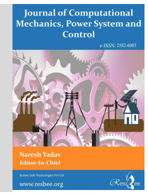
Vol.8 No.1 Jan 2025

Journal of Computational Mechanics, Power System and Control

Received 25 September, Revised 8 December, Accepted 3 January




# A New Method of Detecting Irregular Pulsation Type Ii Using the Wavelet Scalogram of the Magnetic H-Component

**Godfrey Ikeozahu Ojerheghan**
*Department of Physics, Faculty of Physical Sciences, University of Ilorin, Ilorin, Nigeria.*
*godfrey777@gmail.com*

**Isaac Abiodun Adimula**
*Department of Physics, Faculty of Physical Sciences, University of Ilorin, Ilorin, Nigeria.*

**Adeniji Olayinka Olawepo**
*Department of Physics, Faculty of Physical Sciences, University of Ilorin, Ilorin, Nigeria.*

**Arijit De**
*Department of Electronics & Communication Engineering, Netaji Subhash Engineering College, Techno City, Garia, Kolkata, India.*

**Francis Ugbede Salifu**
*Department of Physics, Confluence University of Science and Technology, Osara, Kogi State, Nigeria.*

Abstract: The irregular pulsation Type II (Pi2) is an electromagnetic wave that has a frequency range of 6.6 – 25 mHz. It occurs within the magnetosphere at the onset of substorm just at the end of the growth phase. The 1-second resolution geomagnetic H-field data used in this paper were obtained with the fluxgate magnetometers at four ground stations in low-latitudes; Abidjan (ABJ), Lagos (LAG), Ilorin (ILR) and Addis Ababa (AAB) on selected days. The 1-second resolution of the north-south magnetic component (Bz) data was obtained from the Advanced Composition Explorer (ACE) spacecraft which is situated in the Geocentric Solar Ecliptic (GSE) coordinates. The SuperMAG Lower (SML) index which is an improved version of the Auroral Lower (AL) index was used to identify substorm onsets and their times of occurrence. The coherence of ground H and satellite Bz were filtered using the Pi2 passband. The points at which the filtered coherence of H and Bz were greater than 0.5nT2 were recorded. Applying the wave-packet analysis on the filtered H ground data, the 3D scalogram was used to detect Pi2 spikes, and their universal times (UTs), frequencies, and magnitudes were recorded. It was observed that on days where no Pi2 was recorded by the coherence method, the wave-analysis method revealed that there were Pi2 events. A correlation value of 0.96 between the times of Pi2 occurrence using the coherence method and the times of Pi2 occurrence using the wave-packet scalogram was obtained.

**Keywords:** Supermag Lower Index, Pi2 Spikes, Coherence, Substorm, Wave-Packet

***Nomenclature***

| Abbreviation | Expansion |
|---|---|
| ULF | Ultra Low Frequency |
| GPS | Global Position System |
| HF | High Frequency |
| SML | SuperMAG Lower |
| AL | Auroral Lower |
| MAGDAS | Magnetic Data Acquisition System |
| ACE | Advanced Composition Explorer |
| GSE | Geocentric Solar Ecliptic |
| MATLAB | Matrix Laboratory |
| UTs | Universal Times |

## 1. Introduction

Generally, pulsations are distortions in signals in which fast temporary changes in the amplitudes of the signal from a baseline are either upwards or downwards and then return to the normal state. These distortions are caused by geomagnetic disturbance externally from outside the atmosphere (magnetic storms) or internally from the magnetosphere (magnetic substorms). Auroral substorms are associated with fast changes in magnetic field topology that give rise to the acceleration of energized particles toward the inner regions of the magnetosphere. Geomagnetic pulsations were first observed in the ground-based measurements of the 1859 Great Aurora events [20]. Geomagnetic pulsations with regular magnetic amplitudes are called continuous pulsation (Pc1-Pc6) while those with irregular amplitudes are called irregular pulsations (Pi1-Pi3). Pi2 pulsations are damped ULF waves generally described by an abrupt



https://doi.org/10.46253/jcmps.v8i1.a2

commencement followed by a decay in amplitude which typically only sustains for a few periods ranging from 40 to 150 seconds or frequencies ranging from 6.7 to 25 mHz [2]. Although most Pi2 is explicitly the outcome of the onset or intensification of the substorm expansion phase [15], where the amplitudes of the magnetic field lie in the range of 0.25 to 2.5 nT [27] and some others have been documented during times without substorm activity [26] [11] [12], and [5].

One of the major problems caused by these pulsations is that they enhance GPS delay. The ULF waves propagating down through the ionosphere can cause oscillations in the Doppler shift of HF radio transmissions that are correlated with the magnetic pulsations recorded on the ground [1]. The plasma instability mechanism which is the interchange of momentum between plasma particles and high-frequency noise results in the appearance of an effective "collisional" viscosity, which in turn may, like ordinary binary collisions, induce an increase in the dissipative instabilities [7]. The paper [3] suggested that the frequency variations of pulsations during storms are related to the partial distribution in the ring current in the equatorial region.

The paper [23] agreed that Pi2 is most frequently observed close to the midnight meridian between 20:00 UT and 24:00 UT. At high latitudes, the characteristics of Pi2 pulsations are quite distinct when compared to those at middle and low latitudes; being generated by different mechanisms [8] [14]. At lower latitudes, the Pi2 pulsations are well-defined while closer to the poles they are irregular and complex, polluted by a pronounced level of background noise, particularly in the Pi1 band [21] [16][19]. The paper [29] showed that Pi2 is compressional at lower latitudes and primarily transverse at auroral latitudes. The paper [18] wrote that at high latitudes, Pi2 is encountered exclusively in a limited range of local times around magnetic midnight consistent approximately to the extent of the substorm current wedge.

