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

A. Fathy [a,*], E. Ghamry [b], S. Mahrous [a]

[a] Physics Department, Faculty of Science, Fayoum University, Egypt
[b] National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt

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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).

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

* Corresponding author.
E-mail addresses: afa05@fayoum.edu.eg (A. Fathy), essamgh@nriag.sci.eg (E. Ghamry), sms05@fayoum.edu.eg (S. Mahrous).

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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).

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

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);

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

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):

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

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)
Kuujjuaq	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

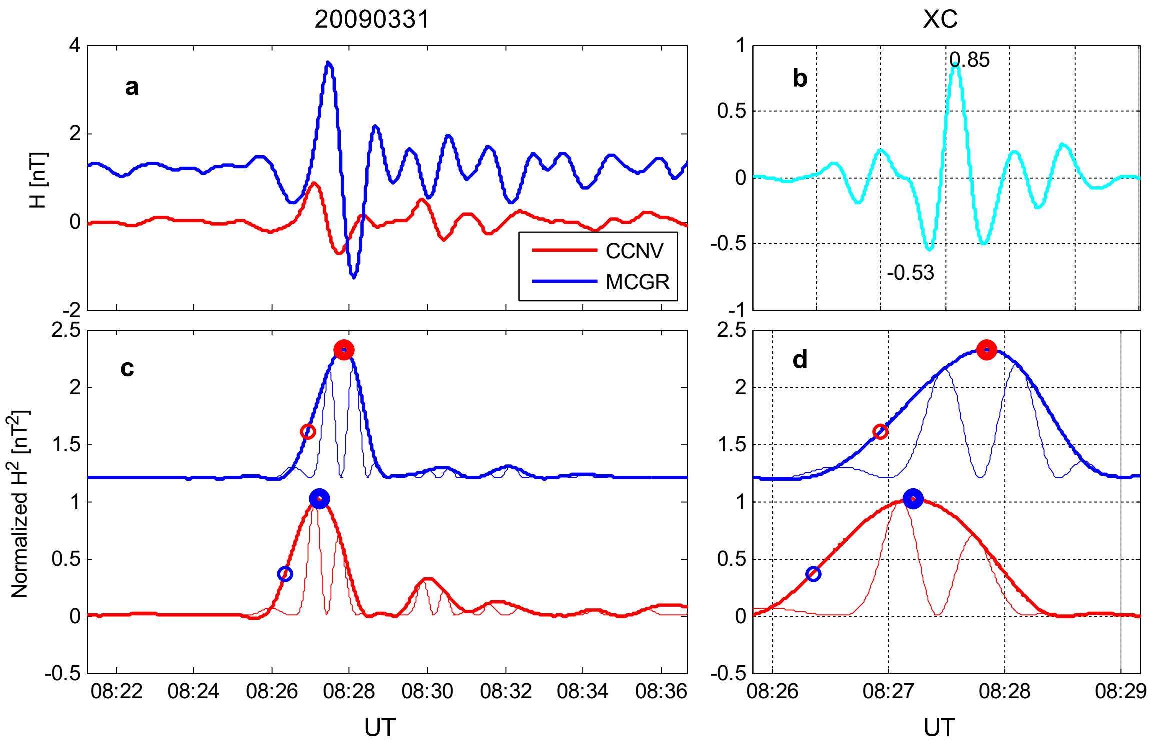

Fig. 1. (a) A typical example of an isolated Pi 2 event observed on 31032009, (b) the cross correlation between the Pi 2 events, (c) the MTE method, and (d) zooming in of Fig. 1c.

