Pc5 ULF waves during the geomagnetic storms on 7–8 September 2017 observed in the Indonesian region

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Abstract. Pc5 ULF waves have attracted significant attention and been studied through theory, simulation, and observations. To understand the generation mechanisms of ULF waves, one should consider frequency characteristics, solar wind parameters, and geomagnetic activity. Observation on Pc5 magnetic pulsations due to solar wind perturbations at the low latitudes currently has not been widely explored. In this paper, we analyzed the amplitude of Pc5 magnetic pulsations during magnetic storms on 7–8 September 2017. We also investigated the effect of shock in the solar wind on the amplitude of Pc5 magnetic pulsation. We used the magnetometer data of four stations in the Indonesian region, which is located at low latitude, the ACE satellite data, and the Dst index. To extract Pc5 magnetic pulsations, we used the second-order of Butterworth filter with applying the Hamming windowing method. The result shows that the fluctuation in solar wind dynamic pressure triggers the Pc5 pulsations with similar waveforms and the same phase in both components of H and D. Large southward Bz component of the interplanetary magnetic field accompanied by the increase of solar wind dynamic pressure caused the large and long duration of Pc5 pulsation.

1. Introduction
Geomagnetic pulsation Pc5 is a hydromagnetic wave, which is the result of the complex interaction between the solar wind and the Earth’s magnetosphere. As well, this pulsation is a quasi-continuous pulsation with the frequency range of 2–6 mHz [1]. The pulsations are believed generated at the magnetopause and then propagate through Earth’s magnetosphere and ionosphere. Finally, the induced ionospheric currents radiate electromagnetic waves traveling to the Earth surface and can be observed from ground-based stations. Earth’s magnetic field observations play an important role in the understanding of the Earth’s electromagnetic environment.

The study of the geomagnetic pulsations Pc5 observed on the ground level has been the subject of many researchers. Research [2] found that the power enhancement of wave spectra at discrete frequencies corresponds to field line resonance. Field line resonances can be excited by several relatively broad sources such as Kelvin-Helmholtz instabilities, transient day reconnection, and step variations of the solar wind dynamic pressure [3]. The ground-based observations on the Pc5 ULF waves have been widely made at high and middle latitudes [4–6]. Studies on the Pc5 ULF pulsations due to solar wind perturbations at the low latitudes are not widely explored. However, the Pc5 geomagnetic pulsations are also observed at low latitudes [7]. The spatial structure of middle and low
latitudes Pc5 has been discussed by [8]. These authors have found a sharp decrease in the pure state total power spectra pulsations with latitude and increasing probability of low latitude Pc5 occurrence with magnetic activity.

Geomagnetic pulsations Pc5 are typical phenomena at high latitudes during recovery phases of magnetic storms and substorms. It is well known that the development of strong magnetic storms leads to a significant reconstruction of large scale structures of the magnetosphere. For instance, auroral zones can extend to subauroral and even middle latitude areas. In such extreme situations, Pc5 pulsations can be observed at low latitudes and, in such instances, the analysis of geomagnetic observations at low latitudes provides useful information. The Pc5 geomagnetic pulsations observed in the Earth’s magnetosphere are mainly driven by the changes of solar wind dynamic pressure, which is implying the energy transfer from the solar wind to the magnetosphere [9, 10].

The magnetic storm in September 2017 is associated with massive flares, which were followed by Coronal Mass Ejection (CME). The CME is the ejection of high energy particles with high velocity and density. As an effect of the CME, the interplanetary magnetic field can be modified by the solar wind stream time by time, increasing the occurrence probability of the magnetic storm. Our paper aims to study strong Pc5 magnetic pulsations during the magnetic storm associated with a storm sudden commencement (SSC) that occurred on 7 September 2017, at 02:00 UT. We analyze a storm-time Pc5 wave activity on 7–8 September 2017.