The middle and low latitudes Pi2 have similar frequency spectra [24]. Although Pi2 pulsations on the dayside are often hidden by signals from other sources, numerous observations of dayside Pi2 have been made over a range of latitudes straddling the geomagnetic equator [22] [25]. The fast mode waves spreading across the ambient magnetic field around midnight make it difficult for Pi2 to be detected on the dayside.

A brief introduction of how Pi2 signals are detected has been done in section 1. The literature review of recent works and their gaps were styled in section 2. In section 3, the methodology used for this work was well documented and in section 4, the results were recorded. We discussed these results in section 5 and concluded the paper in section 6.

## 2. Literature Review

Pi2 was generated during the expansion phase onset by the swift reconfiguration of the magnetotail [17]. Recent research has proved that the passband of Pi2 varies from high latitude to low latitude in terms of their magnetic amplitudes and propagation mechanism [6]. According to [9], when the solar wind speed, v > 430 km-1, the vertical component of the total magnetic field, Bz < 0 nT, the geo-dipole angle, $\theta > 78°$, then a Pi2 event occurs. The drawback of Gussenhoven's conditions is that Pi2 events can occur without any storm. For a quiet magnetosphere where the measure of the general level of geomagnetic activity over the globe for a given day index, ap = 0.

The paper [10] implemented that a Pi2 can be detected when the total magnetic field, $B \leq 6.5$ nT; the vertical component of the total magnetic field, Bz < 2 nT; the geo-dipole angle, $\theta \leq 101°$ and the solar wind speed, $v \leq 390$ km$^{-1}$. Recent works have relegated these conditions for the occurrence of Pi2 since the magnetosphere is a resonant cavity where some of these pulsations resonate in the field lines and drive the field currents into the ionosphere.

For a non-quiet magnetosphere where ap 0 and the planetary 3-hour-range geomagnetic index, Kp > 2, Chae-Woo Jun et al., (2013) suggested that the Pi2 pulsations can be sampled when the Pi2 power value with dominant frequency within the frequency domain (6.7 - 25 mHz) in the 3-minute interval using the Fourier transform method of time series data is more than 0.02 (10-1.7) nT2 and this value is 10 times higher than the preceding 9-minute values and the following 17-minute values. The pitfall of this assumption is that the occurrence of Pi2 is not a function of the power value because when the solar wind speed increases, there is the possibility of increased power by the Pc4 whose frequency bands are within that of Pi2.

The most recent method for detecting Pi2 is the consideration of the Bz value from the satellite data and H-component of the magnetic data on a ground observatory and obtaining their coherence. The author [28] stated that Pi2 pulsations were considered when the compressional oscillations observed at both day and night satellites are coherent oscillations with midnight ground H, with higher amplitudes in the night sector when the coherence level is greater than 0.6. This confirms that the selected daytime Pi2 oscillations are not continuous pulsations (Pc). Characteristics of Pi2s are identical at night and different at day between satellite and ground. Gharmy (2012) suggested that when the coherence of the H- component of the magnetic field on the ground and the Bz of the satellite data is greater than 0.7, then a Pi2 event can be selected. External stimulation such as solar wind pressure, compressional waves are generated inside the magnetosphere and propagate tail-ward reflecting between two boundaries, such as the magnetopause and the plasmapause, giving rise to standing waves at discrete frequencies [13]. Pi2 is associated with a compressional wave, excited by sudden compression of the inner magnetopause at the substorm onset [4]. The Bz satellite data are signatures of the compressive wave.

The methods of detecting Pi2 by previous researchers are changing as new techniques of detecting Pi2 are emerging due to advanced technologies and the development of wave-related software in recent times. This paper presents the newest method to detect Pi2 occurrence which is the wavelet analysis method. A wavelet scalogram is a graphic representation of a signal in terms of its frequency, times of occurrence, and magnitude. The beauty of this new method is that the H-ground data when filtered can show the Pi2 wave-packet spikes which are identified visually. In this study, we examined Pi2 occurrences at the equatorial latitudes where there are high equatorial ring currents that support radio communications.

## 3. Methodology

We used the 1-min SML index which is an electrojet index that is similitude to the AL index downloaded from the SuperMAG website (https://supermag.jhuapl.edu/indices/) for each day considered. The days in which data are well archived are considered for this study. The selected days were 30 August 2006, 1 October 2009, 11 December 2010, and 6 February 2011 for which large amounts of data were available. The SML index is preferred in this work due to its improved spatial coverage of magnetic activities from 110 observatories as against the 12 observatories for AL. The SML index is used to measure the level of substorm activities. The ground H-magnetic data used are 1-sec data obtained from the MAGDAS archives obtained from https://data.icswse.kyushu-u.ac.jp. The data were for the ground stations at Abidjan, Lagos, Ilorin, and Addis Ababa. The parameters of the stations are shown in Table 1. The 1-second resolution ACE satellite data were obtained from the ACE Science Centre Home for the selected days (https://izw1.caltech.edu/ACE/ASC/level2/lvl2DATA_MAG.html). The ACE spacecraft observes and measures magnetic fields from the GSE coordinates.