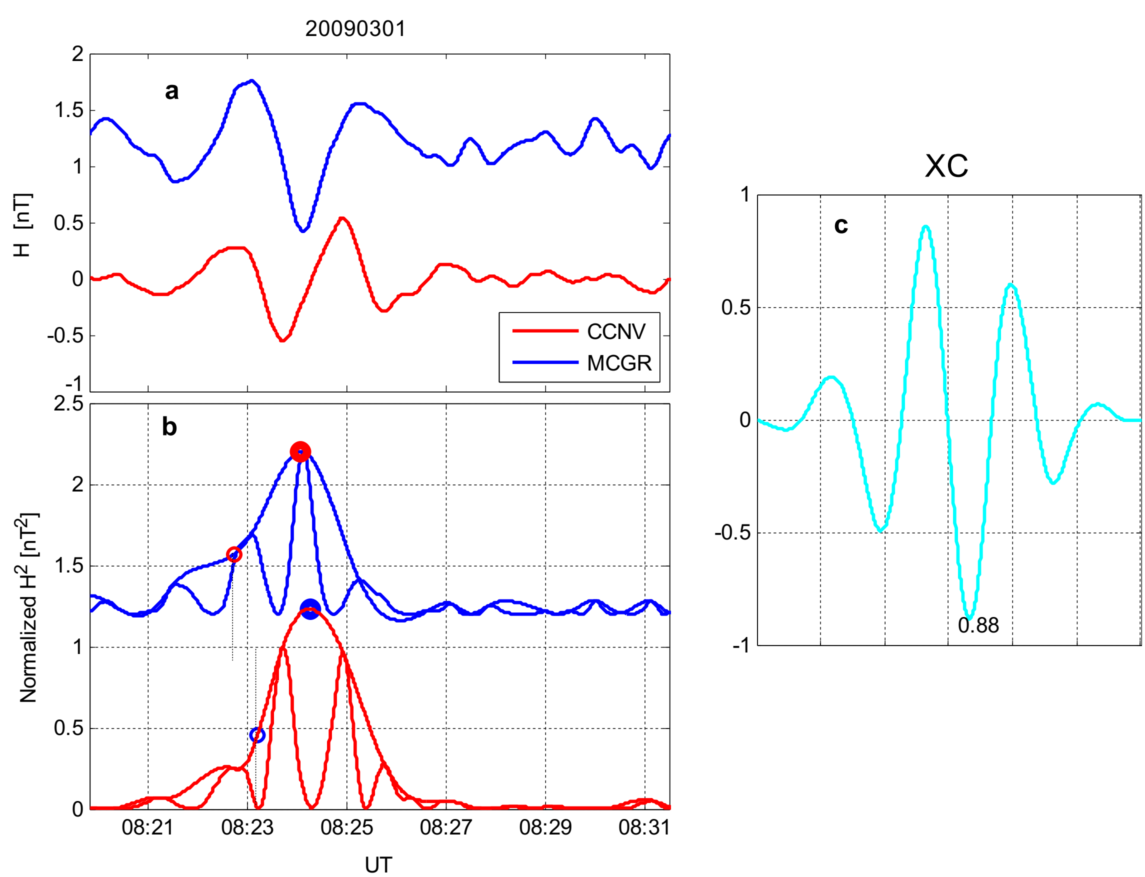

Fig. 2. Illustrates an isolated Pi 2 event has a high cross correlation coefficient (0.88) with a non-symmetric waveform at low and high latitude station. (a) A band pass filtered H component at low and high latitude stations, (b) the MTE H component of both stations and (c) the cross correlation between the two stations.