2. Data

Variations in solar wind-magnetosphere couplings serve as the driving force behind various characteristic geomagnetic disturbances. These disturbances are defined as “magnetic storms”. The Dst index is commonly used in studies of magnetic storms as an indicator of the intensity of the ring current or magnetic storms. Figure 1 shows the variations in geomagnetic indices in September 2017. The various phases of the storm have been named by a study [11], such as (i) sudden storm commencement (SSC); (ii) initial phase; (iii) main phase; and (iv) the recovery phase. A sudden commencement is characterized by a sudden increase in the magnetic field intensity shortly before the main phase. The initial phase begins after the sudden commencement to where the Dst index decreases monotonically. The main phase starts from the end of the initial phase and ends at the minimum value of Dst. The recovery phase began after the main phase and lasted until the Dst recovers to the value before the storm.
Figure 1. Dst index and solar parameters during the period of 5–12 September 2017.

The upper panel of figure 1 shows the Dst index, 2nd to 4th panels show interplanetary magnetic field for $B_x$, $B_y$, and $B_z$ components in nT, respectively, and 5th and bottom panels for proton density (proton/cc) and solar wind bulk speed (km/s). The onset of the SSC$_1$ and SSC$_2$ were identified on 7 September 2017 at 02:00 UT and 8 September 2017 at 11:00 UT, as marked by the blue dashed lines in the figure. There are two minimums of Dst index, as marked as black dashed lines, during 7-8 September 2017, and they indicate that two magnetic storms occurred during that period. We analyzed storm-time Pc5 wave activity during this magnetic storm. The main phase of this first magnetic storm started on 7 September at 22:00 UT with a minimum Dst of about -142 nT and it expands till ~02:00 UT on 8 September. The second storm with a minimum Dst of -109 nT was initiated during the recovery phase of the first magnetic storm, and it then expanded till ~18:00 UT on 8 September. The sudden storm commencement and the 1st and 2nd magnetic storms are labeled with SSC, SP$_1$, and SP$_2$ in figure 1. Red curves represent periods between initial and main phases of storms, while magenta represents the magnetic field during recovery periods of the associated storm. The remain time intervals marked black curves represent pre-storm and post-storm magnetic field data.
In this study, Pc5 magnetic pulsations were extracted from magnetic field variations recorded by ground-based magnetometers in the Indonesian region at Biak (BIK), Pontianak (PTN), Manado (MND), and Kupang (KPG) stations. The location of stations coordinates are as follow: BIK (GG. -1.08, 136.05; GM. -9.37, 207.39; L=1.03), PTN (GG. -0.07, 109.31; GM. -9.75, 181.96; L=1.02), MND (GG. 1.44, 124.84; GM. -7.80, 197.63; L=1.01), and KPG (GG. -10.20, 123.40; GM. -19.58, 194.95; L=1.13) where GG and GM stand for geographical and geomagnetic coordinates, respectively, and L for the magnetic shell. These magnetometers were setup in LAPAN (National Institute of Aeronautics and Space, Indonesia) and BMKG (Meteorological, Climatology, and Geophysical Agency, Indonesia) stations under a research collaboration with International Center for Space Weather Science and Education (ICSWSE), Kyushu University of Japan. The magnetometers record data continuously three components of the magnetic field with a time resolution of 1 second and have high sensitivity. The plot of magnetic data during the period of the storm, as mentioned above, is shown in figures 2 and 3. In those figures, the horizontal axis represents time in day and the vertical axis shows H and D components of the magnetic field for each station.
Geomagnetic pulsations in the Pc5 band ($f\sim2–6$ mHz) are probably the most easily observed ULF waves [12]. Due to their large amplitudes (up to some 100 nT) and long periods (several minutes), Pc5 pulsations can even be detected in magnetograms with low sensitivity and sampling rate (e.g., 1 min). The extraction of Pc5 magnetic pulsations was performed by using the second-order of Butterworth filter by applying the Hamming windowing method. An example of the extraction of Pc5 pulsation in Indonesia at four stations on 8 September 2017 is shown in figure 4.
3. Result and Discussion