***Table 1.*** *List of The Selected Magdas Stations*

| Station | LT | Code | GLat | GLong | GMLat | GMLong |
|---|---|---|---|---|---|---|
| Abidjan | UT+0 | ABJ | 5.36°N | 4.00°W | 8.94°N | 69.36°E |
| Lagos | UT+1 | LAG | 6.52°N | 3.38°E | 8.86°N | 76.90°E |
| Ilorin | UT+1 | ILR | 8.47°N | 4.54°E | 10.57°N | 78.38°E |
| Addis Ababa | UT+3 | AAB | 9.04°N | 38.77°E | 5.31°N | 112.14°E |

The substorm onsets were identified where there is an abrupt decrease in the magnetic field indicating the substorm expansion phase as shown by the SML indices. The timings and SML indices for the onsets are displayed when the 'hand raised' pointer is on the point of onset on the webpage. The UTs of the substorm onsets as displayed by the SML were obtained from the SML data. The raw type of the 1-sec ground data was converted to the original signal using a source code in MATLAB. The original H-signals were normalized and combined with the normalized de-noised Bz data to obtain their coherences. The coherence of H and Bz was filtered using the Pi2 passband of 6.6 mHz to 25 mHz. In this work, a Pi2 event was confirmed when the coherence is greater than 0.5nT2 being the midway for the Bz-H relation. Coherence measures the degree of linear dependency of two waves by testing for similar frequency components. If two signals correspond to each other perfectly at a given frequency, the magnitude of coherence is 1 but if they are totally unrelated, coherence will be 0. Partial coherency which ranges from 0.5 to 0.9 shows some levels of linear dependency for signals whose coherent peaks are low.

However, the Pi2 wave packets are obtained when the original H data is filtered within the Pi2 band. The 2D and 3D scalograms of the filtered Pi2 wave packet were obtained by using the cross-wavelet technique in MATLAB to display any part of the filtered Pi2 signal with a high power magnitude. The visible spikes whose prominences are 0.6 times the magnitude(max) were identified and recorded in terms of its

Frequency, magnetic local time, and magnitude. The UTs of the Pi2 spikes were obtained from the scalogram data. The plot of the UTs of the Pi2 as analyzed by the wavelet analysis method and the UTs of the substorm onsets as shown by the coherence method was done to show the correlation between the two UTs.

# 4. Results

## 4.1 Events on 30 August 2006

The substorm onsets occurred at 05:38UT, 17:00UT, and 19:20UT with corresponding SML indices of -46.48nT, -15.39nT, and -45.34nT respectively as seen in Fig. 1.

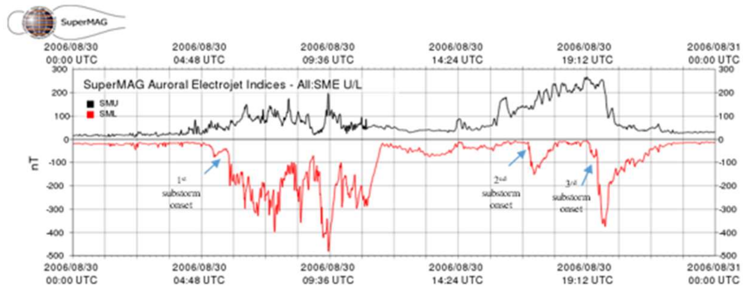



***Fig.1.*** *The SML indices showing substorms on 30 August 2006*

The two stations considered on 30 August 2006 were ILR and AAB. Using the condition of coherence > 0.5,

There was no Pi2 in ILR while there were two Pi2s in AAB at frequency points 12.5 mHz and 16.5 mHz as shown in Fig. 2. Thus, there was no Pi2 event in ILR while there were two Pi2 events identified in AAB.

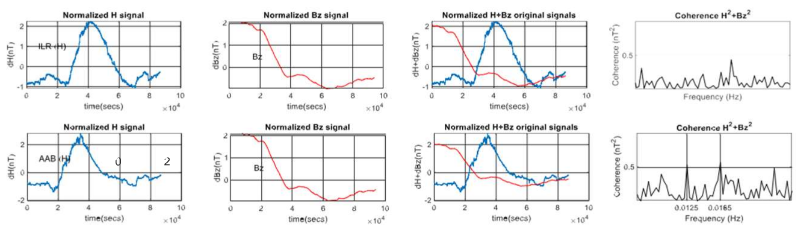
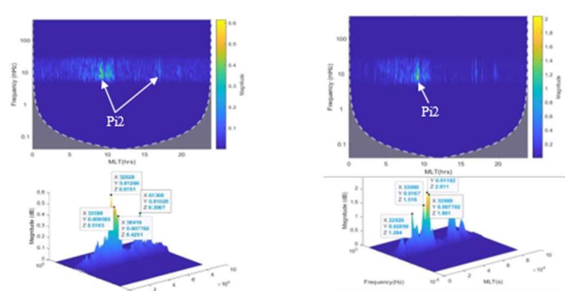



***Fig. 2.*** *The H-component, Bz-component, and the coherence of Bz-H on 30 August 2006*

In the wave packet analysis, the H-data for the two selected stations were denoised separately and then filtered using the passband of a Pi2 using the MATLAB code. The result is displayed and the Pi2 events are selected where the prominence of the spectral spike is more than 0.6 of the magnitude(max) of the scalogram. In this case, the magnitude(max) is 0.6 for ILR and 2.0 for AAB, thus any spike higher than 0.36 for ILR and 1.2 for AAB is selected as a Pi2 spike as seen in Fig. 3. This process was done for all other cases. There were four Pi2 events each in ILR and AAB as shown in Tables 2 and 3 respectively.

This is a clear indication that whereas the coherence method indicated that there were no Pi2 events in Ilorin, the wavelet method showed four Pi2 events. Furthermore, whereas the coherence method indicated two Pi2 events in Adidas Ababa, the wavelet method showed four Pi2 events.