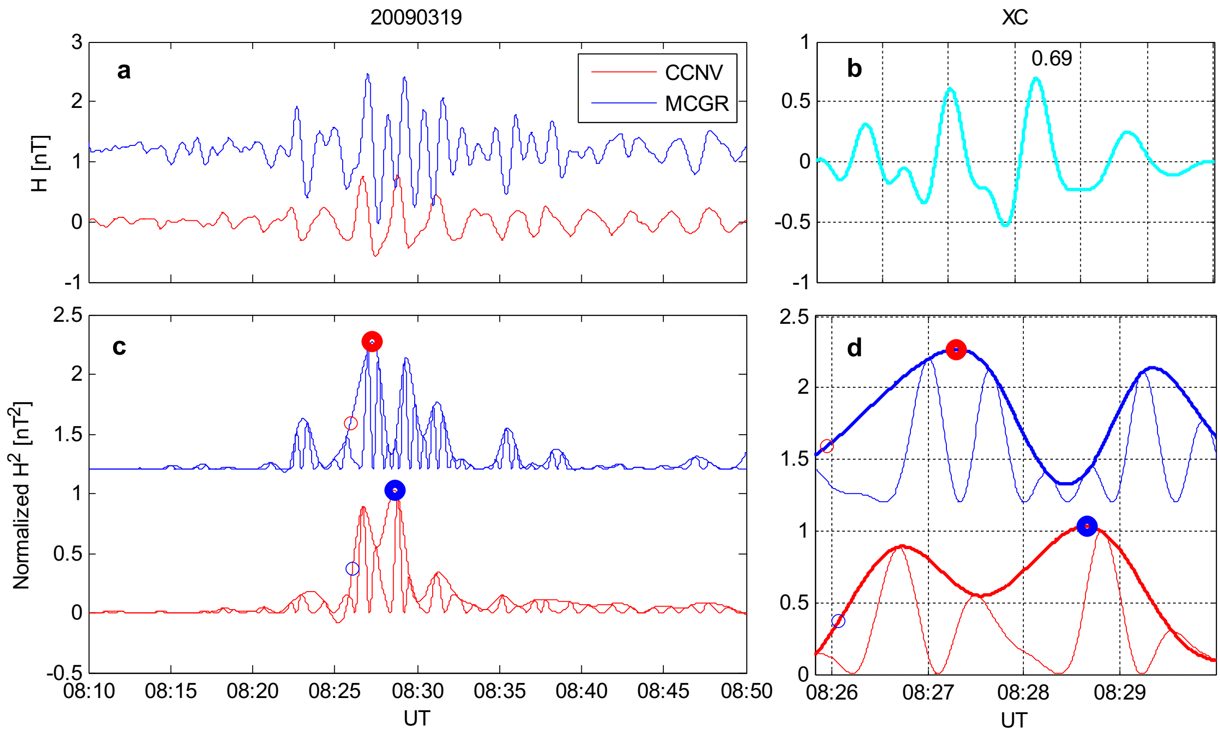

Fig. 3. Illustrates a complicated Pi 2 waveform with consecutive events of time duration ∼20 min in panels 3a and 3c at high latitude station. (b) illustrates the cross correlation coefficient equals 0.69 and (d) is zooming in of (c).

