellites, blackouts, and damage due to extended outages of the electrical grid during the Carrington 1959 geomagnetic storm [7, 8]. Meanwhile, in the nightside, the solar wind causes the auroral substorm (magnetospheric substorms because the reconfiguration of the magnetotail) to be associated with Magnetosphere-Ionosphere coupling [9].

Ultra-low-frequency (ULF) is a wave in low frequency (1 mHz to 5 Hz) or in a period of 150 to 600 seconds [10, 11]. The ULF frequency at 1.7 mHz to 6.7 mHz is referred to the fifth band of pulsation continuous or Pc5 which has the effect of increasing the electron flux at geosynchronous orbits [11].

This study aims to determine the flow of solar wind to the magnetosphere. Solar wind conditions are observed by ACE at interplanetary space. THEMIS detects response of the magnetosphere to the solar wind, and a ground-based Fluxgate Magnetometer to determine how the magnetosphere responds at low-latitude.

2. Data

We use Advanced Composition Explorer (ACE) satellite data, Time History of Events and Macroscale Interactions During Substorms (THEMIS) and ground-based Fluxgate Magnetometer (FM) data at LAPAN Pasuruan.

ACE is a satellite at interplanetary space, has distance 1.5 million km from Earth or at L1 Liberation Point. The ACE data used in this paper is SWEPAM (Solar Wind Electron, Proton, and Alpha Monitor) which has 64 seconds period data and MAG (Magnetometer) which has 1 second data, both of these data have Geocentric Solar Magnetospheric (GSM) coordinates, which can be accessed on Omnmi Web Database.

THEMIS has 5 satellites, P3 (TH-D), P4 (TH-E), and P5 (TH-A) orbits at ~100 km to 12 R_E, while P1 (TH-B) and P2 (TH-C) orbits at lunar equatorial become ARTEMIS [12]. Each THEMIS satellite has 6 instruments. We use THEMIS P3 (TH-D) satellite with the Fluxgate Magnetometers (FGM) instrument. The FGM data used is spin-stabilized data which has 3 second period data and frequency of 0.33 Hz with GSM coordinates which can be accessed through the Omnmi Web Database.

Ground-based Fluxgate Magnetometer (FM) is a magnetometer places at -7.57 112.67 at LAPAN Pasuruan. FM data is magnetic field data with X, Y, and Z directions which has 1 second period data and frequency of 50 Hz.

Geomagnetic storm St. Patrick surged on March 17, 2015, therefore ACE, THEMIS, and Fluxgate Magnetometer data will be processed on March 15-19 2015 to find out how the characteristics of disturbances in the interplanetary space and magnetosphere.

3. Method

SWEPAM, MAG, FGM, and FM data were used to analyze the propagation of the solar disturbance at interplanetary space and Earth’s magnetosphere, observed by space-based and ground-based instruments during geomagnetic storm of St. Patrick on March 17, 2015.
SWEPAM data is used to determine the speed of solar wind at interplanetary space. MAG data is used to determine the condition of the interplanetary magnetic field then calculate to IMF clock angle and IMF cone angle.

The FGM data that will be used is the dayside data, hence, the Dawn/Dusk Asymmetry data must be eliminated [13]. Power Pc5 will be calculated on FGM and FM data to determine the pulsation power of the magnetic field in the magnetopause and low-latitude.

4. Analysis
St. Patrick Geomagnetic storm was caused by Coronal Mass Ejection (CME) on 15 March 2015 at 02:10 UT, appeared as a partial halo CME with an average speed of ~ 668 km/s associated with the C9.1 flare [14]. ACE detected CME at the Interplanetary Space on March, 17 2015, which was marked by the solar wind speed increase to 600 km/s as shown in Figure 1 and magnetic field fluctuating from its normal (1-10 nT) [1] as shown in Figure 2.

![Figure 1. ACE Satellite Observation on Solar Wind Speed (km/s) Data in 11-20 March 2015 (a) Bulk Speed (b) v_x (c) v_y (d) v_z](image-url)
IMF orientations are associated with the properties of Kelvin-Helmholtz Wave (KHW) on the dayside magnetopause. IMF clock angle is defined as the angle between the magnetic field in the y-direction ($B_y$) and the magnetic field in the z-direction ($B_z$) which decreases due to the presence of KHW with an angle $< 30^\circ$ from northward IMF [5]. Figure 3 shows the IMF clock angle of $-85^\circ < \theta < 85^\circ$ in quiet conditions, but it disturbed on March 15, 2015 to March 17, 2015, with the IMF clock angle getting closer to zero, indicated that solar wind particles moving towards Earth, which depends on direction of $B_y$. If $B_y$ is positive, solar wind particles will move to duskward, otherwise they will move to dawnward. IMF clock angle on March 16 2015 at 16:51 UT to 23:41 UT shows $-37^\circ < \theta < 37^\circ$ due to an increase of northward $B_z$ (Figure 2) which represents the existence of KHI. The probability of IMF clock angle to duskward is more influenced by positive $B_z$ (north $B_z$), while dawnward is influenced by negative $B_z$ (south $B_z$) [15].
IMF cone angle ($\phi$) is the angle between the magnetic field in the x-direction ($B_x$) and the resultant ($|B|$) which can detect the energy entering the magnetosphere. IMF orientation associated with Kelvin-Helmholtz instability with IMF cone angle characteristics of $\sim$90° to $\sim$10° investigated by Cluster satellite [5]. Figure 3 shows the increase on the IMF cone angle since March 15 2015 at 16:20 UT by 137.3°, the peak of the IMF cone angle occurred on March 16, 2015 at 23:06 UT with an angle of 165.97°, and decreased on March 17, 2015 to March 18 2015. IMF cone angle can also be interpreted as the magnitude of the angle of the impact of the solar wind at the magnetopause, the bigger the IMF cone angle, the wider magnetopause affected, which causes the geomagnetic storm to get worse. In the same way, IMF clock angle and IMF cone angle show a similar trend when it disturbed: IMF clock angle will get closer to zero that indicate the solar wind particle focused at the sub-solar magnetopause and IMF cone angle will get bigger that represent the perturbed area of sub-solar magnetopause are increasingly widespread. The IMF orientation shows the disturbance earlier than the ACE MAG data (Figure 2), so it is necessary as a preliminary condition to find out geomagnetic storms.