(a) (b)

***Fig. 3.*** *The 2D and 3D scalograms of filtered Pi2 wave packet for (a) ILR and (b) AAB on 30 August 2006*

***Table 2.*** *The Magnitudes, Frequencies, Ut, And Lt of the Four Pi2 Events in Ilr On 30 August 2006*

| Pi2 event | Magnitude (db) | Frequency (m Hz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| A | 0.6151 | 12.66 | 32620 | 0904 | 10:04 am |
| B | 0.5103 | 9.59 | 33590 | 0920 | 10:20 am |
| C | 0.4251 | 7.79 | 36410 | 1007 | 11:07 am |
| D | 0.3907 | 10.28 | 61300 | 1702 | 06:02 pm |

***Table 3.*** *The magnitudes, frequencies, UT, and LT of the four Pi2 events in AAB on 30 August 2006*

| Pi2 event | Magnitude (db) | Frequency (m Hz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| A | 1.284 | 20.56 | 22920 | 0622 | 09:22 am |
| B | 1.981 | 7.79 | 32980 | 0910 | 12:10 pm |
| C | 1.516 | 16.7 | 33090 | 0912 | 12:12 pm |
| D | 2.011 | 11.02 | 33680 | 0921 | 12:21 pm |

## 4.2 Events on 1 October 2009

The substorm onsets occurred at 03:03UT, 03:37UT, 04:58UT, 10:35UT, 14:07UT, 22:11UT and 22:40UT with corresponding SML indices of -75.90nT, -107.73nT, -77.69nT, -64.64nT, -93.89nT, -55.94nT and -54.22nT respectively as seen in Fig. 4.

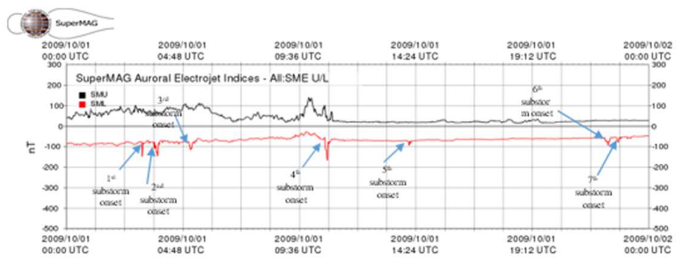



***Fig. 4.*** *The SML indices showing substorms on 1 October 2009*

The two stations considered on 1 October 2009 were ILR and AAB. Using the concept of coherence > 0.5, there was no Pi2 event at both ILR and AAB as shown in Fig. 5.

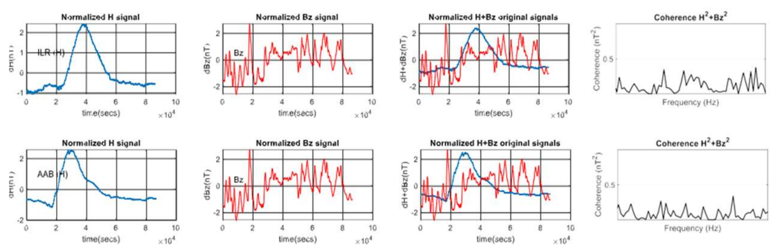



***Fig. 5.*** *The H-component, Bz-component, and the coherence of Bz-H on 1 October 2009*

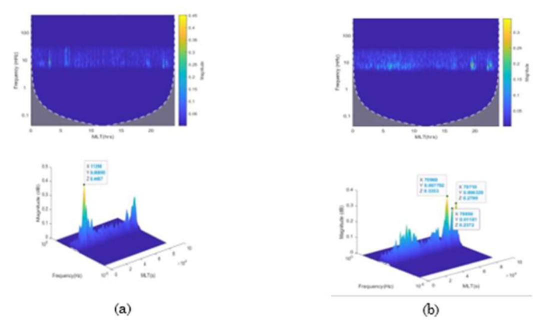



***Fig. 6.*** *The 2D and 3D scalograms of filtered Pi2 wave packet for (a) ILR and (b) AAB on 1 October 2009*

The magnitude of a signal indicates the maximum displacement of the signal from its equilibrium position (zero level). In the frequency domain, the magnitude shows the power level or strength of the signal which is represented by the spectra spikes. In the wave packet analysis, it was shown in Fig. 6 that the magnitude(max) is 0.45 for ILR and 0.3 for AAB, thus any spike higher than 0.27 for ILR and 0.18 for AAB is selected as a Pi2 spike. There was one Pi2 event in ILR and three Pi2 events in AAB as shown in Tables 4 and 5 respectively.

***Table 4.*** *The magnitude, frequency, UT, and LT of one Pi2 event in ILR on 1 October 2009*

| Pi2 event | Magnitude (db) | Frequency (m Hz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| A | 0.4487 | 8.95 | 11250 | 0308 | 04:08 am |

***Table 5.*** *The magnitudes, frequencies, UT, and LT of the three Pi2 events in AAB on 1 October 2009*

| Pi2 event | Magnitude (db) | Frequency (m Hz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| A | 0.3353 | 7.79 | 70960 | 1943 | 09:43 pm |
| B | 0.2799 | 6.33 | 79710 | 2209 | 01:09 am |
| C | 0.2372 | 11.81 | 79850 | 2211 | 01:11 am |

## 4.3 Events on 11 December 2010

The substorm onsets occurred at 00:32UT, 03:39UT, 12:24UT, 14:34UT, 21:12UT and 22:38UT with corresponding SML indices of -37.01nT, -37.33nT, -24.43nT, -38.51nT, -23.27nT and -20.38nT respectively as seen in Fig. 7.