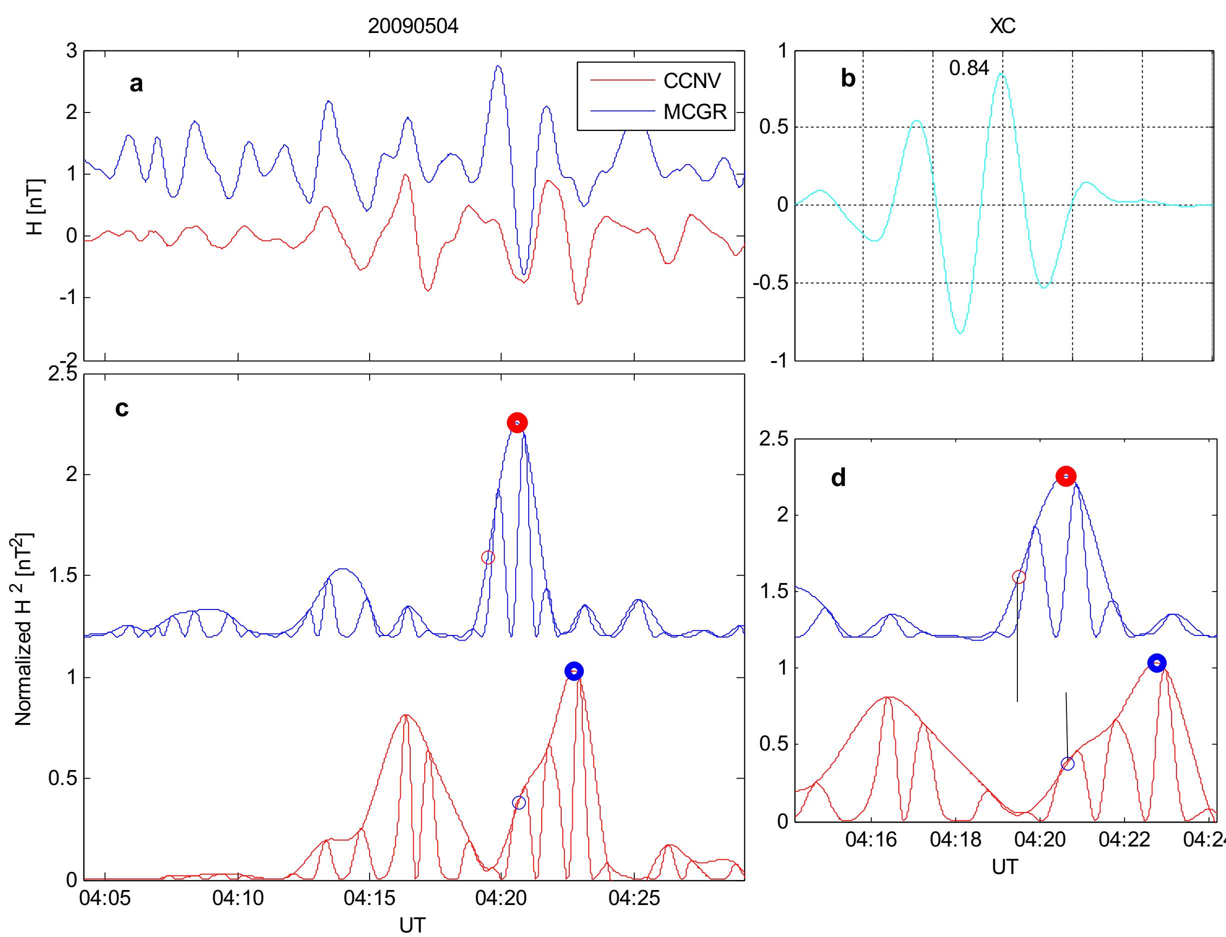

Fig. 4. Illustrates a non-clear Pi 2 onset event at high latitude station (MCGR) observed on 04052009 in panel 4a. (b) illustrates the cross correlation. (c) illustrates the maximum time energy method. (d) Zooming in of (c).

2009-03-01. The Pi2 event at the higher latitudinal station has a gradual increase in its amplitude while the Pi 2 at lower latitude has a sudden jump. We can't exactly determine the onset because the interpolation process makes the maximum peaks positions different. However the event is an isolated and has a high correlation coefficient ~0.88, the XC showed that the lower latitudinal station leads the higher latitudinal station by 32 s, while the MTE showed that the lower latitudinal station delayed from the higher latitudinal station by 28 s (Fig. 2).

Always we have been talking about the very isolated Pi2 single event with a high correlation coefficient > 0.75 between both stations. How about consecutive/train Pi2 events. A typical example of consecutive Pi2 events observed on 2009-03-19 is shown in Fig. 3. The time duration of these consecutive events is ~20 min. The higher latitudinal station showed larger amplitude of the first event in reverse to the lower latitudinal station which begins showing a Pi2 signature of the second event with relatively larger amplitude, while there is no indication of Pi2 observation of the first event. The location of both maxima or 1/e of the maxima showed that the higher latitudinal station leading the lower latitudinal station. The calculation of the propagation time and direction using the XC is 32 s and showed that the lower latitudinal station leading the higher latitudinal station. As we mentioned earlier the Pi2 event has irregular waveform, so that the position of the maximum is different. So the MTE method gives a 7 s time of propagation from higher to lower latitudinal station Fig. 3.

Fig. 4a presents another problem regarding the determination of the Pi2 propagation time using the MTE method for a Pi2 event observed on May 4, 2009. However, fluctuations started earlier with smaller variations at the higher latitudinal station. The MTE method showed that the higher latitudinal station leading the lower latitudinal station by 20 s. The XC showed that the event has a very large XC coefficient ~0.84. The propagation time corresponding to the XC method showed that the higher latitudinal station leading the lower latitudinal station by 3 s. These results are in contrast with the features of the Pi2 propagation from lower to higher latitudinal station. Even if, we choose the minimum XC coefficient, the higher latitudinal station still leading the lower latitudinal station as shown in Fig. 4b.

