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Propagation of irregular magnetic pulsation using cross wavelet and maximum time energy methods

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ABSTRACT

The propagation of Pi2 pulsation provides more invaluable information about the dynamics of the magnetosphere and the transmission of energy during magnetic substorms. Several authors used ground based magnetometers and in situ spacecraft data to map Pi2s propagation using different methods. Few methods have been used to calculate the time of propagation with some cautions. So, several authors compared results with different methods. The current paper compares the time of Pi2 propagation and direction calculated by Maximum Time Energy (MTE) method with the cross wavelet method (XWT). Results show that regardless the low correlation coefficient < 0.75 and the complicated waveform of the Pi2 pulsations or even a non-isolated event, the cross wavelet method has good results with the suggested Pi2 propagation mechanism from lower to higher latitudinal region than the Maximum Time Energy method.

1. Introduction

Pi2 pulsations are naturally occurring waves in the Earth's magnetic field. It has a periodic time within the period range [40–150 s] (Saito, 1969). Several authors connected its appearance on the Earth's surface due to tail reconnection (Keiling et al., 2006; Hsu and Mcpherron, 2007). Others discussed its appearance due to magnetosonic wave transformation into Alfven waves in the magnetosphere, thereby transported along the magnetic field lines into the Earth's ionosphere (Kepko and Kivelson, 1999; Kepko et al., 2001). Although Pi2 considers a good proxy of the substorm onset (Ghamry et al., 2011, 2012), it has been observed in the absence of substorms (Sutcliffe, 1998, 2010) in very quiet geomagnetic conditions, when Kp = 0, (Cheng et al. 2008 and Ghamry et al., 2015).

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There are three major sources of Pi2 pulsations. The first is Plasmaspheric cavity resonance (PCR), the second is plasmaspheric virtual resonance (PVR), and the third is plasmapause surface mode waves (Allan et al., 1986; Zhu and Kivelson, 1989; Lee, 1996; Lee and Lysak, 1999; Jun et al. 2013; Ghamry et al., 2015; Ghamry (2015)). Whatever the source mechanism of the Pi2 pulsation, there is a propagation path and a time of flight from the source energy region to ground. Determination of the propagation time of the Pi2 pulsation is very important in studying its characteristics (Sakurai and Saito, 1976; Saito et al., 1976). According to Uozumi et al. (2004) the issues related to timing the substorm onset is of great importance not only to study the cause and the effects and relationship between Pi2s and various substorm associated phenomena, but also the generation and propagation mechanisms of Pi2 itself. Uozumi et al. (2004) calculated the longitudinal and latitudinal time of propagation of the Pi2 using the maximum time energy method of the wavepacket $\Delta H^2 + \Delta D^2$, while Uozumi et al. (2009) calculate the delay through cross correlating the horizontal component between the two stations. Due to the inconsistency of the phase and the onset of the Pi2 pulsations between the two stations which considers a critical problem for the study of Pi2 timing, Uozumi et al. compared the time delay from the maximum time energy with that obtained at the maximum or minimum cross correlation and selected the one with smaller absolute difference with respect to the maximum time energy method. In addition to this

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problem, timing the Pi2 onset shows another difficulty as the higher latitudinal stations have ±1 min identification of the substorm onset-time of the magnetospheric substorm or intensification (Rostoker et al., 1980). Ghamry and Fathy (2016) released a new method to determine the Pi2 time delay using the cross wavelet technique. According to their statistical analysis of 48 events, the cross wavelet gave more reliable results than the ordinary cross correlation. The aim of the current paper is to compare the time of flight or the propagation time of the Pi2 pulsations between two stations separated in latitude using the cross wavelet and the maximum time energy method.

2. Data sets and event selection

The 48 Pi2 events reported by Ghamry and Fathy (2016) have been studied again in the current work. Data obtained from Carson City (CCNV), Mcgrath (MCGR), The Pas (TPAS) and Kuujjuarapik (KUUJ) stations which belong to the ground magnetometer network of the Time History of Events and Macroscale Interactions during Substorms (THEMIS). The geomagnetic coordinates of these stations are listed in Table 1 (Russell, 2008). The data from these stations have 0.5 s time resolution.