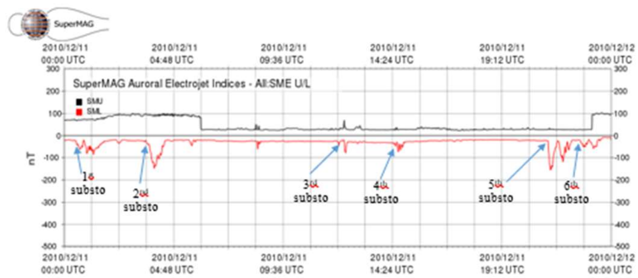



***Fig. 7.*** *The SML indices showing substorms on 11 December 2010*

The four stations considered on 11 December 2010 were ABJ, LAG, ILR and AAB. Applying the concept of coherence > 0.5, there was one Pi2 event each in ABJ, LAG, and AAB while ILR had three Pi2 events as shown in Fig. 8.

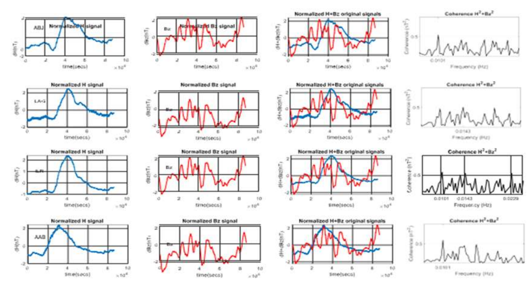
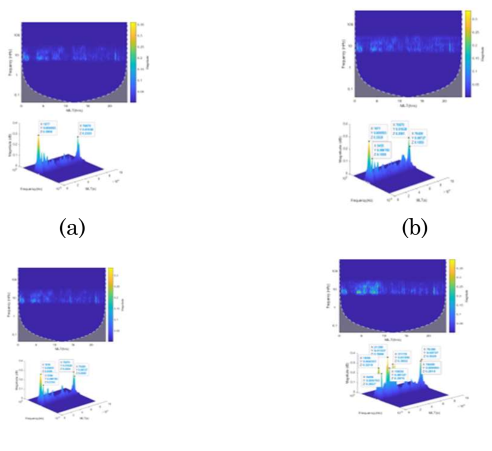


***Fig. 8****. The H-component, Bz-component, and the coherence of Bz-H on 11 December 2010*



(a) (b)

(a) (d)

***Fig. 9.*** *The 2D and 3D scalograms of filtered Pi2 wave packet for (a) ABJ, (b) LAG, (c) ILR, (d) AAB on 11 December 2010*

However, using the wave-packet analysis, it was shown in Fig. 9 that the number of identified Pi2 were 2, 4, 4, and 7 in ABJ, LAG, ILR, and AAB respectively as recorded in Tables 6, 7, 8, and 9.

***Table 6.*** *The magnitudes, frequencies, UT, and LT of the two Pi2 events in ABJ on 11 December 2010*

| Pi2 event | Magnitude (dB) | Frequency (mHz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| A | 0.3598 | 9.59 | 1877 | 0031 | 00:31 am |
| B | 0.2326 | 10.28 | 76670 | 2118 | 09:18 pm |

***Table 7.*** *The magnitudes, frequencies, UT, and LT of the four Pi2 events in LAG on 11 December 2010*

| Pi2 event | Magnitude (dB) | Frequency (mHz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| A | 0.3328 | 9.59 | 1871 | 0031 | 01:31 am |
| B | 0.1939 | 6.78 | 5455 | 0130 | 02:30 am |
| C | 0.1859 | 7.27 | 76430 | 2114 | 10:14 pm |
| D | 0.2501 | 10.28 | 76670 | 2118 | 10:18 pm |

***Table 8.*** *The magnitudes, frequencies, UT, and LT of the four Pi2 events in ILR on 11 December 2010*

| Pi2 event | Magnitude (db) | Frequency (m Hz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| **A** | 0.3308 | 8.95 | 1850 | 0031 | 01:31 am |
| **B** | 0.2124 | 6.78 | 5596 | 0133 | 02:33 am |
| **C** | 0.2028 | 7.27 | 76420 | 2114 | 10:14 pm |
| **D** | 0.2424 | 10.28 | 76670 | 2118 | 10:18 pm |

***Table 9.*** *The magnitudes, frequencies, UT, and LT of the seven Pi2 events in AAB on 11 December 2010*

| Pi2 event | Magnitude (db) | Frequency (m Hz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| **A** | 0.3218 | 8.35 | 1859 | 0031 | 03:21 am |
| **B** | 0.2627 | 6.78 | 5496 | 0132 | 04:32 am |
| **C** | 0.2978 | 7.27 | 19850 | 0531 | 08:31 am |
| **D** | 0.3966 | 13.57 | 21350 | 0556 | 08:56 am |
| **E** | 0.3092 | 15.58 | 31170 | 0839 | 11:39 am |
| **F** | 0.3029 | 7.27 | 76390 | 2113 | 00:13 am |
| **G** | 0.2818 | 9.59 | 76650 | 2118 | 00:18 am |

## 4.4 Events on 6 February 2011

The substorm onsets occurred at 00:48UT, 02:54UT, 06:08UT, 08:43UT, 11:25UT and 16:58UT with corresponding SML indices of -52.38nT, -106.00nT, -116.63nT, -139.97nT, -247.15nT and -332.99nT respectively as seen in Fig. 10.