Regardless the long time duration of the event, the XWT shows that the Pi2 event within the time duration [08:20–08:30] has maximum amplitude with a common period of 130 s. The XWT also showed that the Pi2 at the lower latitudinal station leads the same Pi2 event at higher latitudinal station by 15 s in contrast to the MTE showed that the Pi2 was observed earlier at the higher latitudinal station as discussed in Fig. 3. Arrows in the downward direction indicate the lower latitudinal station leading the higher one Fig. 5.

5. A statistical study

For getting more realistic suggestion of the most probable method to calculate the Pi2 propagation time and direction, a quantitative analysis of 48 Pi 2 events has been done. A list of these events is in Table 2. It illustrates the event number, date, start time, end time, time delay calculated by MTE method, time delay calculated by XC method, time delay calculated by XWT method and the higher latitudinal station used with CCNV station.

We made comparisons between these methods in a statistical way in the perspectives of previous study of Ghamry and Fathy (2016). Fig. 6 illustrates the relationship between the time of propagation on the x-axis and the Pi2 period on the y-axis for the MTE,

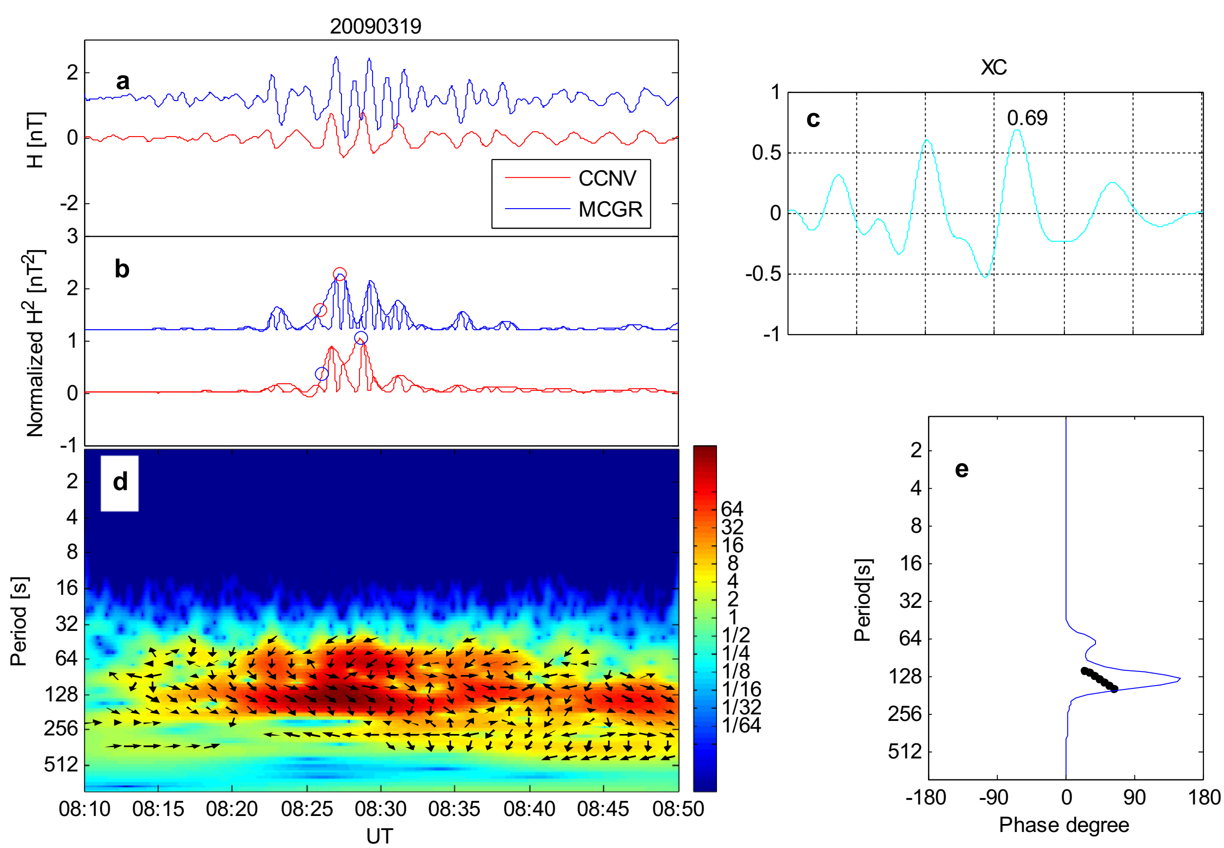

Fig. 5. A typical example of XWT versus XC and MTE. (a) A Pi 2 example observed on 19032009, (b) the MTE method, (c) the XC of the Pi 2 events between the two stations, (d) the XWT and the color bar indicates region of high common power and (e) the cross phase in degree.