3. Analytical methods

3.1. Maximum Time Energy (MTE) method of the H component

Uozumi et al. (2009) suggested a method to calculate the time of propagation of the Pi2 pulsation using the H and D components between two ground stations. Event must have a high correlation coefficient >0.75. The time delay/propagation is defined as the time difference between the locations of $\frac{1}{e}A_{\max}$ of the Pi2 wave packet event at both stations as in Eq. (1).

$$\textit{Time difference} = (T_{\frac{1}{e}A_{\max}})_2 - (T_{\frac{1}{e}A_{\max}})_1 \quad (1)$$

where $A_{\max}$ is the maximum power amplitude of the Pi2 wave packet event, $e = 0.37$, $(T_{\frac{1}{e}A_{\max}})_1$ is represents the onset time of the Pi2 event at the first/lower-latitude station and $(T_{\frac{1}{e}A_{\max}})_2$ is the onset time of the event at the second/higher-latitude station. To make a smooth interpolation, first we filter the raw data in the Pi2 range. Second the filtered data are squared and normalize it by the maximum power amplitude within the event chosen duration time. Second, peaks and its location are being chosen. Third chosen peaks are interpolated into its equivalent length of the time series using the MATLAB Spline function. Then the location of the maximum amplitude and the location of $\frac{1}{e}A_{\max}$ are determined. Finally the time delay is calculated according to Eq. (3). If the time delay is negative, it means the higher latitudinal station detected the Pi 2 wave onset before the lower latitudinal station or in other meaning the Pi 2 propagates from high to low latitude and vice versa.

The interpolation process of the time series into its original length is to exactly calculate the time of propagation between the two stations and the direction. The interpolation process was done using the SPLINE MATLAB toolbox function http://www.mathworks.co.kr/kr/help/matlab/ref/spline.html.

3.2. Cross wavelet spectrum (XWT)

The wavelet transform of a time series is fully explained in Ghamry and Fathy (2016). The wavelet is a powerful analytical method for decomposing the time series because it contains wide types of filters which have different scales (frequency width) and shapes. The phase shift between the two time series is defined as in Eq. (2);

$$\Delta\phi = \tan\left(\frac{W^X}{W^Y}\right) \quad (2)$$

where W^X and W^Y are the wavelet coefficients of X and Y time series in complex form. The cross wavelet transform coefficients of two time series x_n and y_n is defined as $W^{XY}(s) = W^X(s)W^{Y*}(s)$ where W^{Y*} is the complex conjugate of the wavelet coefficients of the time series y_n. Because the cross wavelet spectrum in a complex form it can be defined as $|W^{XY}(s)|$. The cross wavelet coefficients reveal areas with high common power (Grinsted et al., 2004; Torrence and Compo, 1998). We used Grinsted et al. (2004) wavelet toolbox to calculate the mean phase and time delay between the two stations, and then we compared results with the MTE method. The time difference between any pair of stations is calculated as in Eq. (3):

$$\Delta t = \frac{T\Delta\phi}{2\pi} \quad (3)$$

where T is the common Pi 2 period around which the calculation is being performed. The XWT criterion in the current study is similar to that set by Ghamry and Fathy (2016). First, visually we inspect the Pi 2 event at both stations, second the raw data filtered in the Pi 2 range [40–150 s]. Third the XWT applied to the signal over the Pi2 event. Finally the average time delay is calculated within the seven frequencies of the maximum common power according to Eq. (3).

4. Qualitative discussion

For good results using the MTE method, the Pi2 must be an isolated event to accurately determine the time delay of the Pi2 wave between pair of stations. Also the event must have a high correlation coefficient >0.75. These restrictions make the study and the selection of the event is very hard. A typical example is shown in Fig. 2. Pi2 event observed on 2009-03-31 has a high correlation coefficient = 0.85 and the MTE shows that the lower latitudinal station leading the higher latitudinal station as indicated by the location of the maximum peak at the bigger solid circle position, while the smaller solid circle sign refers to the location of 1/e of the maximum peak.

Both the XC and the MTE showed that the lower latitudinal station leading the higher latitudinal station by 15 and 32 s respectively. However the time of propagation is different but the trend is in agreement with the Pi2 propagation mechanism (Fig. 1).

Pi2 has irregular waveform which means it has no usual gradual increased amplitude, but sometimes it has a sudden jump. This behavior is shown in Fig. 2 for the Pi2 event observed on

Table 1
The geographic and geomagnetic location of the stations (Russell et al., 2008).

Station	Code	Geo Lat	Geo Long	Mag. Lat	Mag. Long	L	Midnight (hh:mm)
Kuujuaq	KUUJ	55.3	282.2	65.2	352.0	5.66	04:14
The Pas	TPAS	54.8	258.1	63.0	320.3	5.18	07:04
Mcgrath	MCGR	63.0	204.4	62.2	256.6	4.47	11:30
Carson City	CCNV	39.1	240.2	45.3	304.8	2.00	08:26

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