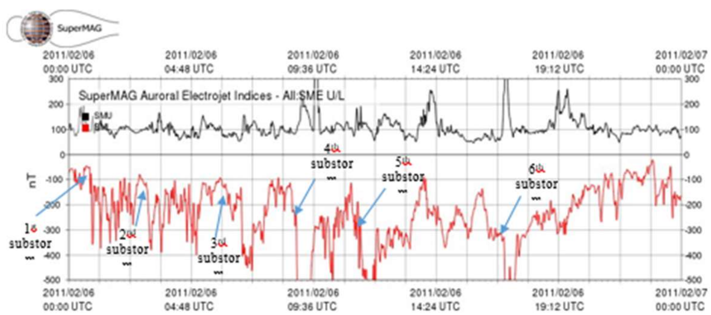



***Fig. 10***. *The SML indices showing substorms on 6 February 2011*

The two stations considered on 6 February 2011 were ABJ and ILR. Applying the coherence method, there was no Pi2 identified in ABJ and one Pi2 was identified in ILR as shown in Fig. 11.

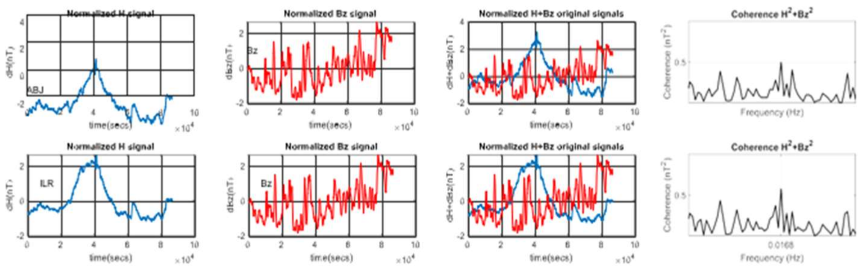


*Fig. 11. The H-component, Bz-component, and the coherence of Bz-H on 6 February 2011*

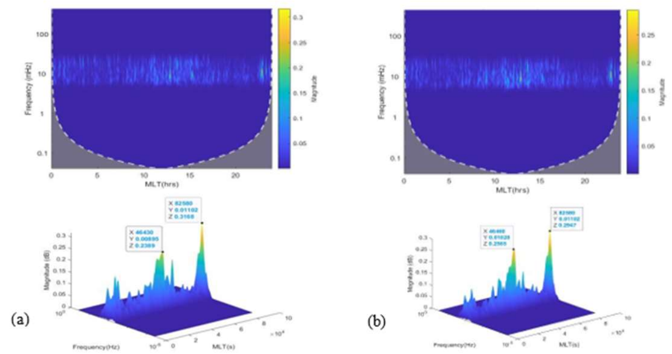


*Fig. 12. The 2D and 3D scalograms of filtered Pi2 wave packet for (a) ABJ and (b) ILR on 6 February 2011*

But, using the scalogram method, two Pi2 each were identified in ABJ and ILR as shown in Fig. 12 and recorded in Tables 10 and 11.

***Table 10.*** *The magnitudes, frequencies, UT, and LT of the two Pi2 events in ABJ on 6 February 2011*

| Pi2 event | Magnitude (dB) | Frequency (mHz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| A | 0.2389 | 8.95 | 46430 | 1254 | 12:54 pm |
| B | 0.3168 | 11.02 | 82580 | 2256 | 10:56 pm |

***Table 11.*** *The magnitudes, frequencies, UT, and LT of the two Pi2 events in ILR on 6 February 2011*

| Pi2 event | Magnitude (dB) | Frequency (mHz) | UT (secs) | UT (hrs) | LT (hh: mm) |
|---|---|---|---|---|---|
| A | 0.2565 | 10.28 | 46460 | 1254 | 01:54 pm |
| B | 0.2947 | 11.02 | 82580 | 2256 | 11:56 pm |

## 5. Discussion

### 5.1 The New Method of Identifying Pi2 using a Scalogram of the Pi2 Wave-Packet

This section has revealed that the sampled days reported not to have any Pi2 event using the coherence method (see Figs. 2, 5, 8, and 11) have Pi2s when the wave-packet scalogram method is used (see Tables 2 – 11). The verification of whether there were Pi2 occurrences or not was undoubtedly confirmed by the new method of Pi2 identification as seen in Table 12. The new method which is the scalogram method is an improved version of the coherence method because it shows the vivid Pi2 spikes with the times of occurrence and corresponding Pi2 frequencies. In this work, the use of SML indices which is an improvement over conventional AL indices coupled with the wave-packet analysis which decomposes the signal into its various frequencies has made the new method clearer and easier to use.

***Table 12.*** *Verification of Pi2 occurrences using the coherence method and scalogram method*

| Selected Days Stations | Pi2 by Coherence > 0.5? (Number of Pi2) | Pi2 by Scalogram spikes? (Number of Pi2) |
|---|---|---|
| 06 August 2006 ILR | Yes (2) | Yes (4) |
| AAB | No (0) | Yes (4) |
| 01 October 2009ILR | No (0) | Yes (1) |
| AAB | Yes (2) | Yes (3) |
| ABJ | Yes (5) | Yes (2) |
| 11 December 2010 LAG | No (0) | Yes (4) |
| ILR | Yes (1) | Yes (4) |
| AAB | Yes (1) | Yes (7) |
| 06 February 2011 ABJ | No (0) | Yes (2) |
| ILR | Yes (1) | Yes (2) |

## 5.2 The Correlation Coefficient between the two Universal Times (UTs)

The UTs recorded by the SML indices show when the substorm onsets occurred. The UTs obtained from the scalograms also show when the Pi2s occurred. Only Pi2s whose prominence of the spectral spike is more than 0.6 of the magnitude(max) of the scalogram were selected to ensure the visual significance of each Pi2 spike. The selection of the two UTs was done randomly as tabulated in Table 13. The Uts recorded by the SML indices were plotted against the UTs obtained from the scalograms and the correlation coefficient, $R^2$ was 0.96. This shows that there is a high correlation between the times of occurrences of Pi2 recorded by the SML indices and the scalogram as seen in Fig.14.