Table 2
List of forty-eight Pi2 pulsations used in this study. Event number, date, start time, end time, time delay calculated by MTE method, time delay calculated by XC method, time delay calculated by XWT method and the higher latitudinal station used with CCNV station.

No	Date yyyymmdd	Time (hh:mm) Start-end	Time delay MTE	Time delay XWT	Pi2 period high latitude	Pi2 period low latitude	High latitude station
1	20080313	07:20–07:45	33.5	−11.4	104.95	104.95	mcgr
2	20080317	09:00–09:30	−11.5	23.9	140	148	mcgr
3	20080317	10:20–10:40	6	19.9	140	117	mcgr
4	20090210	09:20–10:00	−848	29.9	222	210	mcgr
5	20090217	07:15–07:35	10.5	31.6	157	157	mcgr
6	20090301	08:00–08:20	8.5	30.5	187	187	mcgr
7	20090301	08:19–08:35	−28	30.6	198	157	mcgr
8	20090315	08:15–08:30	−19.5	32.7	124	90	mcgr
9	20090315	08:40–09:00	−34	26.1	117	104	mcgr
10	20090317	05:45–06:00	−2.5	20.3	124	117	mcgr
11	20090319	08:15–08:45	−7	15.8	132	140	mcgr
12	20090323	06:03–06:30	44.5	46.4	166	176	mcgr
13	20090331	07:50–08:20	32	15.9	148	157	mcgr
14	20090331	08:20–09:00	35	26.6	187	187	mcgr
15	20090404	07:50–08:20	−436	43.2	222	222	mcgr
16	20090404	05:50–06:20	377.5	38.7	209	198	mcgr
17	20090405	07:40–07:55	12.5	40.4	187	157	mcgr
18	20090407	11:50–12:10	140.5	−5.5	176.5	176.6	mcgr
19	20090408	06:10–06:30	−30	21.5	176	187	mcgr
20	20090410	07:35–07:48	−191	33.9	132	132	mcgr
21	20090410	07:50–08:05	67.5	17.9	93	99	mcgr
22	20090413	04:55–05:10	26.5	44.3	124	124	mcgr
23	20090413	07:45–07:58	47	36.7	157	111.2	kuuj
24	20090413	07:55–08:10	25.5	40.1	198	99	kuuj
25	20090414	09:05–09:20	2	20.9	166.6	124	mcgr
26	20090414	09:20–09:40	−89	20.5	176	132	mcgr
27	20090419	06:45–07:00	−26.5	12.7	111	111	mcgr
28	20090419	06:00–06:15	51	24.2	124	124	mcgr
29	20090420	05:25–05:45	−3.5	54.8	235	132	kuuj
30	20090422	06:25–06:37	47.5	9.4	198	124	kuuj
31	20090422	07:30–07:45	1	24.3	209	140	mcgr
32	20090424	06:16–06:35	−71.5	27.1	117.8	117.8	mcgr
33	20090428	07:45–08:10	−5	10.1	166.5	166.5	kuuj
34	20090428	08:40–09:10	17.5	27.3	166	166	kuuj
35	20090430	08:20–08:45	58	50.8	222	198	mcgr
36	20090504	04:00–04:30	−70.5	23.1	166.5	176	mcgr
37	20090504	08:00–08:22	61	43.9	140	148	mcgr
38	20090504	08:20–08:37	105.5	43.8	157	157	mcgr
39	20090504	08:50–09:15	9	30.3	166.5	166.5	mcgr
40	20090505	04:48–05:12	−5	5.7	148	187	mcgr
41	20090514	06:44–07:05	46.5	17.9	166	157	mcgr
42	20090514	07:25–07:45	6	10.2	198	176	mcgr
43	20090522	01:43–02:10	296	4	264	198	kuuj
44	20090523	06:40–07:00	−204.5	13.2	111	93	mcgr
45	20090523	07:05–07:25	23.5	20.3	235	105	mcgr
46	20090525	08:30–09:00	166	23.3	187	176	mcgr
47	20090526	07:30–08:00	80.5	11.9	210	132	mcgr
48	20090531	09:15–09:45	−15.5	11.5	166.6	176.5	mcgr