The initial phase of the magnetic storm on 7 September 2017 is characterized by SSC$_1$ with large positive (+51 nT) values of the Dst index at 01 UT. This SSC was associated with a shock in solar wind plasma where there was an increase of solar wind velocity from 408 km/s to 582 km/s and an increase of proton density from 3 proton/cc to ~10 proton/cc on 7 September 2017, at 00 UT. This SSC is also accompanied by turning of the Bz component of the interplanetary magnetic field from about +3 nT to -3 nT. The main phase of this magnetic storm developed under a negative Bz component of the interplanetary magnetic field with a duration of about 8 hours, from 02–10 UT on 7 September 2017 with a magnitude of ~7 nT. The main phase continued growth until the Dst index reached its minimum value to -124 nT. However, before the Dst index recover to its initial value, the Bz component of interplanetary magnetic field once again turns to southward with large 29 nT and also accompanied by a sudden increase of solar wind speed to 783 km/s on 8 September 2017 at 01 UT, and then, solar wind velocity continued to increase until reaching its maximum value of 802 km/s on 8 September 2017 at 07 UT. This turning the Bz component of the interplanetary magnetic field is identified as a cause of the second peak in the Dst index of -109 nT on 8 September 2017 at 18 UT.

Figure 4. Filtered signals of Pc5 pulsation for H (left) and D (right) component of the magnetic field on 8 September 2017.
To discuss the Pc5 pulsations observed in the Indonesian region, we first show the evolution of the Pc5 amplitude during the whole period of the magnetic storm, as displayed in figure 5. Figure 5 shows the hourly average of solar wind dynamic pressure on the upper panel, and the panels below represent the hourly average amplitude of Pc5 pulsations from 4 stations in the Indonesian region where the left and right panels represent the H and D component, respectively. From figure 5, it can be seen each peak in solar wind dynamic pressure associated with peak Pc5 pulsation in both components of the magnetic field. This means that the large Pc5 oscillation during the magnetic storms was generated by the strong modulation of the dynamic pressure of the solar wind.

![Figure 5](image)

**Figure 5.** The plot of the hourly average of solar wind dynamic pressure and Pc5 pulsation during the magnetic storm.

The wave pattern of Pc5 pulsations observed in the Indonesian region during SSC1 or the increase of solar wind dynamic pressured that labeled by A in figure 5 is shown in figure 6. The left panel in figure 6 shows the H component while the right panel for the D component of Pc5 magnetic pulsation. From the figure can be seen that the Pc5 pulsations are coherent for all stations in both H and D components. Figure 7 shows the Pc5 waveform associated with increasing solar wind dynamic pressure (SP1) labeled by B in figure 5. From figure 7, it can be seen that fluctuation in solar wind dynamic pressure accompanied by significant southward Bz component of the interplanetary magnetic field triggers the large and long duration of Pc5 pulsation. These Pc5 pulsations also have similar waveforms with the same phase for both H and D components of the magnetic field. Pc5 pulsations that associated with increasing solar wind dynamic pressure (SSC2 and SP2) that labeled by dashed lines C and D in figure 5 also show similar waveforms, but the figure is not shown here.
Figure 6. Pc5 waveform that associated with increasing solar wind dynamic pressure that labeled by A in figure 5.

Figure 7. Pc5 waveform that associated with increasing solar wind dynamic pressure that labeled by B in figure 5.
Finally, Pc5 pulsations observed in the Indonesian region during the magnetic storm on 7–8 September 2017 show a good correlation with the increase of solar wind dynamic pressure in both H and D components. The significant increase of Pc5 pulsation also is associated with the shock in the solar wind. Pc5 pulsations generated by those events show similar waveforms and the same phase for both components. During large Bz component of the interplanetary magnetic field accompanied by the increase of solar wind dynamic pressure, more significant and long duration of Pc5 pulsation were observed.

4. Conclusion
We showed the amplitude of Pc5 magnetic pulsations during the magnetic storm of 7–8 September 2017 using magnetic field data at four stations in the Indonesian region. At the sudden commencement associated with shock in solar wind plasma, we observed large Pc5 magnetic pulsations. Fluctuation in solar wind dynamic pressure triggers the Pc5 pulsations with similar waveforms and the same phase in both components of H and D. Large southward Bz component of the interplanetary magnetic field accompanied by the increase of solar wind dynamic pressure caused the large and long duration of Pc5 pulsation. To understand more detail of the Pc5 pulsation, further study is needed.

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