***Table 13.*** *The randomly selected two UTs by SML indices and Scalogram*

| UTs recorded by SML indices | UTs obtained from the scalograms |
|---|---|
| 0032 | 0009 |
| 0048 | 0012 |
| 0254 | 0132 |
| 0303 | 0133 |
| 0337 | 0308 |
| 0339 | 0531 |
| 0458 | 0556 |
| 0538 | 0622 |
| 0608 | 0839 |
| 0843 | 0904 |
| 1035 | 0910 |
| 1125 | 1007 |
| 1224 | 1254 |
| 1407 | 1702 |
| 1434 | 1728 |
| 1658 | 1943 |
| 1700 | 2113 |
| 1920 | 2114 |
| 2112 | 2118 |
| 2211 | 2209 |
| 2238 | 2211 |
| 2240 | 2256 |

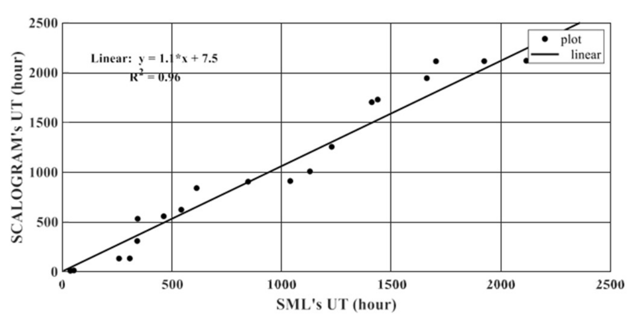



***Fig. 14****. A plot of the two UTs showing their correlation coefficient*

# 6. Conclusion

We examined Pi2 pulsations observed at the four magnetometer stations separated in latitude along the same meridian such as ABJ, LAG, ILR, and AAB stations on some selected days using the coherence method and wave-packet scalogram analysis method which is the new method of detecting Pi2. It has been shown that the days where no Pi2 events were using the coherence method, actually have some Pi2 events as shown by the scalogram analysis method. The H components of the ground stations and the Bz components of the ACE satellite stations on the selected days were analyzed to obtain the coherence of Bz-H at the threshold of 0.5. The wave-packet scalogram method was used to detect Pi2 whereas the coherence method could not. For instance, in the Ilorin station on 30 August 2006 as displayed in Fig. 2, it is discovered that the two frequency points where the coherence value was greater than 0.5 were 12.5 mHz and 16.5 mHz while in the Addis Ababa station on the same day, there was no frequency point that the coherence value was greater than 0.5. Thus, by the coherence analysis, Pi2 occurred at Ilorin but not in Addis Ababa on the same day. Results from this study have proved that there were Pi2 occurrences in both stations on the same day when the scalogram of the Pi2 wave packets was used.

The SML indices gave a wider spectrum of occurrences of substorms while spectral spikes of the wave packets analysis of filtered H signals gave vivid occurrences of Pi2 by the UTs and corresponding Pi2 frequencies. The UTs of the SML indices were plotted against the UTs of the scalogram and their correlation was 96% which shows that the times of Pi2 occurrence recorded by the coherence and scalogram are highly correlated. This new method of detecting Pi2s can be further explored for a better analysis of the magnetosphere-ionosphere relation.