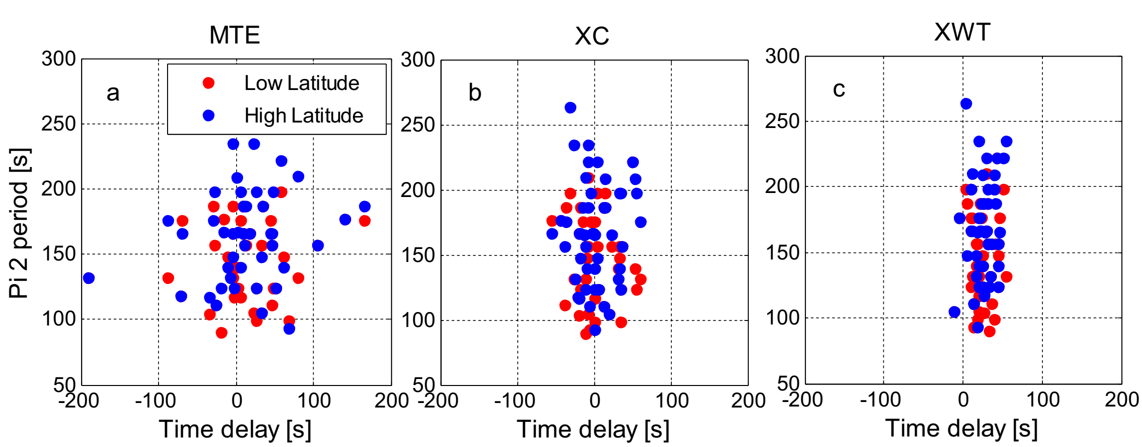

Fig. 6. A statistical analysis of the Pi 2 propagation time between the low and the high latitudinal station versus the Pi 2 periodic time. (a) The maximum time energy method, (b) the cross correlation method and (c) the cross wavelet method. Number of points is twice the number of events because the Pi 2 periodic time is different at both stations. Blue and red dots corresponding to high and low latitude stations.

XC and the XWT as shown in panels a, b and c, respectively. It is worth noting that the number points are twice the number of events because the Pi2 period is different at both stations for the same event. As a convention for the reader the positive time delay means the lower latitudinal station leading the higher latitudinal one and vice versa.

As shown in the three panels the XWT gave more probable results with the Pi 2 propagation mechanism from low to high latitudinal station, only two events showed that the higher latitudinal stations leading the lower latitudinal station.

The MTE and the XC showed that so many of the Pi2 events ~50% observed first at higher latitudinal station. This trend is in contrast with the mechanism of the Pi2 pulsations propagation. Generally speaking from this study the XWT do not affected by the duration time of the event or the waveform of the Pi2 event, because it is only calculates the time delay at the dominant frequency of the common period.

6. Conclusion

The current study presents a comparison between the maximum time energy, cross correlation and the cross wavelet methods to calculate the Pi2 propagation time and direction. Qualitative examples we presented showed that the MTE and XC problems that may face researchers in the calculations of the propagation time and direction of the Pi2 waves. The most common problems are; choosing a single or an isolated Pi2 event, a complicated Pi2 waveform and the Pi2 appearance in a train of Pi2 events. These three problems give serious wrong results to the conventional Pi2 propagation direction between two stations from lower to higher latitudinal station. The frequency domain of the XWT overcomes it through decomposing the signal into its equivalent frequency and its own phase at each time instant.

The XWT statistical results showed that the Pi2 observed first at the lower latitudinal station first, while the XC and the MTE showed that ~50% of the 48 events observed first at the higher latitudinal which is in contrast to the conventional propagation mechanism of the Pi2 pulsation. XWT gave more reliable results than XC and the MTE.

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