The conditions at magnetopause can be observed by THEMIS satellite. THEMIS has altitude of $\sim$100 km to 12 $R_E$, observes through the magenetotail and the dayside magnetopause. During 15-19 March 2015, THEMIS orbits the dayside and nightside magnetopause as shown in Figure 4. The dayside magnetopause observed by THEMIS was at Magnetopause (12 $R_E$), while the nightside occurred in $\sim$ 2 minutes with apogee to 5 $R_E$ at Electron Radiation Belt region. However, this study does not discuss the disturbance in each region of the magnetosphere, but rather the interference in the Pc5 power FGM magnetic field data compared to FM data as shown in Figure 5.
Figure 4. Orbit of THEMIS in 15-19 March 2015. It showed that during 15-19 March, THEMIS observed at Dayside and Nightside [16].

Figure 5. Pc5 power between ground-based fluxgate magnetometer FM (red) and THEMIS fluxgate magnetometer FGM (black).

Figure 5 shows the FGM Pc5 power of THEMIS (black) and FM (red). FGM and FM started to rise on March 16, 2015, indicating there was a disturbance at magnetosphere. Figure 5 also illustrates that the FGM had increased from 16 March 2015 to 18 March 2015, which its peak occurred on March 17 2015. This was because on 17 March 2015 the solar wind speed (Figure 1) and interplanetary magnetic field (Figure 2) reached its peak. The solar wind speed increases to more than 600 km/s and the $B_z$ magnetic field reached -30 nT. It can be ascertained that if southward $B_z$ occurred, then magnetic reconnection will occur and prevents KHW’s growth [17].
In the same case, FM does not show the same characteristics. This is because THEMIS is on the dayside magnetopause which has tremendous magnetic field due to solar wind approaching Earth. Meanwhile, the magnetosphere is a complex structure consisting of magnetopause on the dayside and magnetotail on the nightside. When there is pressure from the solar wind to the magnetopause, the magnetic field will be directed towards the magnetotail and a reconnection occurs in magnetotail [18] (this happened on March 16, 2015, there were two peaks of FM Pc5 power) or reconnection occurs in Magnetopause as a result of southward $B_z$, it will not necessarily result in reconnection in magnetotail [19]. When $B_z$ reached its minimum on 17 March 2015, a reconnection occurred at the dayside magnetopause, which resulted in the FGM Pc5 power reaching its peak.

The determination of Pc5 power from satellite observations and the ground-based magnetometer has a role to determine the conditions in the magnetopause and magnetotail before a geomagnetic storm, therefore the impact due to geomagnetic storms can be minimized.

Figure 6. Hourly Dst Index in March 2015 [20]

The Dst (Disturbance Storm Time) index is an index of magnetic field disturbance observed by a ground-based magnetometer at low latitudes (near-equatorial) [5, 21, 22]. The Dst index aims to find out how big a geomagnetic storm is, indicated by a negative index. Figure 6 shows a severe geomagnetic storm occurred on March 17, 2015 with Dst index -222 nT [4]. The magnitude of the geomagnetic storm has a strong correlation with solar wind speed (Figure 1), and southward $B_z$ (Figure 2) which showed a significant increase on March 17, 2015 [21, 22].

Based on the observations of the IMF orientation, power Pc5, and Dst index, there was time interval. The IMF cone angle and the IMF clock angle show a disturbance since March 15 2015, shortly after CME occurred on the Sun, followed by a surge FGM and FM Pc5 power on March 16, 2015, and geomagnetic disturbances peaked on March 17, 2015. So, by analysing the IMF orientation and Pc5 power, it could be improve the prediction of geomagnetic storm.

5. Conclusion
CME occurred on March 15, 2015 and arrived at interplanetary space (near-Earth) on March 15, 2015 by IMF cone angle and IMF clock angle observations, FGM and FM Pc5 power surged since March 16 2015, and severe geomagnetic storm occurred on March 17, 2015. There was a time interval of propagation of CME at interplanetary space, magnetosphere, and low-latitude ground-based magnetometer. Therefore, observations in these regions strongly support the analysis and improve the prediction of geomagnetic storms.

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