# Compliance with Ethical Standards

**Conflicts of interest:** Authors declared that they have no conflict of interest.

**Human participants:** The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

# References

[1] B.J. Anderson, "Statistical studies of Pc 3-5 pulsations and their relevance for possible source mechanisms of ULF waves", Annales Geophysicae, Vol. 11, pp. 128-143, 1993.
[2] A. B. Collier, A.R.W. Hughes, L.G. Blomberg, and P.R. Sutcliffe, "Evidence of standing waves during a Pi2 pulsation event observed on Cluster", Annales Geophysicae, Vol. 24, no. 10, pp.2719– 2733, 2006.
[3] A. Du, W. Sun, W. Xu, and X. Gao, "The frequency variation of Pc5 ULF waves during a magnetic storm", Earth, Planets and Space, Vol. 57, no. 7, pp. 619–625, 2005.
[4] S. Fujita, and T. Tanaka, "Possible generation mechanisms of the Pi2 pulsations estimated from a global MHD simulation", Earth, Planets and Space, Vol. 65, no. 7, 2013.
[5] E. Ghamry, K.H. Kim, H.J. Kwon, D.H. Lee, J.S. Park, J. Choi, K. Hyun, W. S. Kurth, C. Kletzing, J.R. Wygant, and J. Huang, "Simultaneous Pi2 observations by the Van Allen Probes inside and outside the plasmasphere", Journal of Geophysical Research: Space Physics, Vol. 120, no. 6, pp. 4567–4575, 2015.
[6] E. Ghamry, D. Marchetti, A. Yoshikawa, T. Uozumi, A. De Santis, L. Perrone, X. Shen, A. Fathy, "The First Pi2 Pulsation Observed by China Seismo- Electromagnetic Satellite", Remote Sens., Vol. 12, No. 14, pp. 2300, 2020.
[7] M.B. Gokhberg, V.A. Pilipenko, O.A. Pokhotelov, and V.A. Troitskaya, "On the problems of the interaction between Pc 1/Pi 1 and Pc 4, 5 hydromagnetic waves", Journal of Geophysical Research, Vol. 86, no. A2, pp. 833, 1981.
[8] J. Gupta, and R.J. Stening, "Some Characteristics of Irregular Micropulsations Pi2 at High Latitude Stations", Can. J. Phys., Vol. 49, pp. 2338–2349, 1971.
[9] M.S. Gussenhoven, "Extremely high latitude auroras", J. Geophys. Res. Vol. 87, pp. 2401-2412, 1982.
[10] K.J. Kerns, and M.S. Gussenhoven, "Solar wind conditions for a quiet magnetosphere", Journal of Geophysical Research, Vol. 95: issn: 0148-0227, 1990.
[11] K.H. Kim, K. Takahashi, D. H. Lee, P.R. Sutcliffe, and K. Yumoto, "Pi2 pulsations associated with poleward boundary intensifications during the absence of substorms", J. Geophys. Res., Vol. 110, pp. A01217, 2005.
[12] H.J. Kwon, K.H. Kim, C.W. Jun, K. Takahashi, D.H. Lee, E. Lee, H. Jin, J. Seon, Y.D. Park, and J. Hwang, "Low-latitude Pi2 pulsations during intervals of quiet geomagnetic conditions (Kp≤1)", Journal of Geophysical Research: Space Physics, Vol. 118, no.10, pp.6145–6153, 2013.
[13] S. Lepidi, L. Cafarella, P. Francia, A. Meloni, P. Paolo, and J. Schott, "Low frequency geomagnetic field variations at Dome C (Antarctica)", Annales Geophysicae., Vol. 21. pp. 923-932.
[14] V. Olson, J. Pi2 pulsation and substorm onset. A review, J. Geophys. Res., vol. 104, pp. 17499–17520, 1999.
[15] G. Rostoker, "The polarization characteristics of Pi-2 micropulsations and their relation to the determination of possible source mechanisms for the production of nighttime impulsive micropulsation activity", Can. J. Phys., 45, 1319–1335, 1967a

[16] G. Rostoker, and J.V. Olson, "Pi2 Micropulsations as Indicators of Substorm Onsets and Intensifications", J. Geomag., Geoelectr., Vol. 30, no. 3, pp.135 -147, 1978.
[17] K. Shiokawa, W. Baumjohann, G. Haerendel, G. Paschmann, J. F. Fennell, E. Friis-Christensen, H.Luhr, G.D. Reeves, ¨ C.T. Russell, P.R. Sutcliffe, and K. Takahashi, "High-speed ion flow, substorm current wedge, and multiple Pi 2 pulsations", J. Geophys. Res., Vol. 103, pp.4491–4508, 1998.
[18] H. J. Singer, W. J. Hughes, P.F. Fougere, and D. J. Knecht, "The localization of Pi 2 pulsations: Ground-satellite observations", J. Geophys. Res., Vol. 88, pp. 7029–7036, 1983.
[19] D.J. Southwood, and W.F. Stuart, "Pulsations at the Substorm Onset", in Dynamics of the Magnetosphere, edited by: Akasofu, S.-I., 341–355, 1980.
[20] B. Stewart, "On the great magnetic disturbance which extended from August 28 to September 7, 1859, as recorded by photography at the Kew Observatory", Philos. Trans. R. Soc. London, 423, 1861.
[21] W.F. Stuart, and D.C. Booth, "A study of the power spectra of dPi's and Pi 2's", J. Atmos. Terr. Phys., Vol. 36, pp. 835–849, 1974.
[22] W.F. Stuart, and H.E. Barsczus, "Pi's observed in the daylight hemisphere at low latitudes", J. Atmos. Terr. Phys., Vol. 42, pp. 487–497, 1980.
[23] P. R. Sutcliffe, "The association of harmonics in Pi2 power spectra with the plasmapause", Planet. Space Sci., Vol. 23, pp. 1581–1587, 1975.
[24] P.R. Sutcliffe, and K. Yumoto, "Dayside Pi 2 pulsations at low latitudes", Geophys. Res. Lett., Vol. 16, pp. 887–890, 1989.
[25] P. R. Sutcliffe, and K. Yumoto, "On the cavity mode nature of low latitude Pi 2 pulsations", J. Geophys. Res., Vol. 96, pp.1543–1551, 1991.
[26] P.R. Sutcliffe, "Observations of Pi2 pulsations in a near ground state magnetosphere", Geophys. Res. Lett., 25, 4067, 1998.
[27] P.R. Sutcliffe, D.C. Ndiitwani, H.Lühr, and B. Heilig., "Studies of Geomagnetic Pulsations Using Magnetometer Data from the CHAMP Low-Earth-Orbit Satellite and Ground-Based Stations: a Review", Data Science Journal, Volume 10, 2011.
[28] N. Thomas, K. Shiokawa, and G. Vichare., "Comprehensive study of low-latitude Pi2 pulsations using observations from multi-satellite Swarm mission and global network of ground observatories", Journal of Geophysical Research: Space Physics, Vol. 124, Iss. 3, pp. 1966-1991, 2019.
[29] T.K. Yeoman, M. Lester, D.K. Milling, and D. Orr, "Polarization, propagation and MHD wave modes of Pi2 pulsations: SABRE/SAMNET results, Planet". Space Sci., vol. 39, pp. 983– 998, 1991.